A guide to managing and restoring wetlands in Western Australia

Introduction to the guide

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Acknowledgments

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When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Introduction to the guide', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by J Lawn, Department of Environment and Conservation, Perth, Western Australia.

Contents

PART 1: THIS GUIDE

Why was this guide produced?

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of Western Australia.

A guide to managing and restoring wetlands in Western Australia (the guide) provides information about the nature of Western Australia's wetlands, and practical guidance on how to manage and restore them for nature conservation.

Through the guide and other initiatives, the Western Australian Department of Environment and Conservation (DEC) seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation. It is a free online resource produced by the DEC.

What are the contents of this guide?

The guide consists of multiple topics within five chapters.

Who is this guide for?

This guide is intended to be of assistance to anyone who is, or who is intending to, manage or restore a wetland in WA. This includes landowners, land managers, and natural resource managers, individuals, community members and employees of the public and private sector. As much as possible, the information is written to be accessible to this broad target audience.

This guide is not designed specifically for students or environmental consultants. The guide does not prescribe the actions that should be taken in managing and restoring wetlands and therefore is not suitable to be required to be followed as a condition of approval of any form.

Pink Lake, Lorna Glen Station, north of Wiluna in WA's Murchison/Gascoyne region.
Photo – © J Dunlop.

Distribution details

This guide has been produced in PDF format. Each individual topic is available online free of charge as a PDF that can be downloaded. Please see the DEC website at www.dec.wa.gov.au/wetlandsguide.

Each topic has a 'version' stamp on the front page. DEC recognises that there will be the need to correct, update and improve the information in this guide over time, with Version 1 reflecting the information and resources available to publish this document in 2012.

Updates to the guide (such as new versions) will also be posted on the webpage. You can be notified of updates to the webpage via RSS (real simple syndication); see the webpage for more information.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the webpage www.dec.wa.gov.au/wetlandsguide.

How was this guide produced?

The demand for this guide was formally recognised during the development of the *Wetlands Conservation Policy for Western Australia* in the 1990s. The (then) Water and Rivers Commission initiated this project in liaison with the (then) Department of Conservation and Land Management in the 2000s with the ongoing support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

The Department of Environment and Conservation has continued this work. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors.

The information presented in this guide is the product of the research and endeavours of many individuals in Western Australia and other areas of the globe. The authors have sought to interpret and collate this into a guide that is relevant to Western Australia's wetlands, to promote their sound management and restoration.

The guide, where possible, contains information relevant to all of the state. While the first version of this guide is Perth and south-west centric, the authors have endeavoured to be inclusive of wetlands of the Kimberley, Pilbara, deserts, Goldfields, and South Coast. It is hoped that future versions of the guide will better address statewide issues over time. We appreciate feedback via the form available from www.dec.wa.gov.au/wetlandsguide.

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Acknowledgments

The following people prepared topics of the guide (in alphabetical order):

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Greg Keighery	Christina Mykytiuk	

This guide is the result of the effort and contribution of many people, including those acknowledged below. The information presented in this guide is an attempt to capture the essence of the collective years of research and on-ground work carried out by many people in this state, in Australia and in wetlands in other parts of the globe. The importance of the work carried out by all the people involved in wetland conservation in WA and beyond, and their willingness to contribute and share their knowledge and experience for the preparation of this guide, is gratefully acknowledged.

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The authors have drawn inspiration from the volunteers and land owners who care tirelessly for WA's wetlands; wetland researchers, including those in DEC and Australia's universities; and other professionals with a love of wetlands, including but not limited to the late Shirley Balla, the late Luke Pen, and Professor Phil Jennings.

What wetland information is not covered in this guide?

Scientific methodologies and administrative policies of the state government are not covered in this guide. For example:

- wetland mapping, delineation, classification and evaluation methodologies
- wetland buffer identification methodology
- wetland impact assessment methodology

For more information on these, please see the DEC wetlands webpage: www.dec.wa.gov.au/wetlands.

What wetland types are covered in this guide?

The focus of the guide is natural 'standing', or non-flowing, wetlands that retain conservation value. DEC is the Western Australian government agency with the lead role in the protection and management of these wetlands. Examples of wetlands covered by this guide are shown on the following page.

Seasonally inundated wetlands, such as Lake Eda, near Broome.

Seasonally inundated wetlands, such as salt lakes near Jurien.

Seasonally waterlogged wetlands, such as Hay Park in Bunbury

Intermittently inundated wetlands, such as this one in the Great Western Woodlands

Permanently inundated wetlands, such as Lake Preston near Mandurah.

Permanently waterlogged wetlands, such as Saunders Spring, Mandora Marsh

Seasonally waterlogged slopes, such as this paluslope in the south-west corner of WA

Seasonally waterlogged highlands, such as this palusmont in the south-west corner of WA

What wetland types are not covered in this guide?

The guide does not cover the management and restoration of flowing waters, such as waterways, their floodplains, estuaries and peripheral estuarine wetlands. The management of these wetlands is very important but they often require different management strategies to non-flowing wetlands.

These wetland types are the responsibility of the Department of Water unless these areas are, or are proposed to be, DEC managed estate.

Accordingly this guide does not cover:

- near-shore marine areas – for example, beaches and mangroves
- those wetlands that flow in channels – that is rivers, creeks, wadis and troughs – collectively referred to as 'waterways'
- estuaries or peripheral estuarine wetlands that are influenced by tidal flows
- artificial wetlands.

For more information on the management of waterways, refer to the Department of Water's River Restoration Manual (Water and Rivers Commission 2000) available at www.water.wa.gov.au/Managing+water/Rivers+and+estuaries/Restoring/River+restoration+manual/default.aspx

The focus of this guide is natural wetlands that retain conservation value. Artificial wetlands, including dams, can support wildlife. Readers with an interest in the management of artificial wetlands may find information in the guide to be of use. Other sources of information include:

- *Planting wetlands and dams: a practical guide to wetland design, construction and propagation* (Romanowski 1998).

Examples of wetlands not covered by this guide are shown below.

Near-shore marine areas, such as Roebuck Bay

Waterways – all channel wetlands, including rivers, creeks, wadis, troughs – and their floodplains, such as the Ord River and floodplain

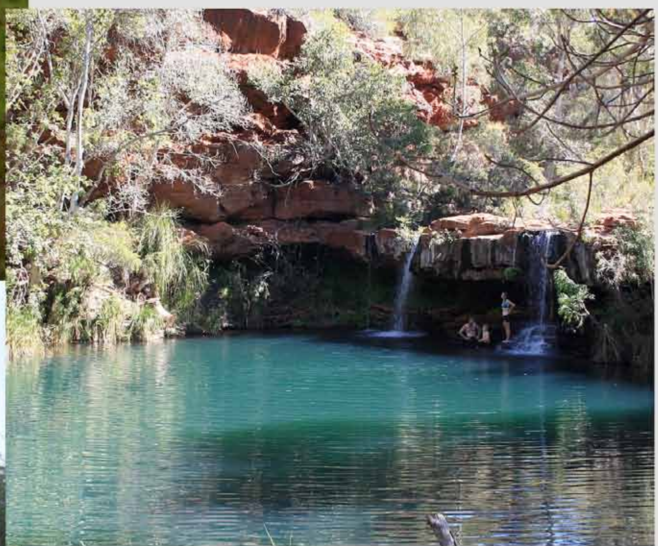
Estuaries and peripheral estuarine areas, such as the Hill River Estuary in the Midwest

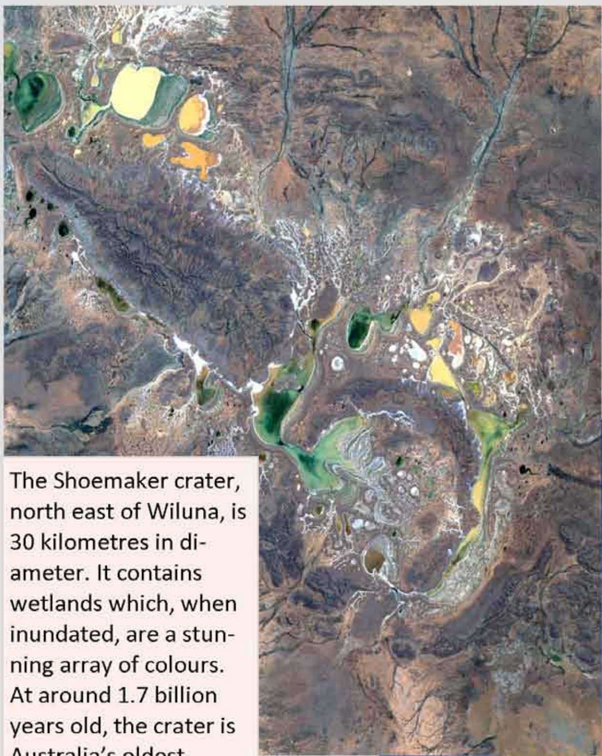
Artificial wetlands, such as this lake in the southern suburbs of Perth.

What principles underpin this guide?

The principles applied during the preparation of this guide include:

- The objective of this guide is to promote the conservation of natural values of WA's wetlands.
- Wetlands are assets to our society and their conservation is a priority. Raising awareness about the significant values of our wetlands is critical to wetland conservation.
- A high proportion of wetlands in WA are located on private land. Additionally many wetlands are located on publicly owned land for which the designated land manager is not a wetland specialist. Initiatives such as this guide are an important way of disseminating guidance to this broad spectrum of wetland managers.
- Although everyone values wetlands differently, they affect the lives of all Western Australians. Wetlands help shape neighbourhoods, towns, cities, farms, stations, properties and parks around the state and play an important role in our sense of place and cultural identity.
- We can't protect, manage and restore all wetlands. WA's wetlands may have competing land use pressures. They yield water, productive land, minerals, peat and other products that help maintain our lifestyles. We also cannot afford to manage and restore all of the remaining wetlands as our financial and human capital is limited and there are many competing demands on these. The conservation of natural biodiversity and geoheritage values should be a priority, and wetlands of high conservation significance should be prioritised over wetlands that are heavily degraded.
- On an on-going basis, decision-making authorities are making decisions about whether activities that will impact wetlands are acceptable; and what investment we will make in protecting, managing and restoring wetlands. The engagement of Western Australians in decisions about wetland conservation is important, as these decisions should reflect the informed position of our society broadly.
- The best nature conservation outcome is to maintain natural wetland processes and values. Since European settlement, there has been ongoing alteration of WA's wetlands to enhance certain features. These features are most commonly habitat for waterbirds, water storing capacity and duration of inundation. Islands, dredging, draining into and clearing have all been carried out to 'enhance' wetlands. Manipulating wetlands 'for wildlife' tends to result in degradation to the wetland or to the broader landscape, as outlined in many of the topics of the guide.
- Our community should be aware of the true cost of managing wetlands. Substantial financial and human capital is often required to protect and manage wetlands.
- Our community should be aware of the true cost of poorly-managed wetlands. Poorly managed wetlands can be a significant liability. Prioritising our investments also needs to be based on the cost of not managing wetlands and altering natural wetlands. These include, but are not limited to, the cost of acidified groundwater aquifers and infrastructure, the loss of water storage, the cost of mosquitoes and midges at nuisance population levels as well as the diseases that mosquitoes are vectors of, the cost of algal blooms, livestock poor health and deaths, and toxic air quality due to peat fires.
- Maintenance of existing wetland values is more cost effective than re-creation of those wetland values.



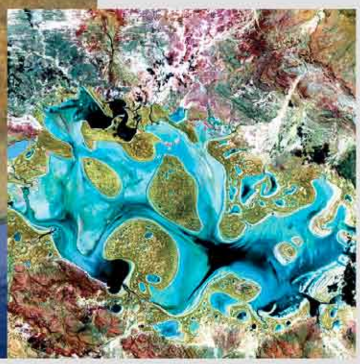


The Shoemaker crater, north east of Wiluna, is 30 kilometres in diameter. It contains wetlands which, when inundated, are a stunning array of colours. At around 1.7 billion years old, the crater is Australia's oldest known impact structure.

Lake Argyle is Australia's largest artificial lake and reservoir by volume, with a storage capacity of 10,760 million cubic metres. It is up to 2000 square kilometres when in flood. At up to 50 metres deep, it is the deepest wetland in WA, but is insignificant compared to Lake St Clair in Tasmania, which reaches depths of 174 metres.

Lake Mackay is one of the largest wetlands in Western Australia. Located in the Gibson Desert, it extends east into the Northern Territory.

Carnegie Lake is one of 75 places on Earth chosen by NASA to be on display in its book of striking satellite images, *Earth as Art* (2012). Lake Disappointment and Shoemaker Crater in WA were also chosen.



Although it is some distance from the ocean, Lake Macleod receives ocean water by subterranean vents, making the water chemistry of the lake unique.

Lake Hillier is one of Western Australia's wetlands that are located on islands. It is a striking wetland, coloured a deep pink due to the presence of algae. It is located on Middle Island on the Recherche Archipelago.

Even the Nullarbor supports wetlands. Tiny limestone rockholes, such as these, are one type of Nullarbor wetland. The much larger 'donga' wetlands also form on limestone in the region.

Bats are one of the more elusive wetland fauna. They are common in wetlands of the Pilbara and Kimberley.

The Kimberley is home to the greatest diversity of frogs in WA, and is considered to be a centre of frog endemism in Australia. It boasts over forty species, out of a total of 216 in Australia.

The rakali is a rarely seen mammal and top-order predator inhabiting permanently inundated wetlands in good condition along the WA coastline.

Birds breed in large numbers when intermittently inundated wetlands in the interior flood.

Incredible living rocks are formed by microbial communities of bacteria and algae. These types of communities are the earliest life forms, known to have existed 3.5 million years ago—outliving dinosaurs. They are now uncommon world-wide but WA has many of the remaining populations.

The prehistoric-looking shield shrimp found in claypans have not changed physically in almost 300 million years.

Most of the fish and crayfish of the south west are endemic to the region. The south west is home to remarkable burrowing species fish and crayfish.

Perth is home to the most endangered tortoise in the world.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PART 2: MANAGING AND RESTORING WETLANDS IN WESTERN AUSTRALIA

What are the safety considerations when managing and restoring wetlands?

All natural areas have a range of natural hazards; the following are those most relevant to WA's wetlands which should be taken into account when visiting or working in wetlands:

- animals: ticks, crocodiles, snakes and wild pigs in particular
- cyanobacteria: avoid all contact with water containing toxic cyanobacteria
- use of chemicals: pesticides should only be handled by people with training
- animal control: firearms, traps, electroshocking all pose risks
- machinery: chainsaws, boats etcetera all pose risks
- electricity: electricity poses a particular risk in proximity to water
- fire: in all wetlands, but particularly peat wetlands, where volatile organic compounds and particulates can be inhaled, and where burning of sediments underground can continue long after the above-ground fire has passed
- drowning
- getting bogged
- dehydration
- water: avoid contacting or ingesting polluted water or water with low pH, or high levels of heavy metals or bacteria

What are the legal considerations when managing and restoring wetlands?

Before embarking on management and restoration investigations and activities, it is critical to ensure that any proposed actions are legal and safe. Key considerations are outlined below.

Authority to enter land and carry out actions

Where you are not the landowner, you must have approval (preferably written) from the landowner or vested land manager prior to entering onto the land containing the wetland and carrying out activities on the land.

Your local government (that is, shire, town or city council) can provide you with the ownership and vesting details of public lands. For information about privately owned land, see Landgate www.landgate.wa.gov.au.

Environmental harm

You must ensure that the actions you take do not cause environmental harm or break other laws. Actions with the potential to cause environmental harm include:

- Earthworks
  This includes digging wetlands deeper and creating islands in wetlands
- Changes to the wetland's water
  This includes draining into, or out of wetlands; altering structures for the conveyance of water, including pipes, weirs and floodgates
- Addition of chemicals
  This includes liming agents, salts, chlorines, and pesticides which may harm wetland values, or when done in a manner that is not consistent with their approved use and application rates
- Clearing of native vegetation
  This includes burning of vegetation
- Introduction of non-native plants and animals

The relevant topics of this guide provide guidance and further resources to aid you in determining whether your actions may cause environmental harm and what permits or other authorisations you may need to carry out an activity. If you are ever in doubt, seek guidance before initiating an activity. Good intentions can't mitigate the impacts of environmental harm!

Regulations that apply to the clearing of planted native vegetation

When planning to plant native vegetation in wetlands, it is important to be aware of the legal ramifications of doing so.

Under section 51A of the *Environmental Protection Act 1986*, "native vegetation" does not include vegetation that is intentionally sown, planted or propagated unless:

- the vegetation was sown, planted or propagated as required under the *Environmental Protection Act 1986* or another written law; or
- it is declared to be native vegetation under the Environmental Protection (Clearing of Native Vegetation) Regulations 2004.

Vegetation that is required to be sown, planted or propagated under a written law will often be as a result of conditions of an authorisation or lease.

Regulation 4 prescribes the kinds of intentionally planted indigenous vegetation that are "native vegetation" and which therefore require a clearing permit or exemption to clear and includes:

(a) Planting that was funded (wholly or partly):

(i) by a person who was not the owner of the land; and

(ii) for the purpose of biodiversity conservation or land conservation.

OR

(b) Intentionally planted vegetation that has one of the following:

(i) a conservation covenant or agreement to reserve under section 30B of the *Soil and Land Conservation Act 1945*;

(ii) a covenant to conserve under section 21A of the *National Trust of Australia (WA)*

Act 1964;

(iii) a restrictive covenant to conserve under section 129B of the *Transfer of Land Act 1983*;

(iv) some other form of binding undertaking to establish and maintain, or maintain, the vegetation.

For the purposes of Regulation 4, biodiversity conservation includes conservation of species diversity, genetic diversity or ecosystem diversity and land conservation includes management of salinity, erosion, soil acidity or waterlogging. Planting includes to sow and to propagate.

Authorisations for activities

Table 1 outlines the authorisations you may require prior to carrying out wetland management and restoration activities.

Table 1. Activities that may require authorisation – a summary

Activity	Authorisation	Legislation	Topic of this guide with more information
Native fauna surveys (including macroinvertebrates)	Licence Permit (freshwater species including fish and crayfish)	*Wildlife Conservation Act 1950* *Fish Resources Management Act 1994*; Fish Resources Management Regulations 1995	Introduced and nuisance animals
Use of traps for land-based non-native species	Permit; plus individual local government authorities may also have requirements	*Agriculture and Related Resources Protection Act 1976* Agriculture and Related Resources Protection (Traps) Regulations 1982	Introduced and nuisance animals
Removal of introduced freshwater species of fish and crustaceans from wetlands	An exemption, approval, authority or licence	*Fish Resources Management Act 1994*; Fish Resources Management Regulations 1995	Introduced and nuisance animals
Relocation, introduction or reintroduction of freshwater species of fish and crayfish	An exemption, written authority or licence	*Fish Resources Management Act 1994* Fish Resources Management Regulations 1995 *Wildlife Conservation Act 1950*	Introduced and nuisance animals
Use of bird traps	Licence	*Wildlife Conservation Act 1950* Wildlife Conservation Regulations 1970	Introduced and nuisance animals
Use of firearm	Licence	*Firearms Act 1973*	Introduced and nuisance animals
Culling of native species for conservation purposes (e.g. kangaroos, Australian white ibis).	A licence may be required	*Wildlife Conservation Act 1950* Wildlife Conservation Regulations 1970	Introduced and nuisance animals
Use of pesticides including baits and 1080	NA	*Health Act 1911*; Health (Pesticides) Regulations 1956	Introduced and nuisance animals

Activity	Authorisation	Legislation	Topic of this guide with more information
Shockwaves	Permit	*Explosives and Dangerous Goods Act 1961;* Western Australian Explosives Regulations 1963	Introduced and nuisance animals
'Take' flora	Licence	*Wildlife Conservation Act 1950*	Legislation and policy
Clearing of native vegetation	Permit	Environmental Protection (Clearing of Native Vegetation) Regulations 2004	Legislation and policy
Use of herbicides	NA	*Health Act 1911;* Health (Pesticides) Regulations 1956	Wetland weeds
Herbicides other than as specified by the label	Permit	*Agricultural and Veterinary Chemicals Act 1994*	Wetland weeds
Burning of native vegetation	Permit	Environmental Protection (Clearing of Native Vegetation) Regulations 2004; *Bush Fires Act 1954*	Legislation and policy, Wetland weeds
Earthworks in/ near wetlands	Development approval	*Planning and Development Act 2005*	Legislation and policy
Construction of drains for saline water	Authorisation	*Soil and Land Conservation Act 1945*	Legislation and policy
Use of surface water	Licence	*Rights in Water and Irrigation Act 1914*	Legislation and policy
Abstract groundwater	Licence	*Rights in Water and Irrigation Act 1914*	Legislation and policy
Affect an Aboriginal site	Authorisation	*Aboriginal Heritage Act 1972*	Legislation and policy

PART 3: THE WETLANDS OF WESTERN AUSTRALIA

How are wetlands defined?

Globally, there are many definitions for the term 'wetland'. These definitions differ in scope, geographic origin and purpose. Some have been developed for the purpose of inventory, some for specific legal application and some to describe habitats of groups of plants or animals.

The Western Australian government uses a number of definitions of the term 'wetland' for various purposes (see text box below). All are inclusive of a broad spectrum of *wet land*. Land where the presence of water gives rise to distinguishable features that can be recognised as being distinct from the surrounding dry land, are identified as 'wetland'. As well as being identified by the presence of water, diagnostic features include the presence of wetland soils (also known as hydric soils) and wetland vegetation.

Areas of permanently inundated land are the best-conserved wetland types in WA. This can be attributed to their being more similar to wetlands of the northern hemisphere and therefore familiar to European settlers. They have been valued for holding and providing water and being habitat for waterbirds. They have also been afforded more protection because they are relatively difficult to use for agricultural purposes or convert to dryland.

Seasonally inundated land is a familiar feature of WA's landscapes, and these tend to be relatively well recognised as 'wetlands'. They are often referred to as 'seasonal wetlands' or 'ephemeral wetlands'. These terms are not used in this guide, because these ecosystems are wetlands all year round, with wet and dry phases, and should be managed as such. Most of the distinguishable features that make them recognisable as distinct ecosystems from surrounding drylands are present or leave diagnostic identifiers during the dry phase.

Intermittently inundated land is often wet or dry for long periods. The vernacular 'salt lake' is one type of wetland readily recognised by many West Australians living in, or familiar with, regional areas of WA, especially north of Perth. These have often been protected by virtue of the fact that they are not suitable for use for agricultural purposes.

Seasonally waterlogged land is least recognised as wetland amongst the general community, despite being a predominant wetland type in the south-west of the state, and where intact, being of high conservation value. Basins, flats, slopes and highlands may all support seasonal waterlogging. These areas are generally very productive agricultural land and there has been widespread clearing and alteration of these wetland types. Permanently waterlogged wetlands, such as mound springs, are generally well-recognised but also used as a water source on rural properties and stations.

extra information

Definitions of 'wetland'

The Australian government is a signatory to the Convention on Wetlands of International Importance (the Ramsar Convention), which defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water depth of which at low tide does not exceed six metres". The Western Australian Government applies this definition during the course of business that relates to its obligations as a signatory to the Convention, for example, when nominating Ramsar sites.

Schedule 5 of the *Environmental Protection Act 1986* defines wetlands as "an area of seasonally, intermittently or permanently waterlogged or inundated land, whether natural or otherwise, and includes a lake, swamp, marsh, spring, dampland, tidal flat or estuary. The Western Australian Government uses this narrower definition in the course of most business.

The wetland types covered in this guide are wetlands in basins, flats, slopes and highlands that do not have a tidal influence. This includes lakes, sumplands, damplands, palusplains, palusmonts, paluslopes, barlkarras, playas and self-emergent wetlands such as mound springs. Descriptions of each of these wetlands are provided below, under the heading 'Wetland classification'.

What do we know about WA's wetlands?

Compared to other states in Australia, the inventory (cataloguing) of WA's wetland is relatively incomplete. This is a reflection of the size of the state and the number and extent of wetlands in WA. DEC coordinates and maintains the wetland inventory of WA, including spatial (mapping) and biological (surveying) inventory. The ultimate objective of wetland inventory is to document wetland information to allow for informed decisions about the use, management and preservation of wetlands.

Wetland mapping

Wetland mapping, as a general term, may encompass one or more of the following:

- the identification of wetlands in the landscape
- the delineation of wetland boundaries
- the identification of characteristics and the grouping of wetlands according to these characteristics (classification)
- the identification of values (evaluation).

Wetland mapping, where available, is used in the processes of land use planning, conservation planning, water planning, controlled burn planning, as well as wetland inventory.

Decision-making authorities use wetland mapping to help prioritise the protection of high value wetlands when making decisions about land, water, fires and investment in wetland protection. However, other characteristics identified through wetland mapping are also very important, for example, controlled burn planning is informed by the location of all peat wetlands, whether or not they are of conservation value, because they need to be carefully managed in relation to fire.

The Environmental Protection Authority and the Western Australian Planning Commission are two of the key decision making authorities in WA in respect of proposals that affect wetlands. These authorities have established a framework for the use of wetland mapping to help guide decisions about land use planning. Land use planning refers to the process by which the government establishes the suitable uses of land, from a regional scale down to the scale of individual properties. The Environmental Protection Authority (EPA) states that, for the purposes of the environmental impact assessment process, the wetlands listed in B.4.2.2 of the *Environmental guidance for planning and development* (EPA 2008) are of high conservation significance and require a high level of protection. The EPA also notes that comprehensive surveys have not been carried out for all regions of the state, and further investigations are required when activities are proposed.

In preparing wetland mapping and considering mapping by third parties, DEC applies a draft framework for wetland mapping, entitled *Framework for mapping, classification and evaluation of wetlands in Western Australia*. The purpose of this framework is to produce coordination and consistency across the state in the approach to wetland mapping, classification and evaluation; certainty that data is collected using valid methodologies; avoidance of repetition in project planning; achievable aims in terms of scope and detail; a mechanism for ensuring that data is made publicly available; and a mechanism to endorse the results at a state level. The WA Wetlands Coordinating Committee oversees the wetland mapping work produced, with the technical input of one of its working groups, the Wetland Status Working Group. Both the Committee and its working group are chaired by DEC. These groups review wetland mapping methodologies and products, and following endorsement by the Wetlands Coordinating Committee, these products can be used as a basis to guide decision-making and made publicly available.

➤ For more information on the Wetlands Coordinating Committee, see the topic 'Roles and responsibilities' in Chapter 5 and the webpage www.dec.wa.gov.au/wetlandscoordinatingcommittee.

Wetland identification

A range of identification tools can be used to identify wetlands at the sub-regional to regional scale. Technological advances, particularly in relation to aerial photography and satellite imagery, provide opportunities to refine and increase the efficiency of wetland identification processes.

Desk top information that is typically used includes aerial and satellite imagery, topographical maps, soil maps and where available, vegetation maps.

The wetland types that are often most difficult to identify from desk top data are seasonally waterlogged wetlands, particularly those with a flat host landform. This highlights the importance of field reconnaissance, verification and random sampling to account for the limitations of desk top identification methods.

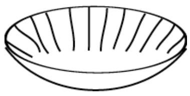
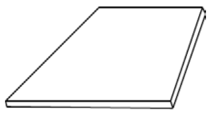
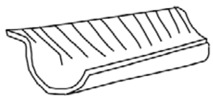
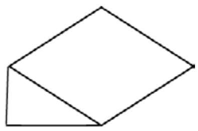
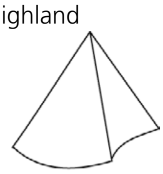
In the field, hydric soils and wetland vegetation are important features to identify for diagnostic purposes.

➤ DEC is preparing information on WA's hydric soils and wetland vegetation to aid wetland identification and delineation work. Once ready, it will be available from www.dec.wa.gov.au/wetlands

Wetland classification

Wetland classification is the identification of characteristics, and the grouping of wetlands according to these characteristics. Different classification systems may be applied, depending upon the purpose. The geomorphic wetland classification system described by Semeniuk and Semeniuk (1995) has been adapted as the primary classification system for wetland mapping in WA. Using the system, wetlands are assigned to one wetland 'type'. A complementary classification system, the Australian National Aquatic Ecosystems framework, is also being used to classify wetlands in addition to the geomorphic classification system. The geomorphic classification system has been applied to wetlands in many areas of the state. It is based on the shape of the host landform and the hydroperiod. Table 2 shows the types of wetlands identified via this system. Wetland classification is primarily conducted using desk top information such as aerial and satellite imagery and topographical maps. Field reconnaissance, verification and random sampling are also important processes in wetland classification.

Table 2. Wetland types according to the global geomorphic classification system, adapted from Semeniuk and Semeniuk (1995) and Semeniuk and Semeniuk (2011).

Water periodicity	**Landform**				
	Basin 	Flat 	Channel 	Slope 	Highland 
Permanently inundated	Lake	-	River	-	-
Seasonally inundated	Sumpland	Floodplain	Creek	-	-
Intermittently inundated	Playa	Barlkarra	Wadi	-	-
Seasonally waterlogged	Dampland	Palusplain	Trough	Paluslope	Palusmont

Wetland evaluation

Evaluation is the process of assessing and documenting a wetland's values by considering information about its attributes and functions.

Considerations include:

- flora
- fauna
- linkages
- water quality
- wetland processes (e.g. hydrological and sedimentological processes)
- geomorphology
- scientific and educational
- cultural

These can be considered in relation to:

- naturalness
- representativeness
- scarcity

It is important to note that a wetland evaluation is not the same process as a wetland condition assessment. The evaluation of naturalness encompasses wetland condition, but it is not the only consideration when determining a wetland's values.

Wetland values need to be interpreted in a regional context and for this reason, evaluation of a region or sub-region should be conducted using a suitably designed method endorsed by the Wetlands Coordinating Committee.

Detailed evaluations enable DEC to assign wetlands to a 'management category'. Decision-making authorities use these management categories to inform their determinations.

Status of wetland mapping in WA

With significant areas of the state yet to be mapped (Figure 3), DEC continues to work upon extending, improving and updating knowledge of wetland extent, distribution and condition in priority areas of WA as resources allow. New mapping projects are often developed in partnership with organisations such as regional and sub-regional NRM organisations and other government departments. Table 3 and Table 4 outline the available mapping datasets and datasets in preparation. Table 5 outlines regional and sub-regional wetland mapping projects not digitised.

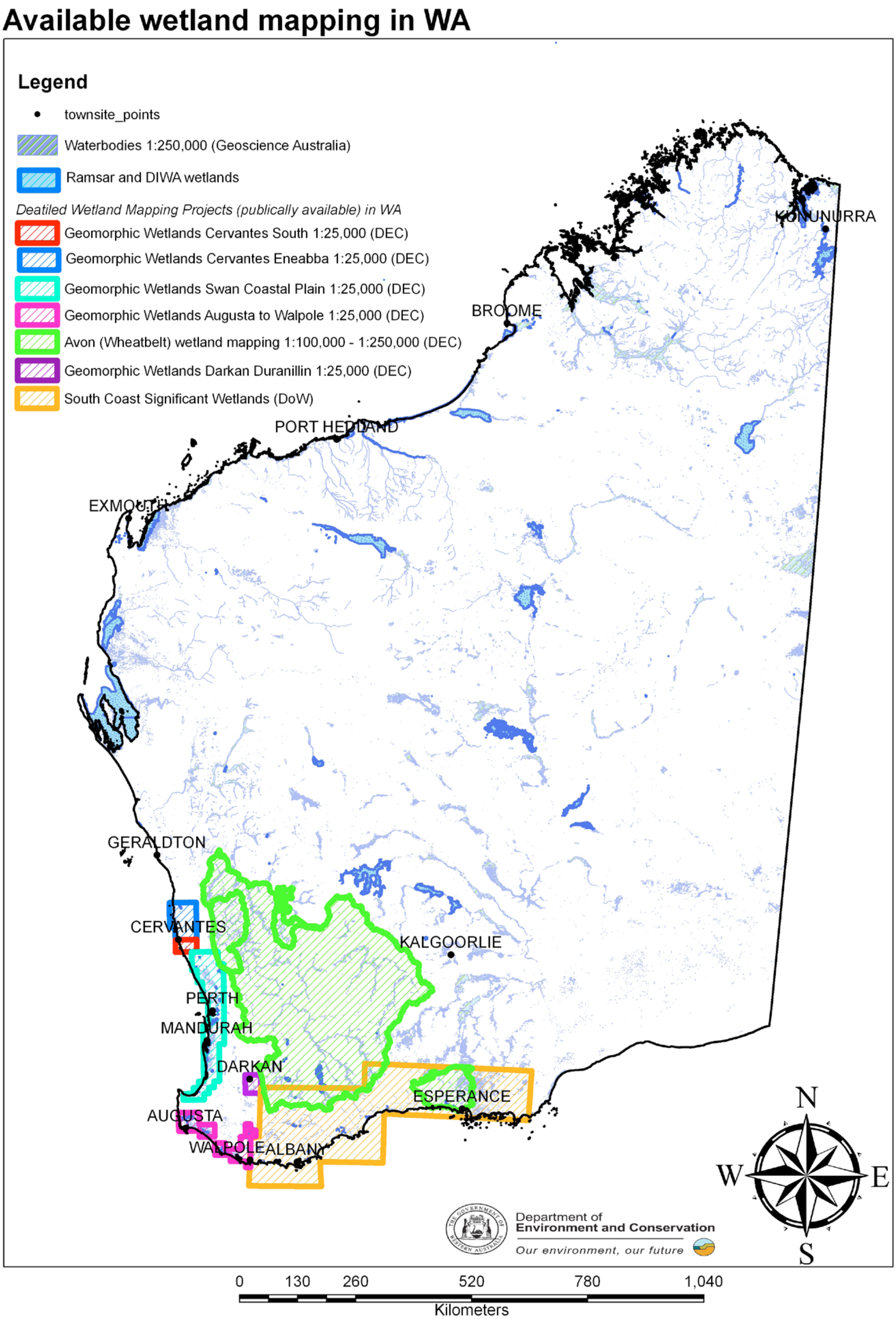


Figure 3. A summary of wetland mapping that is publicly available. See www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-mapping.html for more details.

Table 3. Publicly available datasets of sub-regional spatial wetland mapping as at 2012

Map/project name	DEC region	Scale	Dataset information
Cervantes South	Mid West	1:25,000	Boundaries, wetland types.
Cervantes Eneabba	Mid West	1:50,000	Boundaries, wetland types.
Cervantes Coolimba Coastal	Mid West	1:25,000	Boundaries, wetland types, management categories, consanguineous suites.
Wheatbelt/Avon south (Esperance)	South Coast	1:100,000	Locations, landforms. Evaluation methodology to determine conservation significance is available for application.
South Coast Significant wetlands	South Coast	Based on existing data	'Significance' based on existing data sources
Augusta to Walpole	South West and Warren	1:25,000	Boundaries, wetland types.
Darkan-Duranillin	South West and Wheatbelt	1:25,000	Boundaries, wetland types.
Swan Coastal Plain	Swan	1:25,000	Boundaries, wetland types, management categories, consanguineous suites.
Wheatbelt/Avon (central, east, west)	Wheatbelt & Swan	1:100,000 – 1:250,000	Locations, landforms. Evaluation methodology to determine conservation significance is available for application.

Table 4. Digitised datasets in preparation or endorsement phases as at 2012

Map/Project name	DEC region
Albany urban area, Esperance groundwater area, Hopetoun.	South Coast
Areas of the south-west (Leeuwin Naturaliste Ridge, Donnybrook-Nannup, Margaret River east)	South West
Blackwood Plateau & eastern Scott Coastal Plain	South West and Warren

Table 5. Other wetland mapping projects (not digitised)

Report title	DEC region
Ecological Assessment and Evaluation of Wetlands in the System 5 Region (V & C Semeniuk Research Group 1994). Report to the Australian Heritage Commission.	MidWest
A Systematic Overview of Environmental Values of the Wetlands, Rivers and Estuaries of the Busselton-Walpole Region (Pen, L. 1997). WRC Report # WRAP 7.	South West, Warren
Preliminary Delineation of Consanguineous Wetland Suites Between Walpole and Fitzgerald Inlet, Southern Western Australia (V & C Semeniuk Research Group 1998). Unpublished report for the Water and Rivers Commission.	Warren and South Coast
Preliminary Delineation of Consanguineous Wetland Suites in the Pallinup-North Stirling Region, South Western Australia (V & C Semeniuk Research Group 1999). Unpublished report for the Water and Rivers Commission.	South Coast
Wetlands of the northwestern Great Sandy Desert in the LaGrange hydrological sub-basin (V & C Semeniuk Research Group 2000). Unpublished report for the Water and Rivers Commission.	Kimberley
Wetlands of the Pilbara Region: description, consanguineous suites, significance (V & C Semeniuk Research Group 2000). Unpublished report for the Water and Rivers Commission.	Pilbara
A Preliminary Evaluation of Wetlands in the Esperance Water Resource Region (Ecologia Environmental Consultants 2000). Unpublished report for the Water and Rivers Commission.	South Coast

case study

The importance of wetland mapping – the Swan Coastal Plain example

The most detailed mapping has been produced for Perth and surrounds, encompassing the coastal plain from Wedge Island to Dunsborough, which is part of the Swan Coastal Plain. The mapping was originally produced by Hill, Semeniuk, Semeniuk and Del Marco (1996), with subsequent digital updates by the custodial agency (Water and Rivers Commission, Department of Environment and now Department of Environment and Conservation). The digital map of wetlands for this area is entitled *Geomorphic Wetlands Swan Coastal Plain* dataset. DEC is custodian of this dataset. It is publicly available online for both viewing and downloading (see below). It shows the location of wetlands, their boundary and data describing each wetland's attributes. This includes a unique feature identifier (UFI) assigned to each wetland. It also identifies the wetland type assigned to each wetland as a result of the application of the geomorphic classification system, described previously. In addition it identifies the wetland management category that is assigned to each wetland as a result of a wetland evaluation process, also described previously.

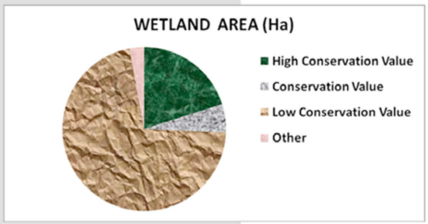
The *Geomorphic Wetlands Swan Coastal Plain* dataset is used by local governments, the Western Australian Planning Commission, the Environmental Protection Authority, the Department of Environment and Conservation and the Department of Water to help guide decisions that may affect these wetlands.

The wetlands of the Swan Coastal Plain are subject to change over time because Perth's dense population drives intensive land and water use and modifications to the natural environment. For this reason, the *Geomorphic Wetlands Swan Coastal Plain* dataset is not static. It is maintained as a live dataset with several updates per year. If the values of a wetland have changed over time, there is a process by which an individual or party may provide sufficient information to enable DEC to review the values of the wetland, and make changes as warranted to the dataset. This can apply where the values of the wetland have declined, or if wetland management and restoration activities have resulted in an increase in wetland values, or where it is believed that the evaluation is incorrect.

➤ For more information on this process, see the *Protocol for proposing modifications to the Geomorphic Wetlands Swan Coastal Plain dataset* (DEC 2007), available from www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-mapping/geomorphic-wetlands-swan-coastal-plain-dataset.html

case study

The Swan Coastal Plain is the area between Jurien and Dunsborough. More than 25 per cent of this land area is wetland. However, most of it has been heavily degraded.

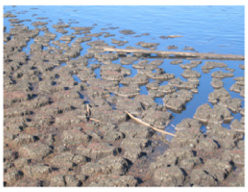


Twenty-nine sites are identified as nationally significant in the Swan Coastal Plain IBRA region (some sites contain more than one wetland).

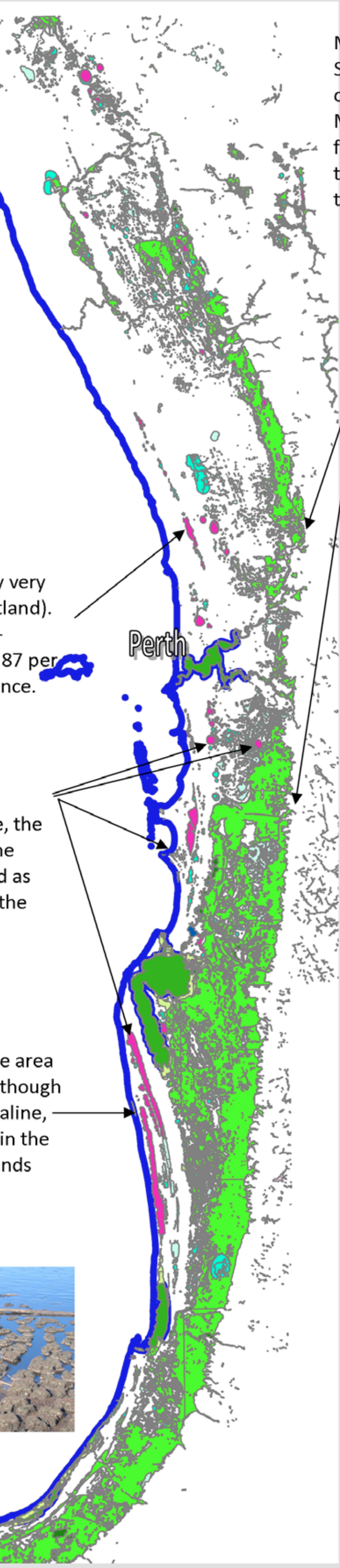
Permanently inundated basins (lakes) are naturally very scarce (3.9 percent by area of the total area of wetland). They are shown in pink on this map. They are well-conserved compared to other wetland types, with 87 per cent retaining values of high conservation significance. Most occur on the western Swan Coastal Plain.

Thomsons Lake, Forrestdale Lake, the Yalgorup wetlands system and the Becher wetlands are all identified as internationally significant under the Ramsar convention.

Most wetlands in the area are relatively fresh, though a number are very saline, including a number in the Peel-Yalgorup wetlands system.



A range of organic and mineral components form wetland sediments on the Swan Coastal Plain. These include diatomaceous earth, peat, calcilutite and other matter of organic origin.



Many of the wetlands north of the Swan River are sustained by their connection with the Gnangara Mound groundwater system. Their fate is intimately tied to that of the mound and our use of the water in the mound.

All of the area mapped in light green is seasonally waterlogged flats, or palusplains. They occur on the eastern side of the coastal plain.
Palusplains are the most extensive in terms of area, accounting for 66 per cent of wetland area between Wedge Island and Dunsborough.

Palusplains have sustained the most extensive degradation in terms of area: more than 94 per cent of the area of palusplain is heavily degraded such that it no longer retains conservation value.

Biological and physico-chemical inventory

Biological and physico-chemical wetland inventory in WA is primarily conducted ad-hoc and much of the data is in report form rather than being collated into databases. While many of these reports are unpublished, many published reports can be found in DEC's library catalogue: http://science.dec.wa.gov.au/conslib.php.

WetlandBase (http://spatial.agric.wa.gov.au/wetlands) is a publicly available database that provides data on WA wetlands. Point data from surveys and sampling is available, and includes data on water chemistry, waterbirds, aquatic invertebrates and vegetation. Note that DEC is preparing an alternative to WetlandBase, scheduled for release in 2013, that will continue to make this data publicly available.

WetlandBase stores data from many of the significant wetland inventory projects conducted over the last twenty years:

- Resource condition monitoring: surveys of forty-five significant wetlands across WA by DEC in 2008. See www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-data/wetland-condition-monitoring.html
- South West wetlands monitoring: surveys at twenty-five wetlands between Mandurah and Augusta between 2006 and 2008, conducted by DEC. See www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-data/south-west-wetlands-monitoring.html
- 40 Wetlands Study, Murdoch University
- Jandakot Mound Monitoring Program, Murdoch University
- Gnangara Mound Monitoring Program, Edith Cowan University
- Aquatic Projects Database (Salinity Action Plan Survey), DEC
- Annual Waterfowl Counts in South West WA, DEC
- Waterbirds in Nature Reserves of South West WA, DEC
- South Coast Regional Wetland Monitoring Program, Department of Water

Other notable surveys with a wetland component include:

- Pilbara Region Biological Survey 2002–2012, in which over 1000 collections were made in aquatic areas. See www.dec.wa.gov.au/our-environment/science-and-research/biological-surveys/pilbara-biological-survey.html

Other databases with available data include:

- *NatureMap* www.naturemap.dec.wa.gov.au

  NatureMap is a collaborative website of DEC and the Western Australian Museum. It presents the most comprehensive and authoritative source of information on the distribution of WA's plants and animals. It is an interactive tool designed to provide users with comprehensive and up-to-date information on plants, animals, fungi and other groups of biodiversity. It can be used to produce maps, lists and reports of WA's plant and animal diversity.

- *Freshwater fish distribution in Western Australia* database http://freshwater.fish.wa.gov.au

  This spatial dataset by the Department of Fisheries enables users to search all available information on the distribution of native and introduced freshwater fish and crustaceans in WA.

What are the cultural values of Western Australian wetlands?

Wetlands form a part of our cultural identity and history. Wetlands directly affect the lives of millions of Western Australians, helping to shape neighbourhoods, towns, cities, farms, stations, properties and parks around the state. They form part of our sense of place.

Cultural values of wetlands include:

- spiritual values
- recreation values
- commercial values
- resource values
- scientific values

Much has been written about these values, so they won't be covered here in any detail. The case study and profiles on the following pages provide examples of the scope and diversity of cultural values.

Photo – Wetlands Section/DEC.

case study

Aboriginal values of WA wetlands - by Melissa Bastow, DEC

Humans have valued and utilised wetlands in Western Australia for at least 40,000 years and many of these traditional practices area still continuing today (Balla, 1994). Prior to European settlement, Aboriginal people gathered in large groups around wetlands to take advantage of the rich diversity of game, vegetables and building materials in substantial supply. Resources and materials commonly consumed or collected by early Aboriginal people include water, fish, waterfowl, large mammals, frogs, reptiles, roots, yams, nuts, fruit, fungi, fibre, paperbark and wood. Anthropological and archaeological evidence has demonstrated that resource usage from Aboriginal populations was the densest around wetlands and rivers (McGuire, 1996).

Historically, wetlands were utilised as congregation points, camping sites, pathways and direct access tracks for the migration of inland people (O'Connor et al, 1989 & 1995). Wetlands were also used as access tracks to locate ceremonial places, for example, as occurred at Yanchep, Loch McNess, which was used as a track and camping ground.

Many wetlands in Western Australia contain significant evidence of evolutionary and archaeological past including fossils and Aboriginal remains. All fresh water sources, in particular wetlands and inland rivers, were important to Aboriginal people, and there is a higher likelihood of finding artefacts around freshwater sources (Goode).

A number of different archaeological site types and artefacts are discovered near wetlands, however, the most common is surface artefact scatters, which are sites containing three or more artefacts together in association (O'Connor et al. 1989 and 1995). Some of the other common artefacts discovered near wetlands include marked trees, quarries, middens, seed grindings, habitation structures, engravings, stone arrangements, structures and factory sites, paintings and quarries.

Aboriginal people viewed wetlands as an intricate part of their heritage, culture and way of life and conducted many ceremonial and burial events in their proximity. Wetlands hold values which are significant in the customs, folklore, traditional lifestyle and spiritual beliefs of Aboriginal groups. Of special spiritual and cultural values to the Aboriginal people in the south-west of Western Australia is the Waugal (WRC 2002).

The Waugal is an ubiquitous, dreaming ancestor referred to in the majority of past Aboriginal mythological stories. The Waugal (also known as Wagal, Wagyl, Uocol, Beermarra, Warlu and Wompi) is the serpent spirit of the water who, according to local Aboriginal tradition, created the rivers, wetlands, valleys and other landscape features wherever it travelled (Goode). It has been noted (Bates 1985) that places where the Waugal camped during its travels formed wetlands and deep river pools which have become sacred and significant sites to Aboriginal people. Today, the Waugal is documented to be sleeping in a variety of locations including the deep river pools (Mundrooroo) and at the foot of Kings Park (Green 1979).

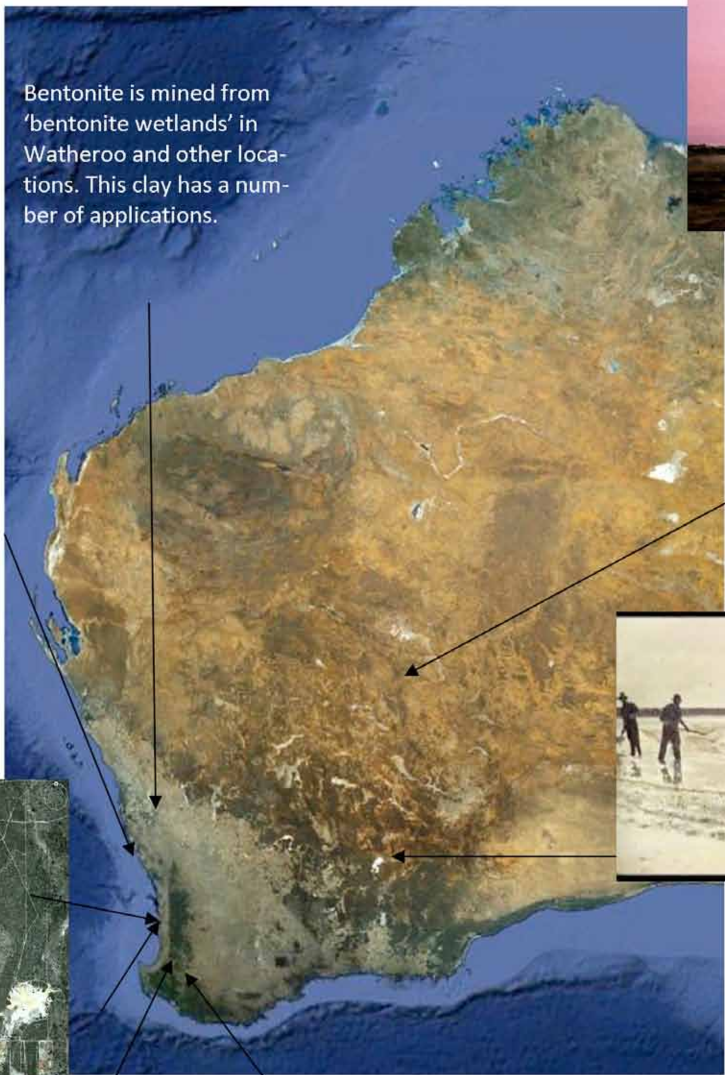
References to the Waugal are widespread throughout Australia, however, records are most abundant from the Nyungar people who live in the southwest of Western Australia. Most of the major rivers, creeks, pools, swamps and lakes which drain the Darling Escarpment on the Swan Coastal Plain, are believed to be associated with the Waugal (O'Connor et al, 1989 and 1995).

Early mythological records of the Waugal focus on its creative and spiritual punitive force and the connection between the land and people. Contemporary Nyungar people discuss the destructive and healing powers of the Waugal and its bringing of clean water. Modern anthropologists document that the Waugal is not just a spirit living in the watercourses, but a being which dies when a water source dries up.

In contemporary times, Aboriginal people continue to value and use wetlands for traditional as well as for modern uses including recreation and ecotoursim (McGuire, 1996). DEC recognises that Aboriginal people are the traditional custodians of the lands and waters it manages, and supports Aboriginal people connecting with country. The ability to carry out cultural activities on country is an important part of Aboriginal culture and connection to the land. Recent changes to the Conservation and Land Management Act 1984 have extended the opportunities for Aboriginal people to access DEC-managed lands and waters for customary activities. For more information, see www.dec.wa.gov.au/aca. Aboriginal groups are also active in the management, protection and conservation of wetlands.

A raft of algal production projects are underway in the Pilbara and the Wheatbelt to make commercial use of algal products. In the Midwest, Hutt Lagoon is the world's largest microalgae production plant—a 250 hectare series of artificial ponds used to farm *Dunaliella salina*. This microalga gives the lagoon its colouring and is used to produce beta-carotene, a source of vitamin A used in vitamin supplements, and a food colouring agent used in products such as margarine, noodles and soft drinks.

Gypsum is mined from wetlands including some in the Jurien area. Gypsum has a number of uses.



Bentonite is mined from 'bentonite wetlands' in Watheroo and other locations. This clay has a number of applications.

Many wetlands in the interior are used as discharge sites for mine waters.

Diatomaceous earth has been mined from a number of wetlands, including Lake Gnangara.

Salt has been mined from wetlands since settlement. In Lake Lefroy it has been harvested since 1945. It was initially shovelled by hand into hessian bags and packed into horse-drawn carts. Later on, trucks were used, but sometimes sank into the sediment under their heavy loads. This operation was later moved to Lake Deborah in the early 1970s.

Peat has been mined from many wetlands in Perth and the south-west.

Silica sand mining in the south-west often occurs in areas containing waterlogged wetlands.

Recreational fishing is a popular pastime at Lake Kununurra. Baby barramundi are being released in the lake to ensure a sustainable fishing program.

An annual freshwater swim event at Lake Argyle that aims to promote a healthy lifestyle through swimming while encouraging visitors to the East Kimberly.

The Herdsman Lake Wildlife Centre, in the centre of the Perth metro area, is involved in environmental education programs for schools and the general community.

Lake Ballard has been transformed into a spectacular outdoor art gallery. World renowned artist Antony Gormley has created 51 unique sculptures that represent the residents of the local town, Menzies.

Lake Walyungup is a shallow saline lake that provides great conditions for seasonal land yacht sailing and model aircraft flying.

Lake Towerrinning is a large freshwater lake with sandy beaches. It's a popular holiday destination for camping, swimming and waterskiing.

The Kepwari Wetland Trail is an interpretive trail designed to highlight the importance of the internationally significant Lake Warden Wetland System at Esperance.

PART 4: GLOSSARY

This glossary is a compilation of glossary terms from each topic of this guide.

Accuracy: closeness to the 'true' value of the parameter being measured

Acid sulfate soils: (also known as acid sulphate soils) all soils in which sulfuric acid is produced, may be produced or has been produced in quantities that can affect the soil properties

Actual/active acid sulfate soils: (also known as actual acid sulphate soils) soils in which the sulfidic minerals have oxidised and the pH has fallen to very low levels

Acute toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent in a short time (usually less than 24 hours)

Adaptive management: an approach that involves learning from management actions, and using that learning to improve the next stage of management

Adventitious roots: roots that arise from mature plant tissue such as stems or trunks and which take up oxygen and nutrients in inundated conditions

Aeration: the addition of oxygen to the water column of a wetland

Aerenchyma: interconnected air-filled spaces within plant tissue that transport air from plant parts above the water or saturated soils to the roots

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Aestivating: being in a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Algae: a general term referring to the mostly photosynthetic, unicellular or simply constructed, non-vascular, plant-like organisms that are usually aquatic and reproduce without antheridia and oogonia that are jacketed by sterile cells derived from the reproductive cell primordium; includes a number of divisions, many of which are only remotely related to one another

Algal bloom: the rapid, excessive growth of algae, generally caused by high nutrient levels and favourable conditions

Alkalinity: a solution's capacity to neutralise an acid

Allochthonous: derived from outside a system, such as the leaves of terrestrial plants that are carried into a wetland

Alluvial soil: soil deposited by flowing water on floodplains, in river beds, and in estuaries

Amphibians: the class of animals to which frogs, toads and salamanders belong. They live on land but develop by a larval phase (tadpoles) in water

Anaerobic: without air (organisms that live in these conditions are anaerobes)

Anaerobic respiration: respiration without oxygen (O_2). Respiration is the process by which organisms convert the energy stored in molecules into a useable form. In most organisms, respiration requires oxygen, which is why breathing by animals is referred to as respiration. However, some bacteria are capable of anaerobic respiration, in which other inorganic molecules (such as sulfur, metal ions, methane or hydrogen) are used instead of oxygen.

Anoxic: deficiency or absence of oxygen

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Aquaculture: the keeping, breeding, hatching, or culturing of fish

Aquatic invertebrates: those animals without a backbone (such as insects, worms, snails, molluscs, water mites and larger crustacean such as shrimps and crayfish) that live in or on water for at least one phase in their lifecycle

Aquatic plant: a plant that grows for some period of time in inundated conditions and depends on inundation to grow and, where applicable, flower

Aquiclude: an impermeable body of rock or stratum of sediment that acts as a barrier to the flow of groundwater to or from an adjacent aquifer

Aquifer: a geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water

Aquitard: a low permeability body of rock or stratum of sediment that retards but does not prevent the flow of groundwater to or from an adjacent aquifer

Artesian groundwater: groundwater confined under pressure

Australian Height Datum: is a fixed survey point from which the elevation of any point in Australia may be measured

Authorisation: a licence, permit, approval or exemption granted, issued or given under the Part V environmental regulations

Bassendean Sands: (also known as the Bassendean Dunes) a landform on the Swan Coastal Plain, comprised of heavily leached aeolian sands, located between the Spearwood Dunes to the west and the Pinjarra Plain to the east

Benefit: the economic, social and cultural benefits that people received from an ecosystem. These benefits often rely on the components and processes which make up a wetland. This term is often used in conjunction with the term ‘services’. See also ‘services’.

Benthic: the lowermost region of a wetland water column; the organisms inhabiting it are known as benthos

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Benthos: organisms living in or on the wetland substrate

Bentonite: a type of clay (aluminium phyllosilicate)

Bioavailable: in a chemical form that can be used by organisms

Biodiversity: encompasses the whole variety of life forms–-the different plants, animals, fungi and microorganisms–-the genes they contain, and the ecosystems they form. A contraction of ‘biological diversity’

Biogeochemical: the chemical, physical, geological and biological processes and reactions that govern the composition of the natural environment, and in particular, the cycles in which material is transferred between living systems and the environment

Biogenic: produced by organisms

Biological control: the control of an introduced plant or animal by the introduction of a natural predator or pathogen, usually bacteria, viruses or insects, or by biological products such as hormones

Biological oxygen demand: a measure of the oxygen in the water column or sediment pore waters that is being used by organisms

Biofilm: bacteria, microalgae, fungi and unicellular microorganisms enmeshed in a hydrated mucopolysaccharide secretion that sequesters ions and isolates microorganisms from the water column. May be present on living and non-living surfaces and substrates.

Biomass: the total mass of biological material (living or dead), usually expressed as live or dry weight per unit area or volume

Bioregion: a territory defined by a combination of biological, social and geographic criteria rather than by geopolitical considerations; generally, a system of related, interconnected ecosystems

Bioremediation: the use of microorganisms to break down environmental pollutants

Birrida: a local Aboriginal name for a seasonally inundated gypsum saltpan wetland in sand dunes in the Shark Bay area. Some have a distinctive central raised platform and moat feature.

Blank: a solution (usually deionised water) that has a value of zero for the parameter being assessed. Used to calibrate meters.

Broadleaf: plants that possess relatively broad flat leaves rather than needle-like leaves

Blue-green algae: an older term for cyanobacteria

Bore: a narrow, normally vertical hole drilled into a geological formation, usually fitted with a PVC casing with slots to allow interaction with the aquifer, to monitor or withdraw groundwater from an aquifer

Botulism: a paralytic disease caused by ingestion or exposure to a toxin produced by the bacteria Clostridium botulinum

Box-subsampler: a watertight box that is divided into a number of cells. A box-subsampler is used when sorting aquatic invertebrates to eliminate observer bias. Dividing the sample into a number of cells which are sorted individually, and in their entirety, reduces the likelihood of preferential selection of larger or more conspicuous taxa.

Brackish: subsaline or hyposaline waters, used in reference to estuarine waters, and often in reference to inland waters

Bradley method: working from the most intact parts of a bushland area out towards more degraded areas, to allow natural regeneration to occur, for example, when weeding

Browse: to feed on leaves, twigs or bark from non-herbaceous (woody) plants, such as trees and shrubs

Buffering capacity: a solution's capacity to resist large or sudden changes in pH

Canopy cover: the proportion of ground surface covered by the leaves and branches of plants when projected vertically downwards

Catchment: an area of land which is bounded by natural features such as hills or mountains from which all surface runoff water flows downslope to a particular low point or 'sink' (a place in the landscape where water collects)

Causation: showing a relationship exists between two variables such that a change in one (the cause) causes a change in the other (the effect). To be sure of the relationship between cause and effect, it is also necessary to show that the effect will not occur if the cause does not.

Charophytes: green algae of the Characeae family; complex algae that superficially look like submerged flowering plants

Chemosynthesis: the process by which organisms such as certain bacteria and fungi produce carbohydrates and other compounds from simple compounds such as carbon dioxide, using the oxidation of chemical nutrients as a source of energy rather than sunlight

Chlorophyll *a*: a light-capturing pigment found in plant and algal cells. Measurement of chlorophyll *a* is used as a surrogate for cell counts of algae.

Chroma: the purity of a colour, or its freedom from white or grey

Chronic toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent over a longer time period (months or years)

Clearing: any act that kills, removes or substantial damages native vegetation in an area. This includes severing or ringbarking of trunks or stems, draining or flooding of land, burning of vegetation and grazing of stock or any other act or activity that causes damage to some or all of the native vegetation in an area.

Colony (algal): a closely associated cluster of cells, joined together or enclosed within a common sheath or mucilage. A colony may incorporate thousands of cells.

Colour: the concentration of dissolved organic materials and dissolved metals in water

Coloured wetlands: wetlands with dissolved organic materials and dissolved metals; on the Swan Coastal Plain, nominally those wetlands with more than 52 g_{440}/m (gilvin)

Community: a general term applied to any grouping of populations of different organisms found living together in a particular environment

Community composition: the plant taxa that occur in a given community

Community structure: the three-dimensional distribution (height and width of foliage) and abundance of plant taxa and growth forms within a community

Confined aquifer: an aquifer deep under the ground that is overlain and underlain by relatively impermeable materials, such as rock or clay, that limit groundwater movement into and out of the aquifer

Consanguineous suite: area/s defining a group of wetland with common or interrelated features

Consumer: an organism that feeds on other organisms, either dead or alive

Contributing offsets: complementary activities which, together with direct offsets, meet the offset principles. These include education, research, removal of threats, and or contribution to an approved credit trading scheme or trust fund.

Control: a subject that is identical to the experimental subject in every way, except that the experimental subject receives the treatment and the control does not. This means that if a change is observed in the experimental subject after the treatment, but not observed in the control, that change could only have occurred due to the treatment.

Corms, bulbs, tubers: specialised underground fleshy storage organs that allow plants to flourish in nutrient deficient soils or to die back and enter a state of dormancy when conditions are extreme, such as during fire or drought

Cosmopolitan: can be found almost anywhere in the world

Critical environmental assets: the most important environmental assets in the state that should be protected and conserved

Critical threshold: a limit of disturbance of vegetation condition beyond which natural wetland processes are unlikely to restore full ecological function

Crown cover: the vertical projection of the outer extent of the crown of a plant. A line around the outer edge defines the limits of an individual canopy, and all the area within is treated as 'canopy' irrespective of gaps and overlaps.

Crustaceans: a class of animals that have a hard exoskeleton (shell) and usually live in the water, for example, crabs, lobsters, yabbies and microcrustaceans

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Cyanobacterial bloom: the rapid, excessive growth of cyanobacteria, generally caused by high nutrient levels and favourable conditions

Data confidence: the degree of certainty with which it is possible to state that a change has (or has not) occurred in a system and what the cause of the change is

Data quality: the degree to which the data set truthfully represents conditions at the monitoring site. High quality data are achieved by eliminating errors from the dataset.

Data visualisation: the technique of summarising a dataset graphically

Datum: an established point on the globe that is used as the reference from which other locations are calculated. Australia uses the Geographic Datum of Australia 1994 (GDA94).

Deciduous: a plant that sheds its leaves annually

Decision making authority: a public authority empowered to make a decision in respect of a proposal. Often abbreviated to DMA.

Decomposer: organisms, mainly bacteria and fungi, which break down complex organic molecules from detritus, liberating nutrients and assimilating carbon

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its physical breakdown. Also known as mineralisation

Desmid: a member of the Desmidialies (Zygnemophyceae) within the Division Chlorophyta (green algae)

Derived proposal: a proposal referred to the Environmental Protection Authority under section 38 of the *Environmental Protection Act 1986* that is declared by the EPA to have been identified in a strategic proposal that has been assessed and granted approval under Part IV of the EP Act

Detritivore: an animal that feeds on detritus

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, freely moving in the open water and forming fossil deposits

Diatomite, diatomaceous earth: siliceous deposits made up of the sedimentary build up of diatom shells (frustules)

Dicotyledons (dicots): flowering plants that typically have seedlings with two cotyledons (seed leaves), a tap root system, and they can form wood and have network leaf venation. Dicots include a range of herbs, shrubs and trees.

Direct offsets: activities which counterbalance the environmental impact of a proposal and are in addition to normal environmental management requirements. This includes restoration (offsite), rehabilitation (offsite), re-establishment, sequestration and acquisition of other land/s under threat for inclusion into conservation estate.

Discharge wetland: a wetland into which groundwater discharges

Disturbance opportunists: responding positively and rapidly to habitat disturbance

Diversity: a measure of the number of species of a particular type and their abundance in a community, area or ecosystem. It can refer to a particular group of organisms, such as native plant diversity or frog diversity.

Dongas: playas (intermittently inundated basins) in the Nullarbor, usually 2–3 metres deep and up to 800 metres in diameter, supporting trees. They hold water for a short time after rain due to their hard clay surface.

Dormancy: a state of temporary inactivity when plants are alive but not growing

Dynamic environment: a process or system which is characterised by constant change or activity

Dystrophic: wetlands that suppress increased algal and plant growth even at high nutrient levels due to light inhibition

Ecological community: naturally occurring biological assemblages that occur in a particular type of habitat

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Ecological linkage: a network of native vegetation that maintains some ecological functions of natural areas and counters the effects of habitat fragmentation; a series of (both contiguous and non-contiguous) patches of native vegetation which, by virtue of their proximity to each other, act as stepping stones of habitat which facilitate the maintenance of ecological processes and the movement of organisms within, and across, a landscape

Ecological water requirements (EWRs): the water regime needed to maintain the ecological values of a water dependent ecosystem at a low level of risk

Ecosystem components: include the physical, chemical and biological parts of a wetland (from large scale to very small scale, e.g. habitat, species and genes)

Ecosystem: a community of interdependent organisms together with their non-living environment

Ecosystem processes: the complex interactions (events, reactions or operations) among biotic (living) and abiotic (non-living) elements of ecosystems that lead to a definite result

Ecosystem services: benefits that people receive or obtain from an ecosystem, including provisioning services (such as food, fuel and fresh water), regulating services (such as ecosystem processes such as climate regulation, water regulation and natural hazard regulation), cultural services (such as spiritual enrichment, recreation, education and aesthetics) and supporting services (such as the services necessary for the production of all other ecosystem services such as water cycling, nutrient cycling and habitat for biota)

Ecotype: a genetically distinct geographic variety, population or race within a species which is adapted to specific environmental conditions. Typically ecotypes exhibit differences in morphology or physiology stemming from this adaptation, but are still capable of breeding with adjacent ecotypes without loss of fertility or vigour

Electrical conductivity (EC): the ability of a solution to conduct an electric current, and is measured as 'specific conductance'; the rate of flow of ions between two electrodes at a fixed distance apart, measured at a known temperature

Electrofishing: a technique in which an electric current is applied to the water in order to temporarily stun fish

Emergent: plants that are rooted below the water surface, but with their shoots and/or leaves above the water

Enacted: to make into law

Endemic: naturally occurring only in a restricted geographic area

Endorsed management plan: a management plan that has been approved and/or modified by the Minister for Environment as he/she thinks fit

Environmental impact assessment: an orderly and systematic process for evaluating a scheme or proposal, including its alternatives where relevant, and its effects on the environment, including the mitigation and management of those effects

Environmental offset: an offsite action or actions to address significant residual environmental impacts of a development or activity

Environmental protection policies: whole of government policies which have been agreed to by Parliament and have the force of law as if part of the Act

Environmental water provisions (EWPs): the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social and economic impacts. They may meet in part or in full the ecological water requirements.

Environmental weeds: plants that become established in natural ecosystems, altering natural processes and leading to the decline of the communities they invade

Ephemeral (plant): marked by short life cycles, usually a single season

Epiphyte: organisms such as bacteria, algae and plants that grow attached to plants

Erosion: the gradual wearing away and movement of land surface materials (especially rocks, sediments, and soils) by the action of water, wind, or a glacier

Euphotic zone: (also known as the 'photic zone' and 'photozone') the section of a water mass penetrated by light of sufficient intensity and of suitable wavelength to promote photosynthesis by aquatic plants

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plant material (phytoplankton, macrophytes or both). May occur naturally over geologic time or may be human-induced.

Evaporation: the change of liquid water into water vapour in the atmosphere

Evapotranspiration: a collective term for the transfer of water, as water vapour, to the atmosphere from both vegetated and un-vegetated land surfaces

Facultative wetland plants: plants that can occur in both wetlands and dryland in a given setting

Feral animals: introduced animals that have escaped, or have been released, from domestication and returned, partly or wholly, to their wild state

Ferns, fern allies: plants with stems, leaves and roots like other vascular plants, but which reproduce via spores instead of seeds or flowers

Filament: cells in a linear series, usually abutting one another, creating threads or strands

Filamentous: a very fine thread-like structure

Fire-responsive: plants which have seed pods that open, seeds that germinate, or epicormic buds or lignotubers that resprout in response to a fire event. Some of these responses are triggered by the chemicals produced in smoke during the fire event.

First flush: the first rainfall for a period of time, resulting in stormwater dislodging and entraining relatively high loads of sediments, particulates and pollutants that have built up in the intervening period between rainfall events, and typically carrying a higher pollutant load than subsequent events

Flocculation: the joining of particles (small objects) into loose masses (floc) in water

Flocculent: loosely massed

Flora: plant species, subspecies and varieties in a given area

Flow-through wetland: a wetland which receives groundwater inputs in some parts of its area and discharges water to the groundwater in other areas

Flyway: a geographic region that supports a group of populations of migratory waterbirds throughout their annual cycle. Up to nine flyways are recognised worldwide

Food chain: a diagram of who eats whom in a simple linear order, representing the flow of energy or nutrients in ecosystems. Two basic food chains are the grazing and detrital food chains.

Food web: a diagram that represents the feeding relationships of organisms within an ecosystem. It consists of a series of interconnecting food chains.

Functioning ecosystem: a community of interdependent organisms together with their non-living environment. A functioning ecosystem is one which has a full suite of these normal resources and functions successfully, interacting within an ecosystem all of the time to maintain a stable sustainable system over time.

Generalist: a species that can live in many different habitats and can feed on a variety of different organisms

Geomorphology: landscape features and shape, at various spatial scales

Geology: the composition, structure and features of the Earth, at the surface and below the ground

Gilvin: a measure of the absorbance of light by humic substances at a wavelength of 440 nm (after filtration through a 0.2 μm filter), expressed in units of g_{440}/m (absorbance at 440 nanometres per metre)

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyungar origin

Goal: a specific statement detailing the desired state of a wetland component or process

Grass: tufted or spreading plant from the family Poaceae. The leaf sheath is always split, a ligule is present, the leaf is usually flat, a stem cross-section circular and all internodes evenly spaced. Some grasses are called reeds (the *Phragmites* and *Arundo* genera).

Grazing: feeding on grasses and other low-growing herbaceous vegetation

Government Gazette: a government publication issued by the State Government which includes details of statutory matters, available from the State Law Publishers

Groundcover: the percentage of ground covered by plant materials (alive or dead) and leaf litter

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater capture zone: the area within which any recharge (infiltrating water) eventually flows into the wetland

Groundwater dependent ecosystems: those parts of the environment, the species composition and natural ecological processes of which are dependent on the permanent or temporary presence or influence of groundwater

Groundwater model: a simplified representation of a groundwater system

Groundwater mound: convex regional mounding of the water table in an unconfined aquifer. The top of the mound is where the water table is highest above sea level. Water flows down gradient of this point.

Groundwater table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Guild: a group of species that exploit similar resources in a similar fashion

Gymnosperms: plants with unprotected seeds, often in cones, including the conifers and cycads

Gypsum: dihydrous calcium sulfate ($CaSO_4 2H_2O$)

Habitat: an area or environment where conditions are suitable for the survival of an organism, taxon or community

Habitat type: 'habitat' is a species specific term, with every taxon having its own environmental requirements. 'Habitat type' is used here to refer to areas where environmental conditions are appreciably different from their surroundings. These differences increase the likelihood that the area may support a distinctive flora or fauna assemblage.

Halophile: a species that shows a preference for saline habitat such as salt lakes

Headwater wetland: a wetland at the top of the wetland chain where water originates

Heartwood: the central, woody core of a tree, no longer serving for the conduction of water and dissolved minerals. Heartwood is usually denser and darker in colour than the outer sapwood.

Herbs: plants with non-woody stems that are not grasses or sedges. Generally under half a metre tall. Most monocots are herbs.

Herbivores: animals that chiefly eat plants

Hybrids: the results of interbreeding between two animals or plants of different species

Hydraulic conductivity: a property of plant material, soil or rock that describes the ease with which water can move through pore spaces or fractures. It depends on the permeability of the material and on the degree of saturation.

Hydroecology: the study of the water regimes required to maintain and enhance conservation values of ecosystems

Hydrogeology: the distribution and movement of groundwater

Hydrology: the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere

Hydroperiod: the periodicity (permanent, seasonal, intermittent) of waterlogging or inundation of a wetland

Hue: the property of colours by which they can be perceived as ranging from red through yellow, green, and blue, as determined by the dominant wavelength of the light

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Humus: the organic constituent of soil, usually formed by the decomposition of plants by soil bacteria

Hypothesis: a concept that is not yet verified but that, if true, would explain certain facts or phenomena

Impermeable: does not allow water to move through it

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site

Indigenous: a species that occurs at a place within its historically known natural range and that forms part of the natural biodiversity of a place

Infiltration: the downward movement of water into the soil profile via spaces between soil particles (called pores) and cracks and fractures in the ground

Inorganic: compounds that are not organic (broadly, compounds that do not contain carbon)

Introduced animals: species of animals that have been intentionally or unintentionally brought into a region where they did not historically occur, usually facilitated by humans

Interception: occurs when rainfall that falls over an area is captured on the surface of vegetation (foliage, stems, branches, trucks or leaf litter). This water may evaporate to the atmosphere or falling to the ground (throughfall).

Interflow: shallow lateral subsurface flow of water, which moves nearly parallel to the soil surface, usually in response to a layer of soil that impedes percolation

Intermittent: present for variable periods with no seasonal periodicity

Interquartile range: the distance between the 25th and 75th percentile

Inorganic carbon: (in a wetland) various forms of carbon in solution from non-organic sources including dissolved carbon dioxide (CO_2), bicarbonate (HCO_3), carbonate (CO_3^{2-}) and carbonic acid (H_2CO_3).

Inundation: where water lies above the soil surface (also called surface ponding)

Invertebrate: animal without a backbone

Ion: an atom with an electrical charge. Used to refer to dissolved salts such as sodium (Na^+) or chloride (Cl^-) in solution.

Ionic composition: the particular ions making up a solution, usually expressed in terms of the relevant dominances of the major (most abundant) positively charged and negatively charged ions in a solution

Juvenile: young or immature

Landform: a natural feature of a landscape such as a valley, mountain, basin or plain

Land capability: the ability of land to be used for a particular purpose or managed in a particular way without becoming degraded

Larvae: juvenile insects (the singular being 'larva')

Leaf litter: dead plant matter including leaves, flowers, nuts, sticks and bark which accumulates on the ground

Lentic: standing water

Lethal effect: where exposure to an agent such as a toxin results in death

Lichen: a composite organism consisting of a fungus and a cyanobacterium living in symbiotic association

Life form: the shape or appearance of a plant that mostly reflects inherited or genetic influences

Lignin: a material (a complex organic polymer) deposited in the cell walls of many plants, making them rigid and woody

Lignotuber: a large woody swelling of the plant stem that occurs at and below the soil surface. Regrowth from lignotubers can occur following fire, drought and grazing.

Limiting nutrient: the nutrient in an ecosystem which limits further growth because it is available at proportionately lower levels with respect to other nutrients needed for primary producers to increase their abundance

Livestock: introduced domestic ungulate (or hoofed) animals

Local planning scheme: a set of provisions that identifies the way land in a scheme area is to be used and developed. It may comprise a scheme map(s), a scheme text and an explanatory report.

Local provenance: local origin

Low-stress livestock handling: a method of herding livestock with prompts rather than force

Luxury uptake: the process by which some organisms take up more nutrients than they need for current growth, instead storing them for future growth

Macroalgae: algae large enough to be seen with the unaided eye

Macroinvertebrate: an invertebrate that, when fully grown, is large enough to see with the naked eye (larger than 0.25 millimetres)

Macropores: spaces in the soil (usually less than 2 millimetres diameter) that include channels created by cracking, old plant roots and soil fauna (such as earthworms). Macropores indicate good soil structure.

Mallees: plants with many trunks (usually 2–-5) arising from a lignotuber. The canopy is usually well above the base of the plant. In Western Australia, most are from the genus Eucalyptus.

Management planning: the process of setting management goals for a site and then developing, implementing and reviewing management strategies to meet these goals

Management strategy: a set of actions that will be undertaken in order to achieve goals relating to a wetland component or process

Mangrove: any of various tropical or semi-temperate trees or shrubs of the genera Rhizophora, Bruguiera and Avicennia growing in intertidal shore mud with many tangled roots above the ground

Marl: fine-grained calcareous material (usually from dead charophyte algae that are able to biogenically precipitate calcium carbonate)

Mean: Representative of the values being summarised due to being intermediate between the extremes of the dataset

Median: The value for which one-half (50%) of the observations (when ranked) will lie above that value and one-half will lie below that value

Mesa: an isolated flat-topped hill with steep sides

Metabolic functions: the processes occurring within a living organism that are necessary to maintain life

Metabolism: the chemical reactions that occur in living things that are necessary to maintain life, including the digestion of food

Methanogenesis: the production of methane by microbes

Metropolitan Regional Scheme (MRS): the region planning scheme for the Perth region

Microalgae: microscopic algae

Microbe: an organism that can be seen only with the help of a microscope for example, bacteria, some algae (also referred to as microorganisms)

Microinvertebrate: an invertebrate that is too small to see with the naked eye (smaller than 0.25 millimetres)

Midges: biting and non-biting species of a number of families within the true flies (Diptera) including the Chironomidae and Ceratopogonidae

Migratory species: those animals that migrate to Australia and its external territories, or pass through or over Australian waters during their annual migrations

Mode: The most commonly occurring value in a dataset

Monitoring: the systematic collection of data, over time, in order to test a hypothesis

Monocotyledons (monocots): flowering plants that typically have seedlings with one cotyledon (seed-leaf) and a fibrous root system. They do not form wood and have strappy leaves with parallel veins. Some herbs and all grasses and sedges are monocots.

Monotypic: a genus with only one species

Motile: capable of motion

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Mycorrhiza: a close physical association between a fungus and the roots of a plant, from which both fungus and plant appear to benefit

Native vegetation: native aquatic or terrestrial vegetation, and includes dead vegetation unless that dead vegetation is of a class declared by regulation to be excluded from this definition but does not include vegetation in a plantation or which was intentionally sown, planted or propagated unless that vegetation was sown, planted or propagated as required under law

Naturalised: plants that spread and persist outside of their normal range of distribution

Niche: the role of an organism in a community, in terms of its presence, activity, habitat and the resources it uses

Nocturnal: primarily active during the night

Non-residual herbicides: (or knockdowns) refer to herbicides that kill existing weeds but have no effect on germinating seeds

Non-selective herbicide: (or broad spectrum) refers to herbicides that kill a wide range of plants

Non-synthetic: of natural origin; not derived artificially by chemical reaction, and free from chemical treatments or additives. Other terms commonly used to describe non-synthetic herbicides include natural or organic herbicides.

Non-woody weeds: refer to weeds with a non-woody green stem

NTU: nephelometric turbidity unit is a measure of the clarity of water. Turbidity in excess of 5 NTUs is just noticeable to most people.

Nuisance fauna: a population of native fauna occurring in densities such that it causes harm to the environment or to humans

Nutrient cycling (wetlands): the transformation of nutrients between different chemical forms, and their transport into and out of wetlands

Nymph: a juvenile insect that closely resembles the adult, but has poorly developed wings

Objective: a statement detailing a short to medium-term result of a strategy, which may relate to an output or outcome as it relates to the state of a threat

Obligate wetland plants: plants that are generally restricted to wetlands under natural conditions in a given setting

Observation bore: a non-pumping well with a long slotted section that crosses the water-table

Omnivorous: feeding on both plants and animals

Organic: compounds containing carbon and chiefly or ultimately of biological origin

Organic carbon: carbon existing in or derived from living organisms including all living and dead plant, animal and microbial material

Organism: any living thing

Osmoconformers: species who are not able to regulate the concentration of their internal fluids, so their internal concentrations reflect that of the solution they are immersed in

Osmoregulators: species that are able to regulate the concentration of their internal fluids in relation to the environment

Outcome: a measurable consequence of the project's activities

Outputs: activities undertaken, or products produced, by a particular project

Oxidation: the removal of electrons from a donor substance

Palatable: pleasant-tasting

Palaeochannel: a channel formed by a palaeoriver (ancient river), infilled with deposited sediments and buried over time, often forming modern-day groundwater aquifers

Paluslope: a seasonally waterlogged slope wetland

Pan-tropical: distributed throughout the tropical regions of the earth

Particulate: in the form of particles (small objects)

Peat: partially decayed organic matter, mainly of plant origin

Percentile: The value below which a given percentage of the data values lie. The pth percentile is the value in the dataset which p% of values is less than. The 25th, 50th and 75th percentile are called quartiles. The 50th percentile is the median.

Perched: not connected to groundwater

Perched aquifer: a local aquifer close to the land surface that receives direct recharge from rainfall, but is above and disconnected from the regional unconfined aquifer

Percolation: flow of water down through soil, sediments or rocks without these being completely saturated

Perennial: a plant that normally completes its lifecycle in two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Periphyton: organisms such as bacteria, fungi, algae and invertebrates that are attached to underwater surfaces including sediment, rocks, logs and plants

Pesticide: any chemical or biological agent intended to kill plant or animal pests

pH: a soil or water quality measure of the concentration of hydrogen ions in a solution, which indicates whether the water is acidic, neutral or alkaline; dissolved hydrogen ions being responsible for giving a solution the properties of an acid

Photodegradation: chemical breakdown caused by UV light

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Physiochemical environment: the physical and chemical environment

Phytoplankton: aquatic organisms that photosynthesise and which float or are suspended in water, drifting with water movements and generally having minimal ability to control their location, such as algae

Piezometer: a non-pumping well, with a short length (often 2 metres) of slotted section at the base often below the water table, which is used to measure the potentiometric surface

Plankton: aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location, such as phytoplankton (photosynthetic plankton including algae and cyanobacteria) and zooplankton (animals)

Plant community: a discernable grouping of plant populations within a shared habitat. A community develops due to a unique combination of geologic, topographic and climatic factors and will be recognisable where those factors co-occur.

Playa: a wetland with a basin landform that is intermittently inundated

Population: in statistics, the term population refers to the entire aggregation of components that are the subject of a study. This may be all the individuals in a biological population, but it may equally relate to a non-biological entity such as quadrats.

Potential acid sulfate soils: (also known as potential acid sulphate soils) soils that can contain significant sulfidic material, which on oxidation can cause the pH of the soil to fall to very low levels

Precipitate: cause a substance to be deposited in solid form from a solution

Precision: minimal variability between measurements

Pre-emergent herbicides: refers to herbicides that kill germinating seedlings when applied to the soil before germination

Primary producer: a photosynthesising organism. Primary producers, through photosynthesis, harness the sun's energy and store it in carbohydrates built from carbon dioxide

Primary production: the production of organic compounds from atmospheric or aquatic carbon dioxide, principally through the process of photosynthesis, with chemosynthesis being much less important

Propagate: grow plant specimens from parent material

Propagule: a unit or a piece of an organism that facilitates the organisms' reproduction. Plant propagules primarily include seeds, spores and plant parts capable of growing into new plants. Invertebrate propagules are usually eggs or, in the case of sponges, gemmules. Protist propagules are usually cysts. Bacteria and algae propagules are usually spores.

Property management plan: Also called a whole farm plan; a working plan for the design and management of a property based on its natural resources, the activities undertaken (such as horse breeding or beef production), the manager's goals and financial considerations

Proponent: the person who is responsible for the proposal, or the public authority on which the responsibility for the proposal is imposed under a written law

Provenance: the place of origin

Pugging: depressions, hoof prints or 'pug' marks made in wet soil by trampling animals

Pyritic sediments: sediments containing iron pyrite

Pyrite: FeS_2, an iron sulfide mineral that is a common component of sulfidic material

Qualitative data: descriptive data; they are collected using techniques such as estimation, categorisation, statements of type or condition, diagrams photographs and maps

Quality assurance: the process of documenting data quality and data confidence by describing how the dataset was collected, analysed and stored

Quality control: the process of detecting errors and determining their magnitude

Quantitative data: data that are measured or counted in some way, for example, the number of plants in a plot or the pH of a water sample

Rainfall: a product of the condensation of atmospheric water vapour that is deposited on the Earth's surface

Ramsar Convention: an international treaty that focuses on the conservation of internationally important wetlands, signed in Ramsar, Iran in 1971 (the Convention on Wetland of International Importance Especially as Waterfowl Habitat)

Range: The difference between the maximum and minimum value in a dataset

Range ends: Populations at the margins of the area to which a species is native

Recharge: the physical process where water naturally percolates or sinks into a groundwater basin

Recharge area: the land surface area over which recharge occurs to a particular groundwater aquifer

Recharge wetland: a term used by geologists to describe wetlands from which water flows out of into the groundwater, 'recharging' it

Recruitment: addition of new individuals to a population (usually through reproduction)

Red list criteria: developed by the International Union for the Conservation of Nature (IUCN) to allocate species of flora and fauna into threat categories of critically endangered, endangered and vulnerable, based on their likelihood of becoming extinct

Redox: the removal ('oxidation') or addition ('reduction') of electrons

Redox potential: the potential of chemical substances to undergo two (coupled) types of chemical change: the removal ('oxidation') or addition ('reduction') of electrons

Reduction: the addition of electrons to an acceptor substances

Reference range: a quantitative and transparent benchmark appropriate for the type of wetland

Reference wetland: a wetland used to provide a model for planning a management project

Refugia: restricted environments that have been isolated for extended periods of time, or are the last remnants of such areas

Region planning scheme (region scheme): a planning scheme prepared for matters of state or regional importance to enable effective planning and coordination of land use and development. Also known as a region scheme.

Regional open space: land defined under a region scheme, regional structure plant or sub-regional structure plant as a parks and recreation reserve or regional open space reserve, to accommodate active and passive recreation such as major playing fields and/ or regional conservation and environmental features

Regulation: a law made under the authority of an Act of Parliament

Rehabilitation: the re-establishment of ecological attributes in a damaged ecological community although the community will remain modified

Reintroduction: the deliberate release of a species in an area which is part of its natural historical range but in which it no longer occurs

Replication: repeating an experiment several times and collating all the results. It allows the error margin of the measurements and natural variations in the subjects to be discounted from consideration.

Representativeness: how well a series of measurements reflect the full range of values in the system being measured

Reserved: set aside for public purposes

Residual herbicides: refer to herbicides that remain active in the soil for some time and may kill germinating seeds and susceptible plants

Resilience: capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Restoration: returning an ecological community to its pre-disturbance or natural state in terms of abiotic conditions, community structure and species composition

Revegetation: return vegetation (indigenous or otherwise) to an area

Rhizome: a horizontal, underground stem which bears roots and leaves and can usually persist, even if above-ground parts die back

Rhizosphere: the area of soil immediately surrounding plant roots, which is altered by their growth, respiration, exchange of nutrients etc

Ringbark: to completely removing a strip of bark around the trunk or main stem of a tree or shrub, causing its death

Riparian: habitats adjacent to waterways and estuaries

Rotational grazing: a type of controlled grazing system. Paddocks are usually subdivided into smaller pastures and grazed at higher intensities for shorter periods (to achieve more even grazing), then spelled (or rested).

Rush: see the definition of ‘sedge’

Salinisation: the process of accumulation of salts in soils, waters or sediments

Salinity: a measure of the concentration of ions in waters, soils or sediments. This measurement is used to describe the differences by waters that are considered ‘fresh’ (with very low concentration of ions) and those that are considered ‘saline’ (with high concentrations of ions)

Salts: ionic compounds comprised of cations (positively charged ions, such as sodium, Na^+) and anions (negative ions, such as chloride, Cl^-)

Salt scald: a bare area of ground caused by secondary salinisation, in which vegetation has died and solid salt is visible

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia, Halosarcia, Sarcocornia, Sclerostegia, Tegicornia* and *Pachycornia,* belonging to the family Chenopodiaceae

Sampling: the process of selecting a set of individuals that will be analysed to yield some information about the entire population from which they were drawn

Sampling point: the precise place at which a sample is taken

Saprotroph: an organism that absorbs soluble organic nutrients from inanimate objects (e.g. from dead plant or animal matter, from dung etc)

Sapwood tissue: specialised plant tissue that transports water and minerals upwards from the roots to the stem, via capillary action

Saturated: the state in which all available spaces are filled with water

Savanna: a grassy woodland, grassland with small or widely spaced trees so that the canopy is always open allowing a continuous layer of grasses underneath

Scalping: involves slicing off the top layer of soil which contains weeds and weed seeds, leaving the surface bare in preparation for revegetation

Scheme: a redevelopment scheme, a region planning scheme, a local planning scheme or a State planning policy to which section 32 of the *Planning and Development Act 2005* applies, or an amendment to any of these

Scum: froth or floating matter on the water surface

Seasonal: present during a given period of the year, recurring yearly

Secondary salinisation: a human-induced process in which the salt load of soils, waters or sediments increases at a faster rate than naturally occurs

Sediment: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology

Sedimentation: the process by which soil particles (sand, clay, silt, pebbles and organic materials) suspended in water are deposited or settle to the bottom of a water column

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Sediment pore water: water present in the spaces between wetland sediment grains at or just below the sediment surface. Also called interstitial waters.

Seed dispersal mechanisms: the means by which plants distribute their seeds, for example via wind, water, birds and insects, etc

Selective herbicide: refers to herbicides that have been developed to kill a particular type of plant (e.g. grasses)

Semi-confined aquifer: an aquifer deep under the ground with leaky aquitards

Senescence: the natural aging and subsequent death of an organism

Sensitivity: the ability to distinguish between different values in the parameter being measured

Services: benefits that people receive or obtain from an ecosystem. This term is often used in conjunction with the term 'benefits'. See also 'benefits'.

Shallow aquifer: another term for unconfined aquifer

Shelterbelts: belts or rows of trees and shrubs planted to provide protection against prevailing winds

Shorebirds: those birds commonly found wading near the shores of wetlands, beaches, mudflats and lagoons in search of food. They include plovers, sandpipers, stone-curlews, snipes, pratincoles, oystercatchers, stilts and avocets.

Shrubs: plants with one or more woody stems and foliage all or part of the total height of the plant

Significant proposal: a proposal likely, if implemented, to have a significant effect on the environment.

Slightly disturbed: ecosystems that have undergone some changes but are not considered so degraded as to be highly disturbed. Aquatic biological diversity may have been affected to some degree but the natural communities are still largely intact and functioning. An increased level of change in physical, chemical and biological aspects of these ecosystems is to be expected.

Soil texture: the distribution of grain sizes of the mineral particles in a soil

Soluble: able to dissolve

Solubility: a measure of how soluble a substance is

Sorting (aquatic invertebrates): picking individual organisms from a sample to form a sub-sample

Spatial scale: the minimum size of an area about which data are collected

Spawn: eggs surrounded by jelly; generally applied to a group of eggs

Species: a group of organisms capable of interbreeding and producing fertile offspring, for example, humans (Homo sapiens)

Species richness: the total number of species (in a defined area)

Spelling: of a paddock or pasture, involves removing livestock grazing pressure for a period of time so that vegetation can regenerate

Spicule: minute, needle-like body made of silica or calcium salts found in some invertebrates

Spore: a reproductive structure that is adapted for dispersal and surviving for extended periods of time in unfavourable conditions

Stable stratification: stratification which persists for much longer than a day (often months)

Stakeholder: individuals, groups or institutions that have an interest in or will be affected by a project's activities.

Standard deviation: A measure of how closely the values in a dataset are clustered around the mean

Standard error: A measure of how close the sample mean is likely to be to the population mean

State Environmental Policies (SEPs): non-statutory policies which are developed by the EPA under provisions of Part II of the EP Act through public consultation and are adopted following Cabinet consideration and approval

Statute: a law enacted by the State or the Federal Parliament

Stocking rate: the number of livestock that can consistently be kept on an area of pasture all year round with minor additional feed and without causing environmental degradation

Stolons: stems that usually run horizontally along the soil surface

Stomata (plural of stomate): pores in leaves and stems used for gas exchange

Stonewort: a term applied to Chara species that precipitate and deposit calcium carbonate on their surfaces

Stormwater: water flowing over ground surfaces, in natural streams and drains as a direct result of rainfall over a catchment. It consists of rainfall runoff and any material (soluble or insoluble) mobilised in its path of flow

Strategic proposal: a future proposal that will be a significant proposal; or future proposals likely, if implemented in combination with each other, to have a significant effect on the environment

Strategies: in the context of management planning, a set of actions that will be undertaken in order to achieve goals relating to a wetland component or process

Stratify: separate the water column into distinct layers

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between these layers

Stratum: (plural strata) a visibly conspicuous layer of photosynthetic tissue within a plant community

Stromatolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate (see also 'thrombolite')

Structure plan: a plan that provides a framework for the coordinated provision of land use, development, infrastructure and allocation of services at either the regional, district or local level. Not always a statutory requirement.

Study site: the wetland that is being monitored

Subdivision: the division of land into lots

Sublethal effect: where exposure to an agent such as a toxin is insufficient to cause death, but may result in other adverse impacts

Submerged: a plant that is entirely underneath the surface of the water

Substrate: a generic term denoting the material forming the floor of a wetland and its surrounds. It is used here because the term 'soil' is not inclusive of organic substrates.

Succession: progressive change in species composition and/or structure that occurs following disturbance of a site

Succulent: plants which have specialised fleshy, soft and juicy tissues designed for the conservation of water e.g. cacti

Sulfate reduction: the chemical process where sulfate is joined with hydrogen and gains electrons

Summary statistics: measures that express the central tendency and variability of a dataset; most commonly mean, median, mode, range, standard deviation, standard error and percentile

Superficial aquifer: another term for unconfined aquifer

Surfactant: a substance that helps water or other liquid to spread or penetrate. Also known as a wetting agent or penetrant.

Surficial aquifer: another term for unconfined aquifer

Surface run-off: water that flows down slope over the ground surface; also called overland flow

Surrogate measure: another component of the system that shows a correlated response to the management issue being evaluated

Survey location: the area of the wetland where a survey is completed

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Symbiosis: a relationship in which dissimilar organisms live in close association, and which is mutually beneficial to both organisms

Tannins: complex organic compounds (polyphenols) occurring in various plants

Taxa: a taxonomic group (the singular being taxon). Depending on the context, this may be a species or their subdivisions (subspecies, varieties etc), genus or higher group.

Temporal: of or pertaining to time

Temporal variations: changes that occur over time

Terminal wetland: a wetland at the bottom of the wetland chain. It receives water from other systems but water generally does not exit it other than through evaporation or seepage into the ground (or occasional flooding overflow in large events).

Thermal water pollution: the excessive raising or lowering of water temperatures above or below normal seasonal ranges as a result of the discharge of hot or cold effluents

Thermocline: the narrow vertical layer within a body of water between the warmer and colder layers where a rapid temperature change occurs

Threat: any factor that is currently or may potentially negatively affect wetland components or processes. A threat can be currently active or present (such as weeds), or a potential threat (such as a proposal to expand a picnic area into native vegetation in good condition).

Threatened ecological community: naturally occurring biological assemblages that occur in a particular type of habitat that has been endorsed by the WA Minister for Environment as being subject to processes that threaten to destroy or significantly modify it across much of its range

Threatened flora: flora that has been assessed as being at risk of extinction or is rare or otherwise in need of special protection and gazetted as such by the Minister for Environment. These species are commonly referred to as declared rare flora.

Threatening process: processes that threaten the survival, abundance or evolutionary development of a native species or ecological community

Thresholds: points at which a marked effect or change occurs

Thrombolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate (see also 'stromatolite')

Throughflow wetland: a wetland that lies between headwater wetlands and terminal wetlands (or the sea) in a wetland chain. It receives water from upgradient wetlands and supplies water to downgradient wetlands.

Total dissolved solids (TDS): a measure used to approximate the concentration of ions in wetland water (that is, total dissolved salts/salinity). It will usually over-estimate these as TDS includes dissolved organic compounds.

Total grazing pressure: describes the combined impact of all grazing animals – domestic, wild, native and feral – on the vegetation, soil and water resources of a particular area

Transparency: a measure of the degree to which light is able to penetrate the water column

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour.

Treatment: subjection to some agent or action. In the case of a monitoring program, the treatment will be the management regime that is expected to cause some change in the condition of the site

Trees: plants with a single trunk and a canopy. The canopy is less than or equal to two thirds of the height of the trunk. No lignotuber is evident.

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response e.g. further investigation

Tolerance limits: the upper and lower limit to the range of particular environmental factors (e.g. light, temperature, salinity) within which an organism can survive. Organisms with a wide range of tolerance are usually distributed widely, while those with a narrow range have a more restricted distribution

Total nitrogen: the sum of all chemical forms of nitrogen

Total phosphorus: the sum of all chemical forms of phosphorus

Trophic: relating to nutrition, food or feeding

Trophic classification: the classification of an ecosystem on the basis of its productivity or nutrient enrichment

True colour: a measure of colour which includes the influence of humic substances and other dissolved substances such as iron, measured in true colour units (TCU)

Tubers: specialised fleshy storage organs of the stem that are present in some plant species, usually found underground

Tufa: a porous rock composed of calcium carbonate and formed round mineral springs

Tumulus mound spring: peat-formed mound spring

Turbid: the cloudy appearance of water due to suspended material

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Turn out location: the site at which livestock are released into a fresh pasture

Unconfined aquifer: an aquifer close to the land surface which receives direct recharge from rainfall. Its upper surface is the water table. Also referred to as a superficial or surficial aquifer.

Understorey: the layer of vegetation beneath the main canopy

Unstable stratification: layers form in the wetland water column each day (usually in the afternoon) and mixing occurs over night

Vacuole: a storage compartment found within a cell

Value (soils): the property of a colour by which it is distinguished as bright or dark; also known as luminosity

Values: the internal principles that guide the behaviour of an individual or group and determine the importance that people place on the natural environment and how they view their place within it

Vascular plants: plants with defined tubular transport systems. Non-vascular plants include algae, liverworts and mosses.

Vegetation: combinations of plant species within a given area, and the nature and extent of each area

Vegetation structure: the three-dimensional distribution of plant material. It includes the horizontal spacing of plants and the vertical heights or layers

Vegetative: a stage or structure of a plant that is concerned with feeding, growth or asexual reproduction, rather than sexual reproduction

Vegetative reproduction: a type of asexual reproduction found in plants. Also called vegetative propagation or vegetative multiplication.

Vertebrate: animal with a backbone

Vision: the desired state or ultimate condition that a plan is working to achieve which is usually expressed in the form a statement

Water budget: the balance of all of the inflows and outflows of water

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from sediment pore waters of inundated and waterlogged wetlands)

Water cycle: Continual circulation of water between the land, the oceans and the atmosphere. Also called the hydrological cycle.

Waterlogged: saturation of the soil

Water quality: the quality of water relative to its natural, undisturbed state

Water regime: the specific pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Water table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Waterbirds: birds that have specialised beaks and feet that allow them to swim, dive and feed in water. Examples include egrets, crakes, herons, ducks, swans and grebes.

Weed: a plant that requires some form of action to reduce its harmful effects on the economy, the environment, human health and amenity, and can include plants from other countries or other regions in Australia or Western Australia

Wetland: an area of seasonally, intermittently or permanently waterlogged or inundated land, whether natural or otherwise, and includes a lake, swamp, spring, dampland, tidal flat or estuary

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

Wetland conceptual model: a simplified diagram that expresses ideas about components and processes that are important to the ecosystem

Wetland components: the physical, chemical and biological parts of a wetland, from large-scale to very small scale e.g. habitat, species and genes and include the physical form of the wetland, wetland soils, physicochemical properties of the water and the wetland flora and fauna

Wetland flora: wetland plant species, subspecies and varieties in a given area

Wetland hydrology: the movement of water into and out of, and within a wetland

Wetland plants: plants that inhabit wetlands

Wetland processes: the dynamic physical, chemical and biological forces within a wetland, including interactions that occur between wetland organisms, within the physical/chemical environment, and the interactions of these

Wetland state: the ecological characteristics of a wetland as they exist at a particular time

Wetland typology: a process of classifying wetlands according to characteristics of their hydrological, morphological, chemical and biological factors

Wetland vegetation: combinations of wetland plants in a given area, and the nature and extent of each area

Wetting agent: a substance that helps water or other liquid to spread or penetrate (also known as a surfactant or penetrant)

Woody weeds: perennial weeds with woody stems including shrubs, trees and some vines

Zooplankton: tiny invertebrates and protozoans floating or suspended in the water that drift with water movements, generally having little or minimal ability to control their location

A guide to managing and restoring wetlands in Western Australia

Wetland management planning

In Chapter 1: **Planning for wetland management**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Wetland management planning' topic

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Recommended reference

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When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Wetland management planning', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by C Mykytiuk, Department of Environment and Conservation, Perth, Western Australia.

Contents

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'

INTRODUCTION

This topic is intended to assist technical officers in local, state government and non-government organisations, landholders, community groups and others working in the field of wetland management and conservation to develop, implement and evaluate the effectiveness of wetland management plans. It aims to provide guidance on wetland management planning in a simple and user-friendly manner.

There are many methods for undertaking the process of management planning, each of which is slightly different and uses different terms. The process provided and the terminology utilised in this topic draws upon many widely-used methods.

Due to the variability of the situations in which management planning may occur, it is not possible to provide a detailed step-by-step methodology that will suit all situations. Instead this document will present the key steps in the process and will refer readers to other sources of information for methodologies to assist in completing these steps. In the topic the management planning processes has been broken down into four main stages (each with multiple steps). These stages are:

- Stage A: Pre-planning
- Stage B: Planning
- Stage C: Implementing
- Stage D: Evaluating and adapting.

Assumptions and limitations of this document

It is important to note that this document is for general guidance only. If you are required to undertake a management planning process or prepare a wetland management plan as a requirement or legal obligation, you must follow any guidance provided under that requirement or obligation. Please also note that the terminology used in this document differs slightly from that used in the *Guidelines checklist for preparing a wetland management plan*.[1]

Although management planning can be undertaken at a range of different scales from region to individual species, this document deals with management planning at the scale of individual wetlands. This document also assumes that the wetland has already been identified as a priority for management. Providing advice regarding prioritising management between multiple wetlands or between different assets such as wetlands and adjacent dryland vegetation is beyond the scope of this document.

Examples of prioritisation processes include:

- *Local government biodiversity planning guidelines*[2], and additional associated resources including a case study and guidance on prioritising locally significant natural areas.
- Recovery catchments with multiple wetlands, for example, see the *Buntine-Marchagee natural diversity recovery catchment recovery plan: 2007-2027* (Department of Environment and Conservation, 2008).[3]

What is management planning and why is it important?

Adaptive management: an approach that involves learning from management actions, and using that learning to improve the next stage of management[4]

Management planning is the process of setting management goals for a site and then planning, implementing and evaluating management strategies to meet these goals. It must be emphasised that it is a process and is not just about preparing a plan, although documenting information in a written plan is an essential part of the process. Successful management planning processes can be seen as an on-going cycle of plan-implement-evaluate (Figure 1). This cycle is also referred to as **adaptive management**.

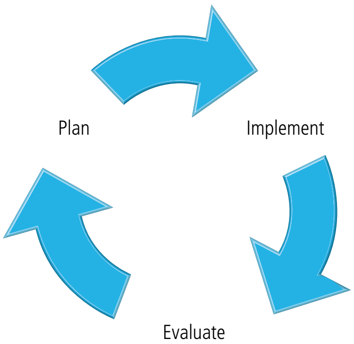


Figure 1. The adaptive management cycle; plan, implement, evaluate.

There are a number of benefits of undertaking management planning that can include:

- establishing a long-term vision and clear goals and objectives for the site to guide management
- gaining consensus amongst stakeholders on the management of the site, minimising potential for future conflict
- engaging with and working effectively with stakeholders to improve the management of the site
- ensuring that management actions undertaken will contribute to achieving the vision, goals and objectives for the site, resulting in efficient usage of time, money and human resources
- having an adequate monitoring program to enable the success or failure of management actions to be evaluation, improving future management
- maintaining effort and consistency in the management of the site and
- utilising the prepared management plan to secure funding for the site.

Principles of successful management planning

There are a number of essential principles to successful wetland management planning including:

- custom-made - as no two wetlands are the same, the management planning process and the outcomes will be unique for each wetland
- adaptive management – management is modified as conditions at the site change or new information becomes available regarding the success or failure of management strategies

- on-going **stakeholder** consultation and involvement – stakeholder consultation and involvement is an on-going process and should be initiated from an early stage in the process
- don't postpone the process until all the information is available – although as much information should be collected as possible, don't allow a lack of information to delay the management planning process, it is unlikely that all the information will ever be available. Build the collection of more information into the management planning process, where appropriate.

Stakeholder: an individual, group or institution that has an interest in or will be affected by a project's activities

Custom-made

All wetlands are unique; as such the management planning processes and outcomes of the process will be different for each wetland. Wetland management planning needs to be tailor-made for individual wetlands and it is unlikely that a management plan prepared for one wetland will be suitable for another.

Adaptive management

Adaptive management is at the heart of successful management planning. The key to adaptive management is continual evaluation of the effectiveness of management strategies and adapting them accordingly. Management strategies may be adapted if conditions at the site change or if a strategy is not achieving the outcome it was selected to achieve.

➤ For additional detail on evaluating and adapting a management plan see the section 'Stage D: Evaluating and adapting' in this topic.

On-going stakeholder consultation and involvement

There are a number of benefits of on-going stakeholder consultation and involvement in a management planning process including:

- improving the quality of the planning process and outcomes of it
- gaining new perspectives and solutions
- forming beneficial partnerships to assist in project implementation
- promoting confidence in the process
- fostering a sense of ownership amongst stakeholders
- increasing the understanding of the wetland's values
- reducing the potential for conflicts.

Stakeholders may include neighbours, nearby land managers and landowners, community groups or organisations and local and state government agencies and utility providers if there are overhead or underground services located within or adjacent to the management planning area.

It is important that stakeholder consultation and involvement is initiated as early as possible and continues throughout the management planning process.

extra information

Stakeholder consultation and involvement

For information on incorporating Aboriginal cultural heritage into a wetland management plan see:

Swan Catchment Council (2008). *Aboriginal cultural heritage management plan template 2008*[5]

For more information on stakeholder consultation and involvement see:

Community involvement framework (Department of Environment, 2003)[6]

Interim industry guide to community involvement (Department of Environment and Environmental Protection Authority, 2003)[7]

Facilitation toolkit: A practical guide for working more effectively with people and groups (Keating, Colma DM, 2003)[8]

Consulting citizens: A resources guide (Department of Premier and Cabinet Citizens and Civics Unit, 2003)[9]

Consulting citizens: Planning for success (Department of Premier and Cabinet Citizens and Civics Unit, 2003)[10]

Consulting citizens: Engaging with Aboriginal Western Australians (Department of Premier and Cabinet Citizens and Civics Unit, 2004)[11]

Don't postpone the process until all the information is available

In any management planning process, all the information will never be available. Rather than waiting for all the information to be available, which may never happen, management planning should proceed using the best available information and wherever possible expert advice to verify and add to the available information. Expert advice can be very valuable and can often be used in lieu of documented information. The collection of baseline surveys and other information can be built into the management plan.

KEY STEPS IN THE MANAGEMENT PLANNING PROCESS

The key stages and specific steps in the management planning process are outlined in Table 1 and then described in more detail in the sections below. The key stages of the process are: pre-planning, planning, implementing and lastly evaluating and adapting. Although management planning is being presented as a linear process, in practice, it may be far from linear with many steps overlapping and at the completion of some steps, previous steps may need to be revisited and revised. The process may be a relatively straightforward one or it may be complex and time consuming. The complexity of the process will depend on a number of factors including:

- the size of the site being considered
- the number of landowners and land managers
- the numbers of other stakeholders
- the complexity of the site in terms of the values to protect and the threats to address
- requirements for the plan and the level of detail stipulated in these requirements
- consultation and approvals processes.

As previously mentioned, because of the variability of the situations in which management planning may occur, it is not possible to provide a detailed step-by-step methodology that will suit all situations. Instead this document presents the key steps in the process and refers readers to other sources of information for methodologies to assist in completing these steps. Table 1 shows the key steps in the management planning process. Figure 2 shows the same steps in diagrammatic form.

Table 1. Key steps in the management planning process.

STAGE	STEP
Stage A: Pre-planning	**Step 1**: Defining the process
	Step 2: Understanding the wetland
Stage B: Planning	**Step 1**: Identifying values and developing a vision
	Step 2: Identifying key components and processes, assessing condition and setting goals
	Step 3: Identifying and ranking threats
	Step 4: Selecting management strategies and setting objectives
	Step 5: Preparing an implementation plan
Stage C: Implementing	Implementing management strategies and monitoring activities
Stage D: Evaluating and adapting	Auditing the results of the plan, and re-assessing the plan itself

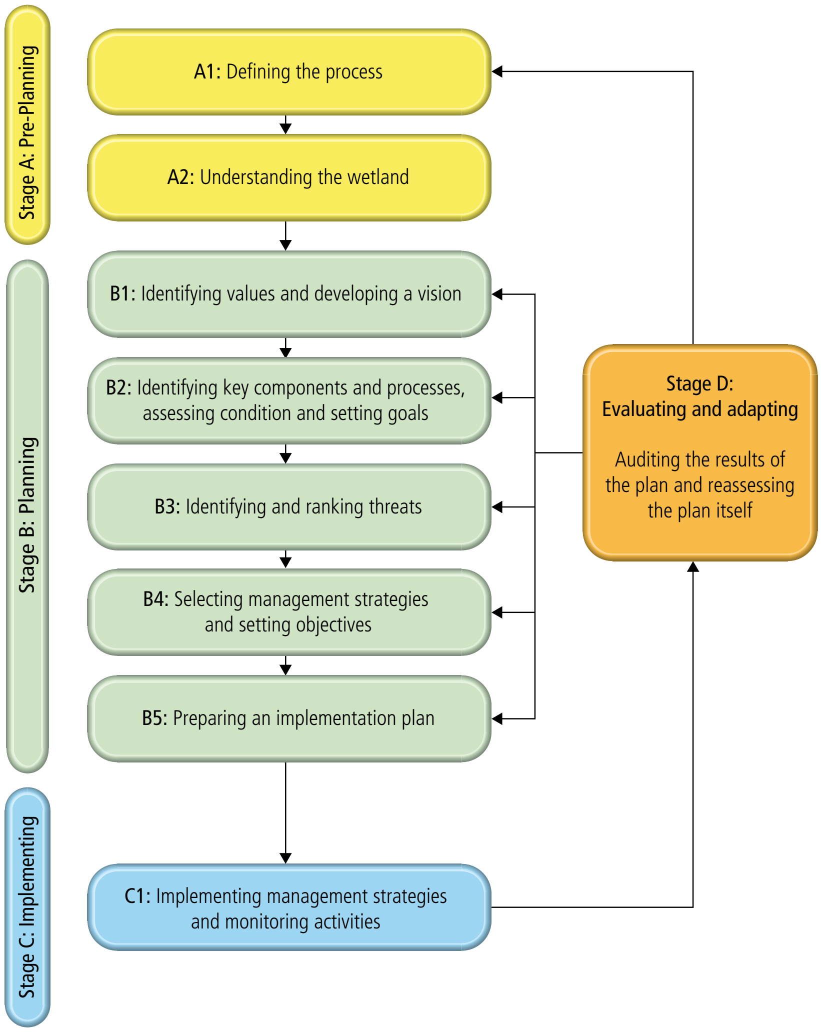


Figure 2. Key steps in the management planning process.

STAGE A: PRE-PLANNING

This is the stage at which the decision is formally made to undertake a management planning process. At this stage important decisions are made on how the planning process will proceed. It is also at this stage that information will begin to be collected to gain an understanding of the management area. Gaining this understanding is critical to being able to undertake a successful management planning process. There are two steps in the pre-planning stage:

1. defining the process
2. understanding the management area.

Step 1: Defining the process

The aim of this stage is to clarify a number of key aspects of the process including the project team, any requirements for the plan and importantly the scope of the plan in terms of the geographic area it will cover and broad timeframes for its preparation, implementation and review.

Project team

Regardless of whether the process is being undertaken by professionals or volunteers, it is important that the roles and functions of project team members are established during the early stages of project definition. There may be a number of different roles in the project team as outlined in Table 2. While a management planning process may be triggered by a third party, such as a community group, the process should ideally be managed by the owner or manager of the land. If a consultant is to going to be employed to write the plan on behalf of the owner or manager, it will be necessary to prepare and agree upon a project brief and nominate an individual as 'contract manager'. In this case a project team will be assembled by the contractor.

Table 2. Potential roles and functions of a management planning project team.

Role	Function
Project manager	Although leadership may be shared between team members, one individual should be appointed as overall leader for the project.
Core project team	A small group who are ultimately responsible for overseeing the management planning process.
Full project team	Complete group of people involved in preparing, implementing and, evaluating and adapting the management plan.
Project advisors	People not on the project team, but who may provide advice or feedback at any stage of the process.
Stakeholders	Individuals, groups, or institutions who have a vested interest in the management area and/or who will potentially be affected by the management strategies. If someone is a key stakeholder it may be appropriate to include them as a member of the project team. For more information on stakeholders see the 'On-going stakeholder consultation and involvement' section above.

Ramsar Convention: an international treaty that focuses on the conservation of internationally important wetlands signed in Ramsar, Iran in 1971

Successful stakeholder partnerships

Many successful management plans have been based on a strong partnership between different stakeholder groups, including government and community organisations. Strong partnerships can be achieved by either party inviting the other to become a member of the core project team, a project advisor or stakeholder.

Such partnerships between organisations are effective as long as there is a clear understanding on roles, responsibilities and funding contributions, which can be established through a formal, written partnership agreement.

Contextual information

It is important to identify any contextual information which will guide or inform the management planning process. Specifically, this will include any requirements for the plan as well as any other information that provides context to the plan such as regional catchment plans and previous management plans for the site.

Requirements for the plan

It will be important to identify if there are any requirements for the plan as these may influence the process and guide the contents of the plan. In particular this information will inform the scope of the plan, any requirements for consultation approvals and potentially the project team and stakeholders. There are a number of situations in which the preparation of a wetland management plan may be required through a statutory process such as a condition of development, subdivision or scheme amendment approvals. In the case of wetlands of international significance listed under the **Ramsar Convention**, the development of wetland management plans are not statutory but are a tool for achieving obligations of the international treaty.

In such situations it will be necessary to follow the relevant requirements or frameworks. For instance, for management plans developed for wetlands listed under the Ramsar Convention, it is a requirement that they describe the benefits that humans gain from that wetland, and management strategies associated with these benefits.

➤ For more information on wetland management plans required to be prepared as a condition of a development, subdivision or scheme amendment approval, or local government development application see *Guidelines checklist for preparing a wetland management plan* (Department of Environment and Conservation, 2008).[1]

➤ For more information on the preparation of wetland management plans for wetlands of international significance listed under the Ramsar Convention see:

- the Australian Government's Australian Ramsar management principles webpage: www.environment.gov.au/water/topics/wetlands/managing/aust-ramsar-management-principles.html
- Ramsar Handbook18 *Managing wetlands: Frameworks for managing wetlands of international importance and other wetland sites*[12]

Supporting information

There is a wide range of information which may provide context to the management planning process or the contents of the plan including:

- relevant international, national or state plans
- relevant regional or catchment plans
- previous versions of the plan or other management plans for the site.

➤ For more information on relevant plans contact the relevant local government, regional natural resource management organisation or local DEC office. See the topic 'Funding, training and resources' in Chapter 1 for contact details for these groups.

Scope of the plan and the process

Defining the scope of the plan and the process will assist in keeping it focused and preventing it from getting out of hand. There are a number of elements of the scope that need to be defined including:

- geographic – the physical area that the management plan will cover
- temporal – the timeframe for the planning process as well as the term of the plan itself and
- resources – the resources that are available for both the planning process implementation of the plan. Key resources include money, staff, skills and equipment.

Geographic

The management plan area typically includes the wetland(s), wetland buffer and any other adjacent areas, such as dryland vegetation, where activities will be controlled in accordance with the plan.

The buffer adjoining a wetland assists in maintaining the ecological processes associated with the wetland, and aims to protect the wetland from potential adverse impacts such as contaminated surface water flows caused by adjacent land uses. A buffer can also assist in protecting the community from potential nuisance insects, for example, midges. To maintain wetland values, it is important to determine, protect and manage an adequate buffer. If the wetland buffer is outside of the management plan area, potentially because it is under the control of a different land manager or owner, careful consideration should be given to how the plan will influence the management of the wetland buffer.

➤ For more information on wetland buffers see Chapter B4 of *Environmental guidance for planning and development*.[13] A new methodology for determining wetland buffer requirements is in preparation. Refer to the DEC website www.dec.wa.gov.au/wetlands for more information.

Areas adjacent to the buffer are often also included in wetland management plans. If not appropriately managed, land uses in these adjacent areas can change the wetland's natural water, soil and biotic regimes (e.g. grazing, parkland, housing and picnic areas).

In some instances the inclusion of numerous wetlands in one management plan may be considered. This may be a wise decision if a number of wetlands are inter-connected through surface or groundwater and hence are part of a single system. An example of this is the wetlands in the Buntine-Marchagee Catchment, the management of which has been addressed in the *Buntine-Marchagee natural diversity recovery catchment recovery plan: 2007-2027* (Department of Environment and Conservation, 2008).[3]

In some instances, the wider geographic area that the plan will seek to influence should also be defined. For example, a land development company may influence activities within the boundary of a new residential or industrial subdivision in which the wetland is located. In this instance the plan should address strategies for the new subdivisions. A farmer may choose to identify management strategies for the paddocks surrounding the wetland, or even for the entire farm.

Temporal

Preparing the plan

There are a number of factors that will potentially influence the timeframe for the preparation of a management plan, the extent of some of these factors will not be known until late in the process. As such, although a timeframe for the preparation of the plan will be set, it may need to be revised later in the process. Factors that will potentially influence the timeframe of the plan's preparation include:

- the size of the site being considered
- the number of landowners and land managers
- the numbers of other stakeholders
- the complexity of the site in terms of the values to protect and the threats to address
- requirements for the plan and the level of detail stipulated in these requirements
- consultation and approval processes
- the format of the final product, whether it be a map accompanied by a couple of pages of text or a document hundreds of pages in length.

Implementing and reviewing the plan

There is no standard length of time a plan should last for (that is, a term or timeframe). Some wetland management plans are applicable for a single year while others are for twenty or more years. The important thing to keep in mind when deciding upon a time period for a management plan is the realistic length of time that will be required for the goals of the plan to be achieved. For example, if one of the goals of a management plan is: 'By July 2019, the extent and cover of native vegetation and native plant species richness at the site is equal to or greater than levels in 1999' and the threat which needs to be mitigated to achieve this is weeds, you would expect it to take at least five years before any results are achieved.

Financial

When making the decision to undertake a management planning process and prepare, implement and, evaluated and adapt a management plan it is important to be aware of the costs involved in undertaking this process from start to finish. Potential costs involved in preparing, implementing and reviewing the management plan may include:

- employment of staff and contractors
- cost of holding meetings
- undertaking surveys of the site (flora, fauna etc)
- materials and labour for implementation.

At this early stage it is unlikely that the full cost of each stage will be known but it is important to budget for each stage and recognise early in the process any potential shortfalls in funding.

Step 2: Understanding the management area

In order to successfully manage a wetland it is essential to have an understanding of the management area including the wetland itself. The aim of this step is to begin to gain this understanding and to gather enough information to inform the subsequent steps of the management planning process including:

- identifying key values
- identifying key wetland components and wetland processes
- setting goals for the condition of key components and processes
- identifying and ranking threats
- selecting management strategies.

Table 3 provides a guide for the type of information that should be collected during this stage of the process. Importantly, this step of the process is about what is and is not known about the site. Undertaking this step towards the beginning of the management planning process will allow any knowledge gaps to be identified and addressed early. Subsequent steps in the process, including identifying values, identifying key wetland components and processes and identifying and ranking threats will enable further detail to be added to the information collected during this step.

There will be a range of sources for this information including:

- written documents including reports and plans (both published and unpublished)
- electronic databases and datasets
- expert advice
- anecdotal information
- on-ground investigations.

Although there may seem to be an infinite amount of information that can be collected at this stage of the process, the information gathered should be limited to that which is relevant to the management of the wetland(s). At this stage it can be very useful to carry out an initial, broad assessment of the management area to gather much of this information.

Table 3. Information that will assist in undertaking a management planning process.

Type of information	Examples
Administrative information	• a description of the geographic extent of the management area (as defined in Stage A, Step 1) • location, name and description of the wetland • current tenure, ownership, vesting, purpose and management arrangements, including adjacent reserves and properties • local and regional scheme zoning and land use (existing and proposed) within and adjacent to the management area • infrastructure such a fences, pathways, boardwalks and buildings (existing and proposed) within and adjacent to the management area

<table>
<tr><th>Type of information</th><th colspan="2">Examples</th></tr>
<tr><td>Administrative information</td><td colspan="2">• wetland boundary, classification (wetland type) and, if available, the assigned wetland management category and unique feature identifier number (UFI)
• natural wetland group (e.g. consanguineous suite).
• recognised conservation significance of the site
o representation of the wetland within an international, national, regional and local context
o bioregion values (e.g. Interim Biogeographic Regionalisation for Australia; biodiversity hotspot)
• requirement for the plan (e.g. WAPC subdivision condition)
• subdivision and/or development plans (as identified in Stage A, Step 1)
• regional, sub-regional and catchment plans which provide context for the plan (as identified in Stage A, Step 1)
• legislation and government policies that apply to the management area.</td></tr>
<tr><td>Management actions</td><td colspan="2">Gather any available information on previous or current management actions that have been undertaken at the site.</td></tr>
<tr><td>Values</td><td colspan="2">At this stage it is only necessary to gather any existing information on the values of the site as the values of the site will be examined further in the next stage of the process. For additional detail and specific examples of wetland values see ‘Step 1: Identifying values and developing a vision’ in Stage B.</td></tr>
<tr><td>Components & processes of the wetland</td><td colspan="2">Gather any available information regarding the historic, current or predicted future state of each component and process. For additional detail and specific examples of wetland components and processes see ‘Step 2 Identifying key components and processes, assessing condition and setting goals’ in Stage B.</td></tr>
<tr><td></td><td>Components
• Physical form
• Wetland soils
• Hydrology
• Water physicochemistry
• Biota (animals, plants, algae, fungi, bacteria etc)</td><td>Process types
• Climate
• Geomorphology
• Hydrology
• Energy and nutrient processes
• Processes that maintain animal and plant populations
• Species interactions
• Physical processes</td></tr>
<tr><td>Threats</td><td colspan="2">Gather any available information regarding the historic, current or predicted threats to the site. For additional detail and specific examples of threats see ‘Step 3 Identifying and ranking threats’ in Stage B.</td></tr>
</table>

STAGE B: PLANNING

This is the most critical stage of the management planning process. At this stage the goals and objectives for a site are determined and the strategies for achieving these selected. It is also at this stage that methods and timeframes for the implementation and review of these strategies are decided. This stage of the management planning process can be broken down into five steps:

1. identifying values and developing a vision
2. identifying key components and processes, assessing condition and setting goals
3. identifying and ranking threats
4. selecting management strategies and setting objectives
5. action planning.

Ecosystem services: benefits that people receive or obtain from an ecosystem, including provisioning services (such as food, fuel and fresh water), regulating services (such as ecosystem processes such as climate regulation, water regulation and natural hazard regulation), cultural services (such as spiritual enrichment, recreation, education and aesthetics) and supporting services (such as the services necessary for the production of all other ecosystem services such as water cycling, nutrient cycling and habitat for biota)

Step 1: Identifying values and developing a vision

Identifying values

Values are the internal principles that guide the behaviour of an individual or group. Values determine the importance that people place on the natural environment and how they view their place within it.[14] Associated with values are the benefits and services that people receive from the natural environment; these are often called **ecosystem services**. Differing values may result in people pursuing different objectives in relation to wetland management and restoration, having different reasons for desiring a commonly agreed outcome or favouring different mechanisms to achieve it. Because of this, it is important to be explicit about the values that are driving wetland management and restoration to ensure that the identified values are not incompatible.[14] For example, although two people may value a wetland because its water can sustain animals, one person may want to dig out the wetland so that it supports a particular group of animals while another person may want it to remain the way it is to support a different group of animals. These values may be incompatible. Table 4 provides examples of wetland ecosystem services.

Table 4. Ecosystem services of wetlands.[15,16]

Supporting	Biodiversity (including connected habitat and provision of vital flow regimes). Nutrient dispersal and cycling Soil formation Seed dispersal Habitat to support primary production
Cultural	Recreational opportunities Provision of destinations for tourism Aesthetic values translating into utility for visitors and changes in land values close to wetlands Provision of cultural values Provision of historical values Source of intellectual and spiritual inspiration Scientific discovery

Regulating	Hydrological flow regulation and groundwater recharge/discharge (where water is used for consumptive uses) Carbon sequestration Climate regulation (macro) Local climate regulation and influence on precipitation Water flow regulations and potential mitigation of flood risk Storm and storm surge protection Purification of water as part of a multi-barrier water treatment train Prevention of saline intrusion Purification of air quality Other waste decomposition and detoxification Crop pollination through the provision of habitat for pollinators Pest and disease control through the provision of filtering services and buffers etc
Provisioning	Food (e.g. fish, crustaceans, game, crops (e.g. rice), wild foods, spices etc.) Water (both for consumption and as inputs to other production such as irrigation) Water storage (wetlands can be a substitute for dams) Water transport Fibre, fuel and other raw materials used in economic production Provision of other industrial inputs (e.g. pharmaceuticals) Genetic material (e.g. ornamental species) Energy (e.g. input to hydropower, or biomass fuels)

The identification of key values is an important step in the management planning process as the purpose of each subsequent step is to contribute to the protection of these values. All values of the management area should be identified and described in detail. If multiple values are identified, as is likely to be the case, the project team (in consultation with stakeholders if appropriate) should rank the values in order of priority and determine which values are a priority for protection. In identifying these priority values it should be ensured that all of the selected values are compatible with each other. If some values are considered to be incompatible with each other, this issue needs to be resolved before the management planning process can proceed any further.

example

An example: Values

Table 5. Example of key wetland values and their associated benefits and services.

Value	**Benefits and services**
Intrinsic value	habitat for migratory and local waterbirds
Aesthetic value	attractive natural landscapes
Recreation value	bird watching, bushwalking and horse riding.

Developing a vision

A vision is the desired state or ultimate condition that a plan is working to achieve which is usually expressed in the form a statement. There is no hard and fast rule on what a vision should or should not include. As a suggestion it may articulate the desired state of the natural environment as well the values driving the management and restoration of a site (e.g. ecosystem service values, opportunity values etc). A good vision should be relatively general, inspirational and simple so that it can be remembered by all members of the project team.[17]

example

An example: Vision

A vision reflecting the values identified in the previous step and the desired state of the natural environment.

To be recognised by the community for its international significance as a habitat for migratory waterbirds and be maintained for its aesthetic and recreation values to be enjoyed by present and future generations. Where natural wetland components and processes are able to function and evolve.

Developing a vision is essential to ensure that all involved in the management planning process are working towards achieving the same thing. Going through the process of developing a vision can also assist in building common ground and language among stakeholders. A vision will also ultimately guide management goals and actions and can be useful to refer back to when facing difficult problems or decisions. In some cases, instead of a vision a set of 'guiding principles', 'principle management objectives', 'broad goal' or similar will be prepared.

Step 2: Identifying key components and processes, assessing condition and setting goals

Key components and processes

After the values of the site have been identified, the next part of the process is to identify the key 'components' and 'processes' that need to be managed to maintain these values. Wetland components are physical, chemical and biological parts of a wetland, from large to very small scale and include the physical form of the wetland, wetland soils, physicochemical properties of the water and wetland flora and fauna (see Table 6). Wetland processes are the forces within a wetland and include those processes that occur between organisms and within and between populations and communities including interactions with the non-living environment and include sedimentation, nutrient cycling and reproduction (see Table 7).[18]

Table 6. Wetland components. Adapted from Department of the Environment, Water, Heritage and the Arts, 2008.[18]

Component	Examples
Physical form	Area of the wetland Wetland form (e.g. depth, shape and bathymetry)
Wetland soils	Site and soil profile characterisation Soil profile classification Soil physical properties (e.g. constituents, structure, texture, consistency and profile) Soil chemical properties (e.g. organic content, nutrients, sulfides, acid neutralising capacity, salts and pH) Soil biological properties (e.g. soil organisms such as bacteria and fungi, invertebrates – shellfish, mites and worms)
Physicochemical soil	Nutrients (e.g. nitrogen, phosphorus) Electrical conductivity Cations and anions pH

Component	Examples
Physicochemical water	Nutrients (e.g. nitrogen, phosphorus) Electrical conductivity Cations and anions Turbidity Temperature Dissolved oxygen pH Nutrient cycling Light attenuation
Biota	Plants Vertebrate fauna (e.g. fish, amphibians, reptiles, waterbirds, mammals) Invertebrate fauna (e.g. insects, crustaceans, worms) Algae Fungi Bacteria

Table 7. Wetland processes. Adapted from Department of the Environment, Water, Heritage and the Arts, 2008.[18] Original source DSE (2005).[19]

Process type	Example
Climate*	Rainfall Temperature Evaporation Wind
Geomorphology*	Topography/morphology Connectivity of surface waters Water source Soils Sedimentation Erosion
Hydrology*	Water balance/budget (water flowing in, water flowing out) Groundwater infiltration and seepage Surface–groundwater interactions Water regime (the pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, duration, frequency, extent and depth, and variability of water presence).
Energy and nutrient dynamics	Primary production Nutrient cycling (nitrogen, phosphorus) Carbon cycling Decomposition Oxidation–reduction
Processes that maintain animal and plant populations	Reproduction Regeneration Dispersal Migration Pollination
Species interactions	Competition Predation Succession Herbivory Diseases and pathogens

Process type	Example
Physical processes	Stratification Mixing Sedimentation Erosion Evaporation Infiltration

*For some wetlands these processes may be viewed as components or broken down into their components.

The challenge of this step is to identify the 'key' components and processes. To achieve this, a two stage process is recommended:

1) Identify as many components and processes as possible.

2) Identify and describe the most critical components or processes that need to be managed to maintain the values, benefits and services of the site.

Expert advice will almost certainly be needed to complete this step of the process.

example

An example: Key components and processes

Examples of key wetland components and processes required to maintain the values, benefits and services previously identified.

Table 8. Example of key wetland components and processes and their link to values, benefits and services.

Value	Benefits and services	Key components and processes	Reasoning for selection of component or process
Intrinsic value	Habitat for migratory and local waterbirds	Waterbirds	Value directly dependent on presence of waterbirds
		Wetland and dryland vegetation	Direct source of food and shelter for waterbirds and source of food and shelter for other fauna on which waterbirds feed
		Hydrology	Critical for maintaining all other components and processes
Aesthetic value	Attractive natural landscape	Wetland and dryland vegetation	Presence of wetland and dryland vegetation contributes significantly to attractiveness of the landscape
		Hydrology	Presence of water contributes significantly to attractiveness of the landscape
Recreation value	Bird watching, bushwalking and horse riding.	Birds (including water birds)	Value directly dependent on presence of birds
		Wetland and dryland vegetation	Presence of vegetation critical for undertaking 'bush 'walking and indirectly to maintain presence of birds

Setting goals

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site

The ultimate aim of wetland management and restoration is to maintain or restore wetland components and processes which sustain the reasons we value the wetland. In order to assess whether or not management is being successful, 'goals' for key wetland components and processes will need to be set. In this context a **goal** is a specific statement detailing the desired state of a wetland component or process. Goals should be 'smart':

- **s**pecific – the component or process is clearly defined as it its desired state
- **m**easurable – there is some way of measuring what will be achieved
- **a**chievable – the goal is realistic given the resources available
- **r**elevant – the goal is relevant to the vision for the wetland
- **t**ime-bound – there is a time by which the goal is met that is realistic, feasible and meaningful.

When setting goals it is important to keep in mind that the components and processes to which these goals relate will form a set of '**indicators**' which will need to be measured as part of a monitoring program.

It may not always be possible or realistic to be able to measure all key components and processes. Instead goals may be set for a limited number of components and processes, or it may be necessary to set goals for surrogates instead. There are times when it is not practical to measure a component or process. This may be because it is cryptic, slow to respond to environmental change, expensive to assess, poorly understood or simply difficult to quantify. In such cases a surrogate measure may be used. This is another component or process of the system that shows a correlated response. An example of a surrogate measure is the use of aquatic invertebrate community composition to draw conclusions about water quality.

➤ For additional detail on surrogates see the topic 'Monitoring wetlands' in Chapter 4.

If the current and desired state of key components and processes is not known, it will be necessary to obtain this information to be able to set and assess progress towards achieving goals. An excellent understanding of wetland components and processes will be needed to undertake this step of the processes, as such in most instances expert advice will be required.

example

An example: Goals

Examples of goals for selected components and processes previously identified.

Component: Waterbirds

By July 2019, the number of species (species richness) of waterbirds at the site is equal to or greater than 1999 levels.

Note: this goal assumes that the number of species of waterbirds at the site in 1999 is known.

Component: Vegetation

By July 2019, the extent and cover of native vegetation and native plant species richness at the site is equal to or greater than levels in 1999.

Note: this goal assumes that the extent and cover of native vegetation and native plant species richness in 1999 is known.

Distinguishing between outputs and outcomes

When setting project goals and objectives there is often some confusion between outputs and outcomes. Outputs are activities undertaken, or products produced, by a particular project. An outcome, on the other hand, is a measurable consequence of the project's activities. For example, a project may output 20 kilometres of stock exclusion fencing around a wetland. The outcome of this may be a 10 per cent increase in native vegetation biomass within the fenced area, due to reduced grazing pressure. Outputs are steps along the way to achieving the desired outcome. In the context of the management planning process being presented in this topic, goals should always relate to an outcome while objectives (which are discussed later in the document) may relate to an output or outcome.

Step 3: Identifying and ranking threats

This step involves identifying current and potential threats to key wetland components and processes and then assessing how critical each threat is to determine whether there is a need for a management strategy. In this context a **threat** is considered to be any factor that is currently or may potentially negatively affect wetland components or processes. A threat can be currently active or present (such as weeds), or a potential threat (such as a proposal to create a picnic area within an area of native vegetation in excellent condition).

Identifying threats

When discussing threats it is useful to make a distinction between two elements of threat; the source of the threat and the actual stress it causes.[20] For example foxes (threat) eat waterbird eggs resulting in reduced breeding success of the birds (stress). This distinction isn't always easy to make but is an important one to make when it comes to selecting management strategies. When identifying threats it is important to focus on those impacting on the key wetland components and processes identified Step 2. Some common threats to wetlands are shown in Table 9.

➤ For additional detail on a number of common threats to wetlands see the topics in Chapter 3 'Managing wetlands'.

Table 9. Common threats to wetlands.

Threat	Stress on wetland component or process
Altered hydrology	Death of native vegetation due to excessive/insufficient water, change in the ecological character of the wetland
Acid sulfate soils	Death of plants and animals due to acidification of wetland waters
Weeds	Reduction in extent and cover of native vegetation due to competition by weeds
Water and soil pollution/contamination	Death of plants and animals
Diseases such as Phytophthora dieback	Decline and or death of native vegetation
Introduced fauna	Reduction in animals diversity due to predation and competition with introduced animals
Livestock grazing	Reduction in extent and cover of native vegetation due to physical damage and competition by weeds
Secondary salinity	Decline and or death of native vegetation and reduced richness and abundance of aquatic animals
Inappropriate fire regime	Reduction in extent and cover of native vegetation and reduction in richness and abundance of animals

example

An example: Identifying threats

Table 10. Example of key component and processes and the identified threats.

Key components and processes	Threats
Birds (including waterbirds)	Introduced predators
Wetland and dryland vegetation	Weeds - arum lily
Hydrology (water balance and water regime)	Over-extraction of groundwater

It is common to find that many threats are inter-connected and that multiple threats may be contributing to a single stress. For example over-abstraction of groundwater may result in a decrease in the duration, extent and depth of inundation (altered water regime) which may in turn result in a decline in the extent, cover and diversity of vegetation. A decrease in the duration, extent and depth of inundation may allow for an increase in the extent and cover of arum lily, contributing to decline in the extent, cover and diversity of native vegetation (see Figure 3). The interrelationships between threats can be very complex and it is wise to seek expert opinion for this part of the management planning process. To unravel these relationships, it may be useful to create a web diagram as shown in Figure 3. These diagrams can also help you to understand the synergies and cumulative nature of existing and potential threats on the wetland.

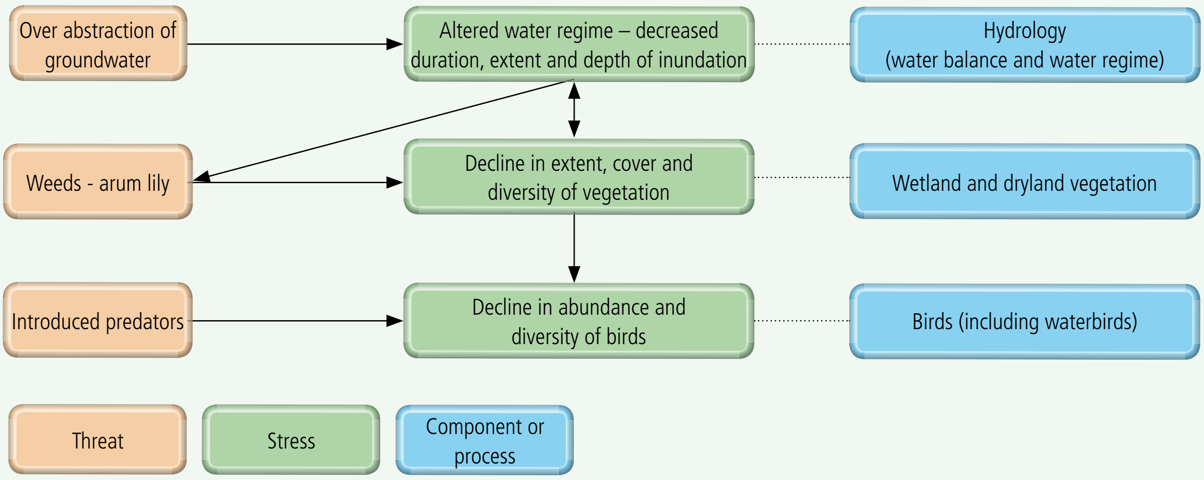


Figure 3. Web diagram illustrating the inter-connectedness of the threats 'weeds' and 'over-extraction of groundwater'.

Threat ranking

If more than one threat has been identified, as will nearly always be the case, a process of 'threat ranking' needs to be undertaken to determine which threats are a priority for management. Threat ranking can be undertaken for a site as a whole or applied to each key wetland component and process (as identified in Step 2). There are numerous threat ranking (sometimes also called risk assessment) methodologies available using different assessment criteria (effect, scope, severity etc.) and different scoring systems (e.g. quantitative versus qualitative and absolute versus relative ranking). Regardless of which methodology is selected, the most important thing is that the methodology is well document and clearly explained so that other can repeat the process. It is also critical that any assumptions or decisions made whilst applying the threat ranking are also documented.

The key aim of assessing the significance of the threat to the wetland is to determine whether there is a need for management for this specific threat to a wetland value(s), and therefore the development of a management strategy.

An example of a threat ranking methodology is presented below.

example

An example: Threat ranking

This methodology utilises a relative scoring system where for each criteria; 'scope', 'severity' and 'likelihood' each threat is given a rank relative to the other threats.

1. Rank each threat for 'scope'

Scope: refers to the proportion of the overall area likely to be affected by a threat in a given timeframe (for example, ten years).

2. Rank each threat for 'severity'

Severity: attempts to quantify or categorise the level of damage to the site in the specified time frame.

3. Rank each threat for 'irreversibility'

Irreversibility: is the degree to which the effects of a given threat can be reversed.

4. Add up the ranking scores

Record any recommendations, assumptions or knowledge gaps identified during the threat ranking process.

Table 11. Example of a 'relative' threat ranking for a site as a whole using the criteria 'scope', 'severity' and 'likelihood'.

Threat	Scope	Severity	Irreversibility	Total	Classification
Introduced predators	1	2	1	4	Medium
Weeds - arum lily	2	1	2	5	Medium
Over-extraction of groundwater	3	3	3	9	High

As a result of the threat ranking process, managers should have a clear idea of which threats are a priority for management as well as any knowledge gaps that may require the formulation of a management strategy.

Step 4: Selecting management strategies and setting objectives

In the context of this management planning process the term **strategy** is used to describe a set of actions that will be undertaken in order to achieve goals relating to a wetland component or process. Normally strategies will focus on addressing the threats to components and processes however, it may also be necessary to develop strategies to directly improve the condition of a component or process. Strategies formulated to address a threat may for example include 'weed control' or an 'awareness-raising campaign' whilst strategies formulated to directly improve the condition of a component or process may include a 'captive breeding program' or 'revegetation'.

It is paramount that any threats causing a decline in the condition of the component or process are addressed before any strategies are implemented to directly improve its condition of a component or process.

➤ For additional detail and guidance on management strategies for specific threats see individual topics in Chapter 3 'Managing wetlands'.

Selecting management strategies

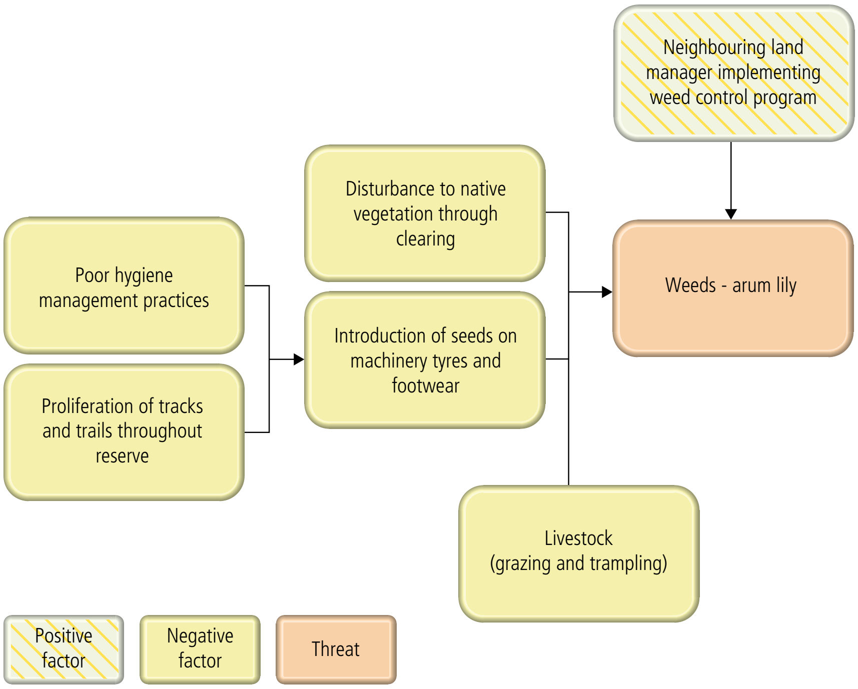
The following methodology for identifying and ranking management strategies has been adapted from WWF Project and Programme Standards.[21]

In order to identify management strategies for each of the high-ranked threats, the following steps should be undertaken (repeat steps 1–3 separately for each high ranked threat):

1. Identify all of the factors affecting the threat including both positive and negative factors.

   For example for the threat 'weeds' look at how weeds are entering and spreading within the site e.g. livestock, machinery used for firebreak maintenance, overland flow of water as well as any positive factors such as a neighbouring landholder implementing a weed control program. A useful way of completing this step is to draw a web diagram or a chain for each threat (see Figure 4 below).

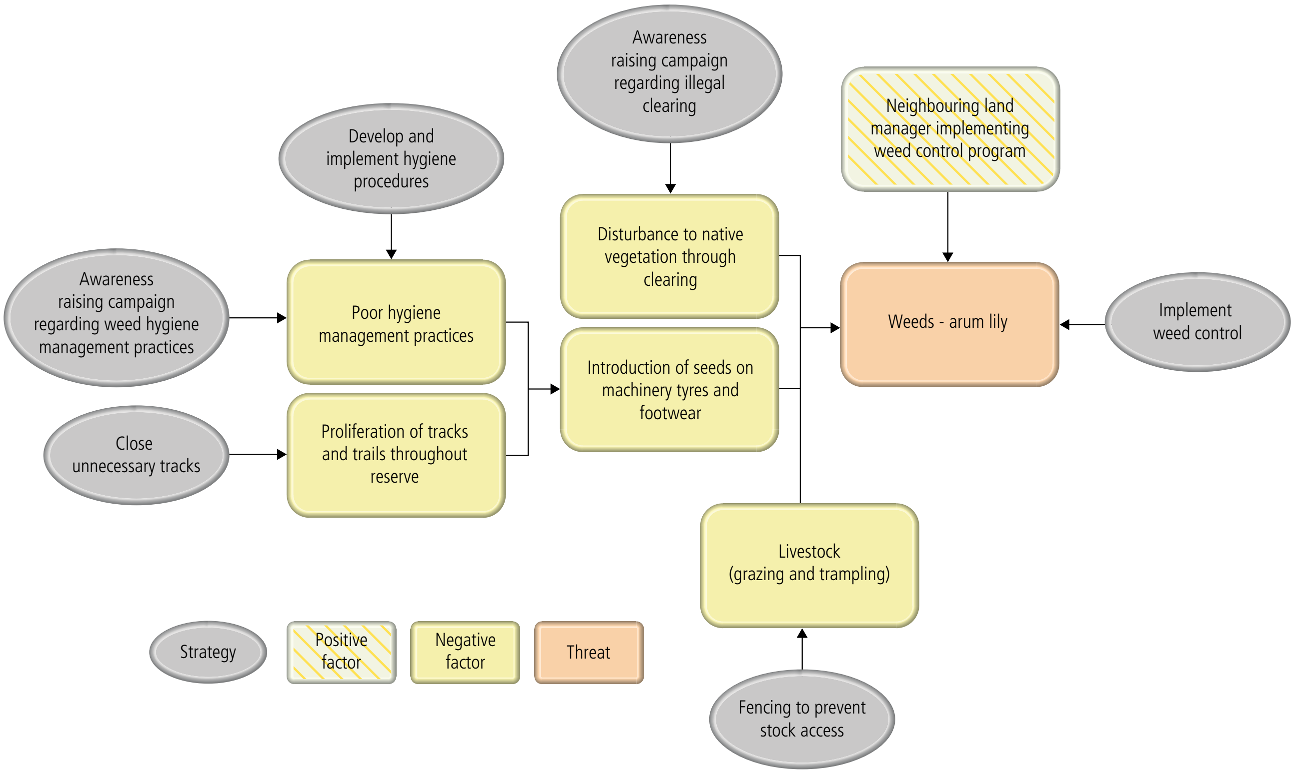
Figure 4. Web diagram showing the threat 'weeds' and the factors affecting weeds.



2. Brainstorm strategies that could be used to counter the threat and the factors affecting it.

   Using the weeds example above, weed control could be undertaken to remove weeds, fencing could be erected to prevent stock access, hygiene procedures implemented to prevent seeds entering via machinery used for firebreak maintenance and unnecessary tracks could be closed (see Figure 5 below). When brainstorming strategies *focus on the causes of a problem, rather than the symptoms.* For example, while weed mapping and control is important, you are going to be forever weeding, unless you identify and address the sources of weeds.

Figure 5. Web diagram showing the threat 'weeds' and the factors affecting weeds and potential management strategies.



3. Narrow down the list of strategies by eliminating those that are not likely to be effective or feasible.

   It is at this stage that some tough decisions may need to be made regarding the feasibility of tackling some threats particularly those such as secondary salinity or altered catchment hydrology which require considerable technical expertise to fully understand the threats and develop appropriate management strategies, require management strategies to be implemented beyond the geographic scope of the management area and will require significant resources for successful management.

4. Repeat the above steps for all other high-ranked threats.

5. Rank potential strategies for all high-ranked threats.

   Even after narrowing down the list of potential strategies by eliminating those that are not likely to be effective or feasible, it is likely that there will be more strategies than can be realistically addressed. To narrow down the number of strategies it may be a good a idea to rank strategies according at a set of criteria such as:

   - Likelihood – how likely is the strategy in being successful in countering the threat/s?
   - Feasibility – are the necessary skills and resources (political, financial and human) available to undertake the strategy?
   - Cost – even if the necessary resources are available, what is the cost of the strategy in comparison to others that may have similar benefits.
   - How many threats will the strategy address – it may be possible that a single strategy will it address a number of threats.
   - Gap – does the strategy fill a gap that isn't already been address by another project? Is there another project already undertaking this strategy?

6. Select strategies and document any assumptions and decisions.

Using the ranking, select the strategies to be implemented. For each selected strategy document any assumptions regarding how the strategy will counter the threat it is selected to address particularly in terms of any awareness-raising or education related strategies (see Figure 6). For each selected strategy, document the threat it will address, and the components and processes that will be maintained or improved by addressing the threat (see Table 12).

Figure 6. Example of an awareness-raising strategy and the assumed steps that need to occur in order for the strategy to be successful.

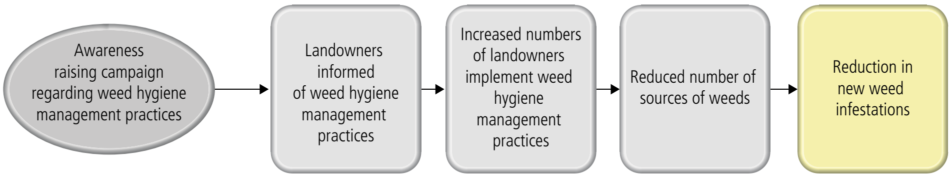


Table 12. Example of relationships between strategies, threats, wetland components and processes and associated goals.

Strategy	To address threat/s	Components and processes maintained or improved	Associated goal/s
Awareness raising campaign regarding weed hygiene management practices	Weeds	Native vegetation	By July 2019, the extent, cover and species diversity of native vegetation is equal to or greater than levels in 1999.
Fox control strategy	Foxes	Birds (including waterbirds)	By July 2019, the number of species (species richness) and abundance of waterbirds at the site is equal to or greater than 1999 levels.

7. Assess whether any strategies to directly improve the condition of key components and processes are required.

Once strategies to address key threats have been developed, it may be necessary to look at each key component and process and decide if any management strategies are required to directly improve the condition of the component or process. If such strategies are required, repeat steps 3 – 6 as described above, relating each step to strategies to directly improve the condition of key wetland components are processes (rather than strategies to address key threats).

➤ For additional detail and guidance on management strategies for specific threats see individual topics in Chapter 3 'Managing wetlands'.

Feasibility of addressing threats

The feasibility of addressing threats needs to be carefully considered when developing and selecting management strategies. Addressing a threat may not be feasible if any of the following are required in order to address it:

- considerable technical expertise to fully understand the threat and develop appropriate management strategies
- management strategies to be implemented beyond the geographic scope of the management area
- significant resources for successful management.

Common threats for which the feasibility of management needed to be carefully considered include altered hydrology and introduced fauna. Both of these issues require specialised expertise, the implementation of management strategies over a large geographical area (usually greater than one manager has control over) and significant resources for successful management.

In such circumstances it may be best to make use of the planning process to define the scope of a further study or plan. Care should be taken to ensure that if issues are deferred or subject to a parallel planning process, their links to the primary management plan are clearly stated and can be incorporated back into the management plan at a later date.

For example the topic 'Managing hydrology' in Chapter 3 describes how the hydrological regime of a wetland is directly affected by land use within a catchment, and drainage and groundwater extraction that occurs. Trying to address catchment management issues within a wetland management plan is likely to be of limited success unless you are in the fortunate position of being able to control and/or influence activities within the entire catchment. An effective approach to addressing catchment-scale issues, without getting caught up in them, is to support the preparation of a catchment management plan for the wetland catchment, or the incorporation of the wetland catchment into a wider natural resource management plan or catchment plan. Alternatively, where a relevant catchment plan exists, refer to it in the current plan, and highlight proposed strategies that address the threats faced by the wetland. Identify management strategies that will complement those in the catchment plan. Identify links between the plans and seek opportunities for investment and external support.

Setting objectives

As previously mentioned, the ultimate aim of wetland management and restoration is to maintain or restore wetland components and processes (which support wetland values). The purpose of the management strategies that have now been selected is to address the threats affecting the wetland components and processes or directly improve the condition of key components and processes. The goals that were previously set will allow the effectiveness of these strategies to be monitored in the long term however, objectives should also be set to monitor the progress of strategies in the short to medium-term.

Objectives are a statement detailing a short to medium-term result of a strategy, which may relate to an output or outcome as it relates to the state of a threat. Objectives should be **SMART**:

- **s**pecific – the desired output or outcome as it relates to the state of a threat is clearly defined
- **m**easurable- there is some way of measuring what will be achieved
- **a**chievable – the objective is realistic given the resources available
- **r**elevant – the objective is relevant to achieving the goals for key components and processes
- **t**ime-bound – there is a time by which the objective is met that is realistic, feasible and meaningful.

For each management strategy, at least one management objective should be set so that the effectiveness of the strategy in the short to medium-term can be evaluated. Where a number of assumptions have been made regarding how the strategy will result in reducing a threat, objectives to monitor these assumptions should also be set (see following example).

example

An example: Objectives

Strategy: Awareness raising campaign regarding weed hygiene management practices

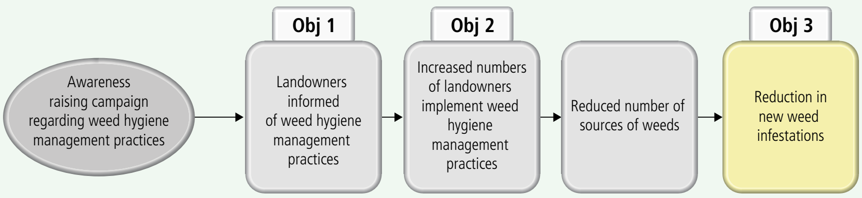


Figure 7. Example of an awareness-raising strategy, the assumed steps that need to occur and the objectives that need to be met in order for the strategy to be successful.

Objective 1: By July 2010 two training events held, informing 100 land managers, living within the Lake Quenda catchment, of weed hygiene management practices.

Objective 2: By July 2011 there has been a 10 per cent increase in the number of land managers, living within the Lake Quenda catchment, implementing weed hygiene management practices compared to the number in 2009.

Objective 3: By July 2011, no new weed infestations as compared to the number in July 2010.

Step 5: Action planning

The final step in preparing a management plan is working out how all of the planning will be put into practice. In this step of the process, management strategies will be broken down into specific actions and for each action, who, when and how much will be determined. Similarly each goal and objective will be broken down into the indicators that will be monitored and for each of these how, when, where and who will be determined.

Implementing management strategies

For each management strategy, the goals and objectives that the strategy will directly or indirectly contribute to achieving should be outlined to make it clear what the particular strategy is trying to achieve. For each management strategy, a series of actions should then be presented to detail the specific works or projects that will be carried under that strategy. At this stage it is important to stick to major activities rather than going into detail of individual tasks. For example stick to 'Obtain quotes for weed control work' rather than 'compile a list of local weed control contractors', 'prepare request for quote documentation' etc. For each action, it is recommended that the following are identified:

- *who* will undertake the action (including any external parties)
- *when* the action will be completed
- *how* much it will cost to implement the action.

It is recommended that the above information be summarised in a table in the plan so that readers can easily gain an understanding of what, who and when actions will be undertaken and how much they will cost (see Table 13). If required, additional detail for each action can be presented. For example 'approximate cost' can be further separated into 'internal funding' and 'external funding required'. This process should then be repeated for each management strategy.

example

An example: Strategy implementation plan

Table 13. Example of an implementation plan for the strategy 'Implement weed (arum lily) control'.

Strategy: Implement weed (arum lily) control				
Objective: By July 2012, the extent of arum lily (percent cover) has been reduced by 50 per cent compared to the 2009 level.				
Contributes to achieving the following goal/s: **Goal**: By July 2019, the extent and cover of native vegetation and native plant species richness at the site is equal to or greater than levels in 1999.				
	Who?	**When?**	**How much?**	**Comments**
Activity 1. Identify priority areas for arum lily control based on vegetation and weed mapping (produced as part of monitoring plan)	Sam Jones Jenny Smith	August 2009	Internal staff costs not applicable – already covered by core funds	
Activity 2. Prepare detailed weed control program for areas A, and B	Sam Jones Jenny Smith	November 2009	NA	
Activity 3. Obtain quotes for weed control work in areas A and B and award contract	Sam Jones	February 2010	NA	
Activity 4. Weed control works undertaken by contractor	External contractor	August 2010	$3,000	Herbicide application between June and September
Activity 5. Inspect weed control works	Sam Jones	August 2010	NA	
Activity 6. Follow up weed control works	External contractor	August 2010	$1,500	Herbicide application between June and September
Activity 7. Inspect weed control works and assess need for revegetation	Sam Jones Jenny Smith		NA	If revegetation is required, develop implementation plan for 'Revegetation' strategy
Total budget:			$4,500	

Once each strategy has been broken down into individual actions with timeframes, it may be useful to compile this information into a Gantt chart for the entire project (see Table 14 for an example). It is also advisable to incorporate monitoring activities and their timeframes into this chart as they are an integral part of any wetland management project. Displaying this information in a Gantt chart will allow for the start and finish dates of tasks to be seen as well as any overlap in the timeframe of tasks. By listing the sequence of actions under each strategy you will be able to check the feasibility of achieving the objective/s of the strategy within the given timeframe and schedule activities into a works program.

example

Table 14. Example of a Gantt chart for a wetland management project showing all management and monitoring activities and their associated timeframes.

	2009				2010				2011			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Strategy: Weed (arum lily) control												
Activity 1. Identify priority areas for arum lily control based on vegetation and weed mapping (produced as part of monitoring plan)												
Activity 2. Prepare detailed weed control program for areas A, and B												
Activity 3. Obtain quotes for weed control work in areas A and B and award contract												
Activity 4. Weed control works undertaken by contractor												
Activity 5. Inspect weed control works												
Activity 6. Follow up weed control works												
Activity 7. Inspect weed control works and assess need for revegetation												
Monitoring												
Strategy: Awareness raising campaign regarding weed hygiene management practices												
Activity 1. Compile information on weed hygiene management practices												
Activity 2. Organise two training events												
Activity 3. Deliver two training events												
Monitoring												

Implementing monitoring activities

During the planning process, goals and objectives have been set in order to measure the success of management strategies in the short, medium and long term. It is now time to determine the what, how, where, when and who for the measurement of each goal and objective. For each goal and objective it is recommended that the following are identified:

- what will be measured (indicator)
- how will it be measured (method)
- where will the measurement be taken
- when will it be measured
- who will measure.

It is recommended that the above information be summarised in a table so that readers can easily gain an understanding of what, how, where, when and who for the measurement of each goal and objective (see Table 15).

example

An example: Monitoring implementation plan

Table 15. Example of a monitoring implementation plan.

Goal: By July 2019, the extent and cover of native vegetation and native plant species richness at the site is equal to or greater than levels in 1999.					
What? (Indicator)	**How?** (Methods)	**When?**	**Who?**	**Where?**	**Comments**
extent and cover of native vegetation and native plant species richness	On-ground survey	Spring 2009 Spring 2014 Spring 2019	Sam Jones Jenny Smith	Lake Quenda	Need to document standard survey methods
Strategy: Awareness raising campaign regarding weed hygiene management practices					
Objective 1: By July 2010 two training events held, informing 100 land mangers, living within the Lake Quenda catchment, of weed hygiene management practices.					
What? (Indicator)	**How?** (Methods)	**When?**	**Who?**	**Where?**	**Comments**
no. of training events no. of land managers attending	Check register of attendees at training events	June – November 2009	Sam Jones	TBA	Exact location and dates of training events will be known by end of May 2009
Objective 2: By July 2011 there has been a 10 per cent increase in the number of land managers, living within the Lake Quenda catchment, implementing weed hygiene management practices compared to the number in 2009.					
What? (Indicator)	**How?** (Methods)	**When?**	**Who?**	**Where?**	**Comments**
no. land managers, living within the Lake Quenda catchment, implementing weed hygiene management practices	Telephone survey of land managers	July 2009 July 2011	Sam Jones	Within the Lake Quenda catchment	Need to define 'weed hygiene management practices'
Objective 3: By July 2011, no new weed infestations as compared to the number in July 2010.					
What? (Indicator)	**How?** (Methods)	**When?**	**Who?**	**Where?**	**Comments**
no. weed infestations	On-ground survey	July 2010 July 2011	Sam Jones Jenny Smith	Lake Quenda	Need to define 'weed infestation' and document standard survey methods

The first and most important step in measuring goals and objectives is to determine what will be measured or the 'indicator'. Take for example the goal 'By July 2019, the extent and cover of native vegetation and native plant species richness is equal to or greater than levels in 1999'. The indicator to be measured in this example is native vegetation. This is a relatively straightforward indicator as it is natural component of the wetland which is relatively easy to measure. For a more complex example take the objective 'By July 2011 there has been a 10 per cent increase in the number of land managers, living within the Lake Quenda catchment, implementing weed hygiene management practices compared to the number in 2009'. In this example the indicator is land managers, living within the Lake Quenda catchment, implementing weed hygiene management practices. This indicator may require some further definition particular in terms of determining what is considered to be a 'weed hygiene management practice'.

➤ For additional detail on selecting and monitoring indicators that are natural wetland components and processes see the topic 'Monitoring wetlands' in Chapter 4.

STAGE C: IMPLEMENTING

This is the most satisfying stage of the management planning process: putting the planning into action. With sound planning, this stage of the process should be relatively straightforward. When implementing a management plan it is important to keep in mind that monitoring, evaluating and reviewing the plan is an integral part of implementation and should be an on-going component of the implementation process.

STAGE D: EVALUATING AND ADAPTING

Regular evaluation of a management plan is essential for adaptive management and as mentioned above should be an on-going component of the implementation process. There are three type of evaluation:

- progress - reviewing what has been implemented
- performance - auditing the implementation of the plan
- complete – re-assessing and adapting the plan itself.

The three types of evaluation should be undertaken at different stages of the management planning process. The three types of evaluation are outlined Table 16.

Table 16. The different types of management plan evaluations.

	Type of evaluation		
	Progress	**Performance**	**Complete**
Stage of implementation	Throughout term of plan	Throughout term of plan	When circumstances or conditions at the site change considerably or at end of the term of the plan
Frequency	Weekly to monthly	Quarterly to annually	As required
Level of detail	Basic	Detailed	Comprehensive
Components for review	Progress of: • Strategy implementation plan, and • Monitoring implementation plan.	Performance of: • Completed strategies • Progress towards objectives and goals.	Complete re-assessment of: • Values and vision • Key components and processes and goals for their conditions • Key threats • Management strategies and objectives to measure their success.

Progress evaluation

Reviewing the implementation of the plan is important to ensure that it is progressing as scheduled. The progress of both the 'strategy implementation plan' and 'monitoring implementation plan' should be reviewed. These should be reviewed on a regular basis, weekly to monthly, depending on the frequency at which the project activities are being implemented. If either of these plans is behind or ahead of schedule, the following questions should be considered:

- What is the cause for the departure from the schedule?
- Are further changes to the schedule expected?
- Does the schedule need to be amended?

If necessary the 'strategy implementation plan' and 'monitoring implementation plan' should be amended accordingly.

Performance evaluation

Auditing the result of a management plan is critical to ensuring that a plan is achieving what it set out to achieve. To audit the result of a management plan, both goals and objectives need to be examined. Progress towards achieving goals and objectives should be reviewed in addition to auditing after the timeframe for the goal or objective has passed. Take for example the goal 'By July 2019, the extent and cover of native vegetation and native plant species richness at the site is equal to or greater than levels in 1999', the progress towards achieving this goal may be reviewed annually in addition to an audit in July 2019. If the progress towards goals or objectives is not occurring as expected or goals or objectives have not been met, the following questions should be considered:

1. Why is progress towards goals or objectives not occurring as expected or goals or objectives not being met?
    a. Is the selected strategy not achieving what it was meant to achieve?
    b. Is there an issue with goal/objective (e.g. it wasn't achievable)?
    c. Is there an issue with both the strategy and the goal/objective?
2. Do any goals, objectives or strategies need to be amended?

If necessary the 'strategy implementation plan' and 'monitoring implementation plan' should be amended accordingly.

Complete evaluation

A re-assessment of a management plan should occur if conditions or circumstances at the site change considerably or at the end of the term of a plan. Changes to the circumstances or conditions at the site which may warrant the re-assessment of a management plan may include:

- new legislation is enacted which affects the management of the site
- change of land ownership
- change in the values that the site it being managed, for example, no longer being managed for recreation or a new component or process is identified as being key to maintain values
- new threat identified
- scope or severity of an existing threat increases.

If any considerable changes to the circumstance or conditions at the site occur, all components of the plan should be re-assessed (see Table 1). Similarly at the end of the term of a plan all components of a management plan should be reviewed, and it is likely that many will need to be adapted accordingly.

SOURCES OF MORE INFORMATION ON WETLAND MANAGEMENT PLANNING

Websites

Foundations of Success

Foundations of Success is a not-for-profit organization committed to working with practitioners to learn how to do conservation better through the process of adaptive management.

www.fosonline.org/

WWF Standards of Conservation Project and Programme Management

www.panda.org/what_we_do/how_we_work/conservation/programme_standards/

Standards of practice for planning and implementing conservation projects and programmes.

The Nature Conservancy: Nature by design

www.nature.org/aboutus/howwework/cbd/science/art19228.html

The basic concepts of Conservation by Design are simple: setting goals and priorities, developing strategies, taking action and measuring results.

Conservation Management System Consortium

www.cmsconsortium.org/

The CMS Consortium (CMSC) is a group of conservation organisations whose aim is to raise standards in conservation and countryside management

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GLOSSARY

Adaptive management: an approach that involves learning from management actions, and using that learning to improve the next stage of management

Consanguineous suite: area/s defining a group of wetland with common or interrelated features[29]

Ecosystem services: benefits that people receive or obtain from an ecosystem, including provisioning services (such as food, fuel and fresh water), regulating services (such as ecosystem processes such as climate regulation, water regulation and natural hazard regulation), cultural services (such as spiritual enrichment, recreation, education and aesthetics) and supporting services (such as the services necessary for the production of all other ecosystem services such as water cycling, nutrient cycling and habitat for biota)

Goal: a specific statement detailing the desired state of a wetland component or process

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site

Management planning: the process of setting management goals for a site and then developing, implementing and reviewing management strategies to meet these goals

Management strategy: a set of actions that will be undertaken in order to achieve goals relating to a wetland component or process

Objective: a statement detailing a short to medium-term result of a strategy, which may relate to an output or outcome as it relates to the state of a threat

Ramsar Convention: an international treaty that focuses on the conservation of internationally important wetlands signed in Ramsar, Iran in 1971

Stakeholder: individuals, groups or institutions that have an interest in or will be affected by a project's activities

Strategies: in the context of management planning, a set of actions that will be undertaken in order to achieve goals relating to a wetland component or process

Threat: any factor that is currently or may potentially negatively affect wetland components or processes. A threat can be currently active or present (such as weeds), or a potential threat (such as a proposal to expand a picnic area into native vegetation in good condition)

Values: the internal principles that guide the behaviour of an individual or group and determine the importance that people place on the natural environment and how they view their place within it

Vision: the desired state or ultimate condition that a plan is working to achieve which is usually expressed in the form a statement

Wetland components: the physical, chemical and biological parts of a wetland, from large-scale to very small scale and include the physical form of the wetland, wetland soils, physicochemical properties of the water and wetland flora and fauna

Wetland processes: the forces within a wetland and include those processes that occur between organisms and within and between populations and communities including interactions with the non-living environment and include sedimentation, nutrient cycling and reproduction

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A guide to managing and restoring wetlands in Western Australia

Funding, training and resources

In Chapter 1: **Planning for wetland management**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Funding, training and resources' topic

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Recommended reference

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When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Funding, training and resources', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by C Denton, Department of Environment and Conservation, Perth, Western Australia.

Contents

INTRODUCTION

This topic provides information on funding, training and resources related to wetland management and restoration.

Funding and training programs change in response to government and non-government priorities and demand, and new resources regularly become available. For this reason, the information in this topic may be updated at regular intervals. If you know of funding, training or resources relevant to WA wetlands that should be listed in this topic, or changed details for listed programs, we would appreciate you letting us know by emailing us at wetlands@dec.wa.gov.au or via the publication feedback form, available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Users should check the currency of program information before planning on accessing support from the programs featured in this topic.

HOW TO USE THIS TOPIC

This topic has been arranged in three sections:

1. funding
2. training
3. resources

➤ For information on the roles and responsibilities of stakeholders, including government and non-government organisations, see the topic 'Roles and responsibilities' in Chapter 5.

FUNDING

This section provides an overview of the main funding opportunities for wetland management and restoration activities. The list is not exhaustive and individuals will need to investigate each option further for more details. There are various funding and grant 'search engines' available on the internet and the most relevant to wetlands are listed in this section.

Funding opportunities are listed under the following headings:

- funding programs
- funding directories
- labour programs
- land sale, purchase or donation
- legal protection
- management agreements

Funding programs

There are many funding programs available for a range of environmental projects and activities. The following funding programs are useful for sourcing funds for wetland management activities.

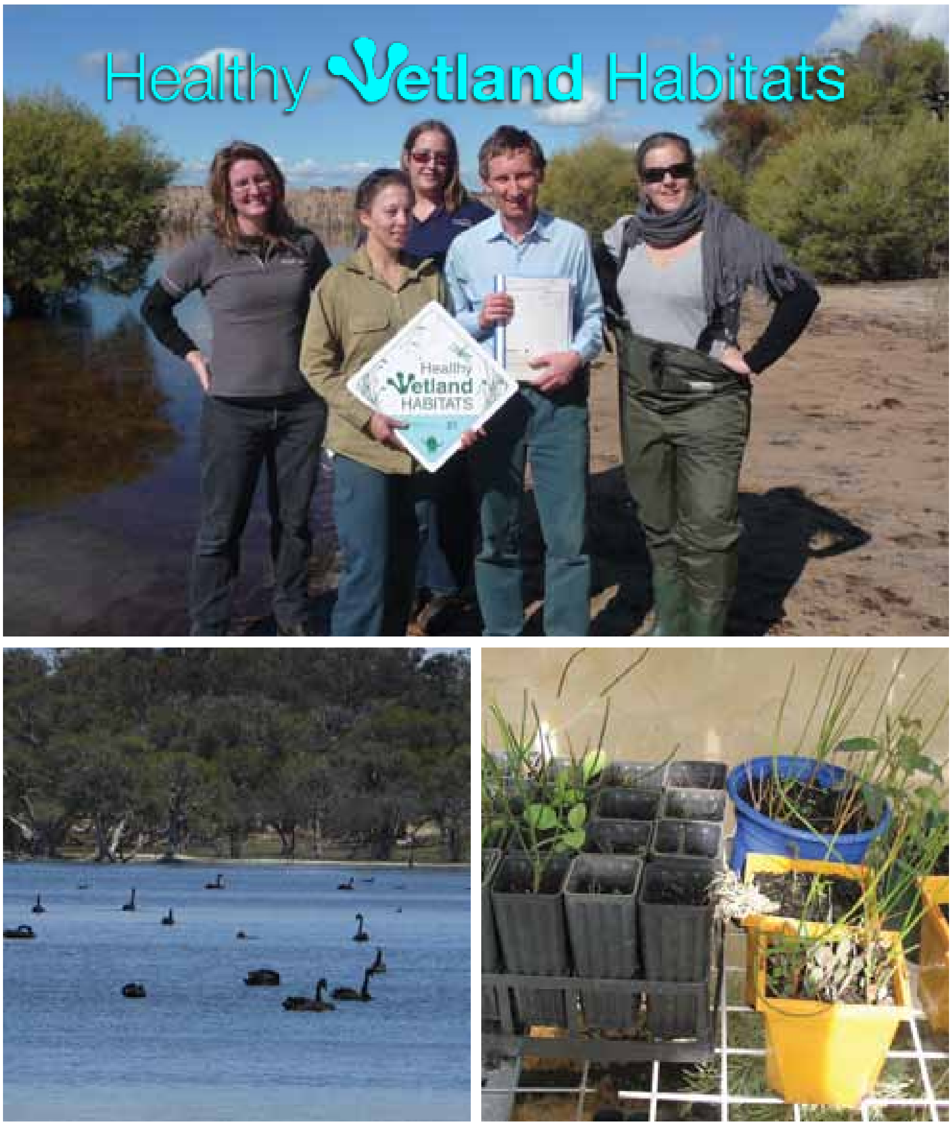

Figure 1. Some of the sites and activities funded by DEC's Healthy Wetland Habitats program. Photos – (top) A Fairs/DEC, (below) A and M Elliott.

Table 1. Funding programs available in Western Australia

Funding program	Funding target	What the program funds	How much funding is available	Funding closing date	For further information	Geographic spread
Biodiversity fund, Australian Government	Land managers of public and private land	Revegetation, weed and introduced animal control, and protecting and managing high conservation areas			www.environment.gov.au/cleanenergyfuture/biodiversity-fund/index.html	National (round two: in WA, south-west and urban waterways and coastal environments)
Busselton Biodiversity Bids, Shire of Busselton	Organisations	Services and activities that deliver environmental benefit	Up to $50,000		www.busselton.wa.gov.au	Shire of Busselton
Busselton Biodiversity Incentives Strategy, Shire of Busselton	Private landholders	Subdivision incentives and rate rebates	Rate rebates of $250–$1,500 annually	Ongoing	Shire of Busselton (08) 9781 0444 www.busselton.wa.gov.au/services/environmental_planning/biodiversity	Shire of Busselton
Caring for our Country (CfoC), Australian Government	Non-government organisations Landcare groups Community groups State and local government Industry Business	Priority targets are identified for each financial year Provides funding for a broad range of sustainable land management and environmental protection work	Over $2 billion in total funding between 2008–2013 The size of the grants range from $30,000–$600,000	Varies	Caring for our Country Information line 1800 552 008 www.nrm.gov.au/funding	National
Community Funding Program, Serpentine Jarrahdale Shire and Byford and Districts Branch of Bendigo Bank ®	Community groups	Project funding such as seed funding for new groups, environmental restoration or facility upgrades	Up to $1,500		Community Development Officer 9526 1137 www.sjshire.wa.gov.au/grant-funding/	Shire of Serpentine Jarrahdale
Community Grants Program, City of Rockingham	Not for profit groups and community organisations	Environmental and conservation initiatives	$500–$2000	Varies	City of Rockingham (08) 9528 0333 www.rockingham.wa.gov.au/Leisure-and-recreation/Grants-and-awards/Community-grants.aspx	City of Rockingham
Community Grants, State NRM Program	Catchment and community groups, industry groups, not for profit organisations, local government authorities and education institutions	On-ground natural resource management action at a local level	In 2012, grants of $10,000–$50,000 were provided from funding of $3 million	Varies	State NRM Office www.nrm.wa.gov.au/grants/state-nrm-program.aspx	State-wide
Community Sponsorship Program, City of Gosnells	Conservation groups and community organisations	Environmental works such as weed control, educational displays, minor equipment and volunteer training and development	Up to $5,500	March 2013	barmstrong@gosnells.wa.gov.au www.gosnells.wa.gov.au/scripts/viewoverview_contact.asp?NID=12657	City of Gosnells
Conservation Zone Rate Rebate, Shire of Serpentine Jarrahdale	Landowners with areas of high conservation value	Reward landowners who protect biodiversity values in bushland and wetland areas	Substantial reductions in shire rates	Varies	Environmental Officer at the Shire of Serpentine Jarrahdale (08) 9526 1111 www.sjshire.wa.gov.au/biodiversity/	Shire of Serpentine Jarrahdale

Funding program	Funding target	What the program funds	How much funding is available	Funding closing date	For further information	Geographic spread
Environmental Community Grants, the Minister for Environment	Private landholders Community groups Conservation/environmental organisations	Biodiversity conservation Sustainable catchment management Protection of high-value areas	Varies; $1.6 million total in 2012	Varies	Environmental Community Grants Coordinator, DEC (08) 9442 0300 grants@dec.wa.gov.au www.dec.wa.gov.au/ecg	State-wide
Gordon Reid Conservation of Natural Heritage Grant (Lotterywest)	Not for profit organisations and local government authorities	Conservation of the state's natural habitats and biodiversity Revegetation activities Research projects	Varies	November	(08) 9340 5270 www.lotterywest.wa.gov.au/grants/grant-types/heritage-and-conservation/natural-heritage	State-wide
Grants to Voluntary Environment and Sustainability and Heritage Organisations (GVESHO), Australian Government	Community based environment and heritage organisations	Conservation and protection of Australia's natural environment and historic heritage	$1.3 million total over the course of the program	Varies	GVEHO Program Team (02) 6274 2422 gveho@environment.gov.au www.environment.gov.au/about/programs/gveho/index.html	National
Healthy Habitats, Shire of Serpentine-Jarrahdale	Landowners	Natural areas of conservation value		Ongoing	Environmental Officer at the Shire of Serpentine-Jarrahdale (08) 9526 1111 www.sjshire.wa.gov.au/biodiversity/	Shire of Serpentine-Jarrahdale
Healthy Wetland Habitats, DEC	Landholders	Technical and financial support Assistance with wetland management plans Activities such as fencing and weed control	Up to $10,000	Ongoing	Healthy Wetland Habitats Coordinator (08) 9219 8788 www.dec.wa.gov.au/hwh hwh@dec.wa.gov.au	Swan Coastal Plain (Perth and surrounds, from Jurien Bay – Dunsborough)
Landcare Community Grants	Landcare groups Coastcare groups	Projects aimed at improving the environment			www.landcareonline.com/funding_opportunity_details.asp?fo_id=9 Some ad hoc projects funded via DAFWA: Natalie Moore (08) 9368 3166 natalie.moore@agric.wa.gov.au.	National
Landowner Biodiversity Conservation Grants, City of Cockburn	Cockburn landowners with property in the Rural, Rural Living and the Resource Zones	Conservation of natural wetland areas on private property	Up to $3,000	Close 31 October each year	Environmental Services Section (08) 9411 3444 www.cockburn.wa.gov.au/Council_Services/Environment/Grants_and_Subsidies/default.asp	City of Cockburn

Funding program	Funding target	What the program funds	How much funding is available	Funding closing date	For further information	Geographic spread
Nature Conservation Covenant Program, DEC	Private landowners	Permanent protection of bushland with high nature conservation values through the placement of a legally binding covenant on their land title. Administration, survey, legal and covenant registration costs Fencing and other management costs Eligibility for funding or rate relief may apply on a case by case basis through other programs	Case-by-case basis Up to $500 to cover the owner's reasonable independent legal costs Up to $10,000 for initial implementation of management actions	Ongoing	Nature Conservation Covenant Program Coordinator (08) 9334 0477 www.dec.wa.gov.au/management-and-protection/conservation-on-other-lands/covenant-program.html	State-wide
Strategic Priority Project Grants, State NRM Program	Regional NRM groups, state government agencies and the Western Australian Local Government Association	Projects that address State NRM Program investment priorities	$10-$15 million in total	Varies	State NRM Office www.nrm.wa.gov.au/grants/state-nrm-program.aspx	State-wide
Swan Alcoa Landcare Program (SALP), Perth Region NRM Inc	Community groups and local governments working with community groups within the Swan and Canning catchments	On-ground works to protect surface and groundwater and biodiversity			Perth Region NRM (08) 9374 3333 enquiries@perthregionnrm.com www.perthregionnrm.com/pr-nrm-programs/swan-river-trust-alcoa-landcare-program.aspx	The catchments of the Swan and Canning Rivers
Water grants and funding, Australian Government	Action on climate change; wise water use; securing water supplies; healthy rivers and waterways	Varies	Varies	Varies	www.environment.gov.au/water/programs/index.html	National

Funding directories

There are many funding directories and websites providing details of funding for a range of environmental projects and activities. The following are links to some of the most comprehensive grant directories and websites that can be used to identify funding and grants programs for wetland protection and management activities.

Table 2. Funding directories useful for sourcing funds for wetland management.

Funding directory	Directory provider	Contact
DAFF grants and assistance	Department of Agriculture, Fisheries and Forestry (DAFF)	www.daff.gov.au/about/current-grants
DSEWCaP grants and funding	Department of Sustainability, Environment, Water, Population and Communities (DSEWCaP)	www.environment.gov.au/about/programs/index.html
EasyGrants newsletter	Our Community (note: there is a subscription fee)	www.ourcommunity.com.au/funding/funding_main.jsp
Grants Directory	Department of Local Government and Regional Development	http://grantsdirectory.dlg.wa.gov.au www.rdl.wa.gov.au/grantandfunding/FundingApplications/Pages/default.aspx
GrantsLINK	Department of Regional Australia, Local Government, Arts and Sport	http://grants.myregion.gov.au
Guide to Community Grants	Parliament of Australia Parliamentary Library	www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/Browse_by_Topic/community
WA Government	Government of Western Australia	http://wa.gov.au/information-about/wa-government/awards-grants-rebates

Labour programs

There are a variety of labour programs that can provide private landowners and local governments with labour, tools and other resources required to undertake bushland and wetland management activities.

Table 3. Labour programs available in Western Australia

Labour program	Who is targeted	What the program provides	For further information	Geographic Spread
Better Earth, Conservation Volunteers Australia	Community groups Park rangers Landcare coordinators Environmental officers Park maintenance staff	Provides a managed volunteer task force under the supervision of a fully trained team leader.	Free call 1800 032 501 (08) 9335 2777 perth@conservationvolunteers.com.au www.conservationvolunteers.com.au	State-wide
Earth Assist, Conservation Volunteers Australia		Supervised volunteering of students in years 10 to 12	(08) 9335 2777 perth@conservationvolunteers.com.au www.conservationvolunteers.com.au/about-us/our-partnerships/rio-tinto-earth-assist	State-wide
Employment Services, Green Skills Inc (Ecojobs)	Environmental projects	Provides skilled environmental personnel for natural resource management contracts and paid casual employment.	Annabelle Newbury (08) 9360 6667 anewbury@greenskills.org.au. ecojobs@greenskills.org.au www.greenskills.org.au	Perth metropolitan area South Coast NRM Region
Green Corps, Greening Australia WA	Resource management organisations Catchment groups Indigenous organisations/corporations Local councils and shires	Greening Australia delivers the national Green Corps training initiative for the Federal Government's Department of Education, Employment and Workplace Relations (DEEWR).	Claire Hudson (08) 9335 0120, (08) 6488 6699 chudson@gawa.org.au.	State-wide rural and remote areas (excluding Rangelands NRM Region)

Land sale, purchase or donation

For some private landholders, managing bushland on their property is a difficult and/or unwanted task. For these landowners, selling their bushland is an attractive alternative. There are a number of programs operating in WA that can facilitate the sale of bushland to conservation-minded members of the public. In some circumstances, government agencies also have funding to purchase bushland considered to be of high conservation value. For some landholders, the option of donating bushland to an organisation is also attractive, particularly if there is an economic incentive to do so (such as taxation benefits).

Table 4. Land sale, purchase and donation programs available to facilitate the sale of bushland for conservation management.

Program	Land sale, purchase or donation	Who is eligible/supported	What the program provides	For further information	Geographic Spread
Bush Heritage Australia	Land purchase	Private landowners Indigenous groups Pastoral lessees	Acquires and manages land of high conservation value and works in partnership with other landowners Manage fire, feral animals and weeds	1300 NATURE (1300 628 873) info@bushheritage.org.au www.bushheritage.org.au	State-wide
Bush Brokers: WWF-Australia, Real Estate Institute of Western Australia (REIWA), and the National Trust of Australia (WA	Purchase and land sale	Landowners Conservation-minded groups and individuals	Aims to promote the sale of bushland as a real estate asset, and thus increase the financial and conservation values of bush blocks in south-west Western Australia to ensure their conservation and sustainable use	info@bushbrokers.com WWF Australia (08) 9387 6444 REIWA on (08) 9755 5123 Natural Heritage Manager at National Trust of Australia (WA) (08) 9321 6088 www.bushbrokers.com.au	State-wide
Government Conservation Land Purchase Program, Department of Environment and Conservation	Purchase of leasehold land Purchase of parcels of freehold remnant vegetation and wetlands in the south-west agricultural zone and Swan Coastal Plain	Landowners Pastoral lessees	Acquires land suitable for establishing a comprehensive, adequate and representative terrestrial conservation reserve system	DEC's Land Tenure Project Officer (08) 9219 8775	State-wide
Land purchasing, Gondwana Link	Land purchase Covenanting	Private landholders	Aims to restore the ecological connectivity between the forests and the semi-arid interior of south-western Australia by building a network of core wilderness areas linked by continuous belts of habitat surrounded by appropriate land uses.	Gondwana Link Director (08) 9842 0002. www.gondwanalink.org	South Coast NRM region
Land Purchasing/Tax Deductable Donation, Australian Wildlife Conservancy (AWC)	Land purchase Donation	Landowners Pastoral lessees	Aims to establish a national network of sanctuaries that protect threatened wildlife and ecosystems by acquiring and managing areas of high conservation significance. AWC's operations are funded primarily by donations.	Australian Wildlife Conservancy (08) 9380 9633 www.australianwildlife.org	State-wide

Program	Land sale, purchase or donation	Who is eligible/supported	What the program provides	For further information	Geographic Spread
Tax deductible donation, National Trust of Australia (WA)	Donation	Government Environmental organisations Private landowners	Land can be donated to the National Trust of Australia (WA) and the donor may be eligible for a tax deduction. Land may subsequently vested in an approved environmental organisation or government conservation department to ensure it is managed for conservation.	National Trust WA Natural Heritage Manager (08) 9321 6088 www.naturalheritage.org.au	State-wide

Legal protection

As with management agreements, legal protection mechanisms will be more appealing to those landholders who are already conservation-minded. The following covenanting programs offer voluntary, legal agreements that can aid in the protection of bushland from future development. Most of the programs outlined below enable landholders to gain access to professional advice and financial incentives.

Table 5. Legal protection mechanisms available to facilitate the protection of bushland.

Program	Who is eligible/ supported	What the program provides	For further information	Geographic Spread
Covenanting Program, National Trust of Australia (WA)	Private landowners	National Trust covenants can be tailored to meet the landowner's needs. They are legally binding and run with the title of the land in perpetuity, although fixed-term covenants are negotiable. Management advice through program. Eligibility for funding or rate relief may apply through other programs on a case by case basis.	National Trust WA Natural Heritage Manager (08) 9321 6088 www.nationaltrust.org.au/wa/natural-heritage	State-wide
Nature Conservation Covenant Program, DEC	Private landowners	Enables landowners to permanently protect their bushland with high nature conservation values through the placement of a legally binding covenant on their land title. Advice, stewardship support and management funding through program. Eligibility for other funding or rate relief programs may apply on a case by case basis.	Nature Conservation Covenant Program Coordinator (08) 9334 0477 www.dec.wa.gov.au/management-and-protection/conservation-on-other-lands/covenant-program.html	State-wide
Soil and Land Conservation Act Covenant, Department of Agriculture and Food	Private landowners	Two types of conservation covenants are available to protect land and can apply for an agreed period or in perpetuity.	Office of the Commissioner of Soil and Land Conservation at the Department of Agriculture and Food (08) 9368 3282 www.agric.wa.gov.au/PC_93234.html	State-wide

Management agreements

Management agreements will be most attractive to those landholders who are already conservation minded. These agreements often take the form of voluntary, legal or non-binding agreements that can aid in the protection of bushland from future development. Most programs enable landholders to gain access to professional advice and financial incentives that they would otherwise not be eligible to receive.

Table 6. Management agreements available to facilitate the protection of bushland.

Program	Who is eligible/ supported	What does the program provide	For further information	Geographic Spread
Conservation and Land Management Act Section 16, DEC	Private landowners or lessees	DEC may enter into an agreement with a landowner or lessee to manage the land under the CALM Act, usually where the land is adjacent to other land managed by DEC, and the agreement to manage is a means of more efficiently managing the combined land area. Management agreements might also be considered where DEC has a significant interest in the land, such as the occurrence of a significant area of vegetation, and the land owner or occupier was not wishing to manage those interests.	Contact your local DEC office; see Table 8. 'DEC Regional Headquarters' below.	State-wide
Healthy Wetland Habitats, DEC	Private landowners	Development of a voluntary management agreement for priority actions Technical and financial support	Healthy Wetland Habitats Coordinator on (08) 9219 8788 www.dec.wa.gov.au/hwh hwh@dec.wa.gov.au	Jurien-Dunsborough, including Perth metropolitan area
Land for Wildlife, DEC	Private landowners	Assistance with management plans Technical support	Land for Wildlife Coordinator (08) 9334 0530 www.dec.wa.gov.au/landforwildlife	State-wide

TRAINING

This section provides an overview of the key wetland-related training opportunities available in WA. The following training programs range from general wetland management to rehabilitation techniques. Training programs also provide opportunities for information exchange and networking between like-minded people. Training opportunities have been listed in alphabetical order by the name of training provider. University courses are not listed.

Table 7. Training providers and training opportunities available to wetland managers.

*Please note contact names may change and therefore in some instances only position titles and contact details are given.

Host agency	Training opportunity	Target audience	Contact details
Cockburn Wetlands Education Centre	Occasional training and events can be provided.	Open	www.cockburnwetlands.org.au Contact person: Wetlands Officer 9417 8460
DEC and Southern Cross University	Annual acid sulfate soils professional short course; acid sulfate soil identification, assessment and management. Held in WA and other states.	Environmental consultants, urban developers, contractors, environmental scientists and conservationists, civil and environmental engineers and resource industry professionals	Chrisy Clay, Southern Cross University, Lismore NSW (02) 6620 3095 chrisy.clay@scu.edu.au; www.scu.edu.au/geoscience Acid sulfate soils section, DEC; Manager Stephen Wong (08) 9333 7576
DEC EcoEducation Program	Offers schools, teachers, students and their communities a variety of products and services to generate interest in and action for biodiversity conservation, sustainable living and practical ways to act on conservation issues.	School students	www.dec.wa.gov.au/ecoeducation
DEC Land for Wildlife Program	Workshops or field days are arranged when registered landholders express an interest in learning more about a particular topic, for example 'native plant propagation' or 'acid sulfate soils'. These events are usually also open to the general public.	Open	Senior Project Officer (08) 9334 0427
DEC Ribbons of Blue Program	Provides teachers and their students with practical, hands-on learning experiences focussing on the sustainability of local waterways, wetlands and their ecosystems. Ribbons of Blue has loan equipment and sampling procedures to enable community groups to monitor wetland condition.	School students	Coordinator (08) 6467 5127 http://education.dec.wa.gov.au/ribbons-of-blue.html
DEC Urban Nature Program	Provides field days, workshops, training programs, technical advice and on-ground support for land managers working to protect, manage and restore bushland and wetland in DEC's Swan Region and beyond.	Open	(08) 9423 2900 urban.nature@dec.wa.gov.au
Eastern Metropolitan Regional Council's Bush Skills for the Hills	Bush Skills for the Hills is a series of free, hills-focused workshops for the community. The workshops are a mix of information and practical hands-on sessions designed to give participants both the 'why' and 'how' of managing land, bush and creeks in the hills environment.	Open	www.emrc.org.au/bush-skills-for-the-hills-workshops.html

Host agency	Training opportunity	Target audience	Contact details
Greening Australia WA	Greening Australia WA provides environmental education and training in seed collection and rehabilitation methods.		(08) 6488 6699 general@gawa.org.au
Green Skills Inc.	A Registered Training Organisation scoped to deliver: Conservation and Land Management Traineeships Certificates I – IV in Conservation & Land Management Bushland and wetland management workshops	Eligible applicants	State Manager Training (08) 9360 6667 www.greenskills.org.au anewbury@greenskills.org.au
National centre for groundwater research and training	Groundwater short courses, generalist courses and specialist courses offered in WA and other states	Professional development for NRM practitioners	To subscribe to training emails: cgs@groundwater.com.au (08) 8201 5632 www.groundwater.com.au
Piney Lakes Environmental Education Centre	Workshops and self-guided activities	Community and teacher professional development	www.melvillecity.com.au/pineylakes
Regional NRM organisations	Regional NRM organisations may hold various training events for landholders and community groups at various times.	Varies	Contact your local NRM Region office; see Table 9 below.
Rockingham Regional Environment Centre (Naregebup)	Various educational opportunities including an education program for school students and school holiday program.	Varies	www.naragebup.org.au
Small landholder information service	Provides targeted learning events and resources on sustainable land management.	Landholders of small properties	small_landholder@agric.wa.gov.au www.agric.wa.gov.au/PC_92609.html
Sydney Olympic Park Authority	Wetland Education and Training (WET) Program is for wetland management and policy professionals and academics.		(02) 9714 7888 To subscribe: wetworkshop@sopa.nsw.gov.au
TAFE WA	Various units and courses such as Environmental Science - Management (Cert IV & Diploma).	Tertiary students	www.trainingwa.wa.gov.au/trainingcourses/detcms/portal/
WA Gould League	Environmental education based at Herdsman Lake Wildlife Centre.	Community and school students	www.wagouldleague.com.au
Wildflower Society of Western Australia	The Wildflower Society often conducts information talks for a small cost.	Open	http://members.ozemail.com.au/~wildflowers/events.htm

RESOURCES

This section provides an overview of key resources including:

- conferences and other activities
- DEC information centre
- general contacts and sources of advice
- technical advice
- wetland mapping
- online data sources with information about WA's wetlands
- websites and newsletters

Conferences and other activities

World Wetlands Day: World Wetlands Day is celebrated internationally each year on 2 February. It marks the anniversary of the signing of the Convention on Wetlands of International Importance (Ramsar Convention) in Ramsar, Iran, on 2 February 1971. In celebration of World Wetlands Day, state governments, community organisations and non-government organisations hold various activities across the country. For more information see www.environment.gov.au/water/topics/wetlands/world-wetlands-day/index.html and www.dec.wa.gov.au/management-and-protection/wetlands/internationally-recognized-wetlands-ramsar.html

Annual WA Wetland Management Conference: the Cockburn Wetlands Education Centre holds a conference annually on/close to 2 February each year, marking World Wetlands Day. The conference provides an annual opportunity to exchange information and ideas between wetland practitioners, with a focus on the latest developments about how to effectively manage and restore wetlands. For more information see http://cockburnwetlandscentre.wordpress.com/

DEC Information Centre

Visitors to DEC's Information Centre have access to a wide range of library resources suitable for professionals, teachers, students, community groups and the general public. These can be viewed at the DEC Information Centre, located at The Atrium, Level 4, 168 St Georges Terrace, Perth WA 6000 (08) 6467 5226. For more information, see

www.dec.wa.gov.au/about-us/about-dec/3369-information-centre.html.

To search the DEC Conservation Library catalogue, see http://science.dec.wa.gov.au/conslib.php. Loans and article copies are available through the interlibrary loan/document delivery service provided by institutional and public libraries.

General contacts and sources of advice

DEC regions

The following table contains the current contact details for DEC regional headquarters. People can be directed to the appropriate district office, work centre or DEC officer through these contacts. WA DEC Regions are shown in Figure 2. Note that these details can change, see www.dec.wa.gov.au/index.php?option=com_content&view=article&id=6518&Itemid=1563 for current listings.

Table 8. DEC regional headquarters and phone numbers

DEC regions and regional headquarters	Phone number
Atrium (central administration)	(08) 6467 5000
Goldfields Region, Kalgoorlie	(08) 9080 5555
Kimberley Region, Kununurra	(08) 9168 4200
Midwest Region, Geraldton	(08) 9921 5955
Pilbara Region, Karratha	(08) 9143 1488
South Coast Region, Albany	(08) 9842 4500
South West Region, Bunbury	(08) 9725 4300
Swan Region, Bentley	(08) 9423 2900
Warren Region, Manjimup	(08) 9771 7988
Wheatbelt Region, Narrogin	(08) 9881 9222

Figure 2. Boundaries of DEC regions and locations of regional headquarters.

Regional NRM organisations

Regional natural resource management (NRM) organisations coordinate a range of resources and information relevant to wetlands. Regional NRM organisations can provide assistance and details of relevant sub-regional organisations. They are outlined in Table 9 and the boundaries are shown in Figure 3.

Table 9. Regional NRM organisation contacts

NRM regional organisation	NRM Sub-regions
Northern Agricultural Catchments Council www.nacc.com.au (08) 9938 0100	Greenough Moore River West Midlands Yarra Yarra
Perth Region NRM www.perthregionnrm.com (08) 9374 3333	North North-East East South Coastal
Rangelands NRM WA www.rangelandswa.com.au (08) 9485 8930	Kimberley Pilbara Gascoyne-Murchison Goldfields-Nullarbor
South Coast Natural Resource Management Inc. www.southcoastnrm.com.au (08) 9845 8537	Albany Hinterland Esperance Mallee Esperance Sandplain Fitzgerald Biosphere Kent Frankland North Stirlings Pallinup
South West Catchments Council www.swccnrm.org.au (08) 9780 6193	Blackwood Cape to Cape Geographe Leschenault Peel-Harvey Warren
Wheatbelt NRM www.wheatbeltnrm.org.au (08) 9670 3100	Avon Lockhart Yilgarn

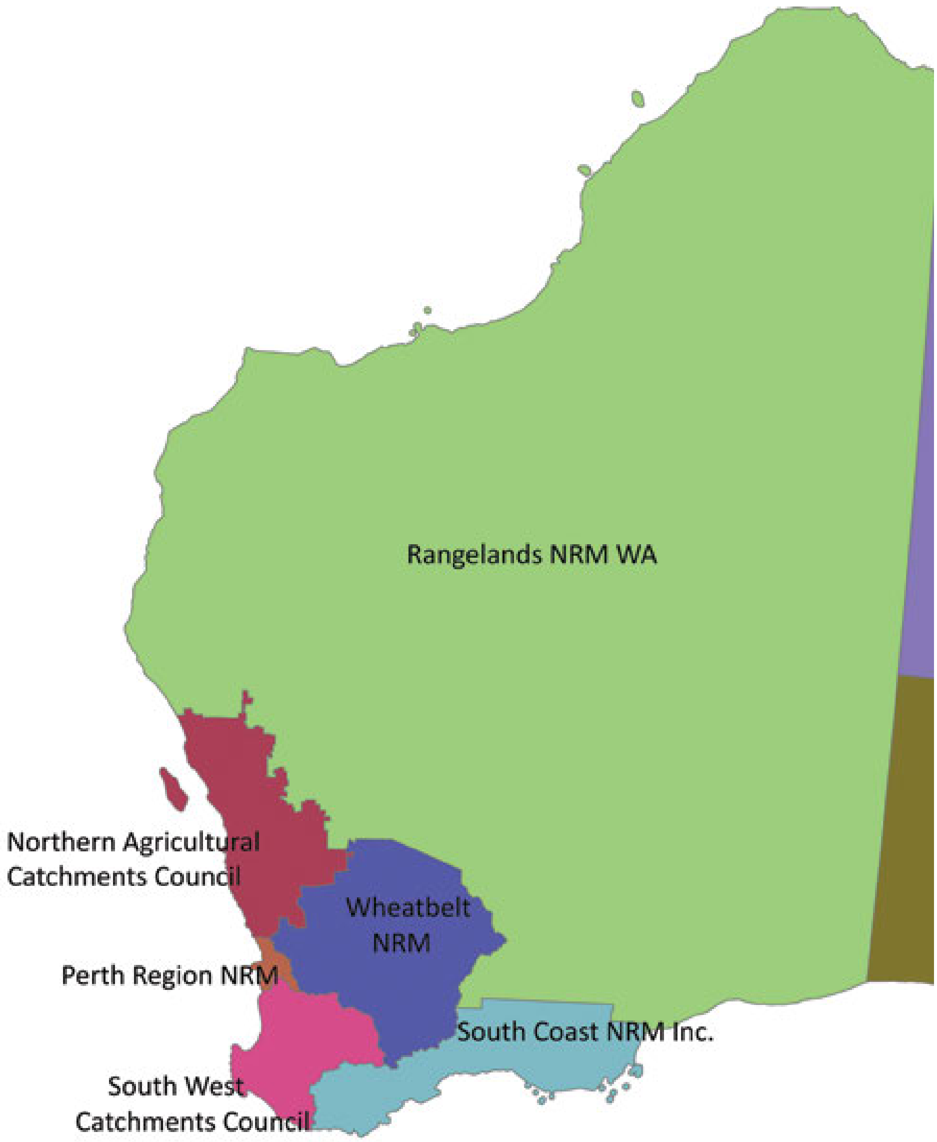

Figure 3. Regional NRM organisation boundaries

Local Government

The Western Australian Local Government Association (WALGA) is a non-government organisation that lobbies and negotiates on behalf of the 142 local governments of WA: http://walga.asn.au

It also provides a list of all of WA's local government websites: http://walga.asn.au/AboutLocalGovernment/CouncilWebsites.aspx

Environment centres

Western Australia's environmental education centres are very important and greatly increase community awareness and the capacity of individuals to make decisions and implement positive management actions for wetlands on their property, or the public properties they are involved in managing through Friends-of groups or other associations.

Education centres that incorporate nearby wetlands into their activities include:

- Canning River Eco Education Centre: www.canning.wa.gov.au
- Cockburn Wetlands Education Centre: www.cockburnwetlands.org.au
- Henderson Environment Centre: www.stirling.wa.gov.au
- Herdsman Lake Wildlife Centre (WA Gould League Inc): www.wagouldleague.com.au
- Naragebup Rockingham Environment Centre: www.naragebup.org.au
- Piney Lakes Environmental Education Centre: www.melvillecity.com.au
- South West Environment Centre: www.swecwa.org

Volunteering

Volunteering WA www.volunteeringwa.org.au

Technical advice and expertise

The following programs can provide landholders and community groups with technical advice in order to gain an understanding of wetlands on their land and the management practices they need to employ to protect them. The programs outlined below currently deliver technical assistance through a variety of mechanisms ranging from education materials to one-on-one advice from trained staff.

Table 10. Programs available to provide technical advice on wetland management

Program	Who is eligible/ supported	Advice provided	For further information	Geographic spread
Bush Brokers. World Wildlife Fund (WWF) Australia, Real Estate Institute of Western Australia (REIWA), and the National Trust of Australia (WA)	Conservation-minded groups and individuals Buyers and sellers of bush	Manual for buyers, sellers and realtors Checklist and information brochures for buyers and sellers of bush Case study documents	info@bushbrokers.com WWF Australia (08) 9387 6444 REIWA (08) 9755 5123 Natural Heritage Manager at National Trust of Australia (WA) (08) 9321 6088 www.bushbrokers.com.au	State-wide
Environmental Defenders Office (WA) Inc.	Community groups and individuals who cannot otherwise afford assistance	Legal advice and representation on public interest environmental law issues	Environmental Defenders Office (WA) Inc. (08) 9221 3030, 1 800 175 542 edowa@edowa.org.au www.edowa.org.au	State-wide
Healthy Wetland Habitats, DEC	Private landholders	Wetland management advice	Healthy Wetlands Coordinator (08) 9219 8788 www.dec.wa.gov.au/hwh hwh@dec.wa.gov.au	Jurien-Dunsborough, including Perth metropolitan area
Land for Wildlife, DEC	Private landholders	Bushland and wetland management advice	DEC Land for Wildlife Senior Project Officer (08) 9334 0427 www.dec.wa.gov.au/landforwildlife	State-wide

Program	Who is eligible/ supported	Advice provided	For further information	Geographic spread
Seed Management Services, Greening Australia WA	Commercial service to clients in government, industry, the private sector and community	Direct technical advice and training on best practice seed collection and rehabilitation methods Advice on suitable native species Technical advice on revegetation planning and direct seeding	Seed Management Services Co-ordinator (08) 9335 8933 bsmith@gawa.org.au	State-wide
Urban Nature, DEC	Land managers, associated community groups	Technical advice relating to wetland and bushland management	Urban Nature Coordinator (08) 9423 2900 urban.nature@dec.wa.gov.au.	DEC's Swan Region and beyond
Wetlands Section, DEC	Land managers Community groups	Advice on managing wetlands	wetlands@dec.wa.gov.au	State-wide

Wetland mapping

Wetland mapping has been undertaken, to varying degrees, in some regions of WA (Figure 4). Mapping scale and type of information collected varies with each project but ranges from 1:25,000 to 1:250,000 and information may include wetland location, boundary, type and values. Additional mapping projects, particularly in the midwest and south-west, are in development. As mapping projects are finalised, datasets containing this information are made publicly available. Public access for viewing and downloading datasets is outlined in the next section 'Online data sources with information on WA's wetlands'. For more information about wetland mapping in WA, see the topic 'Introduction to the guide'.

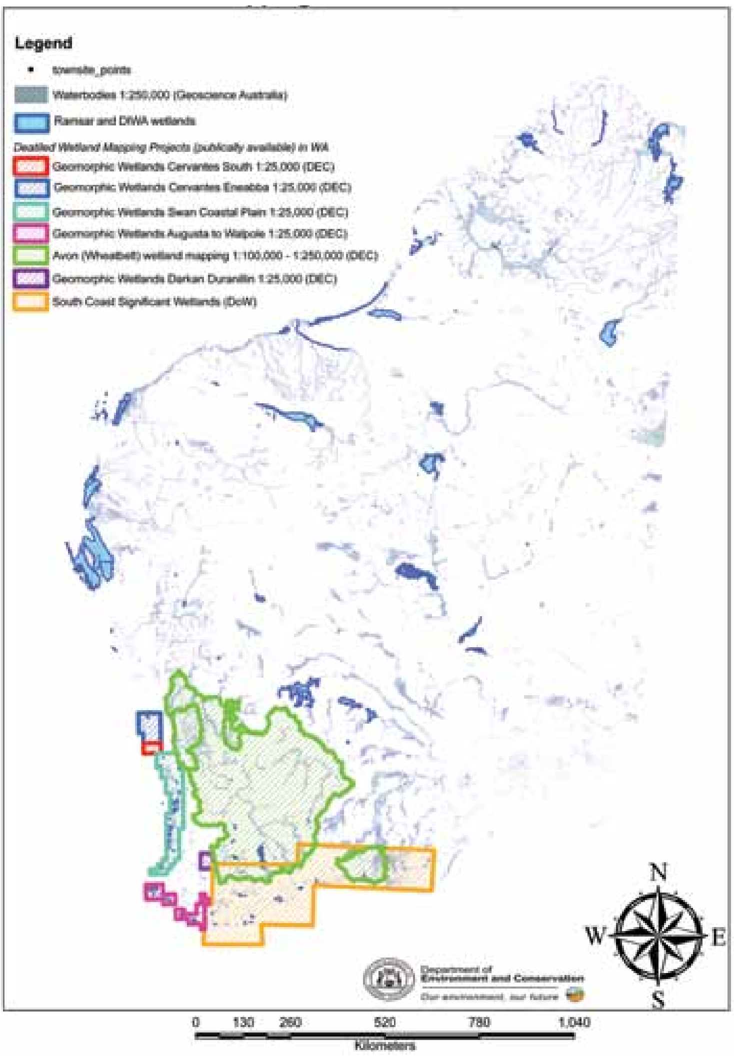

Figure 4. Areas of WA where wetlands have been mapped. Image – Wetlands Section/DEC.

Online data sources with information on WA's wetlands

The Australian Wetlands Database provides online access to information on internationally important wetlands, that is, Australia's Ramsar wetlands; and nationally important wetlands, that is, sites listed in the online directory of important wetlands of Australia. http://environment.gov.au/water/topics/wetlands/database/index.html

Landgate's WA Atlas is a basic map viewer enabling users to see what WA data is available and to do some simple mapping functions. The following wetland datasets are available via https://www2.landgate.wa.gov.au/slip/portal/home/home.html:

- *Geomorphic Wetlands Swan Coastal Plain* dataset
- *Geomorphic Wetlands Augusta to Walpole* dataset
- *South Coast Significant Wetlands* dataset
- *Ramsar Sites Western Australia* dataset
- *Lakes Environmental Protection Policy* dataset
- *South West Agricultural Zone Wetlands Environmental Protection Policy* dataset

It also provides cadastral information (for example, property boundaries and numbers).

For information and instructions on how to view these datasets go to: www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-mapping.html. Additional mapping projects, particularly in the midwest and south-west, are in development. As mapping projects are finalised, datasets containing this information are made publicly available.

DEC's **NatureMap** enables users to produce maps, lists and reports of WA's flora and fauna diversity. Wheatbelt wetland mapping is also available on NatureMap. http://naturemap.dec.wa.gov.au/

DEC's **WetlandBase** is an interactive database by DEC, with web hosting by the Department of Agriculture and Food WA, available via www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-data/wetlandbase.html or via http://spatial.agric.wa.gov.au/wetlands. *WetlandBase* provides a comprehensive online resource of information and data about Western Australian wetlands. It provides spatial data, such as wetland mapping, and point data, such as water chemistry, waterbirds, aquatic invertebrates and vegetation sampling results. DEC is preparing an alternative to *WetlandBase*, scheduled for release in 2013, that will continue to make this data publicly available.

Google Earth enables viewing of aerial photography and, where available, aerial photography over time (time series) www.google.com/earth.

Landgate's **Map Viewer** enables viewing of aerial photography and, where available, aerial photography over time (time series). It also provides cadastral information (for example, property boundaries and numbers). https://www.landgate.wa.gov.au/bmvf/app/mapviewer/

Websites and newsletters

ASSAY (acid sulfate soil newsletter) is provided by the NSW Department of Primary Industries and funded by the Australian Government. To subscribe contact Simon Walsh simon.walsh@dpi.nsw.gov.au or see www.dpi.nsw.gov.au/aboutus/resources/periodicals/newsletters/assay.

Australian Society for Limnology (ASL) is a professional association for scientists and managers of inland waters, including rivers, streams, lakes, reservoirs and estuaries. See www.asl.org.au

Bushland news is the newsletter of DEC's Urban Nature Program, produced quarterly to support community involvement in bushland conservation. To subscribe, email urban.nature@dec.wa.gov.au. Current and archived issues are available at www.dec.wa.gov.au/management-and-protection/programs/urban-nature/bushland-news.html

COOEEads provides a weekly email listing of jobs, conferences and training opportunities in the outdoor education/ recreation; environmental education/extension; and conservation/park management fields in Australia and New Zealand. To subscribe visit www.cooeeads.com.au.

DEC wetlands webpage www.dec.wa.gov.au/wetlands provides information on WA's wetlands and details of DEC programs.

DSEWCaP wetlands webpage http://environment.gov.au/water/topics/wetlands/index.html provides information on Australia's wetlands and details of the Australian Department of Environment, Sustainability, Water, Communities and Population programs.

Small Landholder Information Service (AgWA) provides a specialised website for landholders wishing to manage land sustainably. To subscribe see www.agric.wa.gov.au/PC_92609.html

WATSNU newsletter by DEC is a newsletter about the conservation of WA's threatened species and ecological communities, many of which are wetlands. To subscribe, email Gemma.Grigg@dec.wa.gov.au or Jill.Pryde@dec.wa.gov.au. For current and archived issues see www.dec.wa.gov.au/management-and-protection/threatened-species/watsnu-newsletters.html

WetlandCare Australia (WCA) is a national not-for-profit, non-government science-based organisation with a mission to support the community in the protection and repair of Australia's wetlands through action-based partnerships with governments, landholders, natural resource managers, researchers and the community www.wetlandcare.com.au. Their email bulletin is WetlandLink, subscribe from www.wetlandcare.com.au/index.php/news/wetlandlink-newsletter

Wetlands Australia magazine is a twice-yearly publication by the Department of Sustainability, Environment, Water, Population and Communities. It brings together information and resources from across Australia relating to wetlands conservation, management and education. To subscribe and for current and archived issues go to http://environment.gov.au/water/publications/environmental/wetlands/wetlands-australia/index.html

A guide to managing and restoring wetlands in Western Australia

Wetland hydrology

In Chapter 2: **Understanding wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Wetland hydrology' topic

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When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Wetland hydrology', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by C Mykytiuk, J Lawn and R Lynch, Department of Environment and Conservation, Perth, Western Australia.

Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction'.

Introduction

Over time, wetlands have formed where water has accumulated at or close to the ground surface for periods sufficient to form wetland characteristics. Water creates and defines wetlands and distinguishes them from dryland ecosystems, affecting every physical, chemical and biological process in wetlands and, in doing so, shaping their ecological character. An understanding of the natural patterning of water in a wetland, and the role it plays in shaping the wetland, is essential when managing it, particularly when the natural water patterns have been, or have the potential to be, affected by human-induced changes.

Wetland water regime has been identified as the highest priority issue in the management of Western Australian wetlands by the WA Environmental Protection Authority.[1] Changes to natural wetland water regimes have resulted from widespread changes to the landscape of WA, such as clearing, development and drainage, as well as water abstraction and climate change.

Managing the natural water regime of a wetland of conservation value is the most essential activity a wetland manager can undertake. Where the purpose of wetland management is nature conservation, the role of a wetland manager is generally to minimise potential human-induced changes to intact natural water regimes. If altered by human activities, restoration and management of a wetland may involve reinstating or improving the water regime, or, if this is not feasible, managing a changing ecosystem. These tasks can be challenging for wetland managers without expertise in hydrology, and in many circumstances it can be essential for wetland managers to liaise with relevant qualified professionals such as hydrologists and hydrogeologists.

This topic provides information on the natural hydrological characteristics of WA wetlands. This understanding forms the basis for managing wetland hydrology. The topic 'Managing hydrology' in Chapter 3 provides more detailed information on the actions that can be taken to manage or restore wetland hydrology.

WHAT ARE THE HYDROLOGICAL CHARACTERISTICS OF WESTERN AUSTRALIA'S WETLANDS?

Water is naturally variable across the Earth, but especially so in Australia, a land 'of droughts and flooding rains'.[2] Its variability in terms of presence and absence, timing, duration, frequency, extent, depth and chemical properties makes each wetland unique.

There is no typical wetland water pattern in WA wetlands, but rather a wide range of naturally occurring patterns. Most, but not all, wetlands in WA dry for a period of time. Across the state wetlands wet and dry at different times and frequencies, for different durations, and wet to different extents and depths. Some receive water at predictable times, while others receive extremely unpredictable inflows. Many of WA's wetlands are very dynamic (changeable). Water depth and extent may change from season to season, year to year, and over the long term. This variability is both normal and natural for most wetlands in WA. Recognising that wetlands are highly dynamic systems is fundamental to their understanding and management.[3]

Wetland water patterns are often described using three terms:

- wetland hydrology
- wetland hydroperiod
- wetland water regime.

It is important to note that these terms mean different things to different people, and are sometimes used interchangeably. The terms, as they are used in this document, are defined below and described in the context of WA wetlands.

Seasonal: present during a given period of the year, recurring yearly

Intermittent: present for variable periods of time with no seasonal periodicity

Inundation: where water lies above the soil surface (also called surface ponding)

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from sediment pore waters of inundated and waterlogged wetlands)

Waterlogged: saturation of the soil

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

Wetland hydrology

Hydrology is the study of the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere. Hydrology can be studied at a range of scales (such as catchment, regional or global) and from different perspectives (for example, focusing on a particular wetland, a river catchment or a groundwater aquifer) depending on the questions being asked. The term has also come to mean, more generally, the properties of water, rather than the actual study of it. The term **wetland hydrology** is used in this more general sense to refer to the movement of water into and out of, and within a wetland.

Hydroperiod

The term **hydroperiod** describes the long-term prevailing hydrological characteristics of a wetland in terms of whether it is predominantly waterlogged or inundated, and the duration (permanent, **seasonal** or **intermittent**). Table 1 shows the wetland hydroperiods that have been identified via a number of wetland mapping projects in WA.

Table 1. Wetland hydroperiods recorded in Western Australia. Adapted from Semeniuk and Semeniuk.[4]

Period of duration	Water presence	
	Waterlogged	Inundated
Intermittent	Not applicable	Intermittently inundated
Seasonal	Seasonally waterlogged	Seasonally inundated
Permanent	Permanently waterlogged	Permanently inundated

Inundated wetlands are those which have free-standing water (a **water column**) above the soil/substrate surface. **Waterlogged** wetlands are those in which the soils/substrate are saturated with water, but where the water does not inundate the soil surface across the majority of the wetland (at their most wet under prevailing conditions). They are saturated to the extent that they develop wetland characteristics, such as wetland soils, wetland plants, and distinct communities from surrounding dryland. The water is present in between sediments as interstitial waters, also known as **sediment pore waters** (Figure 1). These wetlands may waterlog permanently or seasonally. Intact waterlogged wetlands tend to be densely vegetated. Vast expanses of waterlogged wetland in WA have been cleared and used for agricultural and urban land uses.

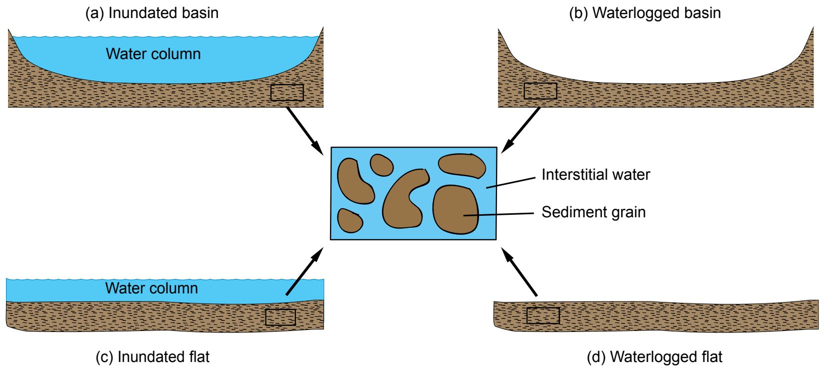

Figure 1. Water columns and sediment pore waters. Image – J Higbid/DEC.

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Permanently inundated wetlands (lakes) are familiar landscape features, and there is a general acceptance of their value as habitat for wetland animals. They support surface water in all years excepting extreme drought conditions.

In contrast, other wetland types do not have the same recognition. Wetlands that are inundated on a seasonal or intermittent basis are often called 'seasonal wetlands' or 'ephemeral wetlands'. These phrases are not used here because these wetlands are always wetlands, not just each period of inundation; they exist as ecosystems over the long term, not just when they are inundated. The broad lack of awareness in WA about these wetland types, and the corresponding value placed upon them, is considered to be one of the most significant barriers to their management and conservation.

To an even greater degree, many people in WA are not familiar with waterlogged wetlands. This is evident in relatively low numbers of these wetland types that are championed by groups and individuals in comparison to inundated areas. These under-appreciated wetland types in fact tend to be naturally very significant for their biodiversity and the role they play in capturing water and nutrients in the landscape.

A change in hydroperiod from one type to another is a significant ecological change to a wetland. A change of hydroperiod changes a wetland's soil and water chemistry and the suite of organisms that can inhabit or make use of a wetland. For example, when a new suburb is built around a seasonally inundated wetland, new residents often wish to see it permanently inundated, to enjoy the views and the experience of being by the water in warm weather. They may also like to see the wetland being used by waterbirds year-round. To achieve this outcome, water needs to be diverted from another part of the landscape or from groundwater. A common outcome is that a few common species of waterbird will be advantaged by the change, while the full, natural suite of waterbirds (and other animals) will no longer use the wetland because it no longer supports the conditions they need for breeding, feeding or roosting. A range of other problems associated with the change in chemical conditions often occur, such as algal blooms, nuisance populations of midge and emissions of gas causing a 'rotten egg' odour.

The following examples provide some insight into the different types of wetlands of WA, based on hydroperiod, and why water is such a driving force in wetland diversity across the state.

Seasonally waterlogged wetlands

Seasonally waterlogged wetlands are common in areas of the north-west, midwest, south-west and south coast. They are best documented in Perth and the surrounding **Swan Coastal Plain** between Moore River and Dunsborough. Of all of the wetland types present in this area, seasonally waterlogged areas are the most prevalent.[5] They are waterlogged in winter and spring and dry in summer. In the event of a very large rainfall event, they may contain surface water for a few hours or days, but waterlogged conditions over the wet season prevail. One type of seasonally waterlogged wetland that covers hundreds of hectares across the eastern side of the Swan Coastal Plain and on the Scott Coastal Plain is palusplain - seasonally waterlogged flats (with 'palus', Latin for marshy, used in reference to the waterlogging).[6] On the Swan Coastal Plain, 66 per cent of the area of wetland is palusplain, most of which has been cleared and used for rural land uses. Figure 2 (a) shows an intact, densely vegetated **palusplain** while Figure 2 (b) shows a degraded palusplain. Other types include seasonally waterlogged basins (damplands) and seasonally waterlogged slopes (paluslopes).

Palusplain: a seasonally waterlogged flat wetland

Figure 2. (a) an intact seasonally waterlogged flat at Hay Park, Bunbury. Photo – J Lawn/DEC; (b) a degraded seasonally waterlogged flat near Dunsborough. Photo – R Lynch/DEC.

Seasonally waterlogged wetlands support a high diversity of wetland vegetation units and often flora. They support a mosaic of vegetation units, especially woodlands, shrublands and herblands (rarely grasslands). These mosaics of often dense vegetation provides habitat for small ground-dwelling mammals, reptiles and birds. The biological diversity of these wetlands is still being discovered; for example, in 2010, in the Perth suburb of Jandakot, a new species of bee was discovered in a seasonally waterlogged wetland in Jandakot Regional Park. This fascinating bee—the 'megamouth' due to the remarkably large jaws of the males—nests in the soil and pollinates wetland plants including the paperbark (*Melaleuca preissiana*) and spearwood (*Kunzea glabrescens*).[7] Residential development is occurring near the only known habitat of this bee.

Permanently waterlogged wetlands

Permanently waterlogged areas also occur in areas of WA. **Mound springs** are a type of permanently waterlogged wetland fed by deep, continuously discharging groundwater sources. The area where groundwater discharges is elevated above the surrounding landscape. It is elevated through the build up of sediment such as clay and/or calcareous (calcium) material brought to the surface, and by the accumulation of **peat** as a result of the wetland vegetation, forming a mound around the area of discharge. These mounds can rise up to two metres above the surrounding landscape and be up to several hundred metres across, and many have a moat of fresh or brackish water surrounding the mound.[8] Mound springs are found in the Kimberley, Pilbara and Midwest regions, the arid interior and Swan Coastal Plain (Figure 3), and include the Mandora Marsh Mounds, Dragon Tree Soak, Bunda Bunda, Big Springs, Black Spring, the North Kimberley Mounds, Mount Salt (calcareous) and Three Spring suite. WA's peat mound springs, often known as **tumulus** mound springs, differ to those of eastern Australia, which are comprised of calcareous **tufa** rather than peat mounds.[8]

Figure 3. A mound spring. Photo – J Lawn/DEC.

Mound springs support a variety of vegetation types, including sedgeland-herbfields, forests, woodlands, monsoon vine thickets and even mangroves. Because they are permanently damp, mound springs have significant conservation value as refuges for plants and animals from the surrounding dry landscape, and they support both **endemic** species and isolated outliers (that is, populations outside of the main distribution of that species).[9] Over geological time, species have had to adapt to changing conditions driven by rising and falling sea levels, aridity and ice ages; most of those that did not change significantly have become extinct or remain only in **refugia** including mound springs and permanently inundated wetlands.[10] For example, the fern *Cyclosorus* ***interruptus*** appears to be found only where permanently wet peaty habitat is present.[9] It is found in the Gingin Brook area north of Perth, and in mound springs in the Kimberley, with no records in between.

Seasonally inundated wetlands

In the north and south of WA there are many seasonally inundated wetlands. Lake Eda near Broome is an example (Figure 4). In the north of the state, the wet season usually falls between October and April and these wetlands typically have their maximum water levels in March following high rainfall between January and March (Figure 5).

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Peat: partially decayed organic matter, mainly of plant origin

Tumulus mound spring: peat-formed mound spring

Tufa: a porous rock composed of calcium carbonate and formed around mineral springs

Endemic: naturally occurring only in a restricted geographic area

Refugia: restricted environments that have been isolated for extended periods of time, or are the last remnants of such areas

Figure 4. Lake Eda, near Broome, is a seasonally inundated wetland in northern WA. Photo – Wetlands Section/DEC.

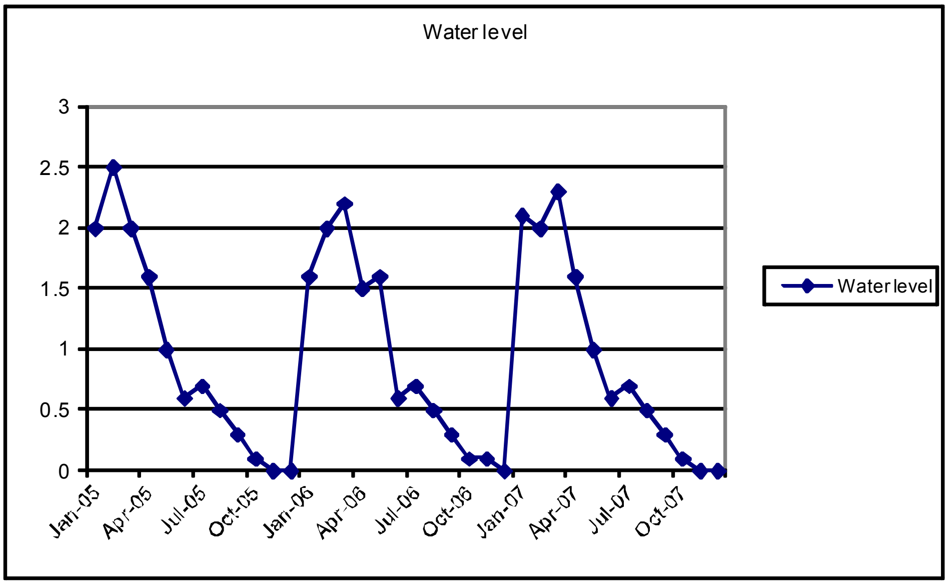

Figure 5. Hydrograph showing the estimated water levels in Lake Eda from January 2005 to December 2007. Water levels estimated from local rainfall data.

Seasonally inundated wetlands typically support a diversity of plants and animals, of which a relatively high proportion of plants are endemic.[11] In addition to perennial species of plants, they typically support a suite of annually renewed species that make many of these wetlands species-rich. They are also important breeding areas for many waterbirds. Small, poorly defined wetlands inundated for a few months account for more than half of the breeding by ducks.[12] On the Swan Coastal Plain, these wetlands are of extreme importance for breeding Pacific black duck and grey teal in south-western Australia.[13] Additionally, in the north these areas are used by crocodiles. Wherever these wetlands occur, they are habitat for frogs adapted to the cyclic wet and dry conditions. A number of seasonally inundated wetlands in the south-west and south coast of the state are inhabited by endemic crayfish adapted to the cyclic wet and dry conditions. For example, the seven *Engaewa* species of crayfish burrow down into the soil as the water recedes, remaining in the damp soil below during the summer dry season. Three of the species are either endangered or critically endangered, due to either the loss of these wetlands or as a result of them becoming drier to the extent that the crayfish cannot survive. Other crayfish, such as gilgies and koonacs, also survive drying by burrowing into damp soils. This burrowing life strategy, an incredible adaptation to WA's seasonally inundated wetlands, is also shared by two species of wetland fish that occur in the south west: the salamanderfish *Lepidogalaxias salamandroides* and the black-stripe minnow *Galaxiella nigrostriata*. Only twenty-two other fish world-wide are known to employ this life strategy.[14]

Intermittently inundated wetlands

Many wetlands in WA are intermittently inundated, including those in the arid interior, as well as some in the south-west. Mungkili Claypan near Wiluna is one such wetland (Figure 6, Figure 7). Some may remain dry for years at a time. These wetlands rely on cyclonic rainfall for inundation. In the arid parts of the state, cyclonic rainfall generally occurs between January and March, however, this may vary from year to year and is likely to continue to do so with climate change.

Intermittently inundated wetlands tend to be subject to high evaporation rates. The sediments tend to accumulate the salts that remain following evaporation of wetland water, meaning that these wetlands can have very saline sediments.

Figure 6. Mungkili Claypan, near Wiluna, is an intermittently inundated wetland in the arid interior of WA. Photos – G Daniel/DEC

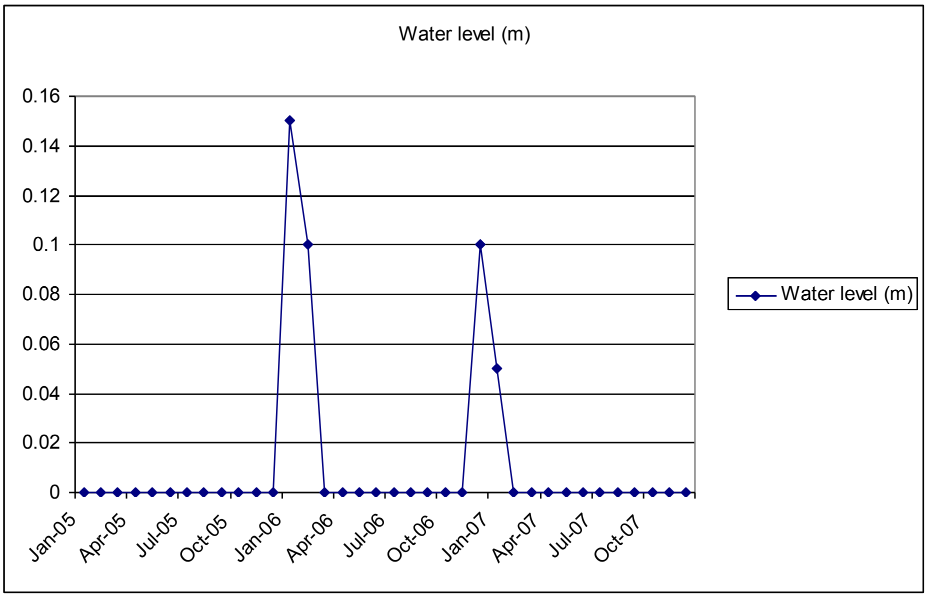

Figure 7. Hydrograph showing the estimated water levels in Mungkili claypan from January 2005 to December 2007. Water levels estimated from local rainfall data.

Intermittently inundated wetlands may seem devoid of life when dry. However, they tend to support resting eggs of small animals, seeds of plants, and spores and cysts of algae and bacteria that can withstand hot, dry conditions. When wet, these wetlands often support an abundance of life, particularly of macroinvertebrates and algae, that while often species-poor, can help drive boom populations of larger animals. Arid zone frogs rapidly respond to the presence of water in these wetlands, with breeding followed by rapid development of tadpoles as water levels fall. More than twelve frog species occur in the arid zone, from a total of eighty-one known in WA. The flat-shelled turtle, *Chelodina steindachneri*, inhabits the most arid region of any Australian turtle: intermittently inundated wetlands in the Pilbara and midwest, extending into the desert. It aestivates for periods of years at a time and can migrate long distances to find water.

Intermittently inundated wetlands can be extremely important waterbird breeding habitat. For example, Lake Ballard (Figure 8), north of Menzies, is inundated once every five or so years on average, usually by single major, summer-autumn rain events of tropical origin; a shallow level of water may persist six to nine months.[15] Brine shrimps, *Parartemia* sp., which survive as cysts during the dry phase, are abundant when the lake fills. These are the main food of the Australian endemic banded stilt *Cladorhynchus leucocephalus* adults and chicks. Lake Ballard is one of the most important breeding sites in Australia for the banded stilt as well as an important migration stopover for many other species of waterbird. Breeding is thought to occur whenever depth over most of the lake reaches 0.3 metres or more. Nests are prepared, typically ten per square metre, on small low islets in colonies of hundreds to tens of thousands. Eggs may be laid within weeks of the lake filling.[15]

Figure 8. Lake Ballard is an intermittently inundated wetland north of Menzies. Photo – Wetlands Section/DEC.

Permanently inundated wetlands

Permanently inundated wetlands are the wetland type that most people think of when they think of wetlands. Permanently inundated wetlands, or lakes, are common in many areas of the world, and have traditionally been the focus of wetland studies in the northern hemisphere. By international standards, WA's lakes are very shallow, and do not freeze over, and as such many aspects of these studies are not as applicable to WA's lakes. In number and area, lakes make up a relatively small proportion of WA's wetland types, but they are often extremely important habitats for specialised wetland species as well as many mobile species that visit wetlands in times of need. In addition to most species of fish, turtles and many species of waterbird, the iconic yet cryptic rakali or water rat, *Hydromsy chrysogaster*, relies on permanent water, including permanently inundated wetlands for its survival. In WA this fascinating mammal occurs in isolated coastal populations in the Pilbara and Kimberley and from Moore River in the midwest to the Fitzgerald River on the south coast.

Lakes are most prevalent on the south coast (Figure 9) and south west but do occur in other regions. They account for less than 5 per cent of the wetlands on the Swan Coastal Plain.[16] They fluctuate in depth and extent of inundation but naturally almost always retain a water column (Figure 10). Most are not more than a few metres deep[15], although a few reach depths greater than 10 metres, such as Lake Jasper on the south coast. Some of the deepest wetlands are artificial (for example, Lake Argyle in the eastern Kimberley, which is 45 metres deep[15]) and many have been artificially deepened (for example, Herdsman Lake in Perth, which has been dredged to a depth of 9 metres in some areas[16], and Lake Richmond in Rockingham, which receives stormwater from the surrounding urban catchment). Countless seasonally waterlogged and inundated wetlands have been dug out, lined or flooded to create permanently inundated wetlands, causing a loss of habitat for the species that originally inhabited these wetlands.

Figure 9. Lake Gore, a permanently inundated wetland east of Esperance. Photo – Wetlands Section/DEC.

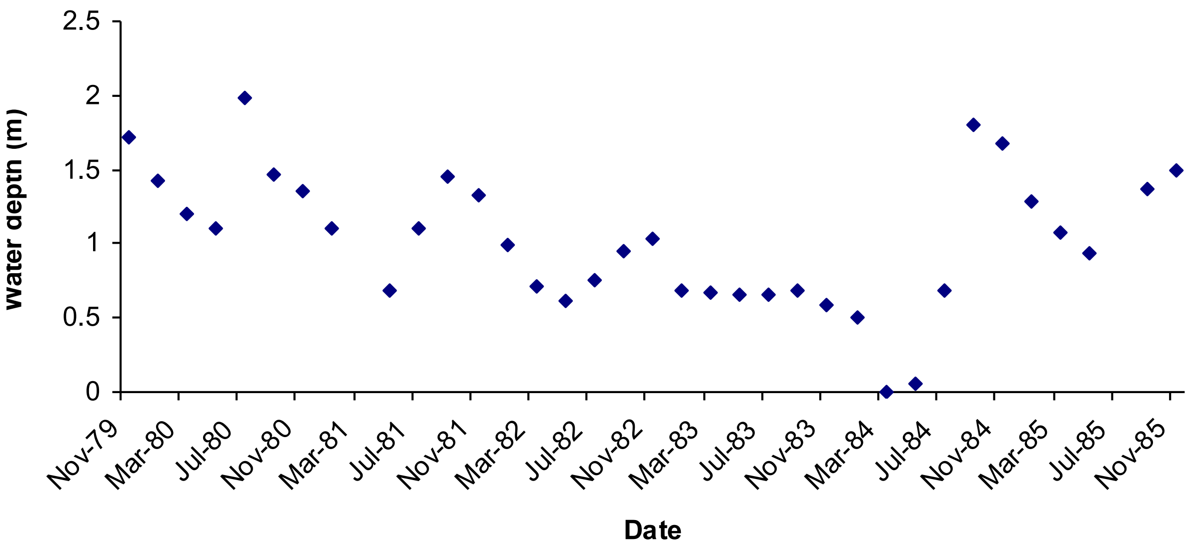

Figure 10. Hydrograph showing the recorded water depths in Lake Gore from November 1979 to November 1985.

Wetland water regime

The **water regime** of a wetland is the specific pattern of when, where and to what extent water is present in a wetland.[17] The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.[18] These are outlined in Table 2. Wetland water regime is also referred to as 'hydropattern' or 'hydrological regime' in many texts.

Table 2. Features of the water regime of wetlands. Adapted from Bunn et al., 1997.[17]

Feature	Definition
Timing	The timing of a wetland being waterlogged or inundated. Within-year patterns are most important in seasonally waterlogged or inundated wetlands (that is, what time of year) whereas between-year patterns and the variability in timing may be more important to intermittently inundated wetlands.
Frequency	How often wetting and drying occur. Ranging from not at all in wetlands that are permanently inundated (lakes) to wetting and drying many times a year. The rate at which wetting and drying occur can also be important.
Duration	The length of time of waterlogging and/or inundation. Duration in days, weeks or even years, varying within and between wetlands.
Extent and depth	The area of waterlogging or inundation and the depth of the water.
Variability	The degree to which the features mentioned above change at a range of time scales (variability in timing mentioned above). Variability is recognised as a significant part of wetland water regime.

Wetland water regime is another term that is used in different ways by different people. Sometimes it is used interchangeably with the term 'hydroperiod'. Although wetland water regime and hydroperiod both relate to when and how much water is present in a wetland, the wetland water regime encompasses much more detailed, specific characteristics of a wetland than its hydroperiod, such as frequency, extent, depth and variability. Knowledge of these specific characteristics can be used by wetland managers when designing wetland management objectives for wetlands of conservation value.

For example, Lake Warden, a permanently inundated wetland near Esperance, naturally fluctuates in depth each year, each dry season exposing a shoreline that is used by wading birds. With clearing of surrounding agricultural land, rising groundwater has resulted in increasing water levels in the wetland, submerging the natural summer shoreline used by waders and slowly killing the dryland vegetation. With their knowledge of Lake Warden's natural wetland water regime, wetland managers have implemented a plan to reinstate the natural hydrology in order to recover the summer shoreline to maintain the wetland's natural values. This accounts for the timing of inundation of the shoreline, how rapidly it is exposed, how long it is exposed, how much is exposed and how much these factors vary naturally from year to year.

Another example relates to the protection of the habitat of burrowing crayfish (species of *Engaewa* and most *Cherax*) in seasonally inundated wetlands in the south-west and south coast. While these wetlands may still remain seasonally inundated, they may not retain the wetland water regime needed for the crayfish to survive. In addition to ensuring that these wetlands inundate to the depth, extent and duration required by the crayfish during winter and spring, it is necessary to ensure that the soil below the wetland remains damp during the dry season, for a given depth and duration, to ensure the crayfish survive the hot, dry summers of the south of the state.

Water regimes can be characterised using a range of parameters which define features of the water regime (timing, frequency, duration, extent, depth and the variability in these). The water regime parameters used might vary between wetlands, because a parameter that is meaningful to describe one water regime may be irrelevant in another. For example, 'season of maximum inundation' might be a meaningful parameter to define a predictable, seasonally inundated wetland, but is irrelevant for a wetland that could contain surface water in any season, or for a wetland that naturally experiences waterlogging but not inundation.

Some of the parameters used to characterise water regimes at wetlands are:

- timing (season or month) of driest and wettest conditions
- frequency of driest and wettest conditions
- duration of driest and wettest conditions
- maximum and minimum depth of inundation or waterlogging/depth to groundwater
- extent (area and location) of inundation or waterlogging
- rate of change in water depth or extent

Extensive studies of wetlands on the Gnangara Mound carried out by wetland scientists of Edith Cowan University, Perth, provides details of wetland water regime at a number of wetlands. The data collected are being used to help develop wetland and groundwater management strategies. For example, Carine Swamp, in the northern Perth suburb of Carine, used to be permanently inundated up until 1996. It now dries out each summer. It reaches its maximum water level, on average 0.89 metres, between August and November. However, it is showing a progressive trend of drying earlier and quicker in the years since 1996. Compounding this, it is showing a progressive trend of greater seasonal variation in surface water levels. This has been attributed to increased stormwater run-off from the surrounding suburbs.[13]

Water regime parameters are best described by a range of values rather than a definitive value. For example, the recorded maximum water depth of a seasonally inundated wetland might vary 'between X and Y metres' in a 10, 20 and 100 year period. When characterising the water regime, the extremes should be recognised as natural to the wetland, unless there is evidence to suggest that the extremes have been caused by altered hydrology. The natural variability should therefore be taken into account when deciding whether a wetland's water regime (and therefore its hydrology) has been altered.

➤ For more information on altered hydrology see the topic 'Managing hydrology' in Chapter 3.

HOW DOES A WETLAND'S HYDROLOGICAL CHARACTERISTICS AFFECT IT?

Water is commonly referred to as the 'driver' of wetland ecosystems. This is because it has such a significant influence on the ecological character of a wetland, from its physical characteristics, to its chemical makeup, to the life that inhabits it.

In particular, water has the following effects on wetlands:

- All life on Earth has particular water requirements, and how much water is present and when it is present in a wetland is one of the factors that determine whether particular plants, animals, fungi, algae and bacteria can inhabit it at a given point in time.
- Water in the environment is physically variable in terms of properties, such as the amount of light it will transmit to plants living in it and the amount of oxygen available in it for animals. These properties are another factor that determines whether particular plants, animals, fungi, algae and bacteria can inhabit a wetland at a given point in time.

- The chemically variable properties of water make it a variable habitat. How salty, acidic or nutrient-laden a wetland is are all factors that determine whether particular plants, animals, fungi, algae and bacteria can inhabit a wetland at a given point in time.

Figure 11 summarises how water shapes the ecological character of wetlands.

The biological, chemical and physical effects of water in a wetland create unique environments. In managing wetlands, it is important to maintain the natural water regime, in order to conserve the biological, physical and chemical diversity they support.

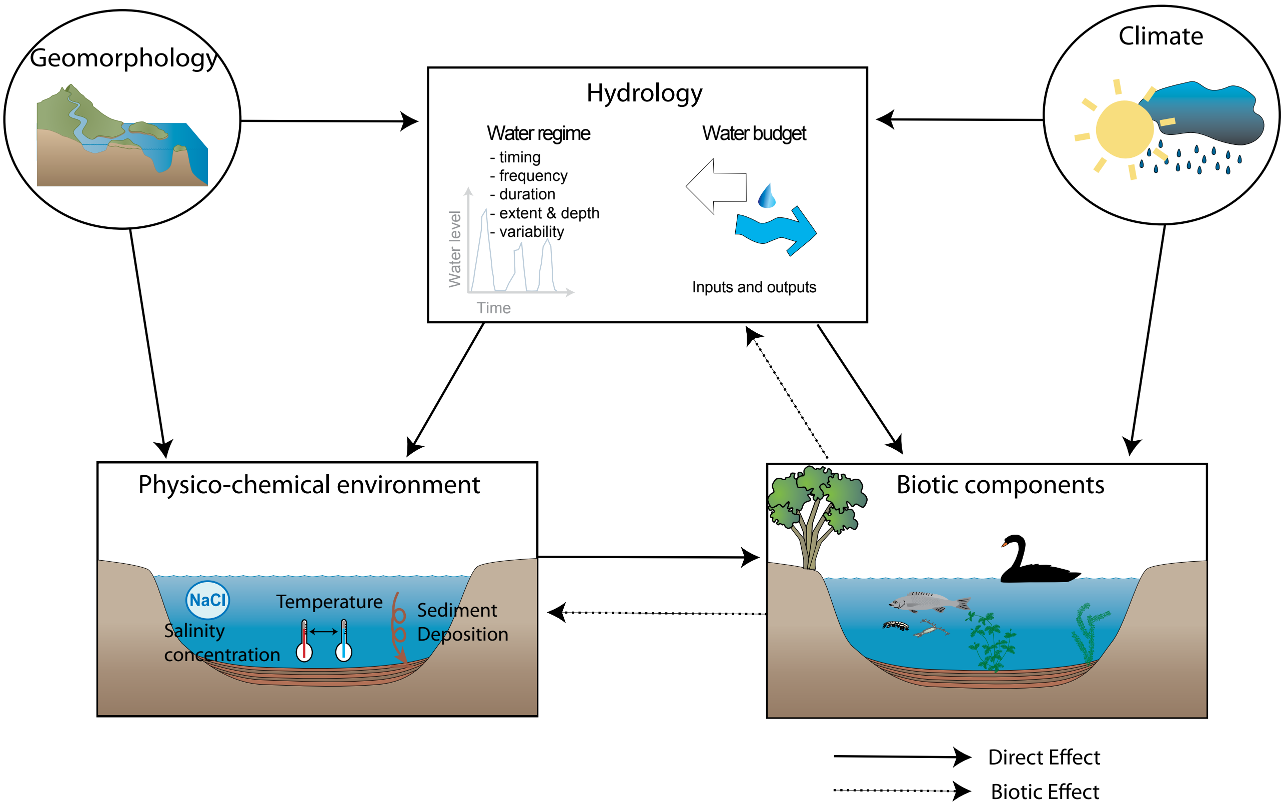

Figure 11. Conceptual model of wetland ecology, illustrating climate and geomorphology as the 'drivers' of wetland hydrology and the inter-relationship between wetland hydrology, physical and chemical components of wetlands and wetland plants and animals. Adapted from Mitsch and Gosselink (2007).[19]

Water availability

One of the most important effects of water regime is determining the availability of water for wetland species to live in, on or in proximity to. In this way, water affects the species composition, richness and abundance of organisms in a wetland.

The presence or absence of species at any given wetland can be explained, in part, by wetland water regime. This is because plant, animal, fungi, algae and bacteria species all have their own water requirements that dictate whether they can survive and flourish in a given water regime. As Jacques Cousteau (1910–1997) noted, the water cycle and life cycle are one.

At a basic level, WA's wetland organisms can be grouped into one of five extremely broad groups:

1. those that inhabit, or need permanent access to a wetland water column
2. those that inhabit, or need access to a wetland water column for a period sufficient

to fulfil part of their annual cycle or life cycle

3. those that inhabit, or need permanent access to saturated wetland soils (without an overlying water column)
4. those that inhabit, or need access to saturated wetland soils for a period sufficient to fulfil part of their annual cycle or life cycle
5. those that, due to an association with other wetland species, preferentially occur in wetlands

Some examples are shown in Figure 12.

Fish, such as Balston's pygmy perch, live in the water column and so require a permanent water column (with the exception of the salamanderfish and the black-stripe minnow).

Although rakali, *Hydromys chrysogaster*, can breathe air, they require permanent water and are highly adapted to a semi-aquatic life.

Almost all of WA's 81 species of frogs need surface water on a seasonal basis to breed and provide habitat for tadpoles. Some need access to a water column year-round and a few don't need it at all.

Verticordia plumosa subspecies *pleiobotrya* is just one of countless plants that live in seasonally inundated wetlands.

The ancient reedia, *Reedia spathacea*, inhabits permanently waterlogged areas in the South Coast. It is a relict from much wetter periods.

Burrowing crayfish, such as those in the genera *Engaewa*, inhabit seasonally inundated wetlands. As the water recedes, they burrow into the sediment and remain in the damp soil until the wetland is once again inundated.

The majestic modong, *Melaleuca preissiana*, inhabits seasonally waterlogged areas in the south-west.

Although they don't rely on them for a specific part of their life cycle, wetlands in the southern Kimberley and Pilbara are part of the habitat of bilbies, *Macrotis lagotis*.

Figure 12. Examples of broad water requirements of some wetland plants and animals.

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Many organisms do not fit neatly into one of these groups; they are useful as broad generalisations only. In reality, each wetland species has specific **water requirements** that determine where and how it lives and reproduces. For example, burrowing crayfish require surface water for a period of the year, as well as saturated soils for the remaining period.

If the water regime of its habitat changes beyond its tolerance, an organism must move to a new habitat on either a temporary, seasonal or permanent basis, or it will die (Figure 13); many smaller animals and annual plants do, typically reproducing first.

Species water requirements explain, for example, why fish are not as prevalent in WA wetlands as in those of the eastern states. The majority of fish need a water column year-round for survival, yet a relatively small proportion of the state's wetlands are permanently inundated. In addition, many of WA's wetlands are not connected to waterways and therefore do not provide a route for fish migration when wetlands dry up.

Most of Western Australia's wetlands are not permanently wet. In response to this transience of water, wetland organisms have many adaptations for surviving or avoiding drought, and this is part of the reason for the uniqueness of our wetland flora and fauna. 'Boom and bust' cycles are a natural part of the population dynamics of many wetland species in Western Australia. When a dry wetland wets, water seeps through the soil and soaks the resting eggs, seeds, spores and cysts, which begin to develop.[20] The influx of water releases a pulse of nutrients from the soil that, together with light and water, provide the resources for germination and growth of algae and plants. Algae and bacteria proliferate, providing food for consumers. A succession of small animals hatch, grow, reproduce and die. Emergent plants flourish, and in inundated wetlands, aquatic plants grow in submerged or floating habits, and both types of plant provide habitats for other organisms. As water recedes, new plants germinate on the exposed soil, flourishing on the nutrients released by **anaerobic** bacteria on drying. If water recedes through evaporation, concentration of the salts may result in increases in salinity. The smaller water volume may also lead to increases in temperature. These types of cues trigger plants, algae, bacteria and animals to prepare for another dry period.[20] Those that cannot tolerate dryness leave, burrow down, or die, first replenishing seed or egg banks.

Figure 13. Tadpoles in a Holocene dune swale wetland near Mandurah, in the Peel region, perished when the water level receded before they had developed into adults.

Anaerobic: without air (organisms that live in these conditions are 'anaerobes')

The life history of an individual organism at any given wetland can also be explained, in part, by wetland water regime. Individuals are adapted to the specific wetting and drying conditions of that wetland. For example, the life history of a submerged plant living in a wetland that is permanently inundated with water is likely to be very different to that of a submerged plant living in a wetland that only holds water for a few months a year. The plant in the wetland that is permanently inundated can rely on the presence of water all year and can put its energy into growing leaves and stems, and becoming larger. The plant in the wetland that is seasonally inundated has strategies to survive dry periods and reproduces quickly before the wetland dries, leaving seeds that can tolerate drying and will grow when there is water in the wetland once more.

In these ways, the water regime influences the composition of the plants, animals, fungi, algae and bacteria found in a particular wetland, and if significant changes to the water regime occur, a change in species composition is likely to follow. [20] Unfortunately the knowledge of the water requirements of wetland species tends to be incompletely known.[18] Conserving all wetland species necessitates protecting the naturalness and diversity of the water regime of WA's wetlands.

Over time, some wetlands develop sediments that help to maintain the water regimes needed to maintain them. For example, the silica left behind in wetlands which support diatoms (a type of tiny algae with glass-like cell walls made of silica) can slowly build up in the sediment, over hundreds to thousands of years, when diatoms die. This diatomaceous earth has a high water holding capacity, which helps maintain soil wetness. Other wetland sediments, such as highly organic substrates like peat, as well as coffee rock and ironstone also serve this function.

➤ For more information on species water requirements, refer to the topic 'Wetland ecology' in Chapter 2.

Oxygen availability

One of the most fundamental differences between wet and dry environments is the availability of oxygen. Oxygen, which is essential to most forms of life, is available in very low concentrations in water. Despite this, a range of specialised plants, animals, fungi, algae and bacteria adapted to reduced oxygen conditions are able to flourish in inundated or waterlogged conditions. The water columns of permanently inundated wetlands tend to have relatively low oxygen levels, particularly deep lakes and those in which the water column develops layers with distinct physical and chemical properties (stratification). In contrast, intermittently inundated wetlands are dry a lot of the time, only intermittently supporting a water column, which may be present for periods of months to years. How deep a wetland is, and how long it is inundated or waterlogged for, influences how much oxygen is available, which in turn affects which species can inhabit it, from fish (which need about 30 per cent oxygen saturation[21]) and birds to bacteria.

Even in water, plants, algae and some bacteria need oxygen to survive. These life forms are known as primary producers because they create food and energy using sunlight, carbon dioxide and nutrients through the process of **photosynthesis**. Animals need the food and energy sources that primary producers make available. In this way, oxygen levels affect the composition, richness and abundance of life in wetlands, and oxygen levels are affected by wetland water regime.

Oxygen levels also affect the rates of organic matter accumulation in wetlands, as the **decomposition** of **detritus** is most efficient when carried out by **aerobic** (oxygen-dependent) bacteria. The alternative is decomposition by anaerobic bacteria, and it is under these conditions that peat and other organic-rich sediments develop most rapidly. The type of sediment present in turn affects the plants and animals and the water-holding capacity of the wetland.

➤ Refer to the topic 'Wetland ecology' for information on oxygen requirements of wetland species, and adaptations to low oxygen conditions.

Another critical function of oxygen availability is that it significantly affects the chemical characteristics of an environment. In particular, it influences nutrient availability, pH, and toxicity. For example, the availability of oxygen influences the availability of nutrients including nitrogen, phosphorus, iron and sulfur (via pH and redox potential).[19] Over the long term, the habitat and chemistry of intermittently and seasonally inundation/waterlogged wetlands varies much more than that of permanently inundated wetlands (Figure 14).

Significant changes in oxygen availability in a wetland can cause major shifts in the ecological character of a wetland, and this is an important reason to maintain natural water regimes. For example, the drying of wetlands that have been inundated for very long periods of time exposes their sediments to oxygen, which can lead to chemical reactions that result in the development of acid sulfate soils, which can have serious harmful effects to the ecosystem (Figure 15).

➤ For further information on oxygen in wetlands refer to the topic 'Conditions in wetland waters' in Chapter 2.

➤ For additional detail on altered water regimes and acid sulfate soils, see the topic 'Water quality' in Chapter 3.

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi; degradation refers to its physical breakdown.[18] Also known as mineralisation.

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Figure 14. The availability of oxygen has a major influence upon wetland chemistry. In this wetland north of Wiluna, the cracking of clays allows for further diffusion of oxygen into the sediment during the dry phase. Photo – J Dunlop.

Figure 15. Oxygen availability determines many of the chemical properties of a wetland. In Gnangara Lake, drying of sediments that have been saturated over the long term has led to the exposure and oxidation of normally inert pyrite materials, causing harmful acid sulfate soils. Image – Google Earth™.

Light availability

Light availability in wetlands with a water column is quite different to that of drylands, because once sunlight reaches wetland waters it is rapidly altered and reduced, so that both the quality and quantity of light available is quite different to what first reached the surface of the water. This affects which organisms can inhabit wetland water columns. Wetland waters that are deep, heavily shaded, turbid or coloured (such as tannin-stained waters) tend to have reduced light levels compared to other wetlands.

Plants and algae are particularly affected by light availability. All plants and algae need light for photosynthesis and in wetlands with a water column they need to remain within the euphotic zone (also known as the photic zone). Put simply, this is the area of the water column penetrated by light of sufficient intensity and of suitable wavelength to enable photosynthesis by aquatic plants. In deep, permanently inundated wetlands, plants are generally limited to the lake margins; whereas algae that can remain suspended and cyanobacteria that can retain buoyancy in the water column can inhabit a much larger area of the wetland.

➤ For more information on the conditions that influence light levels in wetlands, refer to the topic 'Conditions in wetland waters' in Chapter 2.

➤ For more information on the light requirements of wetland species, see the topic 'Wetland ecology' in Chapter 2.

Salt availability

Water entering and leaving wetlands carries with it a range of materials, including salts. Sources of water, such as rainwater, surface water and groundwater can have very different amounts and types of salts.

Salts are compounds comprised of elements such as sodium, potassium, calcium and magnesium, combined with other elements such as chloride, sulfate and bicarbonate. Australian wetlands tend to be dominated by sodium and chloride, and sometimes bicarbonate, whereas in many other regions of the world calcium and bicarbonate dominate.

The availability and concentration of salt in a wetland helps to shape its ecological character. The type and concentration of salts in a wetland has a very strong bearing on the wetland, and particularly on the life forms which will inhabit it. Wetland species are adapted to particular ranges and types of salts in their environment; some saline wetland species may rely on a high level of salinity to function. Wetland species are physiologically adapted to particular ranges or concentrations of salinity meaning that if these concentrations change too much or too rapidly, this can cause a decline in health and even result in mortality. Salinity also affects water clarity, dissolved oxygen concentration, pH and other chemical equilibria in wetland waters.

In general, rainfall has low concentrations of dissolved materials, such as carbon, salts and nutrients. The water quality and chemical processes of a wetland with a rainfall-dominated water budget will reflect this relatively pure water source.[3,22] However, in WA where much of the rainfall is derived from water evaporated out of the Indian and Southern Oceans, rainfall closer to the coast contains significant amounts of salts derived mainly from ocean spray[23] (Figure 16).

The dominant salts in groundwater are sodium, potassium, calcium, magnesium, chloride, sulfate, bicarbonate and carbonate.[24] These salts come principally from rainfall, concentrated by evaporation and often further modified by soils and weathered rocks as the water percolates through these. The salinity of inflowing and outflowing waterways also affects the salinity of wetlands. Seawater intrusion is another potential source of salts to a wetland.

Figure 16. A wetland close to the coast near Preston Beach in south-west WA. Rainfall loaded with salts (due to the proximity to the ocean) combined with a direct input of seawater from seawater intrusion are a source of salts accumulating over a long period of time, resulting in high level of salts and a pH of around 8. Photo - M Morley/DEC.

The water regime of wetlands can have a significant influence on the concentration of salts. In drying wetlands, such as 'evaporative wetlands', the salinity increases due to a concentration of salts in the decreasing volume of water.[18]

Chemically and biologically diverse conditions arise when predominantly saline wetlands receive freshwater inflows at seepage points, which can create complex habitats within a wetland. Similarly a mosaic of saline and freshwater wetlands provide a complex range of habitats. Eatha Spring, for example, discharges fresh to brackish water on the eastern side of Leeman Lagoon near Leeman in the midwest of WA. In many saline intermittently inundated wetlands, smaller lunette wetlands occur that have a low enough salinity to support tadpoles and other species that would not normally be found in saline lakes.[25] In Lake MacLeod, seawater upwelling is responsible for maintaining saline, permanently inundated areas (described in the case study 'Hydrology of Lake MacLeod' near the end of this topic).

➤ For more information on the salt requirements and thresholds of wetland species, refer to the topics 'Wetland ecology' and 'Conditions in wetland waters' both in Chapter 2.

Nutrient availability

A 'nutrient' is any substance that provides essential nourishment for the maintenance of life'.[26] A whole range of substances are nutrients, but in wetlands nitrogen and phosphorus (with the chemical symbols 'N' and 'P'), are usually the two main nutrients of interest. The type and amount of nutrients available in a wetland influence which living things will inhabit it and how abundant those species will be.

Nutrients are carried into wetlands through rainfall as well as surface and groundwater flows. The export of nutrients from wetlands is also largely controlled by the outflow of water. Groundwater tends to have a higher concentration of most dissolved materials, which are picked up as the water moves across and through soils and rocks and delivered to wetlands. The greater the input of water, the higher the input potential of associated nutrients and carbon external to the wetland, which drive wetland productivity.[19]

Fluxes in water levels affect nutrient concentrations. For example, when water levels fall in an inundated wetland, nutrient concentrations increase. In such conditions, algae populations often flourish as do algae consumers such as water fleas including the *Daphnia* species.

The water regime also has an extremely significant effect on the transformations of nutrients into different chemical forms within a wetland.[19] The availability of nutrients to plants and other primary producers depends on their chemical form. The importance of water regime in this regard is related to associated conditions such as redox potential, oxygen availability and habitat for bacteria that are responsible for mediating most nutrient transformations in wetlands.

➤ For more information on the conditions that influence nutrient levels in wetlands, refer to the topic 'Conditions in wetland waters' in Chapter 2.

Organic carbon availability

All plants, animals and microbes must consume carbon in order to survive and grow. The movement of water can often be a major means of transporting carbon contained within organic material from one location to another. Other than mobile animals, there are two sources of organic carbon in wetlands: carbon generated by photosynthesis within the wetland (autochthonous carbon); and carbon imported into the wetland by wind or water movement, including groundwater transporting leached humic substances and overland flow transporting material such as leaf litter from the surrounding land. In practice, the carbon in most WA wetlands is a combination of both internal and external sources. Much of the export of organic matter from a wetland also occurs through outputs of water. If a wetland experiences a large volume of water moving though it (into and then out of it), it is likely to export organic matter at a higher rate.

➤ For further information on the organic carbon availability in wetland waters refer to the topic 'Conditions in wetland waters' in Chapter 2.

pH (acidity/alkalinity)

The pH of water sources to wetlands influences the pH of wetland waters. Rainwater is naturally slightly acidic (as low as pH 5.5), due to dissolved atmospheric carbon dioxide[18,27], but the pH may be rapidly modified by chemical and biological processes once the water enters the wetland (e.g. carbonate buffering, photosynthesis). In wetlands with little biological activity and few reactive minerals, the pH may remain mildly acidic.

The pH of inflowing surface water can be influenced by the characteristics of the catchment. For example, wetlands that receive surface water from granite-dominated catchments may be acidic.[18]

The natural pH of groundwaters in Western Australia is poorly known, due partly to a lack of data, and partly to high variability between sites. However, inflow of highly acidic or alkaline groundwater would have a major influence on the pH of wetland waters. Groundwater discharging from coastal dunes tends to be alkaline due to the carbonate minerals within the aquifer sediments, so wetlands that receive this groundwater are often alkaline. Groundwater in the valley floors of the Goldfields, eastern, central and southern Wheatbelt is thought to be naturally acidic (pH less than 4) and has resulted in the formation of naturally acidic wetlands.[28,29] Rising groundwater due to the clearing of Wheatbelt landscapes has resulted in increased discharge of this water to waterways and wetlands, resulting in the acidification of wetlands in some inland areas.[30]

Wetlands can also be acidified by acid sulfate soils.[31] These soils contain acidity stored as sulfide minerals in permanently waterlogged sediments that, if exposed to the air by falling water levels, can result in generation of strongly acidic soils and waters.[31,32,33]

Acid sulfate soils generally occur in coastal regions of WA in association with estuaries and groundwater systems in sand dunes. Wetlands in southern WA have been acidified by lowering of groundwater levels by decreased rainfall, pumping of groundwater and increased interception of rainfall by land uses such as plantations. Fires after drying can rapidly accelerate the release of acidify from these soils.

➤ For further information on pH of wetland waters refer to the topic 'Conditions in wetland waters' in Chapter 2.

The pH of groundwater can be determined by installing groundwater bores but the origin of the acidity may require further investigation of subsoil geology and historical events such as fires and drought.

extra information

Creating fluxes in the availability of materials

Wetlands that wet and dry tend to have more variation in water chemistry than permanently inundated wetlands. Extreme fluctuations in water chemistry can occur soon after wetting due to the first flush of dissolved material and release of chemicals from the sediment, and just before the water dries completely, due to concentration by evaporation and the reduction in water volume.[18] Changes in water quality during drying and wetting depend on:

1. sediment properties (sediment composition and structure, nutrient and organic content)
2. type of drawdown (gravity or evaporative)
3. extent and timing of drawdown (proportion of drying area, rate of drying, temperature, weathering, timing of drying
4. conditions on rewetting (origin of water, degree of sediment disruption).[18,34]

WHAT DETERMINES A WETLAND'S NATURAL HYDROLOGICAL CHARACTERISTICS?

Climate is the most important determinant of a wetland's hydrology, and it interacts with the landscape to determine where wetlands form and their hydrological characteristics.

The climate determines the incoming and outgoing water in natural landscapes, driving water gains due to rainfall and water losses due to evaporation and transpiration. How the water reaches, moves within, and leaves a wetland is influenced by the landscape which the wetland is part of, as well as the landform of the wetland. Figure 17 shows how climate and landscape shape the natural hydrological characteristics of a basin wetland situated low in the landscape, receiving both surface water and groundwater.

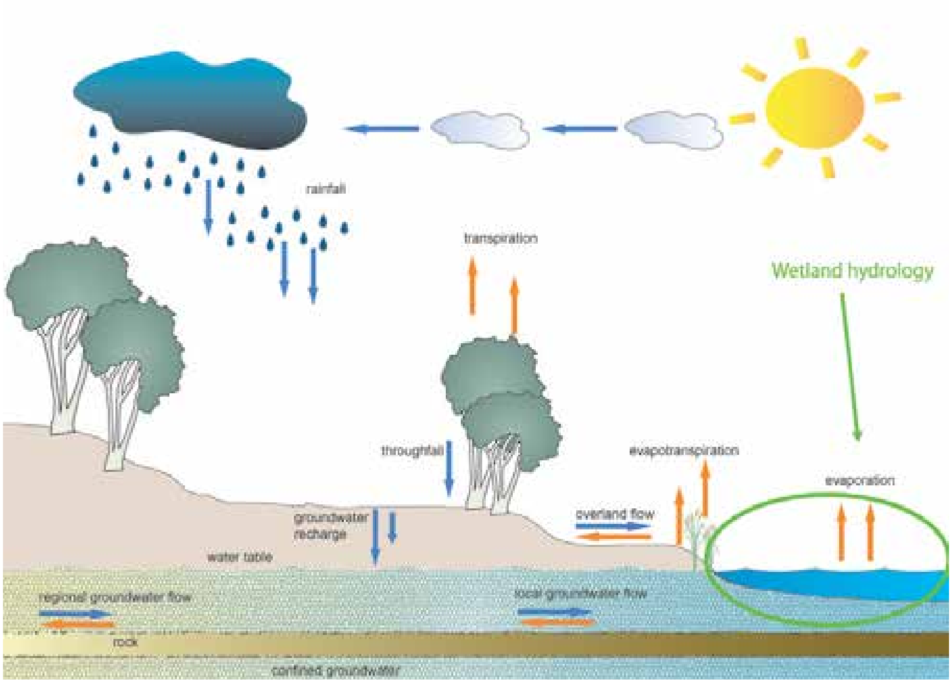

Figure 17. Aspects of wetland hydrology.

Evaporation: the change of liquid water into water vapour in the atmosphere

Transpiration: the process by which water (in the form of water vapour) is lost to the atmosphere by plants across the surfaces of leaves (through small openings called stomata). Transpiration drives the movement of water from the roots to the leaves and is the primary process by which water is lost from subsurface soils to the atmosphere

Evapotranspiration: a collective term for the transfer of water, as water vapour, to the atmosphere from both vegetated and un-vegetated land surfaces

Climate

Climate has a primary influence on the development and characteristics of wetlands, through its effects on the availability of water.

A wetland's hydrological characteristics reflect the balance between gains of water from rainfall, run-off or groundwater inflows and losses of water via **evaporation**, **transpiration**, run-off and groundwater outflows, as shown in Figure 17. Collectively, these are known as components of the water balance. Climate determines the main driving components of wetland water balance—rainfall, evaporation and transpiration—and determines factors such as patterns of recharge to groundwater systems and therefore variation in groundwater discharge and run-off from catchments.

Rainfall provides a direct input of water to wetlands. It is also the source of surface water flows (such as waterways and other, non-channelised overland flow) that may enter wetlands, as well as groundwater that may enter wetlands. The processes of evaporation and transpiration (collectively '**evapotranspiration**') cause the loss of water from the land to the atmosphere. Temperature, wind and vegetation influence these processes.

When rain falls on vegetation, it has two possible fates:

- throughfall – which occurs when rain passes through the vegetation to the surface below
- interception – which occurs when rain is captured on the surfaces of the vegetation (foliage, stems, branches).

The amount of rainfall that is intercepted by the vegetation is dependent on a number of factors including the total amount of rainfall, the intensity of the rainfall and the characteristics of the vegetation (such as the type of vegetation and the strata (or levels)).[19] Rain that is intercepted by vegetation often evaporates to the atmosphere. Some water that reaches the ground infiltrates the soil, may be taken up by roots and returned to the atmosphere through evapotranspiration.[35] In these ways, vegetation can have a substantial effect on the natural hydrologic balance of a catchment.

Evapotranspiration is an important component of the hydrological balance across Australia, because almost 90 per cent of precipitation (rainfall, snow and hail) is returned to the atmosphere by this process.[36] The extent and rates of evaporative losses are highly variable according to season and latitude. Rates of transpiration and evaporative losses to the atmosphere vary greatly with different physical parameters including wind velocity, humidity, and temperature. Generally, evaporation and transpiration are enhanced by increased temperature and wind speed and lower humidity. The rate of transpiration may also affected by the structural and metabolic characteristics of the vegetation.[37]

Wetlands are more common in cool or wet climates than in hot or dry climates, because in cool climates less water is lost from the land via evapotranspiration and wet climates have excess rainfall (rainfall that exceeds evaporative losses[19]). Most of WA is dry and hot for at least part of the year. Rainfall ranges from more than 1,000 millimetres, with low variability, in the extreme south-west and northern areas to less than 250 millimetres per year, with high variability, over most of the interior (Figure 18). Temperatures can be very high (Figure 19) and evaporation rates reflect this, ranging from around 1,200 millimetres per year on the south west coast to over 4,000 millimetres per year in the Pilbara and exceeding average annual rainfall over most of the state. However, at times, rainfall rates exceed infiltration and evaporation, to generate surface run-off, which is a critically important source of water in wetlands as well as other ecosystems including waterways.

WA has three main climate regimes. In the south-west of WA, the regime is described as Mediterranean, with warm to hot dry summers and cool wetter winters. Many wetlands are wet in winter and spring, and dry during summer and autumn. However, major summer storm events can generate very high daily rainfall events.

In contrast, the north of the state is monsoonal with hot and wet summers known as the ‘wet season’ and warm dry winters known as the ‘dry season’. Many wetlands fill during the wet season from October to April and dry out through the dry season.

The rest of the state is characterised by hot dry summers and cool to warm dry winters. Wetlands are relatively less common in the central areas of the state, which are characterised by low rainfall, high temperatures and the highest evaporation rates. In the arid interior, rainfall and surface water flows can be highly unpredictable, and may not occur within the same season in consecutive years. Rainfall in these areas is highly variable and falls on very few days. However, when it does rain, large amounts can fall in a single event causing widespread flooding. For example, in February 1995, very heavy rainfall from a weakened Tropical Cyclone Bobby fell over the Goldfields region. Surface run-off inundated Lake Boondaroo to a depth of 12 metres, with water persisting for several years (Jim Lane pers comm).

Events such as cyclones, major floods and droughts play a major role in the determination of water regimes in some areas, particularly in the north-west and interior of the state, resulting in many wetlands in these areas have highly variable hydrology from year to year.

> *"When Europeans arrived in Australia… they called the dry times 'drought' and the wet times 'flood' and the times of perfect pasture growth 'normal'. The extremes were regarded as aberrations of the 'normal' conditions. However, as records show, extremes of wet and dry are not abnormal – they are part of the natural pattern."*
> – Brock *et al*. (2000).[20]

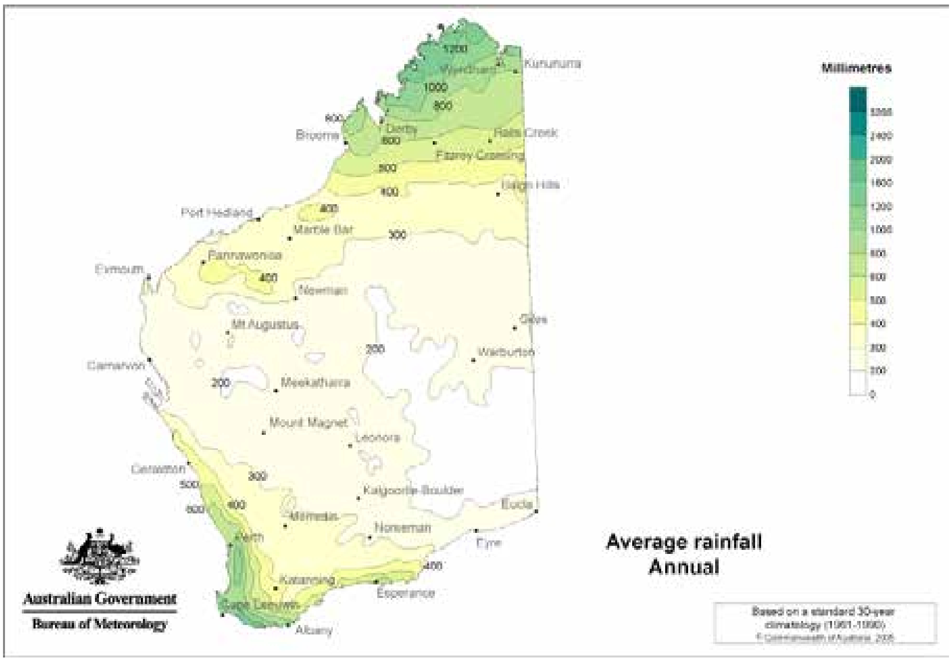

Figure 18. Average annual rainfall for Western Australia. Courtesy Bureau of Meteorology.

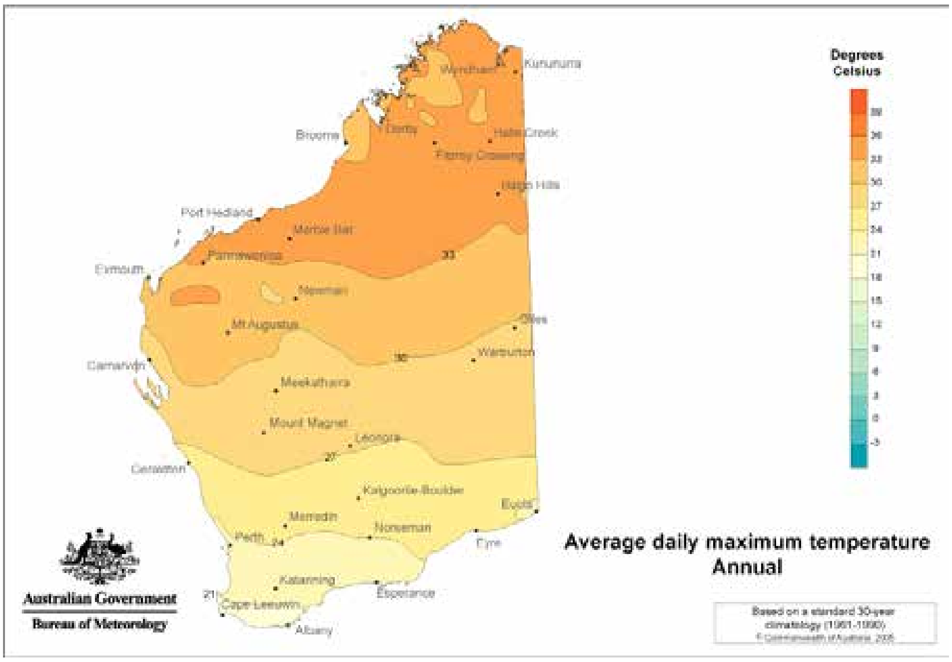

Figure 19. Average annual daily maximum temperature for Western Australia. Based on a standard 30-year climatology (1961–1990). Image - courtesy Bureau of Meteorology.

➤ The Bureau of Meteorology provides an extensive range of information and data about Western Australia's climate and weather: www.bom.gov.au

Water in the landscape - surface water and groundwater

Rainfall that, upon reaching the Earth, is not evaporated or transpired may soak into the soil, run off the soil, or fall directly into a wetland. If rainwater soaks into the soil or runs off it, it may take one of a number of pathways that may lead to the water entering a wetland via surface flows or via groundwater. Water can also leave a wetland by surface or groundwater flows.

Infiltration: the downward movement of water into the soil profile via spaces between soil particles (called pores) and cracks and fractures in the ground

Surface water flows

Run-off

Rainfall is a direct input common to all wetland types described in this document but it is very rarely the only water input into a wetland. Wetlands very high in the landscape (such as on hill tops) may receive no other surface water or groundwater inputs, relying solely on direct rainfall inputs. These wetlands often fare better than other wetlands in the catchment because the likelihood of human modification to their hydrology is less, notwithstanding climate change. Most wetlands receive surface or groundwater flows, both of which are dependent on run-off.

The generation of surface run-off is linked to the process of **infiltration**. The proportion of rainfall that becomes surface run-off depends on many variables, but is strongly influenced by the rainfall patterns and soils. In cool wet regions and in cool wet seasons, a greater proportion of rainfall is converted to run-off. Conversely, at hot times of the year, surface run-off is generally reduced.

The percentage of rainfall that becomes run-off is generally higher in areas where the annual rainfall is higher.[35] Run-off is generated in areas where the rate of rainfall exceeds the rate that this can infiltrate into soils, or when soils reach saturation point. In a wetter region, more of the soil pores are already saturated and it takes less rainfall to generate run-off.[35] In arid areas, where annual rainfall is low, the percentage of rainfall that becomes run-off is generally very low, although it can be high as a result of intense storms when rainfall rates exceed infiltration into soils. The percentage of average annual rainfall that becomes run-off on the Swan Coastal Plain is 25–40 per cent compared with the low rainfall areas of the eastern Wheatbelt which are less than two per cent.[35] For individual rainfall events, however, the percentage that becomes run off can vary around this.

The other factor that influences run-off quantity is the physical features of the land itself. When rainfall falls on the land it enters a catchment. A **catchment** is an area of land which is bounded by natural features such as hills or mountains from which surface water flows downslope to a particular low point or 'sink' (a place in the landscape where water collects).[38] The low point in the catchment can be a wetland, dam, reservoir, creek, river, an estuary or the ocean. The term catchment is mostly used in reference to surface water. The area of the land that captures water by infiltration and delivers it to a groundwater aquifer is called a recharge area (described in the 'Groundwater' section).

The term 'catchment' can be applied at various scales, including wetland or river catchment. The catchment of a wetland includes all the points of land that shed surface water into the wetland. The wetland catchment boundary (or watershed) is a continuous line connecting the highest points of land that contribute water to the wetland (Figure 20). Human modifications can artificially alter the catchment area or the volume of water a catchment receives.

Figure 20. The catchment of this wetland, near Albany in the south coast, is bounded by the ridges that can be seen in the background of this image. Photo – S Randall/DoW.

The shape of the landscape defines the catchment boundary. Convex landforms, such as hills and ridges, promote water flow down slope, such as into different catchments. Concave landforms, such as basins, promote water flows coming together, focusing surface and subsurface run-off. Steep terrain tends to have fewer wetlands than gently sloping or flat landscapes.[19] The steeper the slope, the faster water will flow down slope, causing erosion of the underlying substrate, leading to the waterways, such as creeks and rivers. In basins and on flats, the water slows or stills, forming wetlands.

Catchment size influences surface water flows, because the larger the catchment, the more rainfall it can capture.[35] Catchments vary considerably in size, with the largest catchments belonging to river systems. These catchments include major drainage networks of creeks and rivers and are made up of hundreds of smaller 'sub-catchment' areas, which can be bordered by low hills and ridges and drained by only a small creek or gully. Large catchments may be very complex. The Swan-Avon catchment is the largest catchment in WA. At 12 million hectares, it is roughly the size of Tasmania, with 134 recognised sub-catchments.[39]

Some of the largest wetland catchments in WA lie in the central inland areas. Lake Barlee in the Shire of Menzies (Figure 21) is approximately 80 kilometres long by 100 kilometres wide, covering an area of around 194,380 hectares.[15] Its catchment is larger, covering

Figure 21. Lake Barlee, west of Leonora in the Goldfields, is 195,000 hectares and has a surface water catchment of almost 1.79 million hectares. Image – Google Earth™.

Figure 22. Small rock pool wetlands known as gnammas, such as this wetland at Yorkrakine Rock, form in depressions on granite outcrops in south-west WA, particularly the Wheatbelt. Photo – DEC.

Tannins: complex organic compounds derived from plant materials

1.79 million hectares. Rainfall is low and surface run-off is only generated after rare heavy rain events, and as a result Lake Barlee may only be inundated across its entire extent once every ten years or so.[15] At the other extreme, the catchment of a seasonally inundated 'rock pool' wetland on a granite outcrop (Figure 22) may measure a few square metres.

The surface and sub-surface features of the landscape affect the movement of water in the catchment. Geomorphology, which includes the composition of both surface soils and sub-surface materials as well as the shape of the land surface, influences how water moves over or through the soil and other substrates such as rock.[40] It is a particularly important factor controlling surface and groundwater flow and accumulation.[40] As such it influences the nature of water movement into and out of wetlands. The characteristics of surface soils strongly influence infiltration rates across a catchment and can have a major effect on the flow of water into wetlands.[41] Other factors include vegetation type and density. Overland flow is less common in forested areas where interception and soil infiltration rates are high, but may be common in naturally sparsely vegetated areas or areas where vegetation and leaf litter are removed and soil is compacted.[41]

The nature of the catchment also influences the 'quality' of run-off that reaches a wetland. It can determine the amount of sediments, nutrients, salts, acid, **tannins** and other matter that reaches a wetland, which can influence what organisms can inhabit a wetland.

Soils and geology also influence where water accumulates and persists at the surface. Areas where infiltration of water into the land's surface is low favour the development of wetlands in basins and on flats. This occurs where there are basins in impermeable bedrock. For example, in the Pilbara and Kimberley, many rock pools have formed in rocky basins (Figure 23) and in the Wheatbelt, many small seasonally inundated wetlands form in shallow depressions on granite outcrops.

Figure 23. A rock pool in a basin in the Kimberley.

Perched: not connected to groundwater

Impermeable: does not allow water to move through it

Hydraulic conductivity: a property of plant material, soil or rock that describes the ease with which water can move through pore spaces or fractures. It depends on the permeability of the material and on the degree of saturation

In addition to the landscape features which affect how water is distributed in the landscape, the shape or 'host landform' of a wetland can determine the size and shape of the wetland and in many cases, the water depth.[5] Host landforms are shown in Figure 24 below.

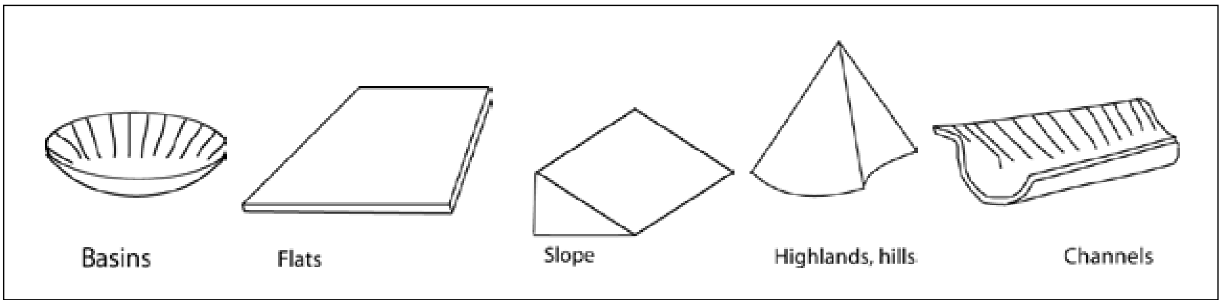

Figure 24. Landforms that become host to wetlands (basins, flats, slopes and highlands) and waterways (channels). Other wetlands, such as mound springs, are self emergent rather than developing in a host landform. Source: adapted from Hill et al. 1996.[5]

Wetlands that receive run-off and rainfall, but not groundwater, are often referred to as **perched** wetlands.[19] Perched wetlands have a layer of **impermeable** or low permeability layer of rock or soil that retains the rainwater and prevents it from infiltrating deeper into the ground (Figure 25). Perching can be caused by various layers, including clays (claypans, clayflats, bentonite wetlands), ironstone, calcrete and granite. A sufficiently thick layer of fine textured soils, such as clays, near the land surface can trap water on or close to the surface because they have a low capacity for water to move through them (low **hydraulic conductivity**; gravels and sands tend to have a higher permeability). Water loss in perched wetlands occurs mainly through evapotranspiration and surface outflows, although perched wetlands formed over a layer of low permeability soils may also have a small amount of leakage into lower layers.[19] In many areas of the state, notably the Pilbara and Wheatbelt, clay soils have resulted in the formation of claypan wetlands (Figure 26). Perched wetlands are not to be confused with perched groundwater (covered in the next section, 'Groundwater').

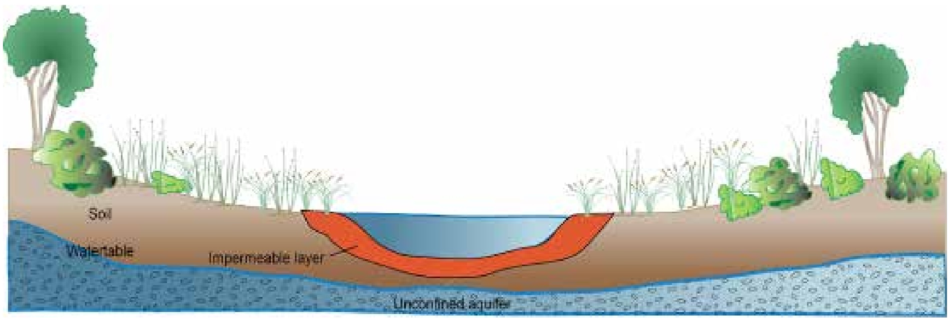

Figure 25. A perched wetland, which receives water from rainfall and overland flow. In this case, although there is groundwater in the vicinity of the base of the wetland, the thick impermeable sediment layer is a barrier between the wetland and the groundwater.

Figure 26. A claypan wetland in the Wheatbelt. Clay has an important role in such wetlands, with the clay lens impeding downward percolation and small particulates being suspending in the water, creating turbid conditions. Photo – DEC.

Flows from other wetlands and waterways

Many wetlands are linked to other wetlands by surface flow. A wetland may form part of a chain in which they receive water from another wetland higher up in the chain as it fills and overflows, and may also output water to the next wetland as it overflows. They may also be at the top of the chain. These wetlands can be described as **throughflow**, **terminal** and **headwater** wetlands respectively. This may be a seasonal occurrence or a rare occurrence after exceptionally high rainfall causing wetlands to link up and flow. Chains of wetlands that naturally flow only after exceptionally high rainfall are common in the Wheatbelt. The water and other materials are held in these wetlands for long periods and only flushed or substantially diluted when water next flows through the chain. Although these wetlands can be quite close to each other, when they are not connected by flows they can have quite distinct physical, chemical and biological characteristics from each other (Figure 27).

Throughflow wetland: a wetland that lies between headwater wetlands and terminal wetlands (or the sea) in a wetland chain. It receives water from upgradient wetlands and supplies water to downgradient wetlands.

Terminal wetland: a wetland at the bottom of the wetland chain. It receives water from other wetlands but water generally does not exit it other than through evaporation or seepage into the ground (or occasional flooding overflow in large events).

Headwater wetland: a wetland at the top of the wetland chain where water originates

Figure 27. The distinctly different physical and chemical characteristics of these wetlands located close to one another is evident even from aerial photography. This wetland chain is west of Miamoon in the Wheatbelt. Image - Google Earth™.

Wetlands may also be hydrologically linked to waterways; this is relatively common in many areas of WA. For example, in the Pilbara the Rudall River flows to Lake Dora in the Great Sandy Desert while Savory Creek flows to Lake Disappointment. In the Kimberley the Sturt Creek flows to Lake Gregory. In the Wheatbelt the Coblinine River and Dongolocking Creek drain into Lake Dumbleyung, and the Lockhart River flows through Lake Kondinin (Figure 28).

Figure 28. The Lockhart River flows through many wetlands, including Kondinin Lake. Image – Google Earth™.

Waterways that flow through wetlands can 'flush' these wetlands, transporting water and associated matter (such as sediments, nutrients, salts, acid and tannins) into and out of them. By depositing or scouring sediment in these wetlands, waterways can also create changes in the wetland shape and bathymetry. These hydrological influences can determine the ecological character of these wetlands.

In some areas of the state, it can be hard to distinguish dryland, wetlands and waterways in times of heavy rains (Figure 29).

Percolation: flow of water down through soil, sediments or rocks without these being completely saturated

Recharge: the physical process where water naturally percolates or sinks into a groundwater basin

Figure 29. A mosaic of ecosystems: braided channels, floodplains, basin wetlands and dryland in WA's Great Western Woodland region. Photo – J Dunlop.

Groundwater

Groundwater is the name given to water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks. Groundwater is surface water that has infiltrated beyond the soil zone (where plant roots generally occur) and percolated down to the saturated zone. The **percolation** of water depends on the nature of the landscape and underlying geology, including the type of soil and rock layers present, and how permeable they are, due to pores between grains and fractures in rock. Anything from none to half of the annual rainfall in a given area may recharge the groundwater. Rates of nearly 50 per cent **recharge** are recorded from areas of pasture in the wetter south-west of WA, to a fraction of a per cent in desert areas.[42]

Groundwater flows very slowly from areas of high water levels (where infiltration is highest) to areas of low water levels (wetlands, waterways and the ocean). It may be present at depths of kilometres below the land surface, and can accumulate very slowly. Some of the deep groundwater below Perth is more than 40,000 years old, and groundwater in the centre of the state may be hundreds of thousands of years old—and yet this is quite young compared to groundwater in an ancient Syrian aquifer, recently found to be close to a million years old. Hydrogeologists have identified a number of major 'sedimentary basins' in WA—Perth, Carnarvon, Canning, Officer-Eucla—while the Pilbara, Kimberley and Yilgarn have mostly local aquifers and fractured rock valleys (Figure 30).

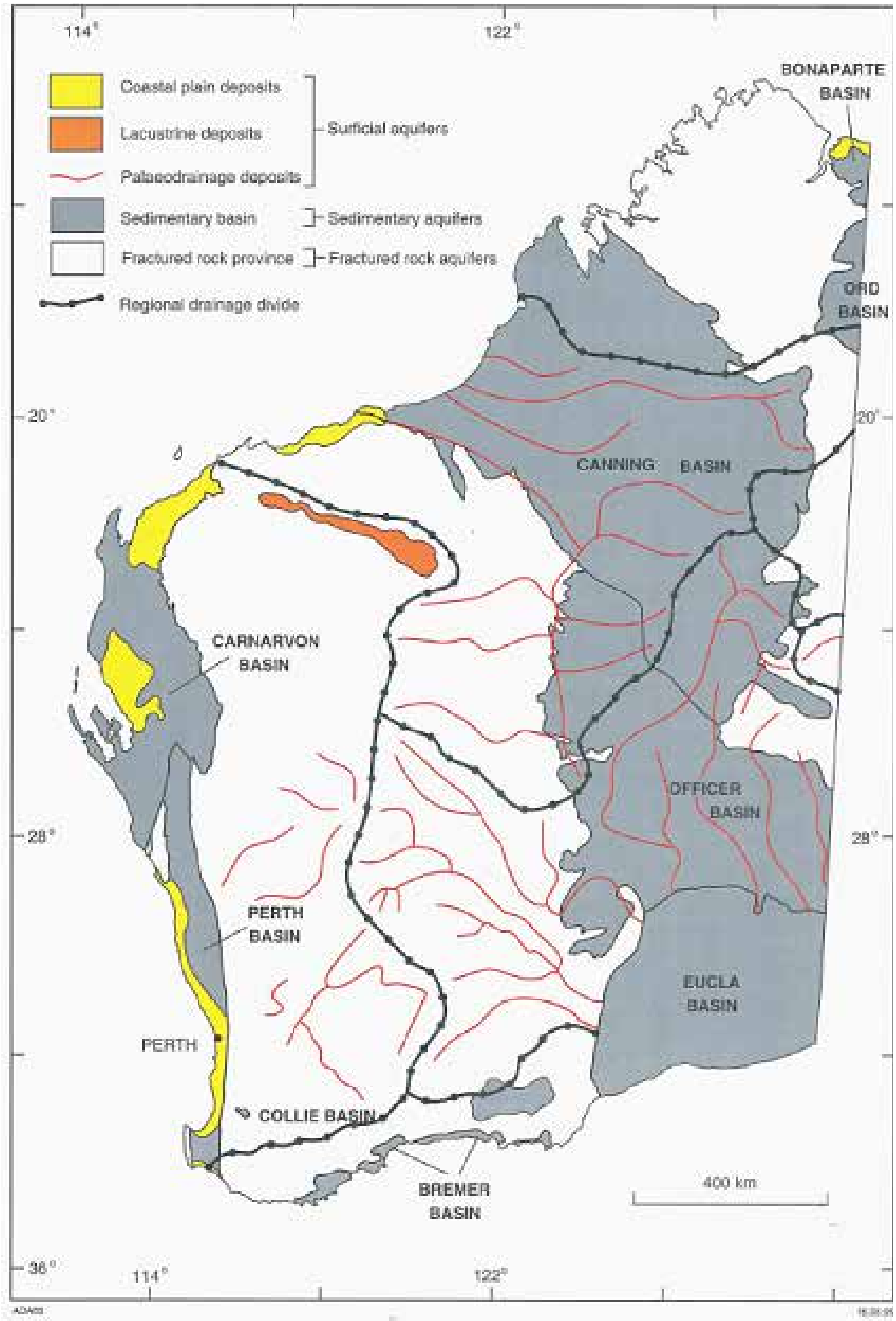

Figure 30. The general location of WA's surficial, sedimentary and fractured rock aquifers. Image – Allen (1997).[43]

The distribution and movement of groundwater encompasses the fields of hydrology and geology and is called **hydrogeology**, and it is studied by hydrogeologists.

Groundwater is a dominant input to some wetlands, whereas other wetlands may receive no groundwater inputs at all. All of the wetlands that receive groundwater inflows are **groundwater dependent ecosystems** (GDEs). Not all wetlands are GDEs (for example, perched wetlands) and not all GDEs are wetlands (for example, GDEs may be waterways, cave ecosystems and so on).

Groundwater is often discussed in terms of **aquifers**, which are geological formations or groups of formations beneath the land's surface capable of receiving, storing and transmitting significant quantities of water. There are two main types of aquifers: confined and unconfined (Figure 31), with both types having an important influence on the creation and maintenance of wetlands.

Hydrogeology: the distribution and movement of groundwater

Groundwater dependent ecosystems: those parts of the environment, the species composition and natural ecological processes of which are dependent on the permanent or temporary presence or influence of groundwater

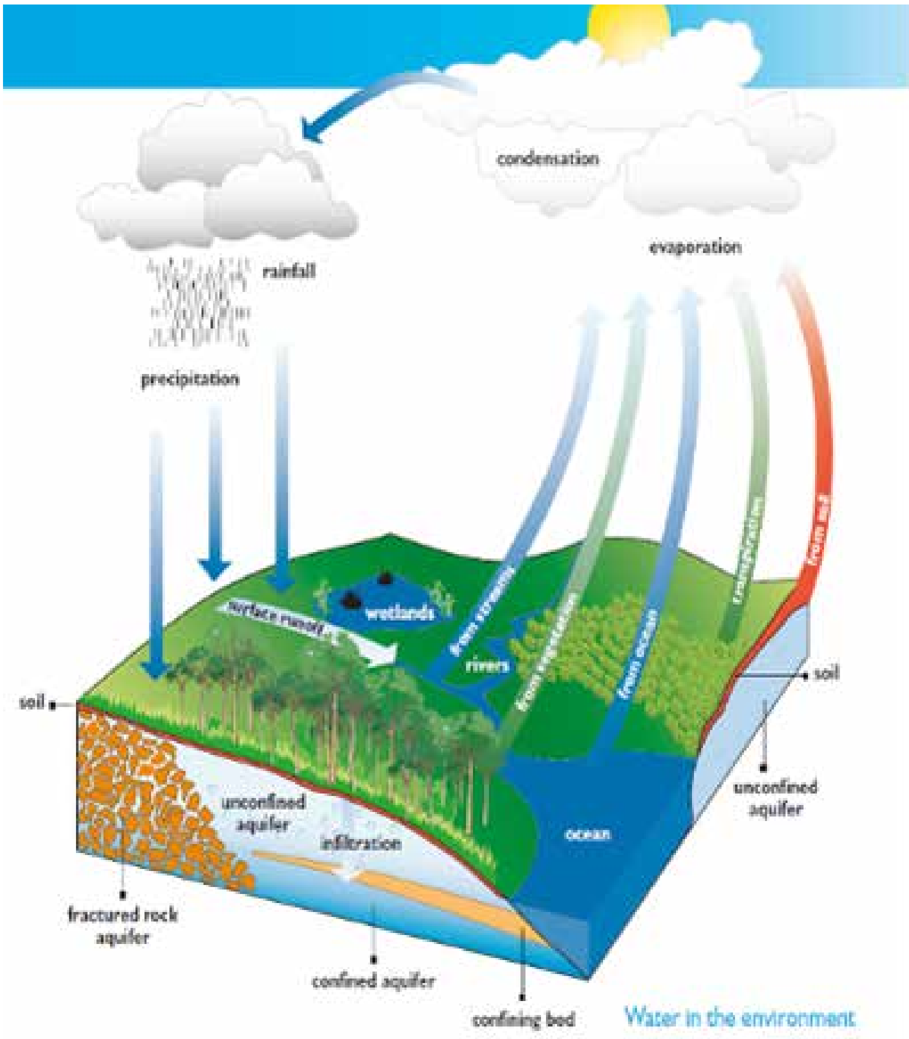

Figure 31. Confined and unconfined aquifers. Diagram – courtesy of Department of Water.[44]

Groundwater depth and flow vary spatially in three dimensions with the sub-surface geology as well as with seasons and over longer time scales. Groundwater flow systems can exist at different scales[23]:

- regional – typically transport groundwater long distances through confined or semi-confined aquifers in sedimentary deposits hundreds of metres thick
- intermediate – typically transport water 5–10 kilometres and may occur in broad shallow valleys, in the sedimentary aquifers of palaeochannels and fractured rock aquifers

- local – typically transport water down slope through an unconfined aquifer that is relatively thin and close to the surface. Recharge and discharge occurs within a few kilometres. This type of flow system is common and widespread in the south-west of WA and is found under 60–70 per cent of the landscape, usually associated with hilly terrain.

At each of these scales, these groundwater systems can determine where wetlands form and how they function in the Western Australian landscape. This is explained further below.

Confined aquifers

Confined aquifers are those aquifers that are overlain by relatively impermeable underground materials, such as clay or rock, which stop water from rising indefinitely. The material that stops the water from moving up or down is an **aquiclude** if it excludes water and an **aquitard** if it merely retards water flow. Aquifers with leaky aquitards are known as **semi-confined aquifers**. The confining layer of an aquifer may be very uniform across its area, or vary in thickness and extent, being thinner or absent in some area. These areas are known as 'windows' and may receive or discharge water to the overlying land surface or unconfined aquifers. Areas where percolating waters enter an aquifer are known as **recharge areas**.

Where groundwater pressures in a confined aquifer is above the top of the aquifer materials, it is described as **artesian**. These pressures can sometimes be above ground level in some areas of the aquifers, resulting in flowing bores or springs. The Great Artesian Basin, across a large area of the eastern states, is the largest groundwater aquifer in the world.

Sometimes barriers within confined or semi-confined aquifers restrict the flow of groundwater, causing local mounding and discharge of groundwater at the surface. Wetlands can form in these receiving areas. The barriers may be faults, intrusions or outcrops of dolerite, siltstone, silcrete or other formations. For example, in the Midwest region, a chain of springs and soaks discharge from the Parmelia aquifer along the Dandaragan Scarp, stretching from near Mingenew to east of Eneabba.[45]

Mound springs are examples of wetlands formed by groundwater discharge, often from confined aquifers. Mound springs are areas where groundwater discharges. The discharge point or area is elevated above the surrounding landscape through the build up of material such as calcarenites or peat, forming a mound around the area of discharge. In WA tumulus (peat-formed) mound springs in the Kimberley, Pilbara, Midwest, arid interior and a restricted area on the Swan Coastal Plain and include the Mandora Marsh Mounds, Dragon Tree Soak, Bunda Bunda, Big Springs, Black Spring, the North Kimberley Mounds, Mount Salt (calcareous) and Three Spring suite. Tumulus mound springs are formed around areas of continuous water discharge and may issue from a discrete vent on top of the mound or seep from the whole surface of the mound without a main outflow channel.[46]. In WA, mound springs occur singularly or in clusters of up to around twenty separated by several metres to tens of kilometres.[8]

Unconfined aquifers

Unconfined aquifers are those that are directly recharged by water from the land surface. They are generally relatively close to the land surface, and because of this are known as **shallow**, **superficial** or **surficial** aquifers. The upper surface of an unconfined aquifer, the point between the completely saturated aquifer material and the partially saturated aquifer material, is known as a water table or groundwater table. The area above the water table is known as the unsaturated zone. The **water table** fluctuates up and down with various influences, such that it can be pictured as a table floating up and down over time. Technically, hydrogeologists identify the water table as the point where the water pressure head (or hydraulic head) is equal to the atmospheric pressure.

Confined aquifer: an aquifer deep under the ground that is overlain and underlain by relatively impermeable materials, such as rock or clay, that limit groundwater movement into and out of the aquifer

Aquiclude: an impermeable body of rock or stratum of sediment that acts as a barrier to the flow of groundwater to or from an adjacent aquifer

Aquitard: a low permeability body of rock or stratum of sediment that retards but does not prevent the flow of groundwater to or from an adjacent aquifer

Semi-confined aquifer: an aquifer deep under the ground with leaky aquitards

Recharge area: the land surface area over which recharge occurs to a particular groundwater aquifer

Artesian groundwater: groundwater confined under pressure

Unconfined aquifer: an aquifer close to the land surface which receives direct recharge from rainfall. Its upper surface is the water table. Also referred to as a superficial or surficial aquifer.

Shallow aquifer: another term for unconfined aquifer

Superficial aquifer: another term for unconfined aquifer

Surficial aquifer: another term for unconfined aquifer

Water table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Unconfined aquifers are relatively well known in coastal WA, particularly because Perth is dependent upon groundwater from two of them (the Gnangara and Jandakot systems). Their role in forming wetlands varies across WA; the understanding of this role is improving as more local water investigations are carried out. For example, a 2005 study determined that the superficial aquifer supported more than 80 per cent of all groundwater dependent ecosystems in the Northern Perth Basin in the midwest, with very small areas attributable to the major confined aquifers (Leederville-Parmelia and Yarragadee Aquifer).[45]

Groundwater mound: convex regional mounding of the water table in an unconfined aquifer. The top of the mound is where the water table is highest above sea level. Water flows down gradient of this point.

Perched aquifer: a local aquifer close to the land surface that receives direct recharge from rainfall, but is above and disconnected from the regional unconfined aquifer

Groundwater mounds occur in unconfined aquifers where the water table forms the shape of a mound (convex or dome shape). Mounds develop in areas of an aquifer where the topography is high, because the rate at which rainwater infiltrates through soil to the watertable is greater than the rate at which groundwater flows horizontally. The rate at which groundwater moves under natural conditions is usually little more than about 5 metres per year.[47] This is because of the limits of saturated flow through aquifer materials and because outflow of groundwater is often constrained. Aquifers discharge to oceans and waterways where the relatively constant levels in these constrain the rate of flow. Groundwater typically flows in a radiating pattern outwards from the top of the mound. Well-known mounds include the Gnangara and Jandakot mounds on the Swan Coastal Plain (described in more detail later); lesser-known mounds occur in other areas of the state, including the Broome aquifer (Figure 32).

In some areas, localised perched groundwater sits above the regional water table. These are known as **perched aquifers** and are localised areas where an aquiclude or aquitard occurs below the surface of the land but above the regional water table. They are hydraulically disconnected from unconfined aquifers and form as a result of percolating water being impeded either seasonally or perennially by soil materials, leading to perching. These perched aquifers are generally shallow and local in extent and can be important in the formation of wetlands. There are many wetlands either known or thought to be formed from perched unconfined aquifers. For example, on the Swan Coastal Plain, a sandy clay layer known as Guildford Clay is an aquitard responsible for perching water and forming wetlands (for example, Lake Muckenburra[49] and Tangletoe Swamp[50]).

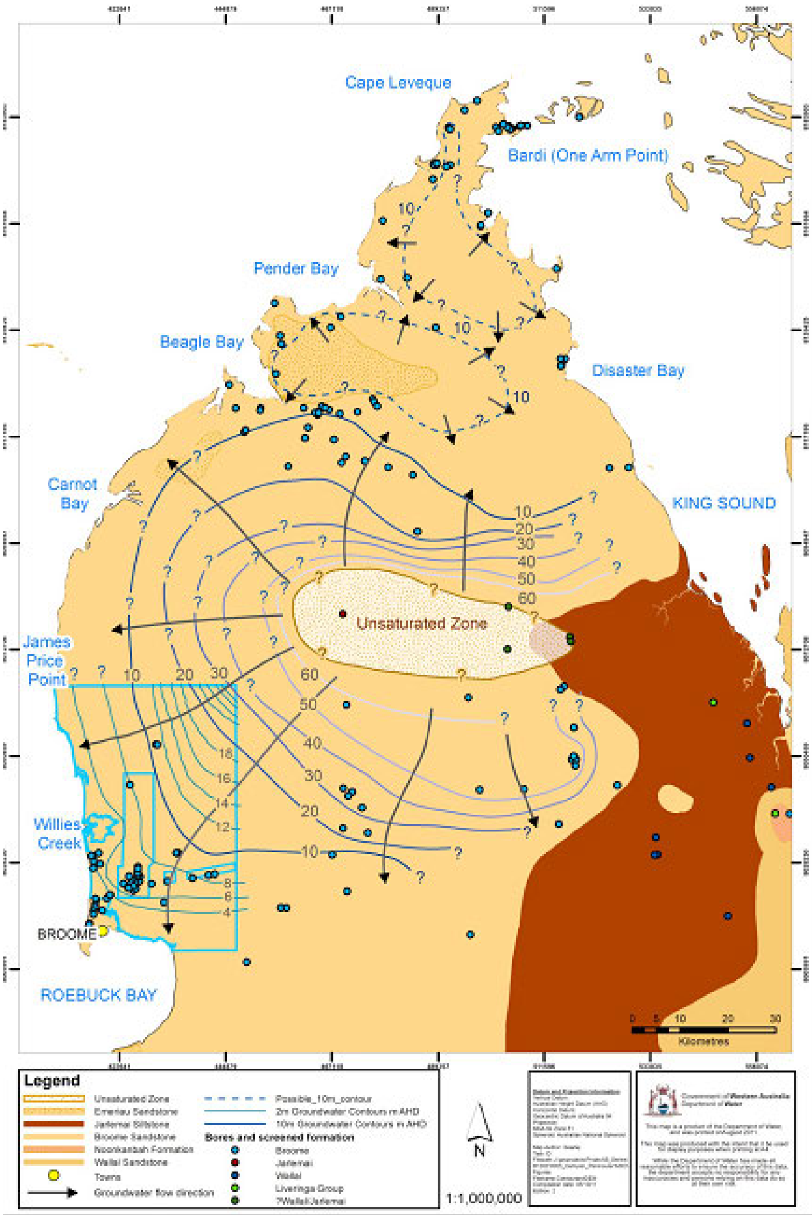

Figure 32. A map of the Broome area, showing multiple aquifers, inferred regional groundwater contours and groundwater flow direction. The circle in the centre represents the top of the mound, and the arrows indicate the inferred direction of groundwater flow. Source – courtesy of the Department of Water.[48]

Groundwater inflow to a wetland can occur when the water level in a wetland is lower than the water table of the surrounding land, resulting in a flow of water from an unconfined aquifer into the wetland.[19] Such wetlands often occur in low-lying areas (topographic lows). These wetlands are surface expressions of the water table and provide 'windows' into the groundwater. The fluctuations in the aquifer are mirrored by the fluctuations in the wetland (Figure 33). These wetlands wet and dry on an annual basis, reflecting the seasonal fluctuation of the water table in response to rainfall. When in contact with the groundwater, the wetland water chemistry more closely matches that of the groundwater. In contrast, when the groundwater disconnects from the wetland during the dry season and evaporation causes the loss of water, the remaining dissolved matter (such as salts and nutrients) becomes concentrated in the smaller volume of water. These groundwater-fed wetlands can experience large variations in both water quantity and quality over a single year.

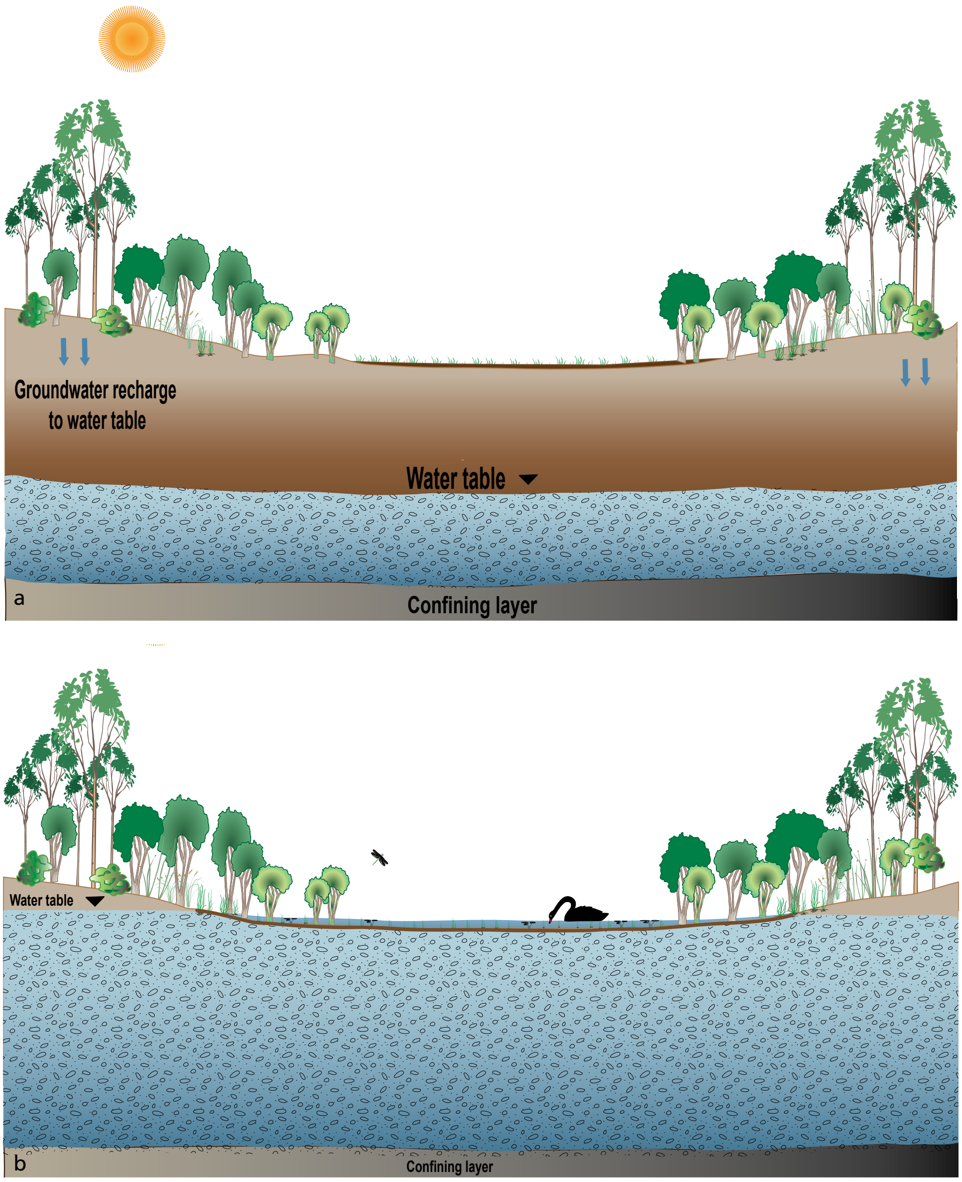

Figure 33. A simplified diagram of groundwater flux; (a) when the water table is far below the wetland, the wetland is disconnected from the groundwater; (b) when the water table is as high as the base of a wetland, water may flow into the wetland. Such wetlands are often said to be 'groundwater fed'. The flux in the height of the water table is mirrored in the wetland.

These groundwater-fed wetlands are also known as discharge wetlands, because groundwater is discharging into the wetland (these terms were coined by groundwater hydrologists, viewing movement from a groundwater perspective rather than a wetland perspective). When at certain times of year the water level in a wetland is higher than the water table of its surroundings, water will flow out of the wetland and into the groundwater.[19] These are **recharge wetlands** which contribute to the groundwater.[19]

Paluslope: a seasonally waterlogged slope wetland

Some wetlands will act as **discharge wetlands** at some times of the year, then become recharge wetlands when the surrounding water table falls below the water level in the wetland. Some wetlands are **flow-through wetlands** which receive groundwater inputs in some parts of their area and discharge water to the groundwater in other areas. Research carried out in the 1990s found that most of the permanently inundated wetlands in Perth and the broader Swan Coastal Plain were flow-through lakes which 'capture' groundwater on their upgradient side (the groundwater capture zone) and release it on the downgradient side (the release zone)[51] (Figure 34, Figure 35, Figure 36). The chemical characteristics of the water flowing out of these wetlands can be quite different to the water flowing into them. The groundwater capture zone of a wetland is the area within which any recharge eventually flows into the wetland.[51] Research on permanently inundated wetlands on the Swan Coastal Plain found the width of the groundwater capture zone to be roughly twice the width of the wetland.[51]

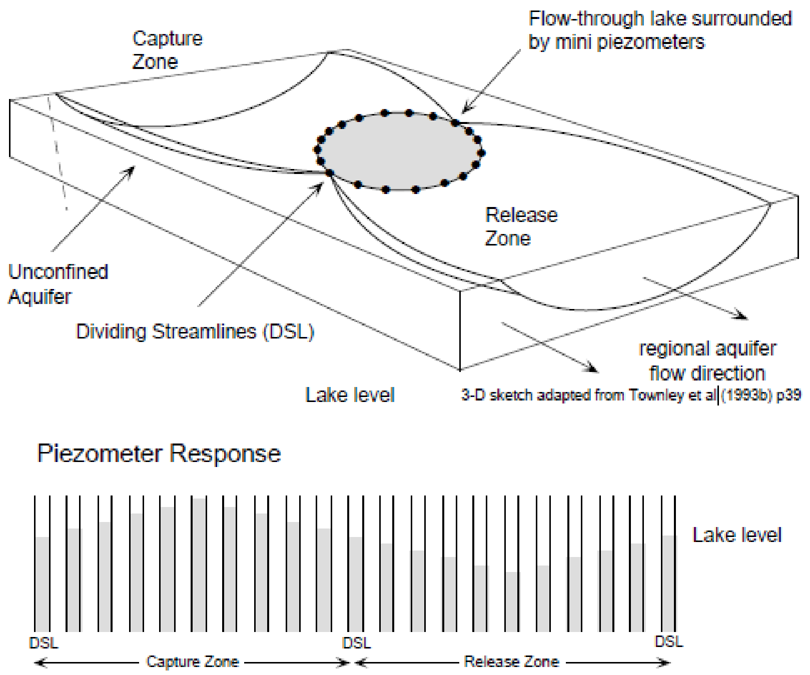

Figure 34. A schematic diagram showing the local capture and release zone of a flow-through wetland relative to the regional groundwater flow. Image - Integrated Mass, Solute, Isotopic & Thermal Balances of a Coastal Wetland: Wetland Research at Perry Lakes, Western Australia 1993-1998[52]

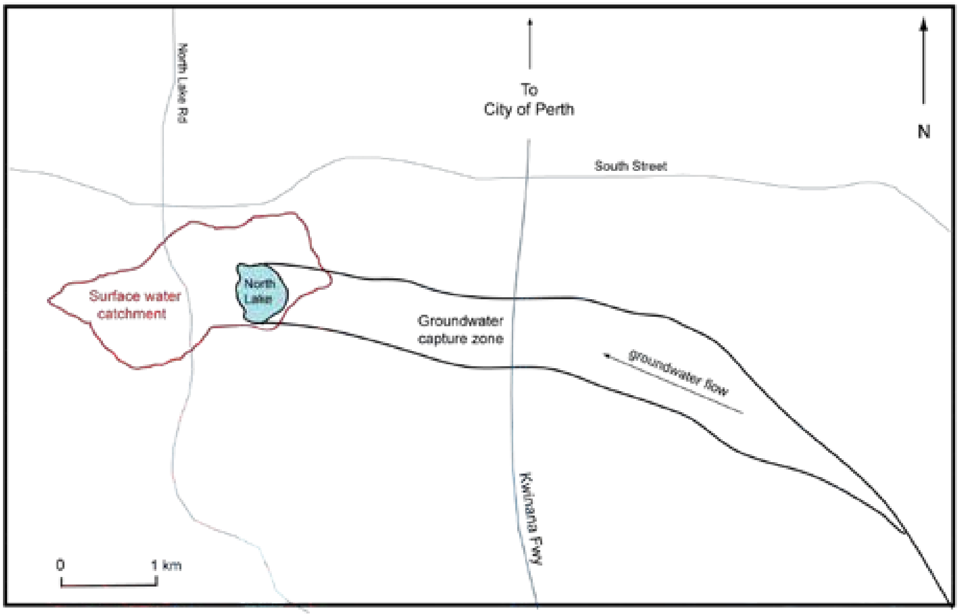

Figure 35. Schematic view of a wetland natural (prior to human modification) surface water catchment and groundwater capture zone, based on North Lake in Perth's southern suburbs.

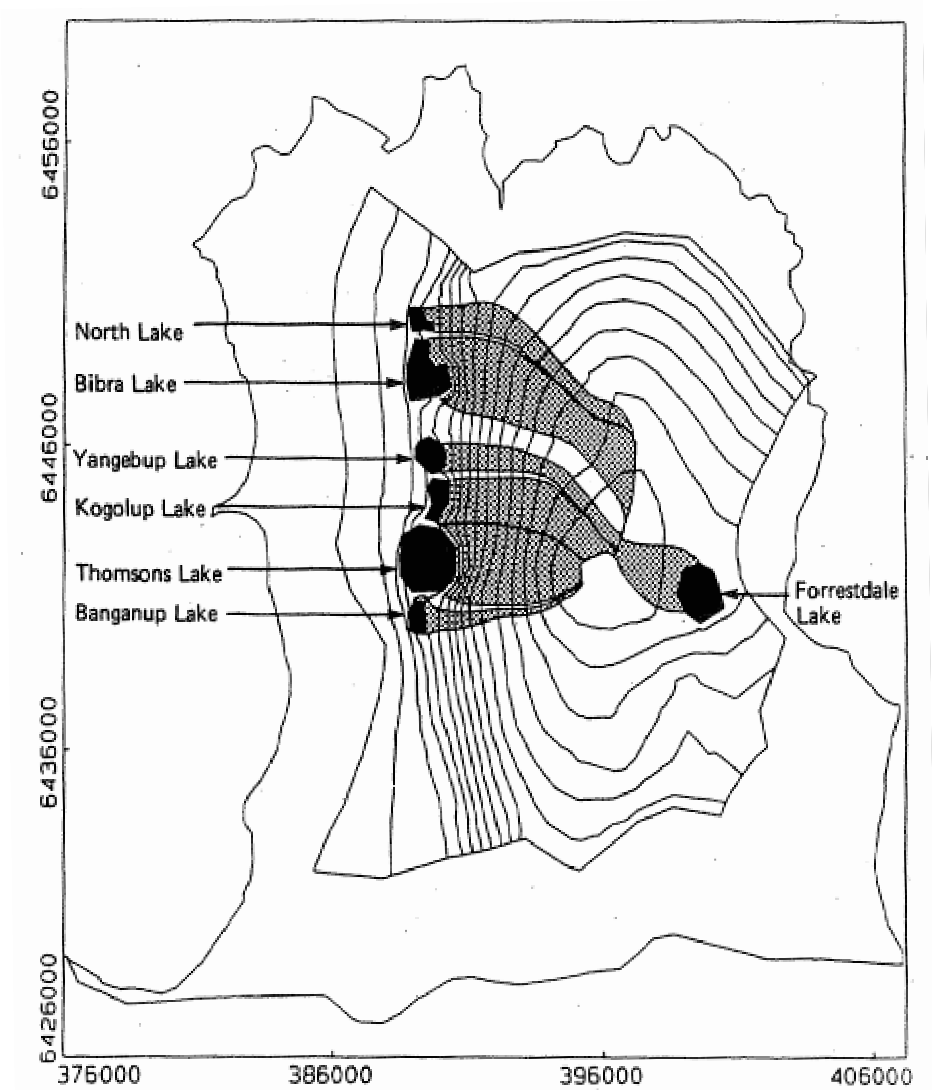

Figure 36. Predicted capture zones for seven lakes on the Jandakot Mound. Source – Townley et al.[52]

Palaeochannel: a channel formed by a palaeoriver (ancient river), infilled with deposited sediments and buried over time, often forming modern-day groundwater aquifers

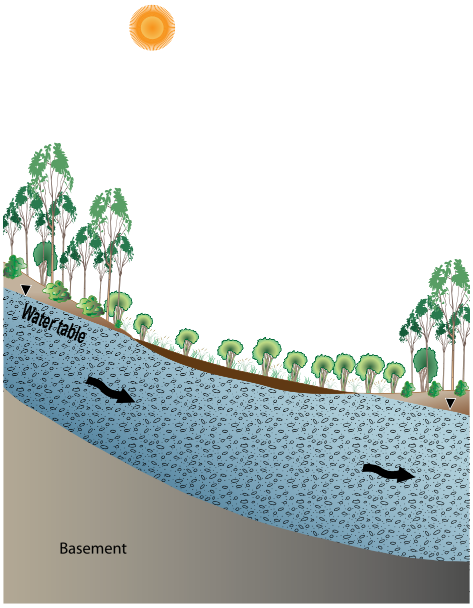

Figure 37. Wetlands can form on slopes, by seepages at the break of slope.

Figure 38. A paluslope in the south-west of WA. Photo – Wetlands Section/DEC.

In Figure 33 and Figure 34, the vertical flux of the water table has reached the land surface at a depression in the landscape. In many areas, it reaches a slope rather than a depression. At the maximum water table level, following rainfall, groundwater discharges on to such slopes and **paluslope** wetlands may form due to the seasonal waterlogging of the soil (Figure 37, Figure 38).

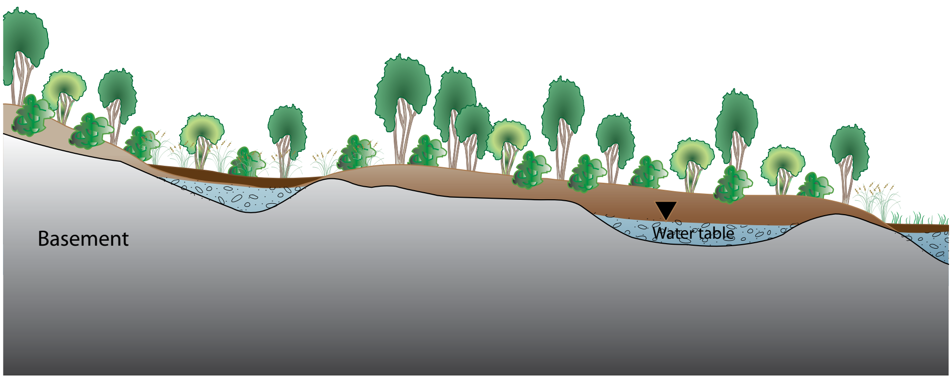

Figure 39. Bedrock highs trap water and force it to the surface, creating wetlands.

Sometimes local mounding and discharge of groundwater from an unconfined aquifer is caused by vertical barriers underground; these are generally localised geological features (for example, bedrock highs, where water is trapped behind the bedrock high and forced to surface; Figure 39).

Many wetlands across WA are fed by groundwater from ancient **palaeochannel**/ palaeovalley groundwater aquifers. These are a variant of wetlands controlled by water table flux in unconfined aquifers, differing in that groundwater flow and occurrence is dominated by the aquifers that have formed in ancient in-filled river channels. Rivers flowing millions of years ago formed river channels in valleys. As the climate became much drier, and the slope of entire geological blocks tilted as the massive Gondwanan continent split, these rivers filled with gravel and sand sediments and ceased to flow. These sediment-filled channels and valleys, which can be more than 60 metres thick, are known as palaeochannels and palaeovalleys respectively (palaeo meaning ‘old’). Over the millennia, these were buried, covered by sediments deposited by erosion, wind and water, and filled with water in the spaces between gravels and sands, resulting in confined, semi-confined and even unconfined aquifers in some cases[53] (Figure 40). These palaeovalleys systems are widely distributed across WA, and are a notable feature of arid WA.[12] However, they are completely concealed and must be found with geophysical methods.

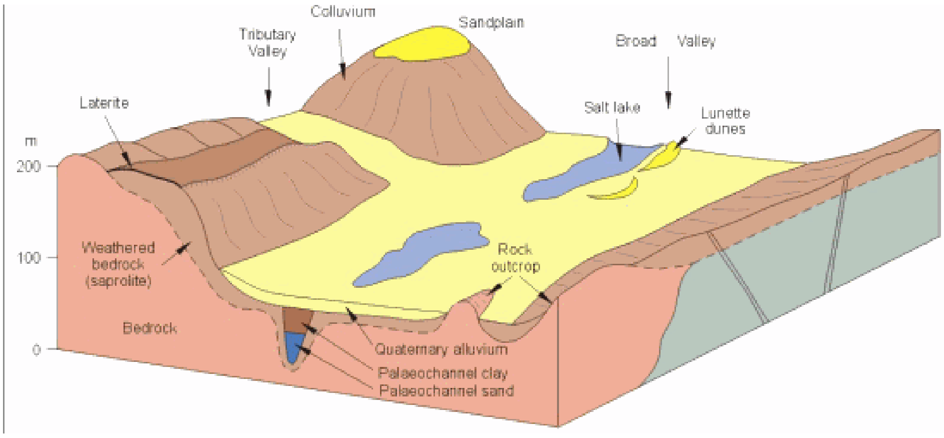

Figure 40. A stylised depiction of Wheatbelt valley geology including a palaeochannel. Image - Commander (2001).[54]

At the modern-day surface, high above the palaeovalleys, these areas are often linear topographic lows, often supporting wetlands, usually elongate chains of wetlands (commonly referred to as playas, salt lakes and clay pans)(Figure 41).[53] It is common for groundwater from the buried palaeochannels to discharge into these wetlands, possibly because of changes in depth to bedrock. This water typically evaporates to form wetlands commonly referred to as salt lakes and salt flats. Figure 30 provides a general indication of the location of palaeodrainage deposits in WA.

Figure 41. The groundwater discharged from a palaeochannel into these wetlands, near Wagin, tends to be rapidly evaporated. Image – Google Earth™.

➤ For more background information on palaeochannel aquifers, see *The Wheatbelt's ancient rivers*.[55] More detailed information for all regions of WA can be found in *Palaeovalley groundwater resources in arid and semi-arid Australia: a literature review*.[53]

extra information

The Gnangara groundwater system

The Gnangara mound is 2,200 square kilometres. At its highest point it is about 70 metres above sea level and slopes away in all directions—east to Ellen Brook, south to the Swan River, west to the Indian Ocean and north to Gingin Brook (Figure 42). On the crest of the mound there is fresh groundwater in the shallowest (superficial) aquifer, up to 60 metres deep. This interacts with the deeper confined Leederville and Yarragadee aquifers and collectively make up the Gnangara groundwater system.

The superficial aquifer occurs in the superficial geological formations, which vary in complexity in an east-west pattern. In an east to west direction the aquifer typically grades from being predominantly clayey, near the Darling Fault (Guildford Clay) to sandy in the central plains (Bassendean Sand and Gnangara Sand) through to sand and limestone on the coastal belt (Tamala Limestone and Safety Bay Sand).

Underneath the superficial aquifer are two other geological formations containing the confined Leederville aquifer (up to 600 metres thickness) and Yarragadee aquifer (greater than 2000 metres thickness). These interact in the Gnangara area but are broad, extending and interacting at least 100 kilometres north and south of the Gnangara groundwater system. There are also a number of smaller aquifers such as the Mirrabooka and the Kings Park aquifer that occur between the superficial and Leederville aquifers.

The Gnangara Mound supports wetlands of local, regional and national significance, as well as wetland species of international significance. Many wetlands receive groundwater discharge from the regional unconfined aquifer, although perched localised aquifers are also very important. The Gnangara Mound is also the source of much of Perth's water supply.

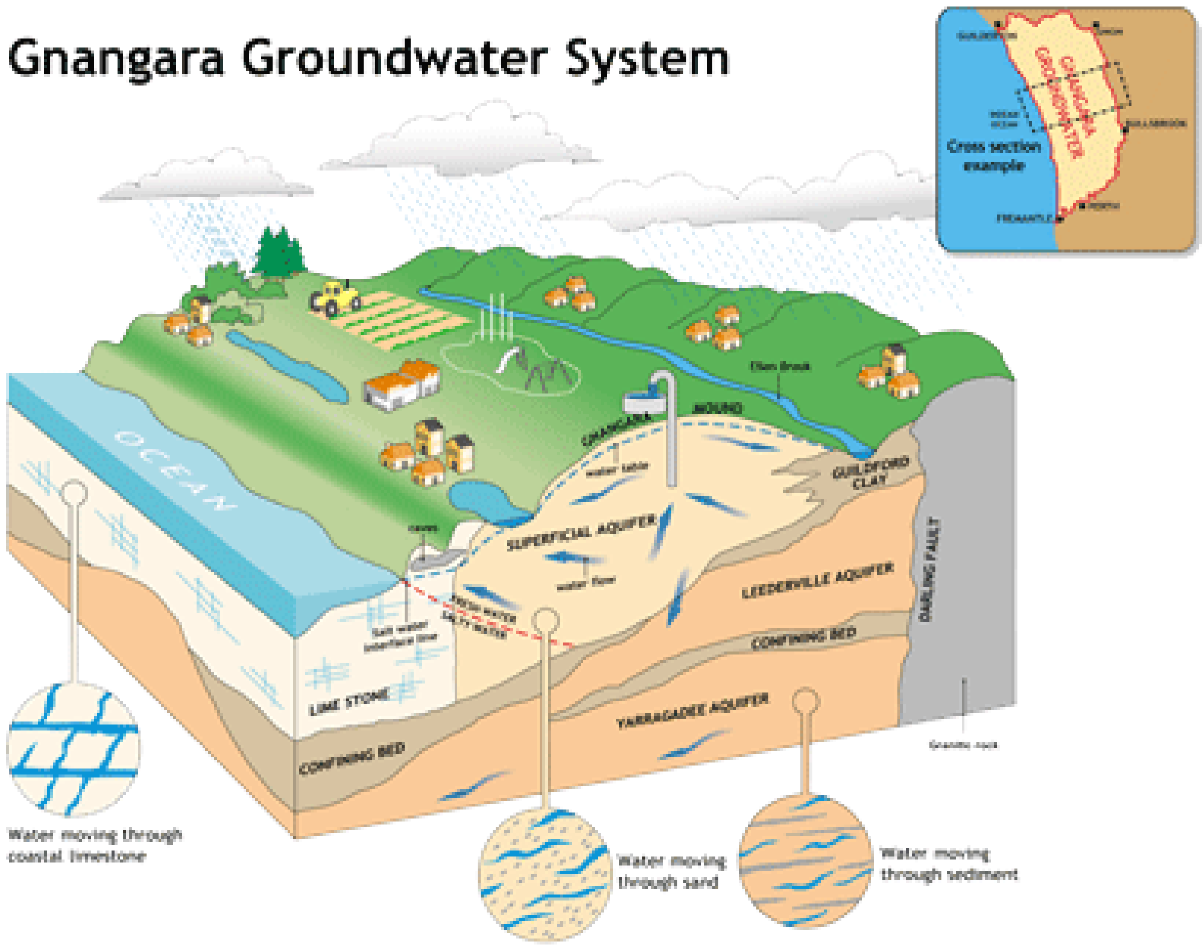

Figure 42. The Gnangara groundwater system in plan view. Image – courtesy of the Department of Water.

extra information

The Gnangara groundwater system (cont'd)

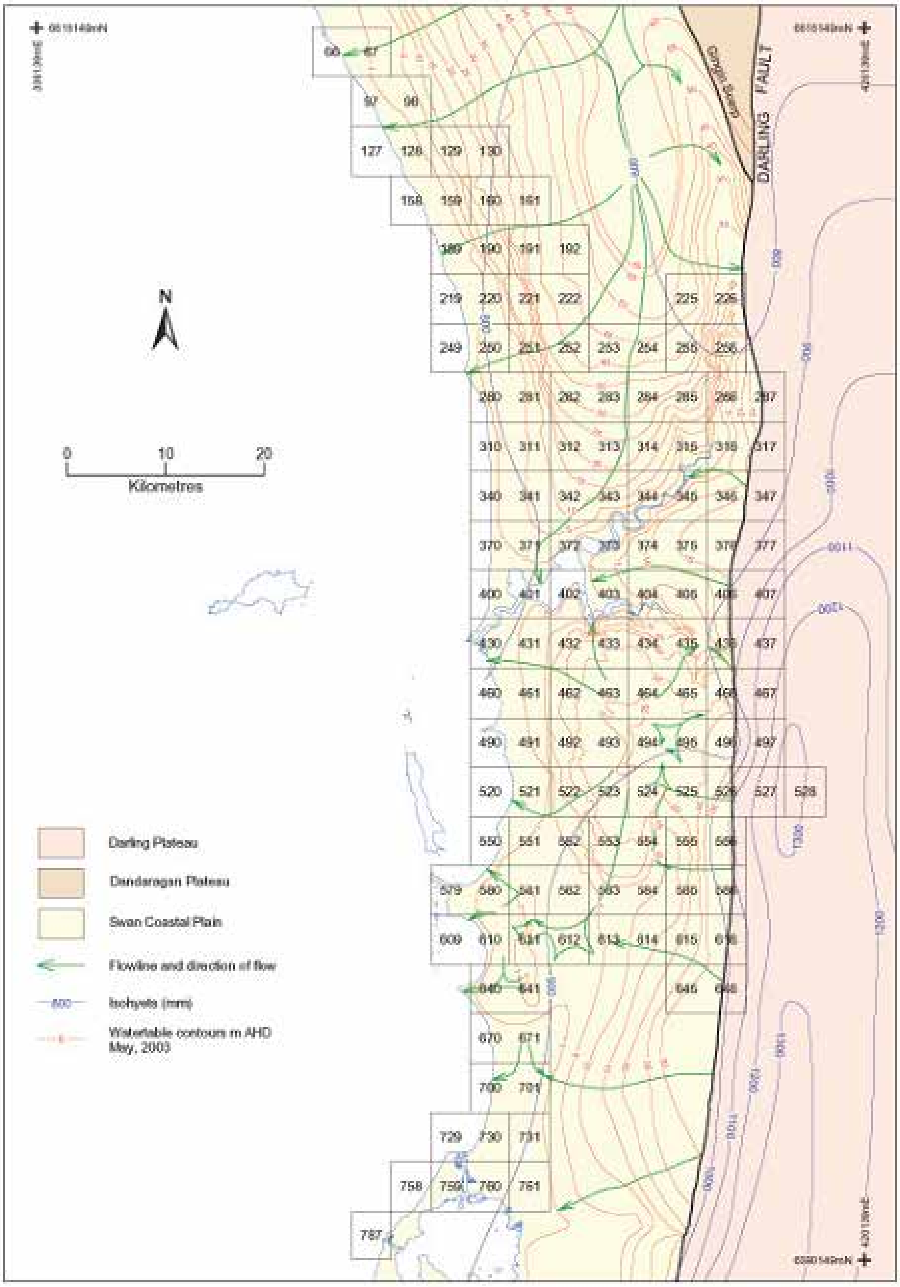

Figure 43. A map of the Gnangara (northern) and Jandakot (southern) groundwater mounds. Source – courtesy of the Department of Water.[56]

➤ The Gnangara Mound is a fascinating groundwater system. More information can be found at the webpage: www.water.wa.gov.au/Understanding+water/Groundwater/Gnangara+Mound/default.aspx

➤ It has been the subject of many detailed studies. For more information see the Gnangara Sustainability Strategy webpage: www.water.wa.gov.au/sites/gss/index.html. *Chapter Four: Wetlands and Groundwater-Dependent Ecosystems*[13] and *Chapter Five: Biodiversity values and threatening processes of the Gnangara groundwater system*[57] is of particular relevance.

➤ For more information on the Jandakot Mound, see www.water.wa.gov.au/Understanding+water/Groundwater/default.aspx

INVESTIGATING SURFACE AND GROUNDWATER INTERACTION WITH WETLANDS

Surface water interaction with wetlands is relatively easy to account for and measure. Rainfall monitoring occurs at sites around WA and monitoring stations are present on many rivers in WA. These provide information on river levels over time, including rainfall from telemetered sites that allows data to be downloaded remotely. It is possible to measure the surface water levels in a wetland manually via a staff gauge (Figure 44) or via telemetered sites. More information on these measurements is provided in the next section.

Figure 44. A staff gauge used to measure the level of inundation at Manning Lake, Cockburn. Photo – J Lawn/DEC.

Groundwater measurements can be more involved, particularly where the properties of the aquifer are not uniform. A lot of groundwater measurements focus upon how close the watertable is to the land surface. Measurements are made with groundwater monitoring **bores**, which include **observation bores** for the water table or **piezometers** for water levels deeper in aquifers. To get accurate readings, it is essential that monitoring bores are installed to industry standards, to ensure that construction is known and that the bores operate well (for example, do not silt up or collapse). It is important to have sound records detailing the construction of a bore, particularly with regard to which part of the aquifer a bore is providing information about. Accurate readings are also achieved by measuring water levels in a consistent way in relation to a point where relative elevation is known. The data collected from a monitoring bore can be graphed to show patterns and trends over time. The hydrograph in Figure 45 is an example.

Watertable data can be reported in various ways, most commonly:

- as the height of the watertable relative to the ground surface of the location. For example, it can be reported that "at location X, the groundwater was 2 metres below ground level on 12 January 2013". This is useful for basic purposes.

- as the height of the watertable relative to a fixed survey point known as **Australian height datum** or AHD, which is at sea level. Most land surfaces in Australia are higher than the sea. Land surfaces along the coast, and other low points may be close to sea level, such as only one or two metres higher, and would be reported as "2 metres AHD", for example. Watertable level can also be reported using this unit of measurement and requires that the point from which water level measurements are taken (usually the top of the bore casing) is surveyed to a land-survey datum point. This allows water levels as metres below the top of the bore casing to be converted to AHD. For example: "at location X, the land surface is 23 metres AHD and on 12 January 2013 the watertable was 21 metres AHD". This means the groundwater was 2 metres lower than the ground surface on the date of monitoring at location X.

Bore: a narrow, normally vertical hole drilled into a geological formation, usually fitted with a PVC casing with slots to allow interaction with the aquifer, to monitor or withdraw groundwater from an aquifer

Observation bore: a non-pumping well with a long slotted section that crosses the water-table

Piezometer: a non-pumping well, with a short length (often 2 metres) of slotted section at the base often below the water table, which is used to measure the potentiometric surface

Australian height datum (AHD): a fixed survey point from which the elevation of any point in Australia may be measured

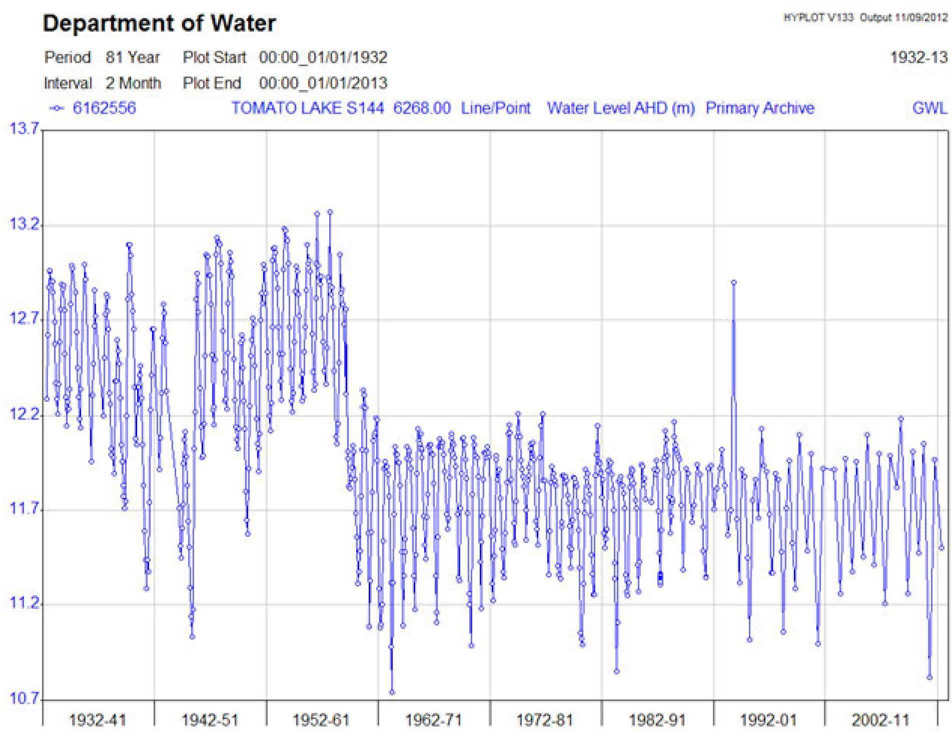

Figure 45. Groundwater measurements can be plotted in the form of hydrographs to show trends over time. Image – courtesy of Department of Water.[58]

This data can also be used to develop averages, for example, the average annual maximum groundwater level (AAMGL) and average annual minimum groundwater level at a bore. Additionally, the data from a network of bores across an area can be used to make generalisations about groundwater patterns and trends across the area. In particular, this data is used to 'map' the height of the watertable. The height of the watertable is presented as groundwater 'contours', as shown in Figure 46. They look similar to land elevation contours. These contours represent points of equal elevation in the water table, in this case the known or inferred historic maximum groundwater levels. These contours also show the direction of groundwater flow, which is perpendicular to the contours from the highest area of groundwater to the lowest area (that is, down gradient).

The sub-surface geological characteristics and associated groundwater systems of many areas of Western Australia can be complex (Figure 47). Interpreting the way these systems work just using groundwater measurements from piezometers can be difficult. In some circumstances it has been necessary to carry out specialist investigations including analysis of chemical isotopes and airborne electromagnetic surveying to develop a better understanding of the conditions. These methods have been used to analyse the Lake Warden catchment, near Esperance.[59] Similarly the Northern Gnangara airborne electromagnetic survey has been initiated because, despite the large number of bores within the Gnangara Mound, the high spatial variability of water retentive layers means that geophysical surveys are a more accurate and efficient method of mapping this critical groundwater resource. This survey will determine the distribution of water retentive layers in the superficial aquifer, map the contact between the superficial and the underlying Leederville and Yarragadee aquifers and define the water table surface.[60]

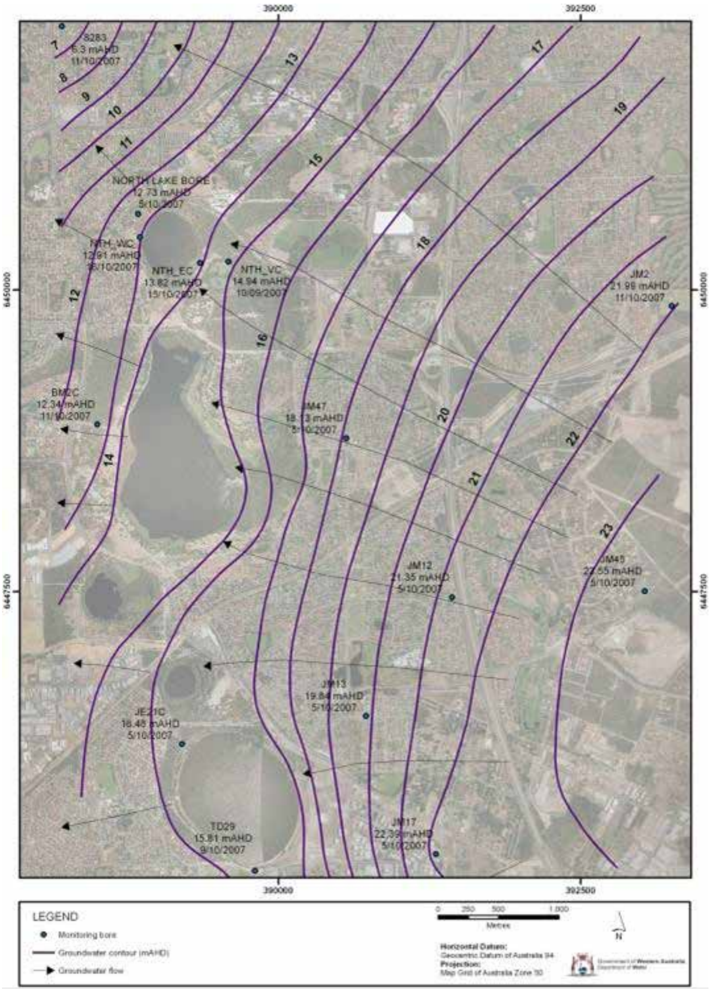

Figure 46. Mapping of the height of groundwater (contours) in the southern Perth area. The arrows indicate the direction of groundwater flow. Image – courtesy of Department of Water.

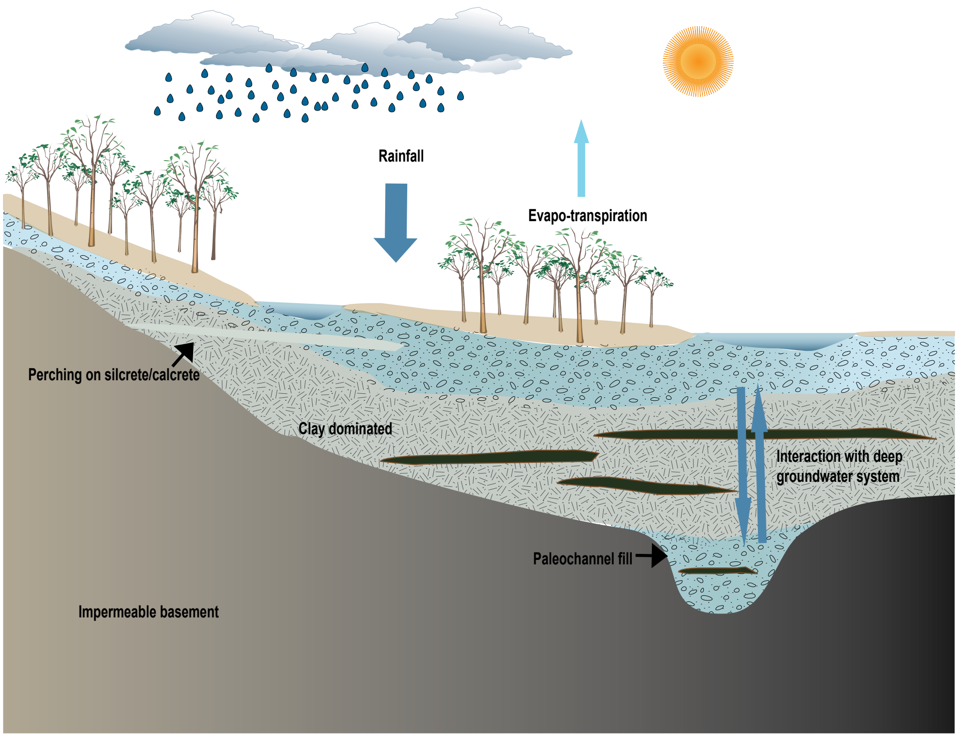

Figure 47. Complex below-ground layering can lead to complex groundwater conditions.

Models are also used to describe groundwater and groundwater-surface water systems. A **groundwater model** is a simplified representation of a groundwater system and it captures and synthesise all of the known information, and where information is not known, identifies any assumptions being made about how the system is thought to work. They may be conceptual, analytical or numeric. Conceptual models are used as visual tools to display the relationships between parts of the groundwater system. They may be simple or more complex, such as shown in Figure 48. Numeric models assign actual quantities to each part of the system. Perth regional aquifer modelling system, or PRAMS, is a regional model of Perth's groundwater. It is used by the Department of Water to manage groundwater in the region and to help predict cause and effect under different scenarios (for example, more or less groundwater abstraction).

While regional groundwater models tend to be useful in understanding regional trends, they are often unsuitable for use at the scale of individual wetlands. In the case of PRAMS, its calibration and resolution are based on a 500 by 500 metre grid size and therefore cannot provide detailed information for local scale management objectives, such as managing individual wetlands, which require smaller grid sizes, higher resolution conceptual models and higher quality calibration. To gain a better understanding of the role of the Gnangara groundwater system's effect on wetlands, the Department of Water have developed local area models (LAMs) at a refined level of detail (50 to 100 metre grid) for five wetlands (Lake Mariginiup, Lake Nowergup, Melaleuca Park, Lake Bindiar and Lexia) have been developed. These local area models provide quantitative tools to assess land and water use impacts on the environment and groundwater systems. These local area models will be used to refine and improve PRAMS so that the impact on wetlands due to changes in the superficial aquifer can be determined.

Modelling of surface water-groundwater interaction sometimes involves the coupling of surface hydrological models with groundwater models.

Models are often used to help determine the potential environmental impacts of proposals assessed by the Environmental Protection Authority under the *Environmental Protection Act 1986*. It is important to be aware that models reflect the information they are based on, and it is possible for them to be wrong. For example, if a model is based upon one year's monitoring data, its predictive capability about how a system works over the long term and how it may respond to events is likely to be extremely limited. Important factors include the type of model used and its suitability for the task at hand, the assumptions built into the model, the integrity of the data, calibration and the stated uncertainty of its outputs.

➤ For more information on groundwater modelling, see the *Australian groundwater modelling guidelines*.[61]

➤ The eWater toolkit www.toolkit.net.au/Default.aspx is a source of software tools and information related to the modelling and management of water resources provided by the eWater Cooperative Research Centre.

➤ For more information on local area models, see the reports listed under 'Local area modelling' at: www.water.wa.gov.au/sites/gss/reports.html

At the wetland scale, the complexity of groundwater flows can be compounded by the complexity of wetland sediments. For example, Figure 49 shows the wetland sediments of Lake Mariginiup on the Gnangara Mound, in the suburb of Mariginiup north of Perth. In winter/ spring, groundwater flows into the wetland on its eastern side, then up to 92 per cent is removed by evapotranspiration; a small amount is recharged to groundwater from the western side of the wetland.[63]

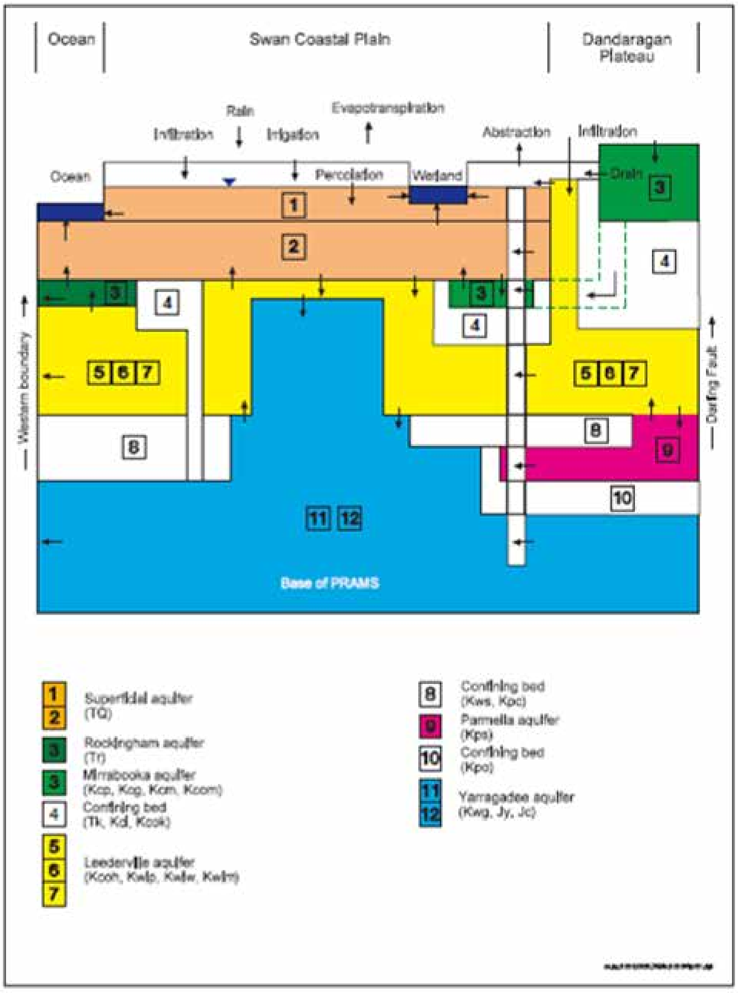

Figure 48. A conceptual hydrogeological model of the Perth groundwater system. Source – Department of Water. [62]

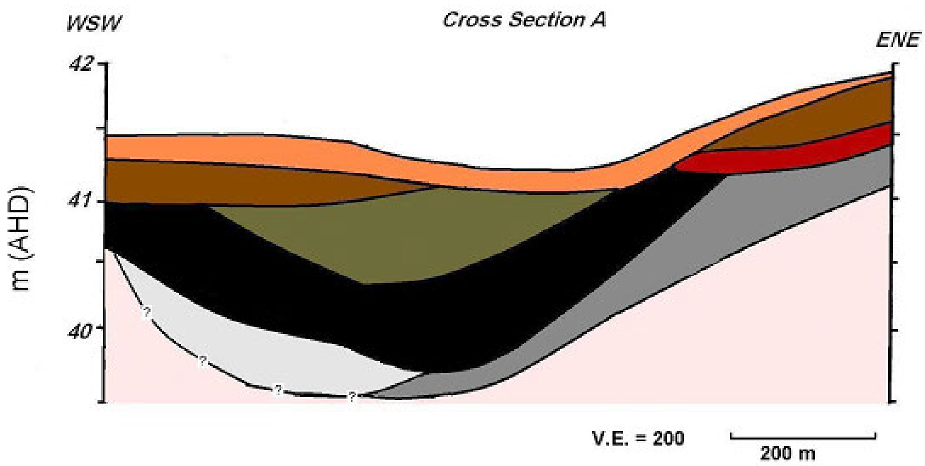

Figure 49. Many wetland sediments are not uniform across a wetland, such as those of Lake Mariginiup, represented here in cross-section. Image – Department of Water.[63]

QUANTIFYING WETLAND HYDROLOGY

Understanding the hydrology of wetlands requires quantifying the main hydrological components of wetlands, namely gains of water via rainfall, surface inflows and groundwater discharge and losses by evapotranspiration, groundwater recharge and surface water outflow (Figure 17). These form elements of the water budget for wetlands and contribute to defining the water regime.

Water budget

The **water budget** of a wetland is the balance of all of the inflows and outflows of water.[19]

Each of these inputs and losses varies seasonally, from year to year and geographically and is governed by the characteristics of a particular wetland including the climate, geomorphology and other characteristics of its catchment.[37]

The water budget can be described by the following equation:

DS (t) = P + Qi + Gi – E - Ev– Qo – Go

Where:

DS = change of water quantity stored in the wetland

(t) = specified time interval

P = rain falling on the wetland

Qi = surface water flowing into the wetland

Gi = groundwater flowing into the wetland

E = evaporation from the water's surface

Ev = evapotranspiration from vegetation and soil

Qo = surface water flowing out of the wetland

Go = groundwater flowing out of the wetland

It is important to use the same units for each parameter e.g. measuring all units in litres.

Determining water budget and associated information

The water budget indicates how important each source of water loss and gain is to the wetland balance.[19] Understanding these contributions allows wetland managers to assess the impacts of alterations to any water inputs or outputs. For example, if it is determined that groundwater is the primary source of a wetland's water, managers can assess the impact that groundwater abstraction is likely to have on the wetland. This information also enables managers to assess other impacts such as the likelihood of contamination of groundwater and surface waters by dissolved pollutants.

A water budget can be quantitative or qualitative. Although rainfall may be easy enough to measure, the other components of evaporation, evapotranspiration and surface and groundwater flows can be much more complicated. Obtaining regular measurements over a long period of time to enable both short-term and long-term trends to be observed can also be challenging.

Techniques range from simple reconnaissance methods, to detailed field measurements (Figure 50), to sophisticated mathematical models. Detailed field studies to quantify the various components are often difficult, expensive and time consuming.

Determining standing water levels and volume

In the case of wetlands that have a water column, the first step is to work out how much water is required to fill a wetland and how this relates to water depth, so that changes in water levels can be used to determine changes in water volumes in a wetland.

Documenting the inundation level of a wetland requires a surveyed depth gauge and some knowledge of the shape and depths (bathymetry) of the wetland. A depth gauge should be positioned at the deepest point of a wetland and should be surveyed to Australian height datum (AHD) or a suitable local height datum.

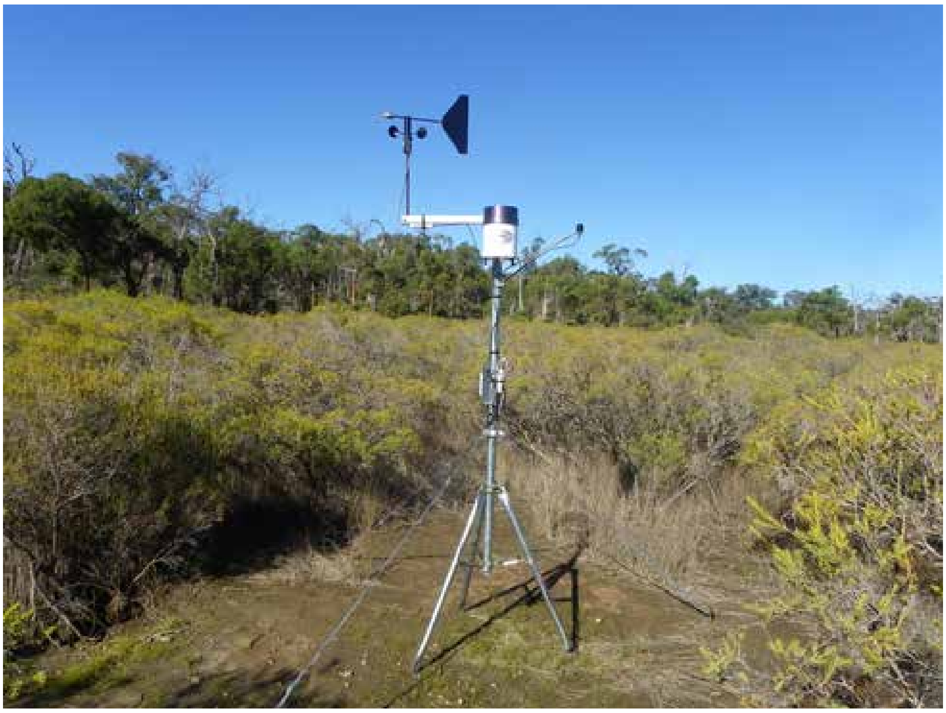

Figure 50. Understanding of the hydrology of a claypan in Drummond Nature Reserve, in the Northern Jarrah Forest region, is being aided by detailed field measurements. Photo – J Lawn/ DEC.

The water level on the depth gauge is recorded regularly to monitor seasonal changes. A bathymetric survey of the wetland will allow a correlation between the depth of water measured on the gauge and the total volume in the basin.

Bathymetric survey involves constructing a three dimensional model of a wetland's floor by taking depth measurements along a number of transects. The measurements must be calibrated to AHD or a suitable local height datum, so that they are relative to a fixed datum, rather than to water level at the time of survey.

The Department of Water has an extensive surface water monitoring network in WA, which forms part of its water information network (WIN). Its records are available online at its water information resources catalogue (WRIC): http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp

Hydrographs are available for many sites, available at: http://kumina.water.wa.gov.au/waterinformation/wrdata/wrdata.cfm

Long-term data on water levels has been collected by the state government for a number of wetlands in the south-west via the South West Wetlands Monitoring Program. A number of reports are available via the DEC library: http://science.dec.wa.gov.au/conslib.php

Determining soil saturation

Soil moisture sensors measure moisture levels in soils, and can be used in wetlands. They are particularly useful for helping to determine the water balance of seasonally waterlogged wetlands, by helping to measure evaporative losses for these wetlands. They are usually designed for agricultural purposes and vary considerably in price.

Estimating rainfall and evaporation

The Bureau of Meteorology has extensive weather and climate records that can be used to estimate rainfall and evaporation rates at a wetland, available at www.bom.gov.au. It is also possible to obtain interpolated climate data for wetlands of interest from the SILO data drill: www.longpaddock.qld.gov.au/silo. This is particularly useful where climate data for a nearby site is not available.

Where a very accurate measure of rainfall or evaporation is required, a rain gauge and an evaporation pan respectively are used. Instructions for measuring these parameters are provided in the topic 'Monitoring wetlands' in Chapter 4. Evapotranspiration is a complex measurement and proxies such as modelling and remote sensing are used if approximations are not suitable.

Estimating waterway inflows and outflows

The Department of Water has an extensive surface water monitoring network in WA, which forms part of its water information network (WIN). Its records are available online at its water information resources catalogue (WRIC): http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp

If records are unavailable or unsuitable, spot measurements of channelised inflows and outflows can be made using a hand-held flow meter, or engineered in-stream device. These devices can be instrumented with water level sensors to determine more continuous estimates of flow volumes. More information is available on these methods from the topic 'Monitoring wetlands' in Chapter 4.

Estimating overland flows

Overland flow is very difficult to measure in the field. If it is important that overland inflow is included in a water balance equation, it will be necessary to use modelling software to calculate the run-off from surrounding land. This will be affected by many factors including rainfall duration, quantity and intensity, topography, soils and geology, land use in the catchment and the nature of surrounding vegetation. Such modelling will require assistance from a professional hydrologist.

Estimating groundwater inflows and outflows

Groundwater levels can be used to estimate groundwater flow, providing that properties of the aquifer such as gradient, direction of flow and hydraulic conductivity are understood. Measuring groundwater fluxes is, however, a difficult task that requires both expertise and specialised equipment. In brief, piezometers and observation bores are sunk into the groundwater at designated locations in the landscape. Existing bores can be used but only if the construction of these can be determined. The depth to groundwater can be measured in an ad-hoc or regular pattern by people, or by automated dataloggers (electronic devices that record and transmit data over time or in relation to location either with a built in instrument or sensor via external instruments and sensors) (Figure 51).

The Department of Water has an extensive groundwater monitoring network in WA, which forms part of its water information network (WIN). Its records are available online at its water information resources catalogue (WRIC): http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp

Hydrographs are available for many sites, available at: http://kumina.water.wa.gov.au/waterinformation/wrdata/wrdata.cfm

If records are unavailable or unsuitable, simple measurements can be readily conducted using existing bores where these are available. One method is to lower a weighted string, known as a 'plopper', down the bore. When the weight can be heard to hit the water, a reading of the depth below surface is taken from the string. Alternatively a water level meter can be used. Regular measurement of the height of groundwater in these bores allows a hydrogeologist to calculate the position of the water table and its direction and rate of flow. Establishing a suitable piezometer or observation bore network and analysing the data require specialised knowledge.

➤ *Groundwater sampling and analysis – a field guide*[64] provides guidance on standard approaches to groundwater measurements.

➤ Minimum standards for the construction of monitoring bores is outlined in Water Quality Protection Note no. 30, *Groundwater monitoring bores*.[65]

Figure 51. A DEC hydrologist showing onlookers a datalogger at a nature reserve. Photo – J Lawn/DEC.

case study

The hydrology of the Mandora Marsh system

The Mandora Marsh wetland (Figure 52) lies across the border between the shires of Broome and East Pilbara in northern Australia and is part of the Eighty-mile Beach Ramsar site.[66] Although no detailed study of the hydrology of Mandora Marsh has been undertaken, anecdotal evidence suggests that there are three main components of the wetland water budget (Figure 53). The most important input of water is surface run-off during periods of cyclonic activity.[67] A lesser contribution to the hydrology of the wetland is the input of channelised flow from Salt Creek. This waterway appears to be fed through a series of springs from a saline groundwater aquifer which may be connected to the ocean.[68] Salt Creek is an important wetland in its own right, as it supports a unique mangrove community. Freshwater springs are the third component of the wetland's hydrology. A shallow, freshwater aquifer is thought to occur within a palaeochannel that discharges into the wetland. Mound springs, such as Saunders Spring (Figure 54), occur where the water from the aquifer reaches the surface. This aquifer is recharged by water from the wetland when it fills following rain, making the hydrology of the wetland important to the persistence of Saunders, and other, springs.

Figure 52. Mandora Marsh near Shay Gap in the Kimberley region of WA. Photo - M Coote/DEC.

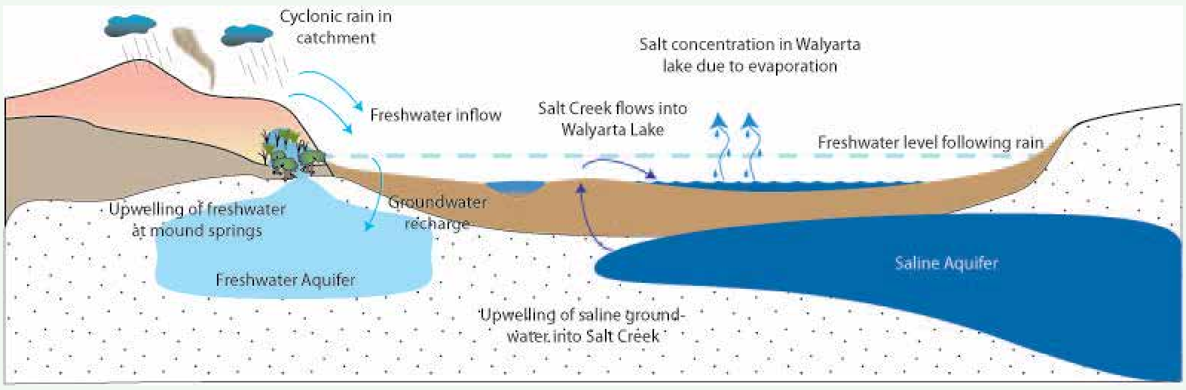

Figure 53. A conceptual model of the water inputs and outputs to Mandora Marsh.[69]

case study

The hydrology of the Mandora Marsh system (cont'd)

Figure 54. Saunders spring, a freshwater mound spring that is part of the Mandora Marsh system. Photo - M Coote/ DEC.

Periodic wide-scale flooding of the Mandora Salt Marsh and surrounding area following heavy rainfall are important. Wetland scientists have identified that it is important that the extent and duration of inundation be maintained, with no additional barriers to flow or extraction of floodwaters occurring. It has been recommended that investigations be undertaken into the hydrogeology of the Mandora Marsh and the environmental water requirements of the groundwater dependant ecosystems.[70]

case study

The hydrology of Lake Gore

Lake Gore (Figure 55) is located approximately 34 kilometres west of Esperance, on the south coast of Western Australia. It was designated as a Wetland of International Importance under the Ramsar Convention in 2001, because of its significance as waterbird habitat and refuge. The main input of water into Lake Gore is from the Dalyup River catchment which contributes over 11,000 megalitres annually (Figure 56). Other hydrological inputs to Lake Gore come from the Coobidge Creek wetlands system (which includes Carbul, Kubitch and Gidong lakes); direct rainfall over the lake surface; and freshwater from a perched aquifer in sand dunes to the south and south-east of the lake. There is also some groundwater seepage which dominates water flow in drier times, however, the amounts are not quantified.[71]

Figure 55. Lake Gore near Esperance in the south west of WA. Photo – S White/DEC.

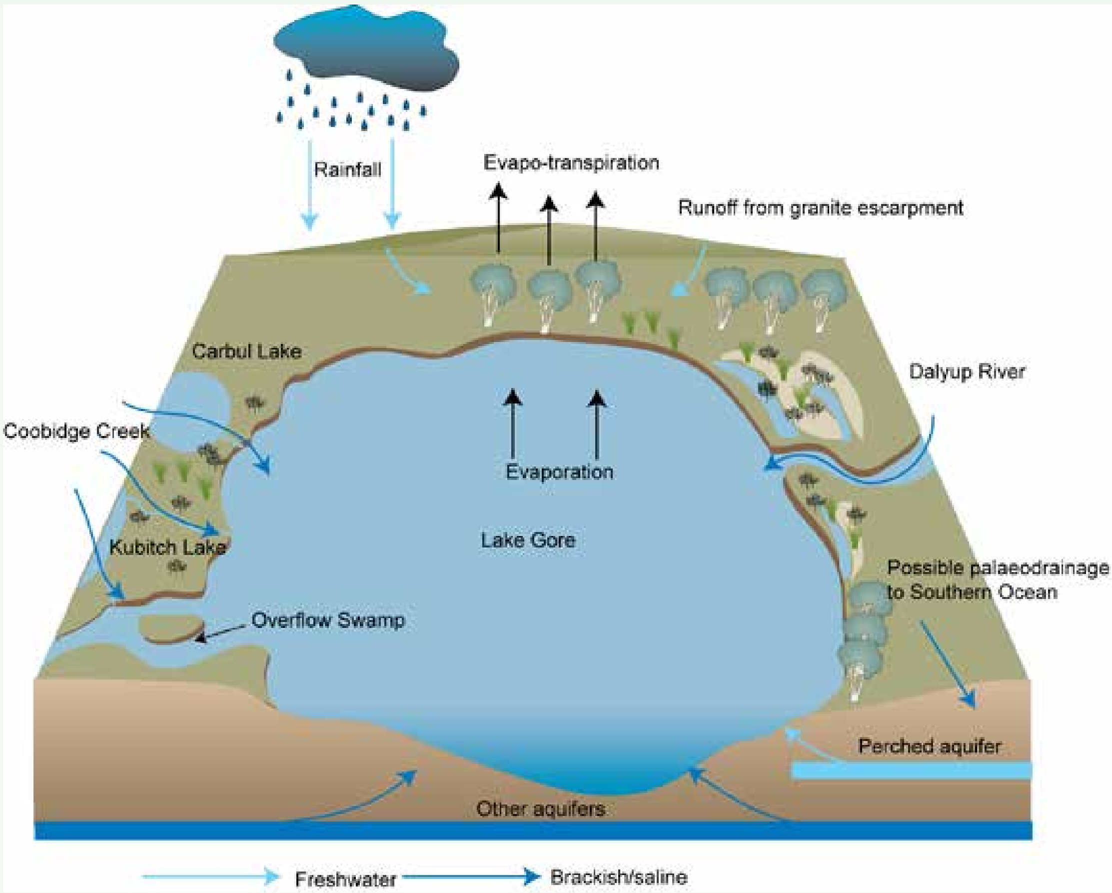

Figure 56. A conceptual model of inputs and outputs of Lake Gore. Image - Watkins (2008).[70]

case study

The hydrology of Lake MacLeod

Lake MacLeod lies approximately 100 kilometres to the north of Carnarvon. It is approximately 120 kilometres long, for most of its length is around 10 kilometres wide and covers an area of approximately 2000 square kilometres.[72] The surface of the lake is normally dry from September to June, though winter or summer rains can result in the lake being wholly or partially covered by surface run-off from the Lyndon and Minilya rivers and other tributaries. Major flooding from the Gascoyne River occurs infrequently, with significant historical flows to the lake occurring in 1960, 1961, 1980, 1995 and 2000. The 2000 flood was the largest recorded over this period with water contributed by all rivers and local rainfall. Most floods occur during the cyclone season (February March) and in mid winter (May June). Surface inflow from the smaller rivers is intermittent and may affect only the vicinity of the river mouths.

In the north west of the normally dry bed of Lake MacLeod lies a unique permanently inundated saline wetland system and its sinkholes and channels which are collectively referred to as the 'Northern Ponds'[72](Figure 57). They are fed by seawater from the Indian Ocean which passes underground through 18 kilometres of coastal limestone and rises up in the site's sinkholes, which are slightly below sea level. Seawater upwelling is continuous, but the discharge rate varies during the day, apparently under influence of twice-daily tides. Consequently the sinkholes, outflow channels and lakes are permanently inundated. Water flows southwards from several main points within the sinkhole network, through a channel system to the main body of water and periodically overflows across a broad mudflat to the terminal wetland. Water discharging from minor sinkholes flows into adjacent saline marshes. Water in the sinkholes may be several metres deep while water in the Northern Ponds system can be in the order of 1 metre in depth.

Figure 57. Part of the permanent 'northern ponds' area of Lake MacLeod. Photo - S Kern/DEC.

SOURCES OF MORE INFORMATION ON WETLAND HYDROLOGY

Websites

Bureau of Meteorology
www.bom.gov.au

Perth Groundwater Atlas Online
www.water.wa.gov.au/ (Tools/Maps and Atlases/Perth Groundwater Atlas)
Shows the depth to water table, groundwater contours and depth of the superficial aquifer and an indication of salinity.

WA Atlas (through the Shared Land Information Portal or SLIP portal)
https://www2.landgate.wa.gov.au/slip/portal/services/wa-atlas.html
Shows mapped wetlands according to geomorphic classification/hydroperiod (choose 'Add layers'>'WMS layers'>'Biology and Ecology').

ABC Science Catchment Detox Game
http://catchmentdetox.net.au/
An interactive online game which shows the impacts of development on catchment condition. The challenge is to repair a damaged river catchment and create a sustainable and thriving economy.

Publications – groundwater investigations

Kimberley

Searle, J.A. (2012). *Hydrogeological record series 57: groundwater resource review Dampier Peninsula*. Department of Water, Perth, Western Australia. www.water.wa.gov.au/PublicationStore/first/101814.pdf

Pilbara

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Midwest

Rutherford, J., Roy, V., and Johnson, S.L. (2005) *Hydrogeological record series 11: The hydrogeology of the groundwater dependent ecosystems in the Northern Perth Basin*. Department of Water, Perth, Western Australia.

South-west

Irwin, R. (2007). *Hydrogeology record series 19: Hydrogeology of the eastern Scott Coastal Plain*. Department of Water, Perth, Western Australia.

GLOSSARY

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Anaerobic: without air (organisms that live in these conditions are 'anaerobes')

Aquiclude: an impermeable body of rock or stratum of sediment that acts as a barrier to the flow of groundwater to or from an adjacent aquifer

Aquifer: a geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water

Aquitard: a low permeability body of rock or stratum of sediment that retards but does not prevent the flow of groundwater to or from an adjacent aquifer

Artesian groundwater: groundwater confined under pressure

Australian height datum (AHD): a fixed survey point from which the elevation of any point in Australia may be measured

Bore: a narrow, normally vertical hole drilled into a geological formation, usually fitted with a PVC casing with slots to allow interaction with the aquifer, to monitor or withdraw groundwater from an aquifer

Catchment: an area of land which is bounded by natural features such as hills or mountains from which all surface run-off water flows down slope to a particular low point or 'sink' (a place in the landscape where water collects)

Confined aquifer: an aquifer deep under the ground that is overlain and underlain by relatively impermeable materials, such as rock or clay, that limit groundwater movement into and out of the aquifer

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi; degradation refers to its physical breakdown. Also known as mineralisation.

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

Discharge wetland: a wetland into which groundwater discharges

Evaporation: the change of liquid water into water vapour in the atmosphere

Evapotranspiration: a collective term for the transfer of water, as water vapour, to the atmosphere from both vegetated and un-vegetated land surfaces

Flow-through wetland: a wetland which receives groundwater inputs in some parts of its area and discharges water to the groundwater in other areas

Geomorphology: landscape features and shape, at various spatial scales

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater capture zone: the area within which any recharge (infiltrating water) eventually flows into the wetland

Groundwater dependent ecosystems: those parts of the environment, the species composition and natural ecological processes of which are dependent on the permanent or temporary presence or influence of groundwater

Groundwater model: a simplified representation of a groundwater system

Groundwater mound: convex regional mounding of the water table in an unconfined aquifer. The top of the mound is where the water table is highest above sea level. Water flows down gradient of this point.

Groundwater table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Headwater wetland: a wetland at the top of the wetland chain where water originates

Hydraulic conductivity: a property of plant material, soil or rock that describes the ease with which water can move through pore spaces or fractures. It depends on the permeability of the material and on the degree of saturation.

Hydrogeology: the distribution and movement of groundwater

Hydrology: the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere

Hydroperiod: the periodicity (permanent, seasonal, intermittent) of waterlogging or inundation of a wetland

Impermeable: does not allow water to move through it

Infiltration: the downward movement of water into the soil profile via spaces between soil particles (called pores) and cracks and fractures in the ground

Interception: occurs when rainfall that falls over an area is captured on the surface of vegetation (foliage, stems, branches, trucks or leaf litter). This water may evaporate to the atmosphere or falling to the ground (throughfall).

Interflow: shallow lateral subsurface flow of water, which moves nearly parallel to the soil surface, usually in response to a layer of soil that impedes percolation

Intermittent: present for variable periods with no seasonal periodicity

Inundation: where water lies above the soil surface (also called surface ponding)

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Obligate wetland plant: generally restricted to wetlands under natural conditions in a particular setting

Observation bore: a non-pumping well with a long slotted section that crosses the water-table

Palaeochannel: a channel formed by a palaeoriver (ancient river), infilled with deposited sediments and buried over time, often forming modern-day groundwater aquifers

Paluslope: a seasonally waterlogged slope wetland

Peat: partially decayed organic matter, mainly of plant origin

Perched: not connected to groundwater

Perched aquifer: a local aquifer close to the land surface that receives direct recharge from rainfall, but is above and disconnected from the regional unconfined aquifer

Percolation: flow of water down through soil, sediments or rocks without these being completely saturated

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Physiochemical environment: the physical and chemical environment

Piezometer: a non-pumping well, with a short length (often 2 metres) of slotted section at the base often below the water table, which is used to measure the potentiometric surface

Rainfall: a product of the condensation of atmospheric water vapour that is deposited on the Earth's surface.

Primary production: the production of organic compounds from atmospheric or aquatic carbon dioxide, principally through the process of photosynthesis, with chemosynthesis being much less important

Recharge: the physical process where water naturally percolates or sinks into a groundwater basin

Recharge area: the land surface area over which recharge occurs to a particular groundwater aquifer

Recharge wetland: a term used by geologist to describe wetlands from which water flows out of into the groundwater, 'recharging' it

Salinity: measure of the concentration of dissolved salts

Saturated: the state in which all available spaces are filled with water

Seasonal: present during a given period of the year, recurring yearly

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

Semi-confined aquifer: an aquifer deep under the ground with leaky aquitards

Shallow aquifer: another term for unconfined aquifer

Superficial aquifer: another term for unconfined aquifer

Surficial aquifer: another term for unconfined aquifer

Surface run-off: water that flows down slope over the ground surface; also called overland flow

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Tannins: complex organic compounds derived from plant materials

Terminal wetland: a wetland at the bottom of the wetland chain. It receives water from other systems but water generally does not exit it other than through evaporation or seepage into the ground (or occasional flooding overflow in large events)

Throughflow wetland: a wetland that lies between headwater wetlands and terminal wetlands (or the sea) in a wetland chain. It receives water from upgradient wetlands and supplies water to downgradient wetlands.

Transpiration: the process by which water (in the form of water vapour) is lost to the atmosphere by plants across the surfaces of leaves (through small openings called stomata). Transpiration drives the movement of water from the roots to the leaves and is the primary process by which water is lost from subsurface soils to the atmosphere.

Tufa: a porous rock composed of calcium carbonate and formed around mineral springs

Tumulus mound spring: peat-formed mound spring

Unconfined aquifer: an aquifer close to the land surface which receives direct recharge from rainfall. Its upper surface is the water table. Also referred to as a superficial or surficial aquifer.

Water budget: the balance of all of the inflows and outflows of water

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from sediment pore waters of inundated and waterlogged wetlands)

Water cycle: Continual circulation of water between the land, the oceans and the atmosphere. Also called the hydrological cycle.

Waterlogged: saturation of the soil

Water regime: the specific pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Water table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Wetland hydrology: is generally used to refer to the movement of water in and out of, and within a wetland

PERSONAL COMMUNICATIONS

Name	Date	Position	Organisation
Jim Lane		Principal Research Scientist	Department of Environment and Conservation

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A guide to managing and restoring wetlands in Western Australia

Conditions in wetland waters

In Chapter 2: **Understanding wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Conditions in wetland waters' topic

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Recommended reference

When referring to the guide in its entirety, the recommended reference is: Department of Environment and Conservation (2012). *A guide to managing and restoring wetlands in Western Australia*. Department of Environment and Conservation, Perth, Western Australia.

When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Conditions in wetland waters', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by L Sim, Department of Environment and Conservation, Perth, Western Australia.

Disclaimer

While every effort has been made to ensure that the information contained in this publication is correct, the information is only provided as a guide to management and restoration activities. DEC does not guarantee, and accepts no liability whatsoever arising from, or connected to, the accuracy, reliability, currency or completeness of any material contained in this guide. Much of the material in this topic was compiled prior to 2009. New information on this subject between the compilation date and publication date has not been captured in this topic.

Contents

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Physico-chemical: relating to physical chemistry. In this guide, used in reference to the physical and chemical characteristics of wetland waters.

INTRODUCTION

The natural physical and chemical conditions in wetland waters significantly influence the characteristics of wetlands, including the living conditions for plants, animals and microbes that live in or visit them. These conditions determine the ability of these organisms to produce or seek out energy sources, and to get, or be exposed to, suitable amounts of light, oxygen, salts, heavy metals and other important substances from water and sediment.

Important physical and chemical conditions in wetland waters include:

- light availability (including shade, turbidity and colour)
- water temperature
- dissolved oxygen
- salinity, conductivity and ionic composition
- stratification
- acidity/alkalinity
- redox potential
- carbon
- nitrogen
- phosphorus
- sulfur

These conditions are an important determinant of a wetland's **ecological character**. The natural variety in these conditions amongst wetlands contributes to the diversity of WA wetlands and their biodiversity.

In order to manage a wetland, whether it is relatively natural or altered, it is important to understand these physical and chemical conditions and the processes driving them.

➤ Managers of wetlands with altered wetland conditions will find this topic a useful foundation for management techniques outlined in the topics 'Water quality' and 'Secondary salinity' in Chapter 3.

The physical and chemical characteristics of a wetland are often referred to as its '**physico-chemical environment**'. The way in which the physico-chemical environment interacts with other aspects of a wetland is illustrated in Figure 1.

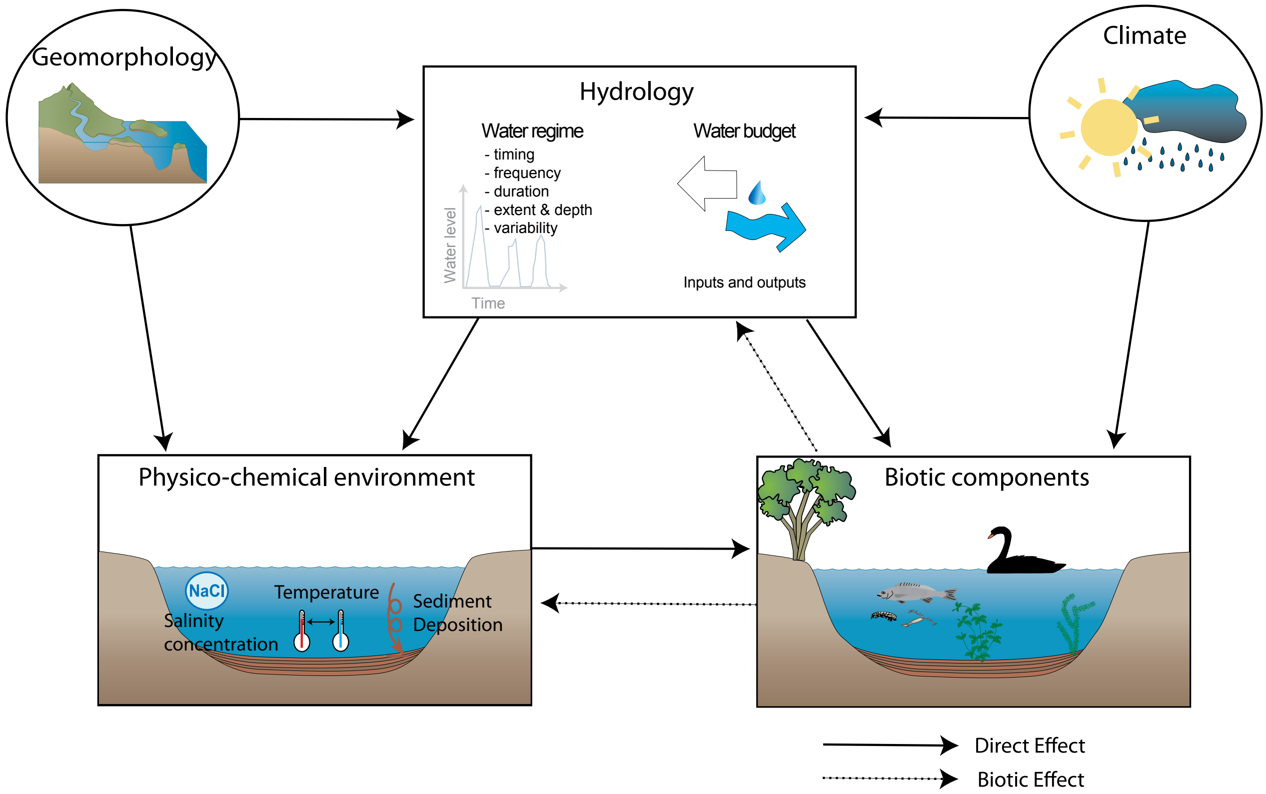

Figure 1. The physico-chemical environment has an important effect on the living conditions of a wetland (adapted from Mitsch and Gosselink 2007).[1]

The plants, animals and **microbes** of a particular wetland are adapted to specific chemical and physical conditions, which can be critical to their ability to survive, grow and reproduce. They may not be able to adjust readily if these conditions change. For example, if water salinity levels get too high, many freshwater wetland plants and animals can no longer survive, or if dissolved oxygen levels become too low, animal deaths such as fish kills may result.

The physico-chemical conditions of wetland waters vary naturally. As shown in Figure 1, this is due to a wetland's hydrology and setting, which influences the types and qualities of inflow waters and whether the wetland holds water on a permanent, seasonal or intermittent basis. It is also influenced by plants, animals and microbes that inhabit the wetland, for example, the composition and structure of the vegetation in and surrounding the wetland. Changing any of these factors can alter the physical and chemical characteristics of wetland waters.

In this topic, two main types of wetland waters are referred to:

- those with free standing **water columns**, which are present in wetlands subject to inundation – these water columns can be either permanently present (in lakes), seasonally present (in sumplands) or intermittently present (in playas and barlkarras) (Figure 2a, c)
- **sediment pore water** (also called interstitial waters) – water which is present in the spaces between sediment grains at or just below the surface and occur in all wetland types including those that are only subject to waterlogging but not inundation, and therefore never develop a distinct water column (in damplands, palusplains, paluslopes and palusmonts) (Figure 2b, d).

Microbe: an organism that can be seen with a microscope, including bacteria and fungi

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from sediment pore waters of inundated and waterlogged wetlands)

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

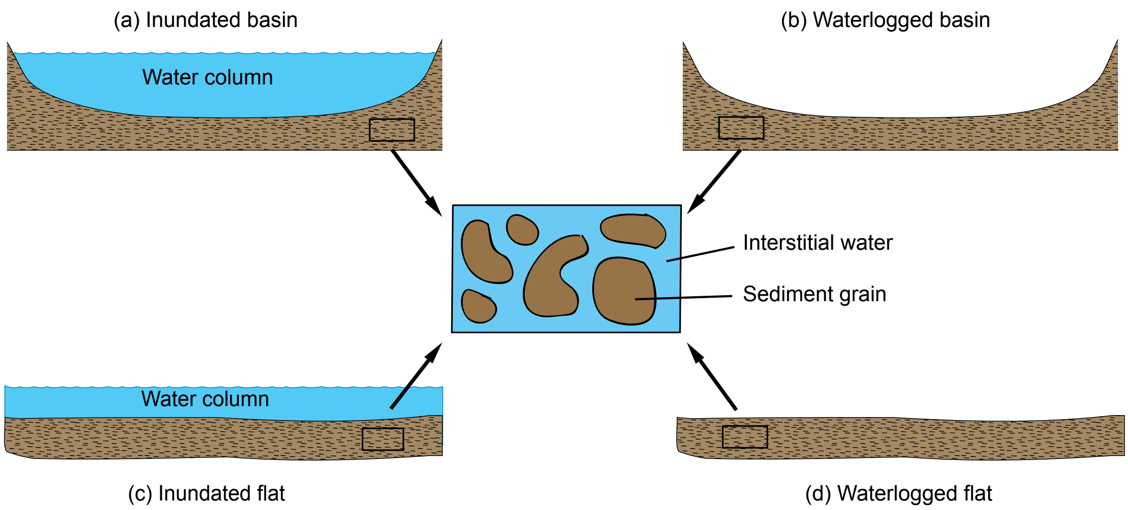

Figure 2. Water columns and sediment pore waters of different types of wetlands: (a) inundated basins; (b) waterlogged basins; (c) inundated flats; and (d) waterlogged flats (also applicable to slopes and highlands). Image – J Higbid/DEC.

Wetland pore waters and the solid **sediments** the pore waters surround are closely related but may have quite different chemistries. Substances that are very **soluble** may end up in pore waters, while some substances will be attached to (adsorbed on to) sediment particles. This topic focuses on the conditions occurring in wetland water columns and pore waters, but in some cases, where conditions in pore waters are most strongly influenced by those in the sediments, or where a parameter is commonly measured in the sediments rather than the pore waters, some discussion of sediments is also included.

Sediment: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology

Soluble: able to dissolve

The characteristics of pore waters and sediments can be more difficult to measure than those of the water column, and therefore they tend to be sampled less often. Consequently, recognised and feasible methods for the characterisation of waterlogged wetland types such as damplands and palusplains may not be available. Despite this, an effort to summarise approaches for the sampling and measurement of both water column and pore waters have been described, except where sampling techniques are very complex or expensive. More detailed descriptions of sampling techniques are presented in the topic 'Monitoring wetlands' in Chapter 4.

Water column chemistry, and less commonly the chemistry of sediment pore waters, is used to measure the condition of wetlands and to monitor their state or characteristics over time. Understanding the physical and chemical conditions in wetland waters and the way they vary between wetland types is critical to understanding how the ecosystem operates and how to restore or rehabilitate degraded wetlands. Effective management or restoration of wetland ecosystems is not possible without an understanding of what these physical and chemical conditions mean and how they interact.

The following sections describe some of the key chemical and physical characteristics of natural wetland waters and the factors that influence these characteristics in Western Australian wetlands.

Sources of general information on wetland water characteristics

ANZECC & ARMCANZ (2000) '8.2 Physical and chemical stressors in Volume 2 Aquatic ecosystems — rationale and background information (Chapter 8)' of *Australian and New Zealand guidelines for fresh and marine water quality*.[2]

Boulton A and Brock M (1999) *Australian freshwater ecology: processes and management*.[3]

Chambers J, Davis J and McComb A (2009) 'Inland aquatic environments – wetland diversity and physical and chemical processes' in *Environmental Biology*.[4]

Davis J et al. (1993) *Wetlands of the Swan Coastal Plain Volume 6 'Wetland classification on the basis of water quality and invertebrate data*.[5]

Wrigley T, Rolls S and Davis J (1991), 'Limnological features of coastal-plain wetlands on the Gnangara Mound, Perth, Western Australia' in *Australian Journal of Marine & Freshwater Research*.[6]

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1. Mitsch, WJ and Gosselink, JG (2007). *Wetlands*, 4 edn. John Wiley & Sons, Inc, New York, USA.

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6. Wrigley, TJ, Rolls, SW, and Davis, JA (1991). 'Limnological features of coastal-plain wetlands on the Gnangara Mound, Perth, Western Australia', *Australian Journal of Marine & Freshwater Research*, vol. 42, pp. 761-773.

LIGHT AVAILABILITY (INCLUDING SHADE, TURBIDITY AND COLOUR)

Contents of the 'Light availability' section

What is meant by light availability in wetlands?

Light availability is considered in terms of the quality, quantity and timing of light reaching wetland waters. Light availability in aquatic ecosystems is quite different to that of terrestrial systems, because once light reaches wetland waters it is rapidly altered and reduced, so that both the quality and quantity of light available is quite different to what first reached the surface of the water. Light availability is really only an important parameter in wetland water columns, since it is only able to penetrate to 0.2–2 millimetres into the sediments.[1]

Why is light availability important in wetlands?

Light plays several critical roles in wetland ecosystems. It is the primary source of energy that is captured, assimilated and flows through wetland food webs, and is also the major source of heat.[2] The availability of light therefore influences the degree to which these modes of energy capture and heat transfer can occur, and this controls the productivity of the ecosystem, and the suite of **metabolic** processes taking place in it.[2]

Photosynthesis

Light is critical for **photosynthesis**; the process of energy capture by 'primary producers': photosynthetic algae, plants and some bacteria. Plants and photosynthetic algae and bacteria contain light-capturing pigments within their cells (such as the chlorophylls) which use the energy from light to generate biochemical energy and to convert carbon dioxide and water to carbohydrates.[3] This process directly or indirectly supports the rest of the wetland food chain through its conversion to **biomass**, as a food source for secondary consumers (herbivores), as food for the predators that feed on the lower order consumers, and ultimately for the detritivores that break down and decompose dead organic matter (as described in the topic 'Wetland ecology' in Chapter 2). Some wetlands, usually those in 'extreme' environments (such as very high temperature, very acidic) are driven by 'chemosynthesis' (a process of energy capture that does not rely on light) rather than photosynthesis, but this is much less common.[2]

The 'euphotic' zone of wetlands (Z_{eu}) is the section of a water mass that is penetrated by light of sufficient intensity and of suitable wavelength to enable photosynthesis by aquatic plants. It approximates the minimum light intensity required for photosynthesis and is delineated by the depth to which 1 per cent of the surface incident light can penetrate[4,5] (Figure 3). It is also known as the 'photic zone'.

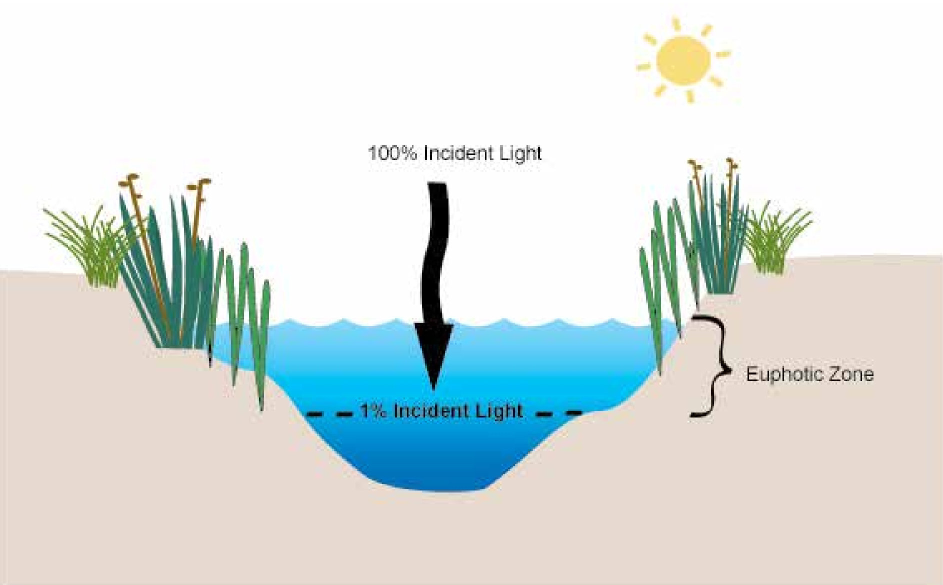

Figure 3. The euphotic zone of an inundated wetland.

Metabolic: the processes occurring within a living organism that are necessary to maintain life

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Biomass: the total quantity or weight of organisms in a given area or volume

Heat

The role that solar radiation plays in providing heat to wetland waters is also critical to wetland ecosystem function, since infra-red radiation, together with visible light (both from the sun), are the primary sources of heat to wetlands.[3,2] This radiation warms wetland waters and can control wetland ecology directly, for example by influencing which species can occur in an ecosystem (due to physiological tolerances, the limits on an organism's ability to function), and the rate at which metabolic processes (such as enzyme activity) are able to occur (see 'Temperature' in this topic for more information). In addition to its direct effects on organisms, water temperature also influences many other physico-chemical parameters including dissolved oxygen and pH (see 'Dissolved oxygen' and 'pH' in this topic for more information).

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

Epiphyte: a plant or algae that grows upon or attached to a larger, living plant

What are acceptable levels of light availability in Western Australian wetlands?

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[4] (known as 'the ANZECC guidelines' in reference to the author institute) **trigger values** for light in wetlands are focused on the depth of the euphotic zone (depth to which photosynthesis can occur), rather than the quality of light. They recommend that where reference information on the wetland (or a similar site) exists, that the euphotic zone depth should not change by more than 10 per cent.[4] Trigger values for turbidity and colour are addressed later in this section.

What affects the light availability in wetland waters and how variable is it?

Four of the major factors involved in controlling the amounts and type of light that is able to penetrate wetland waters are:

- geographic location of the wetland and time of year
- the amount of shading of/in the wetland
- the level of water turbidity (caused by suspended particles including algae)
- the 'colour' of the water.

The availability of light within an aquatic system is a product of these combined factors and varies between geographic regions, wetland types, and over time, and is influenced strongly by land use and degrading processes occurring at or near wetlands.

Geographic location and time of year

The incidence of light to wetlands varies depending on latitude and season, as both of these factors affect the sun's angle relative to the earth, and therefore alter the amount of radiation reaching wetlands.[2] The large size of WA means that it covers a wide range of latitudes, and different regions are subject to different amounts of solar radiation as a result. Light availability to wetlands also varies dramatically over a 24 hour cycle.[3]

Shading

Shading of wetland waters can occur both from within and outside a wetland, and is not always facilitated by large objects or organisms such as shrubs or trees (Figure 4a); for example, shading of submerged wetland plants by **epiphytic** (attached to the plant surface) microalgae (Figure 4b). This can cause aquatic plant decline by decreasing the amount of light reaching the plant's photosynthetic pigments.[6] Floating wetland vegetation (such as waterlilies, *Nymphaea*; duckweed *Lemna*; floating fern, *Azolla*) can also greatly reduce or almost eliminate the penetration of light into the wetland (Figure 4c). Almost all wetland vegetation and **planktonic** organisms shade the **benthic** (bottom) areas of wetlands, reducing the light available for photosynthetic benthic microbes[7] and low-growing wetland vegetation. Algal blooms are one of the most well-known and problematic forms of shading in wetlands with a water column (Figure 4d).

Plankton: aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location, such as phytoplankton (photosynthetic plankton including algae and cyanobacteria) and zooplankton (animals)

Benthic: the lowermost region of a wetland water column

Phytoplankton: photosynthetic plankton including algae and cyanobacteria

(a) overstorey vegetation

(b) epiphytes on *Vallisneria australis* (an introduced macrophyte)

(c) floating macrophyte *Azolla filiculoides*

(d) phytoplankton bloom (North Lake)

Figure 4. Shading of wetland waters. Photos - (a) J Higbid/DEC, (b) P Novak, (c) C Prideaux/DEC and (d) J Davis.

The primary effects of shade on wetland waters are:

- a decrease in the amount of light reaching underlying waters
- a change in the dominant wavelengths of available light (particularly if the wetland is being shaded by wetland vegetation as opposed to inorganic objects such as rocks or buildings)
- a lowering of the temperature of receiving waters.[8,9,2]

The reduction of light and alteration of dominant wavelengths caused by shading means that the more shaded the environment, the more that surface-dwelling organisms (such as floating wetland vegetation and **phytoplankton**) are advantaged, and conversely, the more benthic (bottom)-dwelling organisms (such as many submerged wetland vegetation species or microalgae) are disadvantaged.

Turbidity

The availability of the light penetrating into wetland waters also depends on the amounts and types of substances present in the water to absorb or reflect it.[3] Suspended **particulate** materials have a major influence on light availability as they can change both the scattering and absorption of light.[2] The cloudy appearance of water (turbid water) can be caused both by suspended inorganic (non-biological) particles such as sediment, or by biological materials such as phytoplankton.[10] Varying degrees of inorganic **turbidity** occurs naturally in many Australian wetland systems.[5] In some ecosystems in WA such as claypans, high turbidities occur naturally almost all of the time because of the clay soils (Figure 5a). '**Biogenic**' turbidities, such as phytoplankton blooms, are more commonly an effect of human-induced change to wetlands through increased nutrient loading (Figure 5b). Many introduced species of animals promote turbid conditions. Feral pigs like to wallow in water in hot weather, livestock stir up the sediment when drinking and cooling off, and carp and goldfish vigorously stir up sediment while feeding. Fire can also increase turbidity in the short term in catchments where burning of vegetation is followed by a large increase in catchment erosion.[11]

Particulates: in the form of particles (small objects)

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Biogenic: produced by organisms

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

(a) (b)

Figure 5. Turbid wetland waters: (a) inorganic (sediment/particle) turbidity (b) biogenic (biological/algal) turbidity. Photos - L Sim.

High turbidities have a number of effects on the light environment in wetland ecosystems, and these effects are closely related to shading. Turbidity restricts growth of wetland vegetation by decreasing the amount and quality of light available for photosynthesis. Due to the different photosynthetic adaptations to light and shade of different plant and algal species, high levels of turbidity or shade can change species dominance, especially in phytoplankton. For example, **cyanobacteria** are quite often moderately shade-tolerant, and are also problem species in algal blooms due to the toxins produced by many species.[5] On the other hand, aquatic plants that grow close to the sediment can be severely disadvantaged by turbid conditions.

In addition to the effects on photosynthesis, high turbidities reduce the ability of visual predators to see prey, and therefore may also change habitat use by prey animals, since they no longer need to seek shelter to avoid visual detection.[12] For example, the naturally high turbidity of many claypans in the Avon region protects tadpoles and crustaceans such as clam shrimp, fairy shrimp and shield shrimp from predation by waterbirds, so these wetlands are particularly important for these animals[13] (Figure 6). The Wheatbelt frog, *Neobatrachus kunapalari*, mates in milky pools (Figure 7) in which the resulting tadpoles are usually hidden from view.

Figure 6. Shield shrimp in turbid water in Miamoon Lake, near Wubin in the northern Wheatbelt.

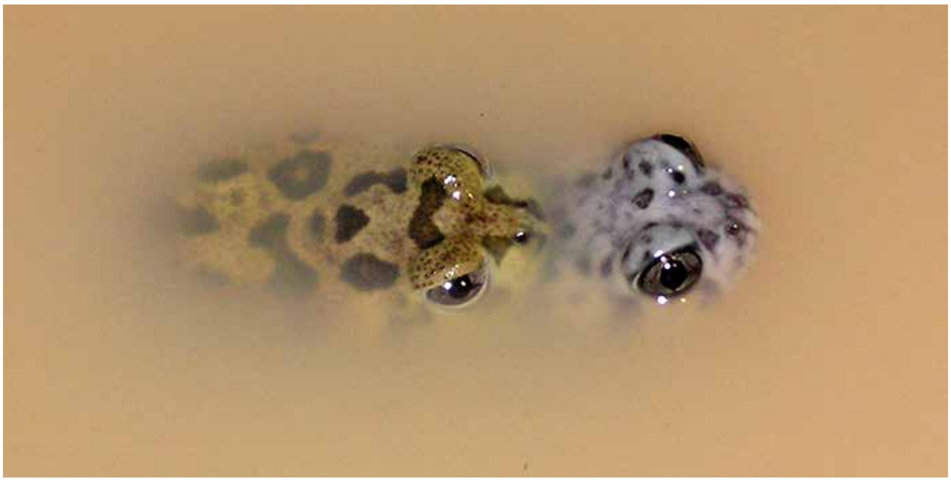

Figure 7. Turbid pools provide protection for tadpoles of the Wheatbelt frog, *Neobatrachus kunapalari*. Photo – courtesy of FrogWatch http://frogwatch.museum.wa.gov.au/

The low light conditions caused by high turbidities may prevent the establishment of bottom-dwelling (benthic) communities (for example, submerged wetland vegetation, benthic microbes), or lead to the loss of previously-established communities. This can often lead to 'positive feedback loops' in which sediments are not consolidated by benthic communities, leading to further turbidity and so on (Figure 8). This continual resuspension of inorganic sediments can also lead to elevated water column nutrient levels, since nutrients in the sediments are constantly resuspended, and sequestration (taking up) by rooted plant material does not occur. This feedback process forms part of the mechanism for maintaining a 'turbid, phytoplankton-dominated state'.

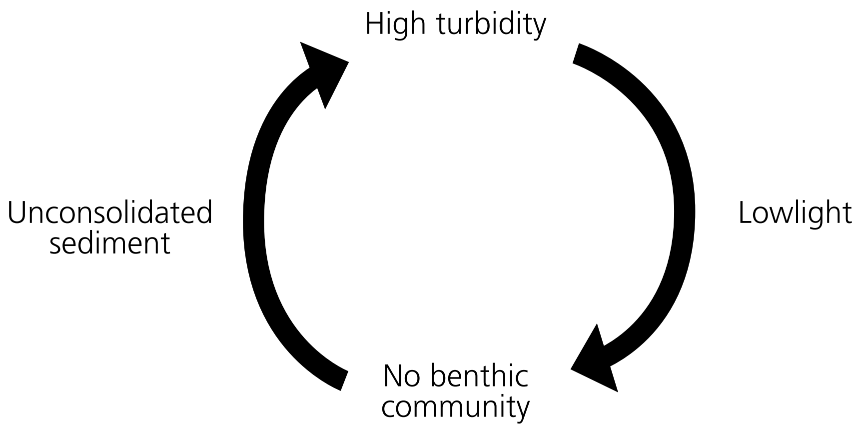

Figure 8. Feedback loop promoting turbid conditions in wetlands. Image – M Bastow/DEC.

Turbidity caused by human-induced processes can have additional effects on ecosystems beyond its influence on light, such as the increased sedimentation of benthic surfaces and organisms.

➤ For more information on human-induced sedimentation and siltation, refer to the topic 'Water quality' in Chapter 3.

Colour: the concentration of dissolved organic materials and dissolved metals in water

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Guidelines for turbidity in Western Australian wetlands

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[4] (known as 'the ANZECC guidelines' in reference to the author institute) provide very broad ranges for turbidity (Table 1) and include the following explanatory text:

'Most deep lakes and reservoirs have low turbidity. However, shallow lakes and reservoirs may have higher turbidity naturally due to wind-induced resuspension of sediments. Lakes and reservoirs in catchments with highly dispersible soils will have high turbidity. Wetlands vary greatly in turbidity depending upon the general condition of the catchment or river system draining into the wetland and to the water level in the wetland.'

Table 1. Default trigger values for turbidity (risk of adverse effects) from ANZECC & ARMCANZ.[4]

Ecosystem type	Nephelometric turbidity units (NTUs)	
Tropical Australia	**Lower limit**	**Upper limit**
Wetlands	2	200
South-west Australia		
Wetlands	10	100

Figure 9. During a 2009 study, Lake Guraga near Cataby was found to have elevated turbidity levels (290 NTU) attributed to suspension of clay sediments by wind.[14] Photo – G Daniel/DEC.

Colour

When used in reference to wetland waters, the term '**colour**' has a more specific meaning than its everyday meaning. It is used to refer to dissolved substances that impart colour to wetland water, rather than other sources of colour such as phytoplankton blooms.[15] Most commonly it refers to dissolved organic materials such as humic and fulvic acids derived from plant material that in high concentrations can impart a yellow or tea colour to wetland waters[16] (Figure 10). **Humic** substances are formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials.[17] However, water 'colour' technically refers to more than dissolved organic materials and also includes dissolved metals such as iron, manganese and copper.[18]

Figure 10. A groundwater-fed wetland near Yarloop in the south west of WA. The water is highly coloured and has a pH of around 5, due to the concentration of tannins (humic acid). Photo - M Morley/DEC.

Colour plays another important role in the availability of light in wetland waters. The presence (particularly in high concentrations) of humic materials or dissolved metals in wetland waters affects which wavelengths of light are able to penetrate to deeper waters (humic materials absorb light at the blue end of the spectrum[3], and also reduces the total incidence of light reaching aquatic photosynthesisers[5,3]). This reduced photosynthetic capability has led coloured systems to be referred to as 'dystrophic' (compare with the terms 'oligotrophic', 'mesotrophic' and 'eutrophic') in indicating that instead of supporting increased algal and plant growth as nutrient levels increase, they are able to suppress this production, even at high nutrient levels, due to light inhibition.[19] This natural suppression can be altered by clearing of wetland and surrounding dryland vegetation, which reduces the input of organic material into the wetland. Clearing of vegetation that provides shade can also speed up the chemical breakdown of humic substances. Many humic substances may be susceptible to chemical breakdown caused by UV light, called 'photodegradation' or 'photo-oxidation', which is likely to occur more quickly in shallow wetlands.[2]

Coloured water does not appear to occur in saline systems although the reasons for this are unclear.[20,2]

Guidelines for colour in Western Australian wetlands

Levels of colour vary naturally depending on the type of wetland. Researchers have proposed that the wetlands on the Swan Coastal Plain are considered 'coloured' beyond 52 g_{440}/m (gilvin).[20] Given the natural variation, the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[4] (known as 'the ANZECC guidelines' in reference to the author institute) have not published guidelines for 'acceptable' levels of colour in wetland waters.

How is light availability measured, and what units are used?

Many different aspects of 'light' in wetland water columns can be measured including clarity, wavelength, irradiance, reflectance, absorbance (including colour), and each of these factors provides different information about the light climate.[16] The most commonly measured parameters are clarity (including turbidity), irradiance and colour.

Figure 11. A Secchi disk being lowered into water. Photo – DEC.

Clarity or visibility is often measured using a Secchi disc (Figure 11). This is a simple technique and can quickly provide an estimate of the depth (in metres) of the euphotic zone (the zone within which photosynthesis occurs), since Z_{eu} is approximately equal to three times the Secchi depth.[5] In highly turbid or coloured lakes, the photic zone may be very small (not far below the surface of the water).

Another surrogate for water clarity is turbidity, which measures the extent to which light is scattered and reflected by particles suspended or dissolved in the water column. A water sample is taken and the light penetration through the sample is measured using a turbidity meter.[21] Turbidity is measured in 'nephelometric turbidity units' (NTU) or the roughly equivalent 'formazine turbidity units' (FTU) (depending on the type of calibration used).

Total suspended solids (TSS) can also be measured by filtering a water sample through filter paper to determine the weight of sediment per unit volume of water.[15]

The amount of light available at different water column depths is usually measured as irradiance ('radiant flux' per unit area) with a light meter.[3] Irradiance is used to calculate the depth of the euphotic zone. This is a more accurate means of determination than Secchi disk depth. Light meters are expensive and accurate readings can be difficult to obtain, since they are affected by wave action, clouds and other shading.[3]

Water colour can be measured in a number of different ways, depending on which component of colour is perceived to be most important in a particular wetland. 'Gilvin' measures the absorbance of light by humic substances at a wavelength of 440 nm (after filtration through a 0.2 µm filter) and is expressed in units of g_{440}/m (absorbance at 440 nanometres per metre). However a more comprehensive standard measure of colour (which includes the influence of other dissolved substances such as iron) is 'true colour' (measured in true colour units, TCU).[18] The pH of the water may influence the colour of the sample, therefore pH should be recorded at the same time as TCU.[18] Measurements in gilvin cannot be converted to true colour units (or vice versa), because the two measures account for different suites of dissolved substances and therefore do not represent the same thing.

➤ For more information on monitoring transparency, colour, turbidity and suspended solids in wetlands, refer to the topic 'Monitoring wetlands' in Chapter 4.

Sources of more information on light availability in wetlands

ANZECC & ARMCANZ (2000) '8.2 Physical and chemical stressors in Volume 2 Aquatic ecosystems — rationale and background information (Chapter 8)' of *Australian and New Zealand guidelines for fresh and marine water quality*.[4]

Kirk, JTO (1994) *Light and photosynthesis in aquatic ecosystems*. 2nd edition.[3]

Water on the Web (2004) 'Water on the Web, monitoring Minnesota lakes on the internet and training water science technicians for the future, a national on-line curriculum using advanced technologies and real-time data'.[10]

Wetzel, R (2001) *Limnology. Lake and river ecosystems.*[2]

Glossary

Benthic: the lowermost region of a wetland water column

Biogenic: produced by organisms

Biomass: the total quantity or weight of organisms in a given area or volume

Colour: the concentration of dissolved organic materials and dissolved metals in water

Coloured wetlands: wetlands with dissolved organic materials and dissolved metals; on the Swan Coastal Plain, nominally those wetlands with more than 52 g_{440}/m (gilvin)

Dystrophic: wetlands that suppress increased algal and plant growth even at high nutrient levels due to light inhibition

Epiphyte: a plant or algae that grows upon or attached to a larger, living plant

Euphotic zone: (also known as the 'photic zone' and 'photozone') the section of a water mass penetrated by light of sufficient intensity and of suitable wavelength to promote photosynthesis by aquatic plants

Gilvin: a measure of the absorbance of light by humic substances at a wavelength of 440 nm (after filtration through a 0.2 μm filter), expressed in units of g_{440}/m (absorbance at 440 nanometres per metre)

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Metabolic: the processes occurring within a living organism that are necessary to maintain life

Particulates: in the form of particles (small objects)

Photodegradation: chemical breakdown caused by UV light

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Phytoplankton: photosynthetic plankton including algae and cyanobacteria

Plankton: aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location, such as phytoplankton (photosynthetic plankton including algae and cyanobacteria) and zooplankton (animals)

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

True colour: a measure of colour which includes the influence of humic substances and other dissolved substances such as iron, measured in true colour units (TCU)

Turbid: the cloudy appearance of water

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

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WATER TEMPERATURE

Contents of 'Water temperature' section

What is meant by water temperature?

'Water temperature' refers to the *in situ* (field) temperature of wetland waters (usually surface waters) and is usually measured in degrees Celsius (°C).

Why is water temperature important in wetlands?

Water temperature is critical to the survival and functioning of wetland plants, animals and microbes as:

- it directly affects **metabolism**
- higher temperatures can be fatal, while low temperatures may slow physiological (mechanical, physical, and biochemical) processes
- temperature may be a cue for spawning or reproduction.[1]

The low temperatures experienced in Western Australian wetlands are unlikely to be lethal, although they can have more severe effects in areas of the world in which wetlands freeze over winter. Instead, the high temperatures that wetland waters may reach in the Western Australian arid zone are of more concern. As is the case for many physical or chemical parameters, the tolerance limits of plants and animals to different water temperature ranges may depend on their life stage, with juveniles often being more susceptible to large changes than adults.[2]

In addition to the direct effects on **organisms**, water temperatures also significantly influence chemical processes in the wetland, such as oxygen solubility[3], leading to secondary impacts on the plants, animals and microbes of wetlands (for more information see the 'Dissolved oxygen' section of this topic). The activity of microbes is directly influenced by temperature, which in turn has a critical effect on **biogeochemical** processes.[4,5] Its strong influence on other physico-chemical parameters means that water temperature must be measured to allow accurate determination of factors such as pH, electrical conductivity (EC) or dissolved oxygen (DO).[6,7]

The ecological effects of natural temperature changes can be quite dramatic if a wetland is also suffering from other kinds of degradation, for example, warm water temperatures during low rainfall season in nutrient enriched wetlands are likely to lead to an increased chance of algae growing to nuisance proportions (algal 'blooms').

What is the natural temperature range of wetlands in Western Australia?

Due to the variability in temperatures across seasons, times of day and with water level, even within the one wetland, it is difficult to set acceptable ranges for wetlands with regard to temperature. No specific guidelines for acceptable changes in water temperature exist for Australian wetlands. The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (known as 'the ANZECC guidelines' in reference to the author institute)[4] water quality guidelines state that:

'…salinity, pH and temperature are three toxic direct-effect stressors that are naturally very variable among and within ecosystem types and seasonally, and natural biological communities are adapted to the site-specific conditions. This suggests that ***trigger values*** *for these three stressors may need to be based on site-specific biological effects data.'*

The ANZECC guidelines suggest that where reference information is available, temperatures should not drop below the 20th percentile (bottom 20 per cent of values) or rise above the 80th percentile (top 20 per cent of values), based on seasonal data.[4]

Metabolism: the chemical reactions that occur within living things that are necessary to maintain life, including the digestion of food

Organism: an individual living thing

Biogeochemical: the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment, and in particular, the cycles in which material is transferred between living systems and the environment

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

What affects the temperature of wetland waters and how variable is it?

The natural factors that can affect the temperature of wetland waters include:

- change in air temperature over the 24 hour day/night cycle
- seasonal changes in temperature (particularly in temperate areas of the state)
- changes in water level.

These are discussed below. The temperature of wetland water can also be affected by human activities including thermal pollution, clearing of wetland vegetation or clearing of vegetation of waterways that feed into a wetland, and global climate change.

➤ Human-induced changes in temperature and their management are discussed in the topic 'Water quality' in Chapter 3.

Much of the warmth of wetland waters originates from solar energy, and is derived from the infrared portion of the sun's rays being absorbed by the water itself and the suspended and dissolved material it contains.[8,3] Water temperature is also affected by ambient air temperature.[9] Solar inputs also vary greatly over the daily 24 hour cycle, with wetland waters warming during the day, and cooling at night.[10]

During the day (and during the warm season(s) of the year) the water column warms up and may either form layers (see the 'Stratification' section in this topic) or be mixed (usually by wind). Regular mixing prevents the surface layers from becoming too warm, and allows bottom layers to increase in temperature, but even without the development of distinct stratification, the water is often warmest at the top of the water column.

Daily temperature fluctuations are greatest in the top layers of the water column or **sediment pore waters** (if the sediments are exposed). In contrast to water columns, sediment pore waters remain largely unmixed, causing temperatures to be different in deep versus surface sediments. Sediment pore water temperatures stabilise quickly with depth and daily 24 hour fluctuations are very small below the top 50 centimetres of sediment.[11] Temperature changes in sediment pore waters may be buffered further if there is a layer of surface water on top of the sediments.

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

Water temperature and related parameters (including pH, dissolved oxygen, salinity) all change markedly with wetland water level, partly because temperature varies more widely when water levels are low.[6] When the volume of water is smaller, its capacity to absorb energy is reduced, and it heats and cools more rapidly. The presence of dissolved (for example, tannins) or suspended material in the water column increases the absorption of heat.[3] In seasonally-drying wetlands, the annual drying phase can lead to extremely high water temperatures and the yearly decline of plants and animals.[6] Low temperatures could cause slowing of processes and inhibition of reproduction in some cases (such as occurs in many wetland plants). The temperature of most WA waters would not often drop below 0°C, so freezing is not commonly an issue.

Temperature interacts with other aspects of climate (for example, rainfall and evaporation) and geology to determine the dominant physical conditions within wetlands.

How is water temperature measured, and what units are used?

Water temperature can be measured both in water columns and in sediment pore waters, but it is not often measured in wetland sediment pore waters except in conjunction with related parameters such as pH. Nevertheless, even small changes in sediment temperatures can significantly affect microbial processes and impact on biogeochemical cycling.[12] In Australia, water temperature, like air temperature is measured in degrees Celsius (°C), with zero degrees indicating the freezing point of water. Water column and sediment pore water temperatures can be measured very simply and easily using a thermometer. In stratified systems, the water temperature may be different at the top and bottom of the water column, and may need to be measured at regular depth intervals (for details see 'Stratification' in this topic and the topic 'Monitoring wetlands' in Chapter 4). Depth interval measurements may also need to be made in pore waters, where temperature is likely to be more stable with depth.

Where possible, wetland water temperatures within a wetland should always be measured at the same time of day to allow comparisons over time. Temperatures taken at different times of day may vary widely due to daily temperature changes. Due to the potentially severe physiological effects of the daily cycle temperature fluctuations on wetland plants, animals and microbes, temperature extremes within a system may need to be monitored using a min–max thermometer or temperature sensor and datalogger (a device that records data over time or in relation to location, which can be left unattended to automatically measure and record information on a 24-hour basis).

➤ For more information on monitoring temperature in wetlands, refer to the topic 'Monitoring wetlands' in Chapter 4.

Sources of more information on wetland water temperature

ANZECC & ARMCANZ (2000) '8.2 Physical and chemical stressors in Volume 2 Aquatic ecosystems — rationale and background information (Chapter 8)' of *Australian and New Zealand guidelines for fresh and marine water quality*.[4]

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Glossary

Biogeochemical: the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment, and in particular, the cycles in which material is transferred between living systems and the environment

Organism: an individual living thing

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

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DISSOLVED OXYGEN

Contents of the 'Dissolved oxygen' section

What is meant by dissolved oxygen?

'Dissolved oxygen' refers to the very small bubbles of oxygen gas that occur in wetland waters, and which are derived from the atmosphere and **photosynthesis** by wetland plants, algae and **cyanobacteria**. Oxygen exists in much lower proportions in water (about 1 per cent) than in air (about 21 per cent).[1]

Why is dissolved oxygen important?

Oxygen is critically important for the function of wetland ecosystems, as it controls and interacts with a wide range of biological and chemical processes. The concentration of dissolved oxygen in wetland waters can determine whether or not plants and animals and different groups of bacteria are able to survive there and what species can survive, as well as influencing many of the chemical characteristics of the aquatic environment.

Oxygen is essential to the basic **metabolic** processes of almost all wetland organisms, since it is needed for respiration. **Respiration** is a process that consumes oxygen and releases carbon dioxide, through which all plants and animals, including humans, and the aerobic (oxygen-dependent) microbes break down nutrients and generate energy.[2] Deoxygenation of waters can therefore quickly result in mortality of oxygen-dependent organisms, since they are unable to undertake basic energy-generating processes.

The levels of tolerance of particular species to different dissolved oxygen concentrations may differ depending on whether the organisms are adapted to cold or warm waters, with cold water species often requiring higher levels of dissolved oxygen than warm water species.[2,1] In addition, the life stage (for example, adult or juvenile, reproductive or growing) also changes an organism's oxygen requirements.[2] Low-oxygen conditions pose a problem for large animals; for example, fish cannot survive in water with less than 30 per cent oxygen saturation.[3] On the other hand, aquatic worms (oligochaetes) and midge larvae (chironomids) can be common in low oxygen conditions.[3] Many wetland plants have adaptations that allow them to survive in low oxygen conditions (Figure 12).

Figure 12. *Schoenoplectus validus* is one of a number of sedges of south-western WA that use pressurised gas flow to transport air from the surface to the roots, allowing them to survive in deeper water than other species. Photo – J F Smith. Images used with the permission of the Western Australian Herbarium, DEC.

➤ For more information on the oxygen requirements of wetland plants and animals, and adaptations to low-oxygen conditions, see the topic 'Wetland ecology' also in Chapter 2.

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Metabolic: the chemical reactions that occur within living things that are necessary to maintain life, including the digestion of food

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

In addition to its direct effects on organisms, dissolved oxygen concentrations also affect the **solubility** of many nutrients and other chemicals in wetland waters and sediments.[4] The effect of dissolved oxygen levels on nutrient availability is significant, and is covered in detail in the 'Nutrients' section later in this topic. When dissolved oxygen concentrations are low, the toxicity of heavy metals and pesticides may also increase, compounding the stress on plants and animals.[2]

Solubility: a measure of how soluble a substance is

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

Anoxic: deficiency or absence of oxygen

What is the natural dissolved oxygen level of Western Australian wetlands?

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (known as 'the ANZECC guidelines' in reference to the author institute) for freshwater systems are presented in Table 2. These **trigger values** apply only to water columns, since sediments are naturally variable and are also often naturally **anoxic.**

Table 2. Default trigger values for dissolved oxygen (DO) (risk of adverse effects) from ANZECC & ARMCANZ.[2]

Ecosystem type	DO per cent saturation	
Freshwater lakes	No data	
Tropical Australia	**Lower limit**	**Upper limit**
Wetlands	90	120
South-west Australia		
Wetlands	90	120

Note: dissolved oxygen values were derived from daytime measurements

These trigger values should be used with caution because they have been derived from a limited set of data from a small area. The trigger values for the south-west of WA have been derived from two years of data collected at forty wetlands within and near Perth and are only representative of basin wetlands of this region that are permanently or seasonally inundated[5], rather than wetlands across the entire south-west of the state. The trigger values from the north-west of the state are derived from an even more restricted study (less than one year) in the Pilbara region.[2]

The lower acceptable limits of dissolved oxygen in wetland waters are relatively high to protect wetlands from reaching low dissolved oxygen saturation, which can rapidly result in mortality of animals. Upper limits for wetland waters are also given, because elevated saturation or concentrations may affect wetland animals or may indicate high rates of photosynthesis, such as those generated by an algal bloom. Florida LAKEWATCH suggests that 'normal' dissolved oxygen concentrations for freshwater environments range from 6 to 10 mg/L, with 3–4 mg/L likely to be stressful for animals.[6]

What affects the dissolved oxygen of wetland waters and how variable is it?

Dissolved oxygen varies widely over time (over a daily 24 hour cycle and across the year) and depends on water regime, biological activity, temperature, salinity and altitude (air pressure).[4] In the lower water column and upper sediment pore waters, it is also strongly affected by the movement of the overlying waters (degree of mixing). These are described in more detail below.

Water regime

The dissolved oxygen levels fluctuate in wetlands that wet and dry. The sediments of dry wetlands are exposed to atmospheric oxygen. As these sediments wet up, the sediment-air interface is replaced with a sediment-water column interface, and the dissolved oxygen that is initially present in the water column typically rapidly decreases due to oxygen consumption by organisms during respiration, notably microbial consumption in the initial wetting-up phase.

Biological activity

Variations in the dissolved oxygen concentration in wetlands occur on two different temporal scales; daily and seasonally. The dissolved oxygen concentration of water tends to be higher during the day (due to net photosynthesis, which produces oxygen) and lower at night (due to net respiration, which consumes oxygen), and in some wetlands can reach very low levels over night.[1] The rise in concentration begins again as soon as the sun rises and wetland plants, algae and cyanobacteria can photosynthesise.[4] In fact, it is often possible to see oxygen beading on benthic mats during the middle of the day when photosynthesis is highest.[3]

Emergent wetland plants improve the dissolved oxygen levels within wetland sediments by transferring oxygen from their leaves to their roots. The area around the roots where oxygen leaks out and aerates the sediment is called the 'rhizosphere' and this environment is important for sustaining microbes important for cycling materials in wetlands.[3]

These effects of oxygen generation and consumption tend to override any diurnal (night and day) influence of temperature on solubility caused by the warming of waters during the day.

Temperature

As stated above, there may be some diurnal (night and day) influence of temperature on solubility caused by the warming of waters during the day. However, in temperate areas of the state, seasonal temperature changes have a noticeable effect on dissolved oxygen concentrations, since oxygen dissolves much more readily in colder water[4], making oxygen concentrations in wetlands generally higher in winter and lower in summer, except when there are algal blooms present. This also means that water is more likely to be well-oxygenated in cooler climates[6,1] (Figure 13).

Figure 13. Angove wetland, on the South Coast, is an example of a high oxygen wetland in WA (cool climate, freshwater, clear water). Photo - K Hopkinson/Department of Environment, Green Skills Inc.

Dissolved or suspended solids

Oxygen is less soluble in waters with high levels of dissolved or suspended solids[7] meaning that highly saline, highly **coloured** or highly **turbid** waters may pose several interacting stresses for the plants and animals (Figure 14). In addition, dissolved oxygen is often present in lower concentrations in the water column of coloured lakes, due to the reducing properties of the **humic** substances dissolved in the water.[4] In many seasonally inundated Western Australian wetlands, as the wetland dries down the stresses of higher temperatures, lower dissolved oxygen, higher salinity and possibly also higher light levels may occur together.[8]

Figure 14. This salt lake near Jurien is an example of a lower oxygen wetland in WA (warm climate, saline coastal wetland). Photo - J Davis.

Rapid deoxygenation of wetland water columns, driven by microbial processes, can occur if large amounts of decaying organic matter enter a wetland, such as through the decay of an algal bloom or the inflow of sewage.[1] This can also occur seasonally, when annual wetland vegetation dies at the end of autumn, but is more likely if a wetland is nutrient-enriched.[2] This deoxygenation occurs because the **aerobic** microbial decomposition of organic matter consumes oxygen.[9] This relationship is so important that often when monitoring wetland condition, the '**biological oxygen demand**' (BOD) of waters may be measured in addition to the level(s) of dissolved oxygen.[10] The biological oxygen demand refers to the amount of oxygen required by microbes to break down organic matter in a sample over a five day period, and is a measure used to estimate how polluted the wetland is.[2,10]

Altitude

The concentration of dissolved oxygen in water decreases with increasing altitude (height above sea level) due to lower air pressure.[4] This effect is more applicable in areas of high altitude such as alpine regions. As most of WA sits between about 300 metres and 450 metres above sea level[11] there are few high altitude locations in the state, so the effects of altitude on dissolved oxygen in WA are considered to be minor.

Colour: the concentration of dissolved organic materials and dissolved metals in water

Turbid: the cloudy appearance of water due to suspended material

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Aerobic: an environment in which oxygen is present; an organism living in or a process occurring only in the presence of oxygen

Biological oxygen demand: the amount of oxygen required by microbes to break down organic matter in a sample over a five day period

How is dissolved oxygen measured, and what units are used?

Dissolved oxygen can be measured in both water columns and sediment pore waters using a dissolved oxygen meter for water columns or a specialised 'microelectrode' or oxygen chamber for the sediments. Note that not all oxygen meters are designed for use in salt water.[3] Water column dissolved oxygen is a commonly used parameter for monitoring wetland condition, but sediment pore water dissolved oxygen is rarely used, since redox is often a more useful measure in this context.

Dissolved oxygen in water columns is usually measured in either concentration (for example, parts per million, ppm or milligrams per litre, mg/L) or percent saturation, which is the water concentration measured relative to both the atmospheric concentration at a particular altitude (air pressure) and water temperature.[8] This means that the concentration of oxygen that represents 100 per cent saturation is lower at higher temperatures.[1] To convert per cent saturation to a concentration (such as milligrams per litre, mg/L) requires knowledge of the barometric pressure (or altitude) and water temperature. If these were not measured at the time of sampling, then values cannot be converted.[1]

The temporal variability of dissolved oxygen in wetland waters and its rapid response to biological processes means that snapshot measurements are not particularly useful, and regular monitoring is required to understand and characterise the dissolved oxygen of a particular wetland's waters.[2]

➤ For more information on monitoring dissolved oxygen in wetlands, refer to the topic 'Monitoring wetlands' in Chapter 4.

Sources of more information on wetland dissolved oxygen

ANZECC & ARMCANZ (2000) '8.2 Physical and chemical stressors in Volume 2 Aquatic ecosystems — rationale and background information (Chapter 8)' of *Australian and New Zealand guidelines for fresh and marine water quality*.[2]

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Glossary

Aerobic: an environment in which oxygen is present; an organism living in or a process occurring only in the presence of oxygen

Anoxic: deficiency or absence of oxygen

Biological oxygen demand: the amount of oxygen required by microbes to break down organic matter in a sample over a five day period, and is a measure used to estimate how polluted the wetland is

Colour: the concentration of dissolved materials (including organic materials and metals) in water

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Metabolic: the chemical reactions that occur within living things that are necessary to maintain life, including the digestion of food

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Saline: water that has a high concentration of ions

Turbid: the cloudy appearance of water due to suspended material

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

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SALINITY, CONDUCTIVITY AND IONIC COMPOSITION

Contents of the 'Salinity, conductivity and ionic composition' section

Ion: an atom that has acquired an electrical charge by the loss or gain of one or more electrons.

What are salts?

Common table salt, or sodium chloride (NaCl), is a well-known salt. In chemical terms, **salts** are ionic compounds comprised of cations (positively charged **ions**) and anions (negative ions). Cations that are commonly present in wetland waters include sodium: Na^+, potassium: K^+, calcium: Ca^{2+} and magnesium: Mg^{2+}. Anions include chloride: Cl^-, sulfate: SO_4^{2-} and bicarbonate: HCO_3^-. Australian wetlands tend to be dominated by sodium and chloride, and sometimes bicarbonate, whereas in many other regions of the world, calcium and bicarbonate dominate.[1,2] The dominance of sodium and chloride in Australian inland wetlands is due to the inland transport of sea spray on rain and dust.[2]

What is meant by salinity, conductivity and ionic composition?

Salinity and total dissolved salts (TDS) are equivalent measures of the concentration of ions in wetland water.[1] These measurements are used to describe the differences between waters that are considered 'fresh' (with very low concentrations of ions) and those that are considered 'saline' (with high concentrations of ions). A salinity scale is given in Table 5. **Total dissolved solids** (confusingly also called TDS) is a measure used to approximate the concentration of ions in wetland water, but which will usually over-estimate salinity since it also accounts for dissolved organic compounds.[1] **Ionic composition** refers to the particular ions making up a solution, usually discussed in terms of the relevant dominances of the major (most abundant) positively charged and negatively charged ions in the water of a particular wetland.[3]

Electrical conductivity (EC) is the ability of a solution to conduct an electric current, and is measured as 'specific conductance'; the rate of flow of ions between two electrodes a fixed distance apart, measured at a known temperature.[1,4] Conductivity is generally only used to measure salinity of less than 5000 millisiemens per centimetre (mS/cm).[2] A relationship between salinity and conductivity can be derived but it is not always accurate in very fresh waters (due to the influence of organic acids)[1] or in very saline waters.[5]

Why are salinity and ionic composition important in Western Australian wetlands?

Effects on wetland species

Salinity (and therefore electrical conductivity) is a natural part of wetlands, although the concentrations and compositions of salts may vary widely between wetlands.[3,5] All wetland species are adapted to particular ranges and types of salts in their environment; some, such as salt marsh or saline wetland species may actually rely on a high level of salinity to function.[6,7] Many of the ions dissolved in wetland water columns and pore waters are essential to life and play important roles in the functioning of particular species and the ecosystem.

In particular, dissolved ions have important functions in the cells and membranes of plants and animals.[6,7] Some species, such as the brine shrimp *Parartemia*, are able to regulate the concentration of their internal fluids in relation to the environment (**osmoregulators**), while others have no ability to do this, and their internal concentrations reflect that of the solution they are immersed in (**osmoconformers**).[6] Many of the common ions (such as sodium: Na^+, chloride: Cl^-, potassium: K^+, calcium: Ca^{2+}) and some of the less common ones are important as mineral nutrients for plant and animal growth.[6,7] This applies both to organisms in wetland water columns, and also to those in the sediments that are bathed in saline pore waters and/or ingesting salt associated with waters and sediments.

Wetland plants, animals and microbes tend to be physiologically adapted to particular ranges or concentrations of salinity meaning that if these concentrations change too much or too rapidly, this can cause a decline in health and even result in mortality.[8,9]

Effect on physico-chemical conditions

In addition to the effects on the physiology of wetland plants and animals, salinity levels affect other physico-chemical conditions in wetland waters including:

- water clarity (salinity can cause aggregation and settling of particles out of solution, increasing water clarity)[10]
- dissolved oxygen concentration (saline waters have a lower capacity for dissolved oxygen)[1]
- pH (high salinity waters can often have a low pH)
- other chemical equilibria (for example, the influence of sulfate on phosphorus cycling[10]).

The composition of the ions that make up a salinity reading may vary from wetland to wetland, although in Australia, saline wetland waters usually have an ionic composition similar to seawater (dominated by sodium, Na^+ and chloride, Cl^- ions).[5] Nevertheless, even relatively small differences in ionic composition may lead to large differences in the toxicity of saline waters for plants and animals.[3] For example, chloride ions are believed to be much more toxic than carbonate (CO_3^{2-}) ions, making it easier for organisms such as invertebrates to tolerate high salinities in carbonate-dominated systems.[11]

➤ For information on the effects of secondary salinity, refer to the topic 'Secondary salinity' in Chapter 3.

What is the natural salinity range of wetlands in Western Australia?

The natural salinity levels of WA wetlands range from fresh to hypersaline.[12,13] Definitions of these salinity categories vary significantly from source to source, but often general usage in Australia refers to 'freshwater' as extending from 0 to about 3,000 milligrams per litre (mg/L), 'saline' from 3,000 mg/L to about seawater (approximately 35,000 mg/L) and hypersaline above this (greater than 35,000 mg/L). Salt lakes can display salinities up to saturation point (Figure 15). The most widely used (international) classification system for natural salt lakes[14] defines a wider a range of categories (Table 3). The use of the word 'brackish' varies; some researchers reserve it solely for reference to estuarine waters and do not use it in reference to inland waters (instead using terms such as 'subsaline' or 'hyposaline'), on the basis that 'brackish' refers to a mix of fresh and marine water, rather than inland saline water.[14] Others use it to describe the range between around 3,000 to 10,000 mg/L regardless of whether the water is estuarine or not.

Table 3. Salinity ranges in Western Australian wetlands

Common usage in Western Australia	Salt lake category[14]	Minimum total dissolved salts (TDS) (milligrams per litre, mg/L)	Maximum total dissolved salts (TDS) (milligrams per litre, mg/L)
Fresh	Fresh	0	500
Fresh	Subsaline	500	3,000
Saline	Hyposaline	3,000	20,000
Saline	Mesosaline	20,000	50,000
Hypersaline	Hypersaline	50,000	NaCl saturation (about 360,000)

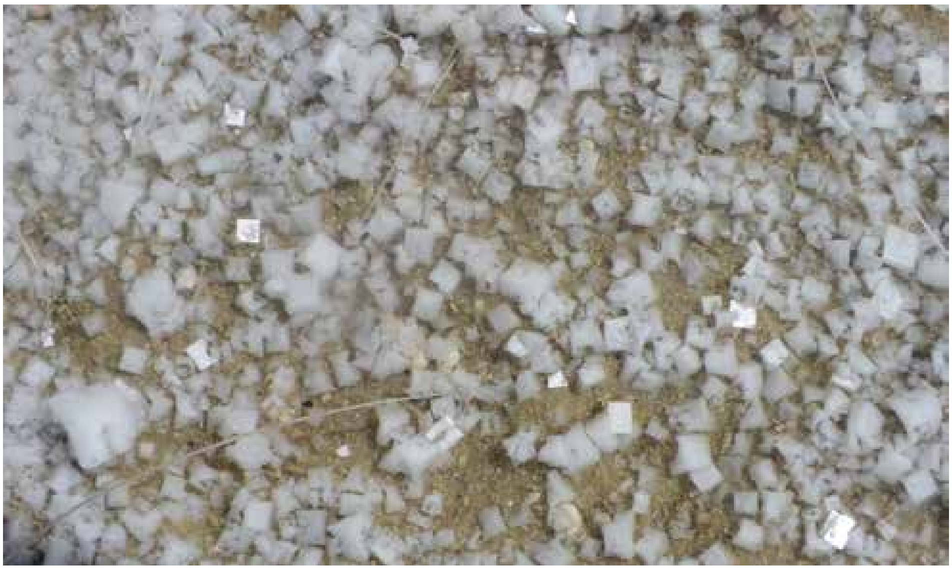

Figure 15. Salt crystals in a wetland in Jurien in the midwest of WA. Photo – J Lawn/DEC.

There are therefore no 'acceptable' limits for salinity change across wetland ecosystems generally, although the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[15] (known as the 'ANZECC guidelines' in reference to the author institute) specify guidelines for conductivity in freshwater wetlands and lakes (Table 4). The difficulty in setting acceptable limits occurs because the natural salinity level of the wetland determines whether salinity (or conductivity) levels are considered to be high or low. As mentioned earlier, changes to either higher or lower salinities can have adverse effects, depending on the physiology of the different plants and animals.

Table 4. Default trigger values for conductivity (risk of adverse effects to freshwater systems) from ANZECC & ARMCANZ.[15]

Ecosystem type	Electrical conductivity (microsiemens per centimetre, $\mu S\ cm^{-1}$)	
Tropical Australia	**Minimum**	**Maximum**
Lakes, reservoirs and [other] wetlands	90	900
South-west Australia		
Lakes, reservoirs and [other] wetlands	300	1500[a]

[a]*Higher values (greater than 3000 $\mu S\ cm^{-1}$) are often measured in wetlands in summer due to evaporative loss.*

The usual ionic composition of Western Australian saline wetlands is similar to seawater (dominated by sodium, Na^+ and chloride, Cl^- ions), but in some cases, especially in fresher systems, other ions such as carbonate (CO_3^{2-}) may be more dominant.[3,5] There are no usual or acceptable ranges of ionic composition in Western Australian wetlands, although as described earlier, changes in ionic composition can potentially be stressful to animals.[11,3]

What affects the salinity, conductivity and ionic composition of wetland waters and how variable are they?

The natural salinity of a wetland depends on factors such as:

- geographic location
- rainfall patterns
- evaporation rate
- geology
- source of inflow water.

In WA, naturally saline wetlands are often associated with coastal areas, where they are influenced by direct seawater intrusion or salt spray, and inland arid areas, where evaporation rates exceed rainfall, and soils are not well-flushed and consequently salts accumulate[13] (Figure 16).

(a) Lake Coogee, a coastal saline wetland, Munster

b) Lake Goorly, an intermittently inundated inland saline wetland, Dalwallinu

Figure 16. Naturally saline wetlands in Western Australia. Photos – (a) L Sim and (b) Wetlands Section/DEC

The 'primary' salinisation of wetland waters is a natural process, and occurs very slowly.[16] Many naturally-saline Western Australian wetlands are saline due to inputs of saline groundwater or seawater intrusion, and in many cases the geological conditions underlying the wetlands also influence whether they are naturally saline or fresh.[16] In contrast, claypans are 'perched' (not connected to groundwater) due to a layer of impermeable clay, and they therefore tend to be filled with rainwater, so many, but not all, are fresh (Figure 17).

Playa: a wetland with a basin landform that is intermittently inundated

Secondary salinisation: a human-induced degrading process in which the salt load of waters or soils increases at a faster rate than naturally occurs


(a)


(b)

Figure 17. (a) In a 2009 study, Muggon claypan in the Murchison was found to be fresh (TDS 80 mg/L) while (b) the nearby Muggon lake was found to be saline (TDS 3300 mg/L).[17] Photos – G Daniel/DEC.

In contrast, many of the saline intermittently inundated wetlands (**playas**) of the south-west occur in the ancient river channels (paleochannels) where saline groundwater seeps up through the permeable sediments.[16]

Wetland water salinity does not vary appreciably over a 24 hour cycle or due to biological activity, but is largely linked to water level (dilution and evapoconcentration) and the salinity of the inflowing and outflowing water. Over much longer time scales, the weathering of rocks and the influx of airborne marine salts also have an influence.[16]

'**Secondary' salinisation** occurs over much shorter time scales and is driven by large-scale hydrological change within a landscape. The agricultural zone of south-western WA has experienced large increases in wetland salinity levels since clearing of the deep-rooted native vegetation for agricultural production caused water tables to rise, bringing salts to the surface, and many of the wetlands in this region are now secondarily salinised (see the topic 'Secondary salinity' in Chapter 3). Both waterlogged and inundated wetland types have been affected.

It is important to note that while the adverse effects of secondary salinisation on freshwater systems are relatively well-known, the sudden freshening of naturally saline wetlands, although less common, is equally stressful for the plants and animals of the wetland.[6,7]

How are salinity, conductivity and ionic composition measured, and what units are used?

Salinity is expressed as a concentration and is usually measured in mass per unit volume (for example, milligrams or grams per litre; mg/L, g/L) or parts per thousand or million (ppt/ppm). These measures are roughly equivalent but at salinities of greater than about 7 ppt, density or specific gravity also needs to be taken into account[1]: ppt = g/L ÷ specific gravity.

An understanding of the limitations of each measure can be useful when choosing a form of measurement, and when interpreting results (Table 5).

Table 5. Key salinity measurements

	Direct measurement or surrogate (substitute)	In-situ or laboratory measurement	Water columns and/ or pore water measurement	Limitations
Total dissolved solids (TDS)	Surrogate for total dissolved salts	In-situ or laboratory	Both	Can over-estimate salinity, as dissolved organic compounds are also included in the measurement. As such not suitable for turbid wetlands.
Electrical conductivity (EC)	Surrogate for total dissolved salts	In-situ	Both	Less accurate in very fresh (due to the influence of organic acids) and very saline wetlands.
Ionic composition	Direct measurement of ionic composition; the sum total provides a direct measure of total dissolved salts.	Laboratory	Both	Very accurate but the cost of laboratory analysis may be prohibitive.

Figure 18. An electronic meter used to measure electrical conductivity in wetlands, with the probe attached and a solution used to calibrate the meter. This model also measures a number of other parameters. Photo – J Lawn/DEC.

There are many models of electronic meter that can be used to measure salinity or electrical conductivity in situ (Figure 18). Conductivity is a simple surrogate (substitute) for the measurement of salinity, which is particularly useful in fresher wetlands. It is easily measured and allows a rapid assessment of whether a wetland has crossed the boundary between fresh and saline. Salinity and conductivity can both be measured in water columns and pore waters. The technique for sediments involves adding sediment to water and mobilising the salts so that they can be measured in the same way.

Salinity data is often presented together with water depths as it is directly affected by evapoconcentration, and water level gives perspective on the time of the hydrologic cycle that the sample was taken.

extra information

How to convert between conductivity and salinity

To convert between conductivity and salinity the following conversion is usually used:

mS/m x 5.5 = mg/L = ppm.

This equation assumes that sodium chloride is the only salt present; the multiplication factor of 5.5 increases with the addition of other common salts and may be as high as 6.[18]

➤ Techniques for measuring salinity, conductivity and ionic composition are presented in the topic 'Monitoring wetlands' in Chapter 4.

Sources of more information on wetland salinity, conductivity and ionic composition

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Radke, L, Juggins, S, Halse, S, Deckker, P & Finston, T (2003) 'Chemical diversity in south-eastern Australian saline lakes II: biotic implications', *Marine & Freshwater Research*.[3]

Williams, W (1966) 'Conductivity and the concentration of total dissolved solids in Australian lakes', *Australian Journal of Marine & Freshwater Research*.[5]

Glossary

Brackish: a mix of fresh and marine water (thus not applicable to inland saline water)

Electrical conductivity (EC): the ability of a solution to conduct an electric current, and is measured as 'specific conductance'; the rate of flow of ions between two electrodes a fixed distance apart, measured at a known temperature

Ionic composition: the relevant dominances of the major (most abundant) positively charged and negatively charged ions in the water of a particular wetland

Osmoconformers: species who are not able to regulate the concentration of their internal fluids, so their internal concentrations reflect that of the solution they are immersed in

Osmoregulators: species that are able to regulate the concentration of their internal fluids in relation to the environment

Playa: a wetland with a basin landform that is intermittently inundated

Salinity: a measure of the concentration of ions in wetland water. This measurement is used to describe the differences between waters that are considered 'fresh' (with very low concentrations of ions) and those that are considered 'saline' (with high concentrations of ions).

Salts: ionic compounds comprised of cations (positively charged ions, such as sodium, Na^+) and anions (negative ions, such as chloride, Cl^-)

Secondary salinisation: a human-induced degrading process in which the salt load of waters or soils increases at a faster rate than naturally occurs

Total dissolved solids (TDS): a measure used to approximate the concentration of ions in wetland water (that is, total dissolved salts/salinity). It will usually over-estimate these as TDS includes dissolved organic compounds.

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

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STRATIFICATION

Contents of 'Stratification' section

What is stratification?

'**Stratification**' in wetlands refers to the division of the water column into distinct layers called the **epilimnion** (top), the **metalimnion** (middle) and the **hypolimnion** (bottom), and results from differences in water density between these layers[1] (Figure 19). Most commonly, the differences in density are due to temperature, but stratification can also be caused by pressure (due to altitude), salinity, and suspended or dissolved particles.[1] Stratification is not relevant to wetlands without a water column, that is, waterlogged wetlands.

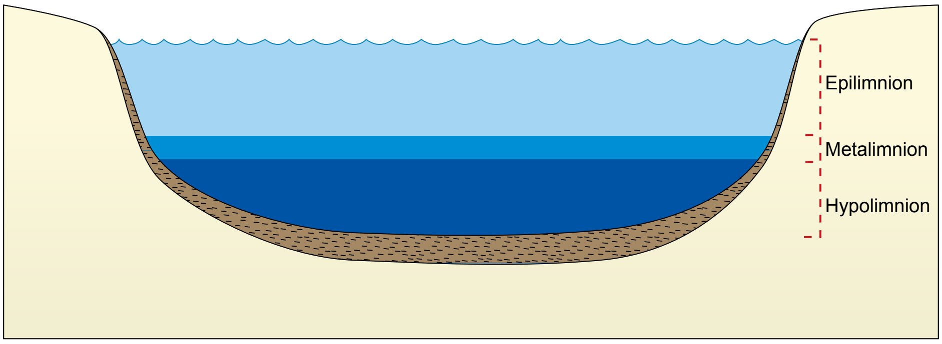

Figure 19. Stratification of a wetland into epilimnion, metalimnion and hypolimnion.

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between these layers

Epilimnion: the top layer of a stratified water column

Metalimnion: the middle layer of a stratified water column

Hypolimnion: the bottom layer of a stratified water column

Anoxic: deficiency or absence of oxygen

When a wetland is thermally-stratified (stratified due to temperature), the top layer is usually the warmest layer of the water column as it absorbs most of the solar radiation. Its position also allows it to remain well-mixed and oxygenated.[2] The bottom layer is the coldest layer and oxygen often becomes depleted (**anoxic**), if no photosynthesis is occurring there to replenish the dissolved oxygen. The middle layer is where the most rapid temperature change with depth occurs.[1,3]

Why is stratification in wetlands important?

The importance of stratification is directly related to its effects on other parameters such as temperature and dissolved oxygen. The creation of distinct layers of water with very different physical and/or chemical properties within one wetland can affect the processes occurring within each layer, and in the wetland as whole, as well as on the survival of plants and animals in these layers.[1,3] For example, if the bottom layer becomes depleted of oxygen, oxygen-dependent animals and bacteria will no longer be able to survive there. Carbon dioxide levels will rise and the pH will fall[4] and anaerobic chemical processes such as increased organic matter decay via methanogenesis (a kind of bacterial breakdown described in the 'Carbon' section of this topic), or the release of phosphate from the sediments will start to occur.[5] Nitrogen and phosphorus may become more abundant in the bottom layer.[4]

Stratification can cause primary productivity to become focused in the top layer of the wetland, instead of occurring as far down in the water column as light can penetrate.[1] As a result, stratification can lead to the development of algal blooms, with rapid population growth taking place in the high light, warm conditions of the top layer, and anoxic conditions in the bottom layer promoting the release of nutrients from the sediments. Regular mixing of the water column (by wind or artificial aeration) can prevent the formation of algal blooms in the surface waters, as well oxygenating the bottom layer.[1]

What is the natural stratification regime of Western Australian wetlands?

There are no guidelines for the acceptable ranges or limits for stratification of waters in natural Western Australian wetlands. Water quality guidelines have instead been set for related parameters such as temperature, salinity and turbidity, as outlined in these respective sections of this topic.

What affects the stratification of wetland waters and how variable is it?

Stratification can be caused by a number of different physico-chemical factors including temperature, salinity, suspended **particulate** matter, dissolved substances or pressure, which all cause the creation of distinct layers of water that differ in density.[1,6] In all cases, the preservation of these layers relies on a lack of mixing between the layers, and the stratification is more 'stable' (less likely to mix) if larger density differences exist between the layers.[2]

The influence of wetland depth

Stable stratification, which persists for much longer than a day (often months), is only likely to occur in deeper waters. Researchers concluded that of the forty-one wetlands they surveyed on the **Swan Coastal Plain**, only wetlands greater than 3 metres deep or strongly coloured would stably stratify.[7] Most natural wetlands in WA are shallow by world standards, and therefore stable stratification due to temperature is likely to be uncommon. It is likely to be more common in man-made waterbodies such as large dams that are deeper than 3 metres. In south-west WA, stable temperature stratification is most likely to occur in summer when more of a temperature differential between surface and benthic (bottom) waters is likely to develop, and there is not as much wind mixing.[1]

Stratification is rarely measured in very shallow waterbodies, as it is often assumed that wind mixing prevents the development of stable layers (Figure 20), but there have been records of regular daily stratification in shallow wetlands in WA, the eastern states of Australia and overseas.[5,8,6] This type of **unstable stratification**, where layers form in the water column each day (usually in the afternoon) and mixing occurs over night, has not been studied extensively in shallow wetlands, and may be more common than previously thought. It makes sense, that since changes in solar radiation and the heating of wetland waters occur over a day or across seasons, this can also cause stratification. In temperate zones, such as the south-west of WA, stratification over a 24 hour daily cycle appears to be most common in summer–early autumn, where a few hours of solar radiation can lead to a significant differential in temperature between top and bottom waters.[5,6] In these same wetlands in late autumn–winter, the waters do not warm sufficiently to cause this difference in temperature.[5,6] In equatorial areas, such as the north-west of WA, where the incidence of solar radiation does not vary much across the seasons, this seasonal difference does not occur; stratification may occur all year round, and its loss is more likely to be due to wind mixing[8] (Figure 20).

Particulates: in the form of particles (small objects)

Stable stratification: stratification which persists for much longer than a day (often months)

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Unstable stratification: layers form in the wetland water column each day (usually in the afternoon) and mixing occurs over night.

Figure 20. Wind mixing of Rushy Swamp, a shallow wetland near Woodanilling, in the South Coast region. Photo - L Sim.

The influence of water chemistry

Natural salt lakes may undergo salinity stratification when fresh rainwater entering the wetland in late autumn or winter sits on top of the highly saline water left at the end of summer[1] (Figure 21a). Unlike temperature-driven stratification (Figure 21b), the salty lower layer often becomes warmer than the fresh top layer.[1] Stratification due to salinity may occur in quite shallow systems as long as there is not too much wind disturbance. Salinity-driven density differences are much greater than temperature-driven differences.[4]

Highly turbid waters, caused by the suspension of inorganic particles (such as clays) in the water column are common in WA (Figure 21c); (see 'Light availability' in this topic). Shallow, turbid wetlands can undergo temporary stratification on hot days, when the top layer of water heats up due to the absorption of heat by suspended particles.[1]

The surface waters of tannin-stained wetlands can also heat up rapidly during the morning but tend to then undergo complete mixing once heat is lost overnight.[4] Researchers have identified this process as an important determinant of habitat for the endemic black-striped minnow, *Galaxiella nigrostriata*, at Melaleuca Park in Perth's northern suburbs.[9] The darkly stained water heats up in the daytime, creating a warm surface layer and cooler water beneath. These cooler benthic waters provide the black-stripe minnow with suitable habitat in hot weather.

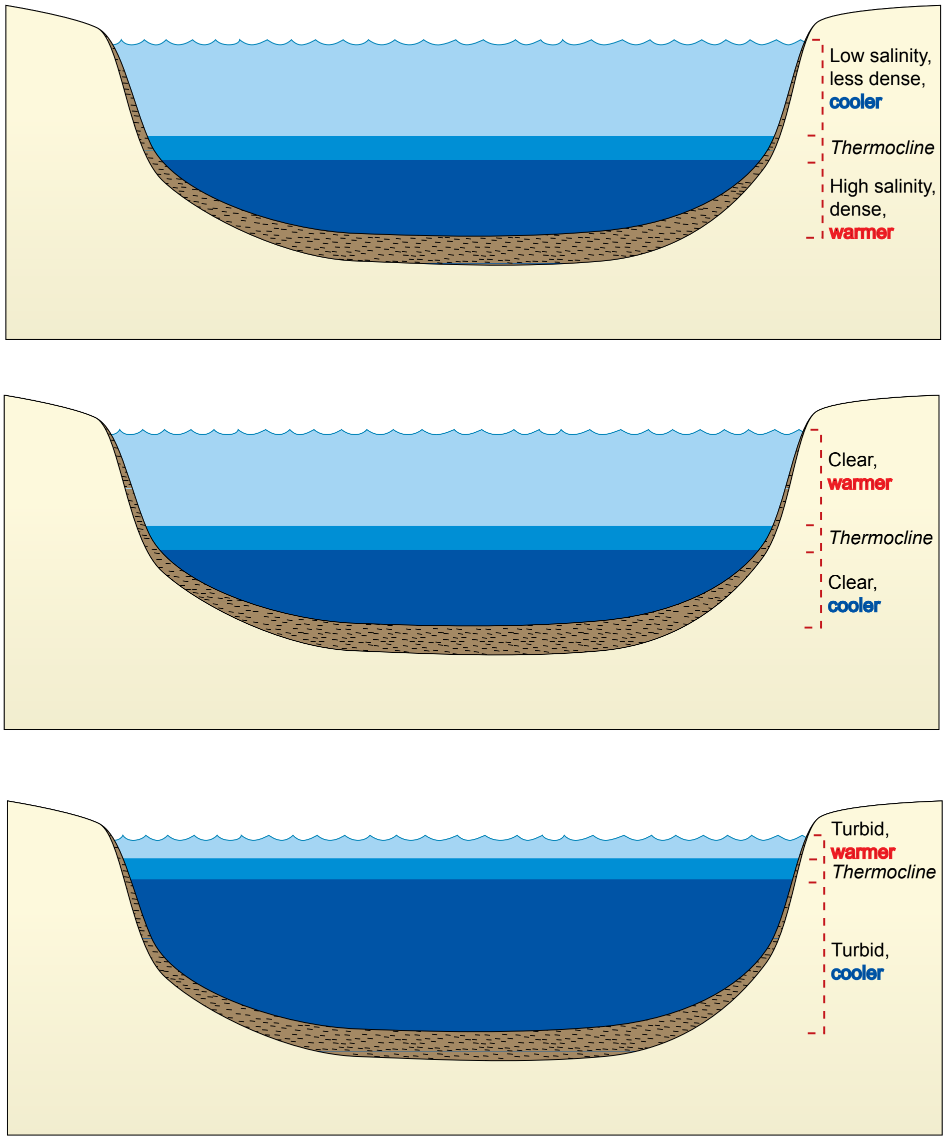

Figure 21. Diagrams of Western Australian stratified wetlands: (top) salinity-stratified; (middle) thermally-stratified; and (bottom) stratified due to suspended particulates.

Thermocline: the narrow vertical layer within a body of water between the warmer and colder layers where a rapid temperature change occurs

Halocline: a sharp vertical gradient in salinity between a relatively fresh water mass and a more saline water mass

How is stratification measured, and what units are used?

Stratification can only be measured in water columns and is not relevant to sediment pore waters. The type of measurements taken to determine whether stratification is occurring depend on the type of stratification (that is, temperature or salinity driven), but since all types of stratification usually lead to a temperature differential between top and bottom waters, the quickest and simplest measurement used to determine stratification is usually temperature. To record the presence of an epilimnion and hypolimnion, sampling needs to include both top and bottom measurements, or for very deep systems, measurements at a number of depths in the water column. If the intention is to plot a **thermocline**, dissolved oxygen profile or **halocline** (types of graphs which show how temperature, dissolved oxygen or salinity change with depth, see Figure 22 for example), measurements are often much more regular; every 5 or 10 centimetres depending on the depth of the wetland.

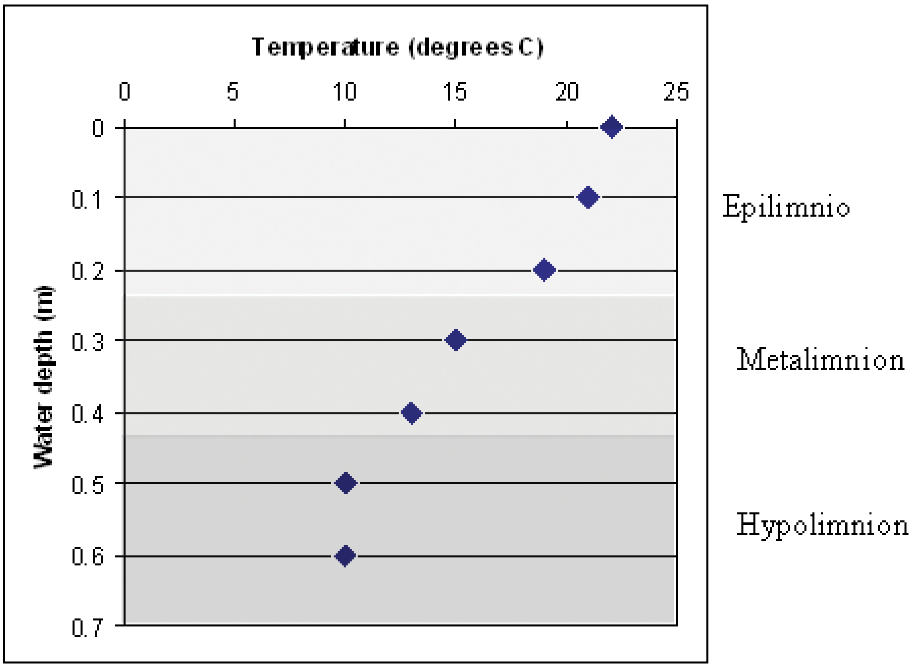

Figure 22. Example of a thermocline, showing difference between temperatures at the top (0 metres) and bottom (0.6 metres) of the water column

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Glossary

Anoxic: deficiency or absence of oxygen

Epilimnion: the top layer of a stratified water column

Halocline: a sharp vertical gradient in salinity between a relatively fresh water mass and a more saline water mass

Hypolimnion: the bottom layer of a stratified water column

Metalimnion: the middle layer of a stratified water column

Particulates: in the form of particles (small objects)

Stable stratification: stratification which persists for much longer than a day (often months)

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between these layers

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Thermocline: the narrow vertical layer within a body of water between the warmer and colder layers where a rapid temperature change occurs

Unstable stratification: layers form in the wetland water column each day (usually in the afternoon) and mixing occurs over night.

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Acidity/alkalinity

Contents of 'Acidity/alkalinity' section

Ion: an atom that has acquired electrical charge by the loss or gain of one or more electrons

What are acidity and alkalinity?

Acidity and alkalinity are chemical properties of water that directly affect the ability of organisms to function, breed and survive in water and soil water. Acidity and alkalinity also have an influence on many chemical reactions in wetlands which help shape their ecological character.

In chemical terms, acidity is characterised by a high concentration of dissolved hydrogen in water. Hydrogen has the chemical symbol 'H', while the shorthand for the dissolved, **ionic** form of hydrogen that produces acidity is 'H^+'.

Alkalinity, on the other hand, is often measured by the amount of carbonate (CO_3^{2-}) in solution.[5] Carbonate and other bases, such as bicarbonate (HCO_3^-), react with and in effect 'absorb' hydrogen ions when the water is acidic and release them when the water becomes basic. This chemical property means that large or rapid changes due to an influx of acidity are resisted (buffered).[3,1] This property is also referred to as 'buffering capacity' and 'acid neutralising capacity'. Stable conditions can be maintained unless the supply of carbonate and bicarbonate ions is exhausted.

What is pH?

'pH' is a soil or water quality measure that indicates whether water is acidic, neutral or alkaline.[1] The term 'pH' is shorthand for 'the potential of hydrogen'.

pH is usually shown on a scale ranging from 0 to 14 (Figure 23). A pH of 0 is extremely acidic; a pH of 7 is neutral and a pH of 14 is extremely alkaline or basic. While a pH of 7 is neutral, the term 'circumneutral' describes the range between mildly acidic and mildly alkaline conditions between roughly pH 5.5 and 7.4.[2] pH can also be a negative value and greater than 14, although this does not occur in wetlands in WA. Some examples of everyday materials of different pH are shown in Figure 23.

pH is a straightforward and commonly used measure. In some circumstances, it is more informative to use measures of total acidity or total alkalinity, as outlined later.

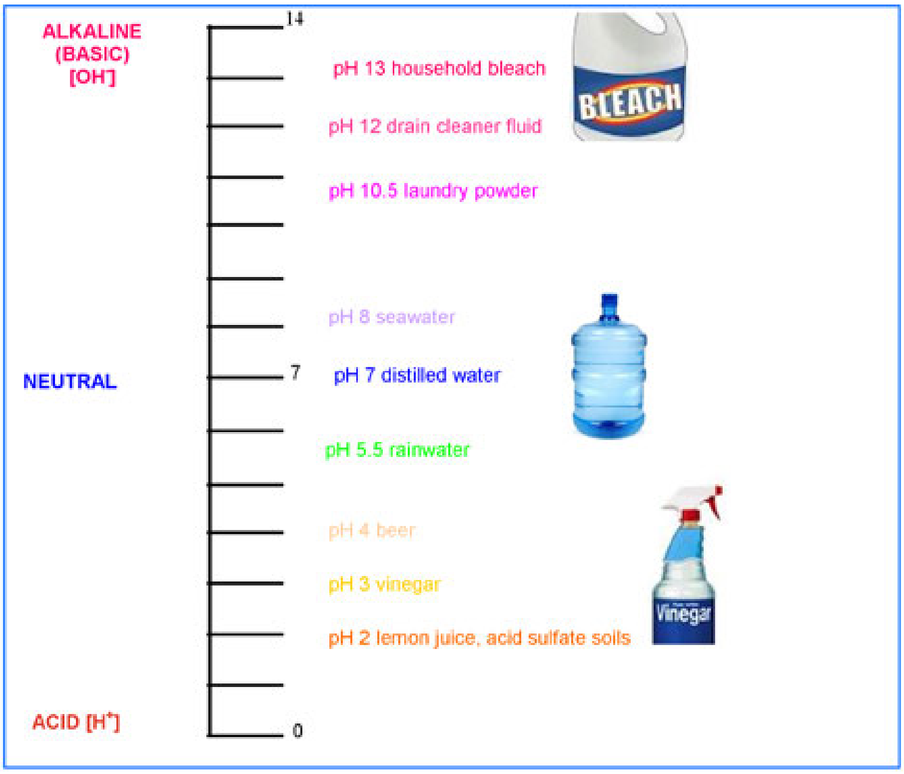

Figure 23. pH scale from acid to alkaline showing examples of acidic and alkaline solutions.

Why are acidity and alkalinity important in wetlands?

Wetland animals, plants and microbes are adapted to particular ranges of acidity/alkalinity for survival, breeding and normal function.[6] Acidity/alkalinity directly affects **organisms** by affecting the function of cells – specifically, the functions of enzymes and membranes. It also has strong effects on wetland organisms by affecting the quality of the water, especially by influencing how **soluble** materials are in water[6,4] including nutrients, carbon dioxide and heavy metals. The availability and toxicity of these materials in a wetland can affect the function and survival of wetland organisms.

While some wetlands in WA are naturally very acidic or alkaline, most have circumneutral or mildly to moderately acidic or alkaline waters, and accordingly most WA wetland plants, animals and microbes are adapted to within this range of acidity/alkalinity. For wetlands in an unaltered state, an aim of management should be to maintain the natural physico-chemical conditions, including the natural range of acidity/alkalinity.

An understanding of the acidity/alkalinity of a wetland, whether it is natural or altered, and whether it is changing over time, can provide insights regarding living conditions and dominant processes in the wetland. However it is important to note that acidity/alkalinity is only one of many factors influencing how suitable a wetland is as habitat for a species. It may only become a dominant factor at very high or low pH, at which point the productivity of most plants and animals is limited.[7]

Importantly, wetland scientists consider that small changes in acidity/alkalinity rarely have large effects on biological systems.[7] A large increase or decrease in pH can result in adverse effects to wetlands, although large decreases are likely to cause more serious problems.[6] Human-induced changes are most commonly an increase in acidity.

Broadly speaking, at a high or low pH, the community structure of aquatic macroinvertebrates, which are a very important part of wetland ecosystems, may be affected. Extremes in acidity/alkalinity can influence the presence and abundance of those **macroinvertebrates** that are either acid or alkaline tolerant, sensitive or specialists (such as 'acidophiles'). This in turn can have an influence on the **food web** of the wetland. For example, studies also indicate that many **species** of diatoms are sensitive to acidity/alkalinity.[8] Diatoms are a type of algae that occur in many Western Australian wetlands and they play an important role in food webs.

In more acidic wetland soils nutrients such as phosphorus, nitrogen, magnesium and calcium may be less soluble and therefore less **bioavailable** to organisms (Figure 24).[9] This may limit biological productivity in very acidic wetlands resulting in low wetland **metabolism**.[7] In particular, **decomposition** processes may be slow[7], meaning that more organic material is stored in forms that can't be used by plants and algae (and so by extension, animals). While cyanobacteria are found in many diverse and extreme environments, they are not found in low pH waters.[6] Researchers noted this during a study of forty-one wetlands on the Swan Coastal Plain (the coastal area between Jurien and Dunsborough), when it was observed that cyanobacterial blooms rarely occurred in those wetlands with a pH of less than 6.5.[10] In some very acidic wetlands, **chemosynthesis**, a much less common form of energy capture, may be prevalent rather than photosynthesis.

With calcium being less soluble, species which need calcium to develop shells may be less prevalent in very acidic wetlands.[4] It has been observed that gastropods (which have a shell) are rare in inland waters with a low pH.[11] On the other hand, species that appear to be acid-tolerant such as the sandfly (Ceratopogonidae) larvae[12] and some mosquitoes[7]

Organism: an individual living thing

Soluble: able to dissolve

Macroinvertebrates: animals without backbones that, when fully grown, are visible with the naked eye. The term is usually used to describe all of the insects, worms, molluscs, water mites and larger crustacea such as shrimps and crayfish

Food web: the feeding relationships of organisms within an ecosystem. Usually depicted as a diagram of a series of interconnecting food chains

Species: a group of organisms capable of interbreeding and producing fertile offspring, for example, humans *(Homo sapiens)*

Bioavailable: in a chemical form that can be used by organisms

Metabolism: the chemical reactions that occur within living things that are necessary to maintain life, including the digestion of food

Decomposition: the *chemical* breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its *physical* breakdown.[16,4] Also known as mineralisation

Chemosynthesis: the process by which organisms such as certain bacteria and fungi produce carbohydrates and other compounds from simple compounds such as carbon dioxide, using the oxidation of chemical nutrients as a source of energy rather than sunlight may be present, and some wetlands may support acidophiles such as the brine shrimp *Parartemia contracta*, which inhabits naturally acidic salt lakes.[13] Acidic lakes may be structurally dominated by **benthic microbial communities**[14] rather than by plants or algae (for more information, see the topic 'Wetland ecology' in Chapter 2).

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Naturally occurring amounts of arsenic and heavy metals in sediments and underlying rocks, such as aluminium, iron, lead, cadmium and mercury, are more soluble at a pH of 5 or less, and can be 'mobilised' under acidic conditions, and manganese availability can also increase.[7,9] These heavy metals in the water may then be taken up by plants or animals in contact with the wetland[4] and this may cause toxic and sometimes fatal effects. Fish are often very susceptible to mobilised aluminium and mass fish kills can be a result of toxic levels. Similarly mobilised aluminium and manganese may cause wetland plants to die.[7,9]

At high pH levels, the availability of iron, manganese, copper and zinc and the nutrient phosphorus is limited.[9] Meanwhile there is more conversion of the nutrient nitrogen from the chemical form of ammonium (NH_4^+) to ammonia (NH_3).[15] While ammonium is a form that can be taken up and used by plants, ammonia can be toxic in large amounts, and sensitive species, such as fish, may not be able to function optimally or survive in these conditions.[4]

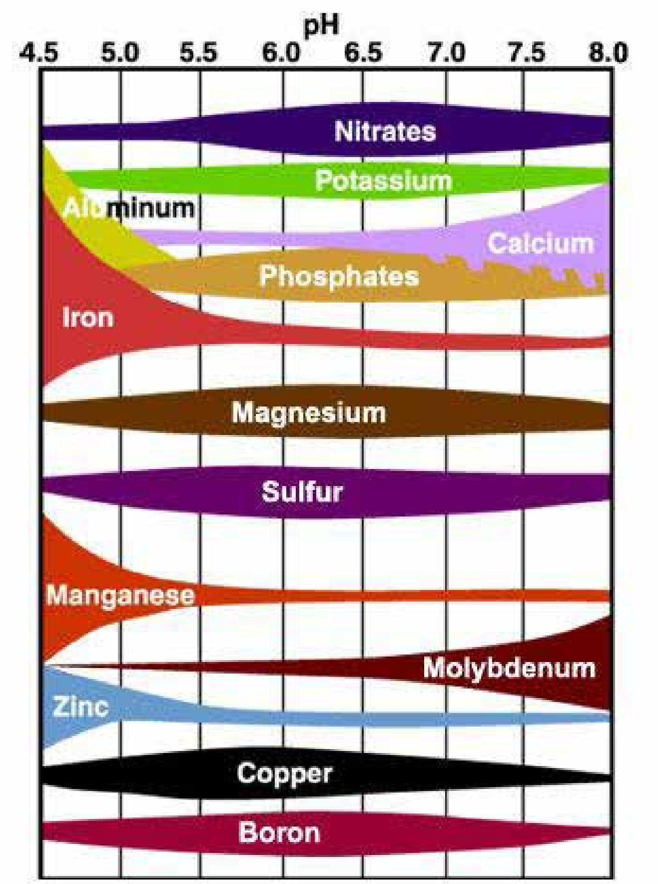

Figure 24. The effect pH has upon nutrient availability under general soil conditions. Image – University of Minnesota.

What is the natural acidity/alkalinity of Western Australian wetlands?

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

Reference range: a quantitative and transparent benchmark appropriate for the type of wetland

The pH of most Western Australian wetlands is naturally between roughly 6.5 and 8, but there are many exceptions to this. Acidity/alkalinity is naturally very variable among and within ecosystem types and seasonally.[6] Due to the existence of a wide range of natural maximum and minimum pH levels (as well as range between the two) in Western Australian wetlands, there is no definitive range for pH in WA waters.

The guidelines available for pH are only relevant to a sub-set of Western Australian wetlands. These are the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (known as 'the ANZECC guidelines' in reference to the author institute).[6] The ANZECC guidelines indicate that the pH in most permanently or seasonally inundated wetlands in WA should not drop below pH 6.0 or exceed pH 8.5 if no negative impact to the ecosystem is to occur (Table 6). These limits provide guidelines for the maintenance of acceptable conditions for plants and animals and default '**trigger values**' which indicate when further investigations may be required to determine the possible causes for pH not being within these desirable ranges.

Table 6. Default trigger values for pH (risk of adverse effects) from ANZECC & ARMCANZ[6]

Ecosystem location, type	pH	
Tropical Australia	**Lower limit [a]**	**Upper limit [a]**
Wetlands	6.0	8.0
South-west Australia		
Wetlands[b]	6.5	8.5

[a] *In highly coloured wetlands (gilvin greater than 52 $g_{440}m^{-1}$)[10] typical pH range 4.5–6.5.*

[b] *Amalgamated values; "freshwater lakes" and "reservoirs": 6.5–8; "wetlands": 7–8.5.*

However, the trigger values for the south-west of WA have been derived from a limited set of data (two years) collected at forty-one wetlands within and near Perth[10] and are only representative of basin wetlands of this region that are permanently or seasonally inundated rather than wetlands across the entire south-west of the state.[6] The trigger values from the north-west of the state are derived from an even more restricted study (less than one year) in the Pilbara region.[6] All trigger values should therefore be used with caution.

Therefore, it is important to consider how relevant these guidelines are for a particular wetland, and to identify, or have professional assistance to identify, an appropriate range in pH for the wetland, taking into consideration the natural factors affecting pH in wetlands outlined in this topic. Where possible, the aim of management should be to maintain the natural conditions of a wetland, including the natural range in pH.

Researchers have established **references ranges** for pH of inundated wetlands of the Wheatbelt region.[17] These reference ranges have been developed by analysing existing pH data from the region. Firstly, permanently or seasonally inundated wetlands in the region with monitoring data were identified as either saline basins, freshwater basins or turbid claypans. Following this, the least disturbed wetlands of each group were identified using expert opinion, and then the data of the least disturbed wetlands were analysed in order to establish a range in pH that may approximate the natural range. Excluding naturally acidic wetlands, the reference ranges are as follows:

- naturally saline basins: 7.8–8.7
- freshwater basin wetlands: 6.8–8.1
- turbid claypans: 8.6–8.9.

As per the ANZECC trigger values, these reference ranges should be used as a guide only and should be supported by site-specific studies if needed, due to the natural variability in pH between wetlands in WA.

extra information

pH - an indicator of wetland condition?

An understanding of a wetland's pH, and pH trends over time, can be very informative for wetland managers. However, initial investigations into the use of pH as an indicator of wetland condition in WA suggest that it could be more meaningful when paired with data of the total alkalinity and/or acidity at sites where the scale of change in pH is beyond that expected.[18]

extra information

Sources of data on pH of WA wetlands

Some data on the pH of wetlands in WA is available from *WetlandBase*[19], the Western Australian Wetlands Database, available online. *WetlandBase* is an interactive database by DEC, with web hosting by the Department of Agriculture and Food WA, available via http://spatial.agric.wa.gov.au/wetlands. *WetlandBase* provides an online resource of information and data about Western Australian wetlands. It provides spatial data, such as wetland mapping, and point data, such as water chemistry, waterbirds, aquatic invertebrates and vegetation sampling results. Note that DEC is preparing an alternative to *WetlandBase*, scheduled for release in 2013 that will continue to make this data publicly available.

What affects the acidity/alkalinity of wetland waters?

The natural factors that can affect the pH of wetland waters include:

- carbon dioxide levels
- sediment type
- quality of incoming water
- variation over time.

With an understanding of these factors, it is often possible to infer the reasons for a wetland's acidity/alkalinity. However, for some wetlands, the reasons can be complex and the investigations required to determine the causes can require research into the chemistry of groundwater, subsoil sediment and geology and an understanding of historical events such as drought, excavation and fire.

The acidity/alkalinity of wetland water can also be affected by human activities including agriculture, industry-causing acid rain, drainage of acid waters into wetlands, and drainage of wetlands leading to acid sulfate soils. All of these typically cause increased acidity.

➤ Human causes and their management are discussed in the topic 'Water quality' in Chapter 3.

Carbon dioxide

The amount of carbon dioxide (CO_2) in wetland waters strongly influences the natural acidity/alkalinity of the water because it reacts chemically with hydrogen (for a brief technical explanation, see the text box 'Why acidity/alkalinity is influenced by carbon dioxide' below).

Carbon dioxide is a gas that is readily available in the atmosphere, and it enters wetland waters directly from the atmosphere as it is quite soluble in water and dissolves easily.[4] Carbon dioxide is also produced by wetland plants, algae, animals and microbes during **respiration**. Once dissolved, it may then be taken up and used during the day by wetland plants, algae and cyanobacteria for **photosynthesis**.[4,10] As a decrease in carbon dioxide tends to increase the pH, elevated rates of photosynthesis in highly productive wetlands may lead to very high pH values. The concentration of CO_2 in wetland water fluctuates in response to these biological processes.

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

extra information

Why acidity/alkalinity is influenced by carbon dioxide

When carbon dioxide (CO_2) chemically combines with water (H_20), it forms carbonic acid (H_2CO_3). Most of the hydrogen ions in the waters of natural wetlands are derived from the chemical process in which carbonic acid (H_2CO_3) breaks down (dissociates) into hydrogen (H^+) and carbonate (CO_3^{2-}) or bicarbonate (HCO_3^-) ions.[4] In the form of a chemical equation, this is shown as:

$$CO_2 + H_20 \rightarrow H_2CO_3 \quad \text{dissociates into} \quad H_2CO_3 \rightarrow CO_3^{2-} + HCO_3^- + H^+$$

Since this process is a major source of H^+, and the effective concentration of H^+ determines pH, the dynamics of pH in water are dependent on those of CO_2.[4]

The relationship between CO_2 and pH also applies in **sediment pore waters**, but gas exchange in this environment is more limited, particularly in submerged sediments, and is not promoted by water movement as it is in surface waters. As a result, a major source of dissolved CO_2 in pore waters is from respiration by animals (such as midge larvae) and microbes living in the sediment pore waters.

Wetland sediment type

The natural acidity/alkalinity of wetland waters in WA is strongly influenced by the chemistry and physical characteristics of the wetland's sediments.[3] In particular:

- Wetlands with calcium-carbonate ($CaCO_3$) dominated sediments tend to be alkaline. They also tend to be buffered against large, rapid changes in pH.
- Wetlands on sandy soils with a lot of organic material may release humic substances (typically 'coloured' wetlands), and this can cause acidic waters (typically 4.5–6.5 pH).
- Wetlands with sediments which contain iron pyrite and which dry may be acidic.

These influences of sediment type generally affect pore waters first and extend to surface waters through diffusion. It could be expected that the acidity/alkalinity of the soil pore waters will typically be more extreme than the water column. The acidity/alkalinity of sediment pore waters may also be strongly influenced by the release of oxygen by plant roots, which may alter redox conditions (for more information, see the section 'Redox potential').

Wetlands with calcium carbonate (limestone, $CaCO_3$) dominated sediments tend to be naturally alkaline (Figure 25). For this reason, many coastal wetlands are alkaline.


(a)


(b)

Figure 25. Naturally alkaline wetlands: (a) Thomsons Lake, Beeliar. Photo - J Davis. (b) A seasonally waterlogged wetland in Port Kennedy. Photo - J Lawn/DEC.

In addition, these wetland sediments containing calcium carbonate are often 'buffered' (stabilised) against rapid changes in pH[3,1] due to their alkalinity. Carbonate acts as a 'buffer' by taking up excess hydrogen ions, and high carbonate concentrations can prevent large or sudden changes in the pH of wetland waters from occurring.[1]

Wetland waters can be naturally acidic (pH of 4–6[7]) if their sediments are rich in organic matter and release **humic** substances (tannic, humic and fulvic acids) from decaying vegetation. Humic substances leach out of the organic matter (mostly decaying plant material) occurring in the top layers of sandy wetland sediments (such as in **Bassendean sands** on the **Swan Coastal Plain**) and become dissolved in the wetland waters.[20] These wetlands are also highly coloured (see the 'Light availability' section of this topic for more information).

Wetland waters can also be naturally acidic if they are rich in iron pyrite (FeS_2, a yellow lustrous form of iron disulfide also known as 'fool's gold') and release sulfuric acid (H_2SO_4) from the **oxidation** of this iron pyrite. Pyritic sediments occur in many coastal wetlands throughout Australia[16], making many of the seasonally-drying wetlands naturally-acidic[21] (Figure 26). However, wetlands may become much more acidic when they are exposed to particularly long or severe periods of drying, leading to the development of **actual acid sulfate soils** (AASS).[21,22] Significant fire events can also cause oxidation and drying of sediments, leading to the development of AASS.[23]


(a)


(b)

Figure 26. Naturally acidic wetlands: (a) a seasonally waterlogged wetland on a slope in Bayonet Head, Albany, slightly acidic due to humic soils. Photo - L Sim/DEC; (b) Lake Gnangara, acidic due to iron pyrite sediments. Photo - J Davis.

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Bassendean Sands: (also known as the Bassendean Dunes) a landform on the Swan Coastal Plain, comprised of heavily leached aeolian sands, located between the Spearwood Dunes to the west and the Pinjarra Plain to the east

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Oxidation: the process of combining with oxygen causing a chemical reaction in which atoms or molecules gain oxygen or lose hydrogen or electrons

Actual acid sulfate soils: (also known as actual acid sulphate soils) naturally occurring soils and sediments containing iron sulfides that are disturbed or exposed to oxygen, causing the iron sulfides to be oxidised to produce sulfuric acid, causing the soil to become strongly acidic (usually below pH 4)

Quality of incoming water

The acidity/alkalinity and quality of water entering wetlands also influences wetland waters. Rainwater is naturally slightly acidic (as low as pH 5.5), due to dissolved atmospheric CO_2[4,3], but the acidity/alkalinity may be rapidly modified by chemical and biological processes once the water enters the wetland (for example, by carbonate buffering or photosynthesis).[4] In wetlands with little biological activity and few soluble minerals, the ecosystem may remain mildly acidic.

The acidity/alkalinity of inflowing surface water can be influenced by the characteristics of the catchment. For example, wetlands that receive surface water from granite-dominated catchments may be acidic.[4]

The natural acidity/alkalinity of groundwaters in WA is poorly known, due partly to a lack of data, and partly to high variability between sites. However, inflows of highly acidic or alkaline groundwaters would have a major influence on the acidity/alkalinity of wetland waters. Groundwater bores can be installed in order to determine groundwater acidity/alkalinity but its cause may require further investigation of subsoil geology and historical events such as fires and drought.

Groundwater discharging from coastal dunes tends to be alkaline due to the carbonate minerals within the aquifer sediments, so wetlands that receive this groundwater are often alkaline.

Deep groundwater in the Wheatbelt is thought to be naturally acidic[24,25] with high iron concentrations and limited amounts of neutralising minerals such as carbonates in the relevant strata. It is most prevalent in the eastern (mainly Avon) and south-eastern (Esperance coastal) zones.[25] Rising groundwater is creating a number of problems in wetlands in these areas including salinity and acidity, particularly in wetlands low in the landscape; those not affected are likely to be at very high risk over the coming decades.[25] These groundwaters contain high concentrations of dissolved aluminium, iron and trace metals like lead, copper and zinc leached from local geological materials by the acidic waters. Dissolved iron and aluminium in particular pose a threat because they represent a major store of hidden acidity not measured by pH alone, by reacting with water and releasing additional hydrogen ions into solution.[25] The presence of organic matter and neutralising minerals like carbonates in the wetlands will affect the degree and timeframe of acidification of such wetlands.

➤ The management of wetlands subject to acidification is covered in the topic 'Water quality' in Chapter 3.

Variation over time

A wetland's pH can naturally vary over time due to:

- the day/night cycle
- water temperature
- wetland water regime

Day/night cycle

pH varies over a 24 hour day/night cycle. The daily fluctuations occur due to two processes; during the day, photosynthesis by algae and submerged wetland vegetation takes up large amounts of CO_2 from the water and raises the pH, making it more alkaline. Respiration (which is predominant at night) by aquatic algae, plants, animals and microbes releases CO_2 and lowers the pH.[4] The alkalinity or buffering capacity of the wetland has an effect on how large this daily fluctuation is. A shallow, densely vegetated lake in central Victoria varied by up to 2 pH units across a day, in response to the processes of photosynthesis and respiration.[16] Wetland species are adapted to normal 24 hour cycle variations in pH. The main implication of daily changes in pH is for surveys and monitoring of wetland water quality. A clearer picture of the natural pH fluctuations in a wetland is gained if time of day is recorded and accounted for when measuring pH.

Salinity: a measure of the concentration of ions in wetland water. This measurement is used to describe the differences between waters that are considered 'fresh' (with very low concentrations of ions) and those that are considered 'saline' (with high concentrations of ions).

Water temperature

Water temperature also influences acidity/alkalinity; increased water temperature leads to an increase in pH.[26] This means that pH is likely to fluctuate over the year in many areas of the state.

Water dynamics

The acidity/alkalinity of the water in the wetland, and the acidity/alkalinity of groundwater and surface water entering a wetland can vary throughout the year because of seasonal hydrological dynamics and processes. These include dilution of the wetland water by progressive rainfall over the wet season; groundwater rise; downward saturated flow; concentration by evapotranspiration; and interactions with sediments such as leaching, ionic mobility and precipitation.

In wetlands that are seasonally or intermittently wet, the pH may vary between the wet and dry phases. In many wetlands pH will typically rise during the 'wetting up' phase (with a brief decline during filling if there is eucalypt leachate in the first runoff) and then fall during the drying phase.[4]

Other physical and chemical factors

Salinity

There is some evidence to suggest that pH decreases as **salinity** increases, but this appears to vary depending on the water chemistry (the relationship may be more prevalent where there are high concentrations of calcium ions, Ca^{2+})[27] and biotic processes (for example, photosynthesis may raise the pH of saline systems).[4]

Fire

Fire in a wetland or its catchment can have an effect on pH, although its influence depends on many factors. In many, but not all wetlands, fire can produce a short-term increase in pH, due to flushing of alkaline ash from the catchment and the combustion of organic soils.[23] A decrease in pH is also possible; the oxidation of sulfur following a fire can result in the development of actual acid sulfate soils, which can have a medium to long term effect on the pH of a wetland.

How is acidity/alkalinity measured?

pH is a straightforward and commonly used measure that is often, but not always, suitable for monitoring trends. Total titratable acidity better approximates total acidity by accounting for stored acidity, as outlined below.

'pH' is a measure of the effective concentration of hydrogen ions in water. The more hydrogen ions (symbol: H^+) in the water, the more acidic the water and the lower the pH reading.[3] As stated earlier, an ion is an atom that has acquired an electrical charge by the loss or gain of one or more electrons; it is used to refer to substances dissolved in solution.

The term 'effective concentration' is used to refer to the concentration of hydrogen ions that 'seem' to be present in a solution. The actual concentration is difficult to measure because hydrogen ions are constantly interacting with water (H_20) molecules. The effective concentration measures the amount of chemical ‘effect’ they are having in the solution.

As pH is represented on a log scale, a difference of one pH unit represents a tenfold change.[4] For example, a wetland water sample with a pH of 4 is ten times more acidic than one with a pH of 5. A difference of 2 units, from 6 to 4, reflects acidity one hundred times greater, and so on.

pH is straightforward to measure in both surface waters and sediment pore waters using a pH meter with different types of probes (Figure 27), depending on whether it is a surface or pore water measurement. In both cases, this requires water to be present, that is, a water column or saturation of the sediments. Since pH varies with temperature, most pH meters also measure temperature to take this into account. If a specialised pore water probe is not available, a ‘suspension’ of one part sediment to five parts water (or for potentially more accurate results, calcium chloride, $CaCl_2$) can be made, and a surface water probe used instead.[28]

Figure 27. A meter that measures pH. Photo – J Lawn/DEC.

extra information

Calculating the mean (average) pH

pH is represented on a log scale[4,3] and the scale runs from pH 0 to pH 14. The log scale means that each change in one pH unit (for example, from pH 4 to pH 3), represents a change in 10 times the concentration of hydrogen ions (for example, pH 3 has 10× greater $[H^+]$ than pH 4).[4] This means that when calculating the mean (average) of pH values, it is not correct to just add the values and divide by the numbers of recordings, i.e. the mean of pH 6 and pH 8 is not pH 7.[4] Instead, the pH values need to be converted to anti-logs, the mean calculated and the result converted back to a log value, as shown:

To calculate the mean of pH 6 and pH 8:

The anti-log of pH 6 = 10^6 = 1,000,000

The anti-log of pH 8 = 10^{15} = 100,000,000

The mean of these two values is (1,000,000+100,000,000)÷2 = 50,500,000

Convert the anti-log back to a log scale: $\log^{10}$(50,500,000) = pH 7.7

A cheaper but less accurate alternative for the measurement of surface or pore water pH is to use a soil or water testing kit, which involves mixing a reactive agent to the sample (water or soil suspended in water), then measuring the colour of the solution.

Since pH changes over time, and with temperature and biological activity, measurements are only representative of field conditions at the time of sampling, therefore pH samples cannot be stored for later analysis. As described, time of day also affects pH, often quite markedly, via the interaction of photosynthesis and respiration with CO_2 dynamics.

pH is usually measured directly and there are no commonly used surrogate measures. In some cases, vegetation composition or diatom community composition may be used as biological indicators of broadly acidic or alkaline conditions but these are not precise measures of pH.[29,2] As diatom valves can be well preserved in soils, fossil diatom assemblages have the potential to be used in palaeolimnological studies to help reconstruct past conditions in wetlands.[8]

➤ For detail on how to monitor pH, refer to the topic 'Monitoring wetlands' in Chapter 4.

Total titratable acidity

In wetlands with acid sulfate soils, both pH and titratable acidity is measured to account for the total acidity values. It is very important to understand that the pH of water measures the available amount of acid in an instant of time. It does not measure acidity that is stored in the water in the form of dissolved iron and aluminium that can later react with water and release additional hydrogen ions into solution. Total acidity, on the other hand, accounts for this. In most natural waters, about 90 per cent of the acidity is stored in the form of dissolved iron and aluminium.

Total titratable acidity is a better approximation of total acidity than pH alone. It may be important to monitor this along with pH if a wetland is at risk of acidification. Commercially produced kits are available for purchase, or can be made using items from the supermarket and pharmacy.

➤ For more information on total acidity and step by step instructions on how to make field kits, see the topic 'Water quality' in Chapter 3.

Total alkalinity

Total alkalinity is a measure of a solution's capacity to neutralise an acid, expressed as the amount of hydrochloric acid needed to lower pH of a litre of solution to pH 4.5. It can be a useful measure of how sensitive a wetland is to acidification. It can be measured in the field or in the lab.

➤ See the topic 'Water quality' in Chapter 3 for the US EPA's classification of wetland sensitivity to acidification on the basis of total alkalinity.

Sources of more information on wetland acidity/ alkalinity

The topic 'Water quality' in Chapter 3.

ANZECC & ARMCANZ (2000) '8.2 Physical and chemical stressors in Volume 2 Aquatic ecosystems — rationale and background information (Chapter 8)' of *Australian and New Zealand guidelines for fresh and marine water quality*.[6]

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Glossary

Actual acid sulfate soils: (also known as actual acid sulphate soils) naturally occurring soils and sediments containing iron sulfides that are disturbed or exposed to oxygen, causing the iron sulfides to be oxidised to produce sulfuric acid, causing the soil to become strongly acidic (usually below pH 4)

Alkalinity: a solution's capacity to neutralise an acid

Bioavailable: in a chemical form that can be used by organisms

Bassendean Sands: (also known as the Bassendean Dunes) a landform on the Swan Coastal Plain, comprised of heavily leached aeolian sands, located between the Spearwood Dunes to the west and the Pinjarra Plain to the east

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Buffering capacity: a solution's capacity to resist large or sudden changes in pH

Chemosynthesis: the process by which organisms such as certain bacteria and fungi produce carbohydrates and other compounds from simple compounds such as carbon dioxide, using the oxidation of chemical nutrients as a source of energy rather than sunlight (see 'photosynthesis')

Decomposition: the *chemical* breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its *physical* breakdown.[16,4] Also known as mineralisation.

Humic: substances formed from the decomposition products of polyphenols such as tannins, which are complex organic compounds derived from plant materials

Ion: an atom that has acquired an electrical charge by the loss or gain of one or more electrons

Metabolism: the chemical reactions that occur within living things that are necessary to maintain life, including the digestion of food

Organism: an individual living thing

pH: a soil or water quality measure of the hydrogen ion concentration, which indicates whether water is acidic, neutral or alkaline

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen.

Pyritic sediments: sediments containing iron pyrite

Redox: the removal ('oxidation') or addition ('reduction') of electrons

Reference range: a quantitative and transparent benchmark appropriate for the type of wetland

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Salinity: a measure of the concentration of ions in wetland water. This measurement is used to describe the differences between waters that are considered 'fresh' (with very low concentrations of ions) and those that are considered 'saline' (with high concentrations of ions).

Sediment pore waters: water which is present in the spaces between wetland sediment grains at or just below the land surface. Also called interstitial waters.

Soluble: able to dissolve

Solubility: a measure of how soluble a substance is

Species: a group of organisms capable of interbreeding and producing fertile offspring, for example, humans (*Homo sapiens*)

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

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REDOX POTENTIAL

Contents of the 'Redox potential' section

What is meant by redox potential?

Redox potential: the potential of chemical substances to undergo two (coupled) types of chemical change: the removal ('oxidation') or addition ('reduction') of electrons

Redox potential refers to the potential of substances in wetland sediment pore waters to undergo two types of chemical change – specifically, the addition ('reduction') or removal ('oxidation') of electrons. Redox is a coupled reaction in which one substance is oxidised by another which, in turn, is reduced.[1] The term redox is a combination of the first parts of each chemical change: *red*uction and *ox*idation.

Gaining a detailed understanding of reduction and oxidation reactions requires a background understanding of chemistry. However it is possible to gain a general understanding of the overall effect of these reactions without such a background. In summary, if a substance is oxidised or reduced, its chemical form is changed, meaning that it may be more or less useful to living things, more or less toxic, and more or less reactive to other substances. Its physical form may change from dissolved in solution to a solid precipitated out of solution, or vice versa.

The reduction and oxidation of substances is an extremely common, extremely important process in wetlands, particularly the sediment pore waters. This form of chemical change affects many substances that play an important role in wetlands, including nitrogen, phosphorus, carbon and sulfur.

What is oxidation?

Oxidation is the removal of electrons from a 'donor' substance, which is a reaction that occurs:

- when oxygen is added to a substance
- when hydrogen is removed from a substance
- when electrons are removed from a substance.

Oxidation is a common reaction that causes effects such as the browning of an apple when cut and left exposed to air and the rusting of iron. A very important oxidation reaction is the oxidation of carbohydrates $(CH_2O)n$ to carbon dioxide (CO_2) by living things.

What is reduction?

Reduction is the addition of electrons to an 'acceptor' substance; the opposite reaction to oxidation. It occurs:

- when oxygen is removed from a substance
- when hydrogen is added to a substance
- when electrons are added to a substance.

The addition of hydrogen and electrons to oxygen gas (O_2) is an example of the reduction of oxygen to water (H_2O).

Why is redox potential important?

Redox conditions influences the availability of energy and concentrations of chemical compounds in wetlands. This in turn affects the types and health of bacteria, plants, algae and animals that live in wetlands.

The physical and chemical form of many substances is a result of being oxidised or reduced. Solid substances may become soluble, and dissolve in solution. For example, iron (ferric iron) in solid form can be reduced to a soluble form (ferrous iron). A nutrient may be changed from a chemical form that cannot be used by plants and algae to one that can be used, creating flow-on effects through the wetland food web. It also affects the extent to which toxins such as heavy metals (like mercury and cadmium) will be available to be taken up by plants and animals (they are more available under reducing conditions).

Anoxic: deficiency or absence of oxygen

Even those substances that are not directly affected by oxidation and reduction may be affected if they interact with other substances that do undergo oxidation and reduction. For example, phosphate (PO_4^{3-}, a form of phosphorus important for plants, algae and some bacteria) is influenced by the chemical form(s) and abundance of iron and aluminium.[1] This occurs by adsorption of the phosphate to compounds such as $Fe(OH)_3$ (iron (III) hydroxide) at low redox potential (oxidising conditions)[2], forming insoluble materials which settle out of the water column. Under reducing conditions, the phosphate becomes soluble and is released into solution in wetland waters, making it available for use by primary producers.

What affects the redox potential of wetland sediment pore waters?

The determinants of redox potential are the presence or absence of oxygen and the pH.

The presence or absence of oxygen strongly affects the redox potential. Redox potential is higher with oxygen. Whether or not a wetland dries out seasonally or intermittently affects whether the upper layers of the sediment will become oxic (that is, oxygen will be present). Similarly, in the water column of a wetland, the oxygenation and mixing of surface waters influences whether the top layers (~ 5 millimetres) will become oxic or **anoxic**, while the deeper layers of sediment tend to be anoxic. Oxygen availability tends to be higher when a wetland is shallow, dries out regularly, has wind or wave action or there are wetland plants that 'leak' oxygen into the sediments via their roots.

Redox potential is also greatly influenced by pH. As pH increases (that is, the pore water becomes more alkaline), the redox potential falls.

Many oxidation and reduction reactions are facilitated by photosynthesis and by different types of bacteria. Organic compounds provide the source of oxidisable material for most wetland bacteria. These bacteria use electron acceptors to oxidise organic material in order to make use of its energy (common inorganic electron acceptors include O_2, Fe^{3+}, Mn^{4+}, SO_4^{2+} and CO_2). The availability of electron acceptors besides oxygen allows bacteria to respire and grow when and where oxygen is not present.[3]

How is redox potential measured, and what units are used?

Redox potential is most commonly measured in the sediments but can also be measured in the water column. It is measured using a redox meter with a probe adapted for use in either water or sediments. These meters are generally fitted with a hydrogen electrode for use in the laboratory or a platinum electrode and a calomel electrode for use in the field.[2] The chemical symbol for redox potential is E_7 or E_h and measured in millivolts (mV). It can be difficult to obtain reliable measurements in the field due to lack of chemical stability between chemical forms or at electrodes and for this reason it is often not measured. However, the usefulness of measuring redox potential is to enable the broad distinction between oxic, anoxic and reducing conditions.[3] Anoxic (oxygen-deficient) conditions suggestive of reducing conditions are often inferred by the presence of black sediments and the characteristic 'rotten egg' smell of hydrogen sulfide. However, it should be noted that the fact that a sediment is anoxic does not necessarily mean that the conditions in it are also reducing.[3]

There are no usual ranges of redox potential in Western Australian wetlands, nor are there recognised acceptable limits. Redox potential can change rapidly within a wetland over a short period of time, particularly with changes in a wetland's water regime and water mixing. The classification of redox potentials is shown in Table 7.

Table 7. Redox conditions and cutoffs in sediments (Bohn 1971)[4]

Description of conditions	Cut-off levels (millivolts, mV)
Oxidising	Greater than +400
Moderately reducing	+100 to +400
Reducing	-100 to +100
Highly reducing	Up to –100

Sources of more information on redox potential

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Glossary

Anoxic: deficiency or absence of oxygen

Oxidation: the removal of electrons from a donor substance

Reduction: the addition of electrons to an acceptor substance

Redox potential: the potential of chemical substances to undergo two (coupled) types of chemical change: the removal ('oxidation') or addition ('reduction') of electrons

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CARBON

Contents of the 'Carbon' section

What is carbon?

Carbon is often referred to as 'the building block of life' as it is a part of all living tissue. Carbon is a key chemical element required for the growth and reproduction of wetland plants, animals and microbes.[1] It is often referred to by its chemical symbol 'C'.

As well as being present within organisms, carbon is present in the atmosphere as the gas carbon dioxide (chemical symbol 'CO_2') and in soil and water. Carbon in wetland ecosystems can be divided into two main groups: organic and inorganic. Organic carbon relates to carbon existing in or derived from living organisms, including all living and dead plant, animal and microbial material in a wetland. It is distinct from inorganic carbon, which in a wetland takes various forms in solution including dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and carbonic acid (H_2CO_3).[2]

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Chemosynthesis: the process by which organisms such as certain bacteria and fungi produce carbohydrates and other compounds from simple compounds such as carbon dioxide, using the oxidation of chemical nutrients as a source of energy rather than sunlight

Particulate: in the form of particles, which are very small portions of matter

Dystrophic: wetlands that suppress increased algal and plant growth even at high nutrient levels due to light inhibition

Why is carbon important in wetlands?

Carbon is a source of energy

All plants, animals and microbes must consume carbon in order to survive and grow. It is a major component of plant and animal tissue and microbial cells.[3]

Plants, algae and some species of bacteria (collectively known as 'primary producers') can use inorganic carbon (such as carbon dioxide, CO_2, or bicarbonate, HCO_3^-) to create energy through the process of **photosynthesis** (with the exception of some bacteria which instead do so via the process of **chemosynthesis**). All other organisms take up the carbon they need in an organic form, that is, in the form of living or dead tissue (these organisms are 'consumers' and 'decomposers' respectively).

➤ For more information on primary producers, consumers, decomposers and the food webs they form, see the topic 'Wetland ecology' in Chapter 2.

Dissolved and **particulate** forms of organic matter are important food sources for invertebrates and microbes (including some bacteria and algae) in wetlands.[2] They consume this carbon in a variety of ways:

- some animals filter their food, in the form of particulate organic matter, out of the water column
- some absorb dissolved compounds
- some graze on algae and fungi colonising the larger particles
- others eat the larger particles themselves.[3]

Carbon affects water conditions

Wetlands with high levels of organic material in their waters may function differently to those which retain little organic material.

For example, wetland waters that are coloured due to high levels of dissolved organic carbon do not support algal/cyanobacterial blooms even at high nutrient concentrations, because there is insufficient light penetration into the water column to allow algal blooms to develop.[4] These wetlands are often referred to as '**dystrophic**' (for more information, see the section on colour within 'Light availability' in this topic).

'Humic' wetlands are often acidic with natural pH levels as low as 4.5 due to the prevalence of organic carbon compounds (humic, tannic and fulvic acids) dissolved in the waters.[5,3] Major physico-chemical influences such as these have flow-on effects for other parameters such as dissolved oxygen, which is lower in waters with high levels of dissolved compounds, and photosynthesis, which may be suppressed both by low light and low pH.[6] Semeniuk (2007) reported that in some Becher wetlands (near Rockingham, south of Perth) the water is calcium carbonate saturated and has a pH of 8–8.5 when residing in the underlying dune sand and in the carbonate mud deposits of the wetland, but as it travels through the humic material of the wetland its pH can fall to 7–7.8.[7]

Particulate organic matter also has a strong influence on light and temperature within the aquatic environment, as it absorbs and refracts light, causing the water to heat up more quickly, and may cause it to stratify.

Carbonate, an inorganic form of carbon, buffers wetland waters from large changes in pH.

The movement of carbon can influence the cycling of other important chemical elements such as nitrogen and phosphorus due to their incorporation into organic compounds and subsequent movement through food webs. Another reason that carbon plays an important role in ecosystems is because it frequently forms chemical bonds with other elements including hydrogen, oxygen, nitrogen and sulfur (creating 'organic compounds'), and therefore becomes involved with the cycling processes of these other elements through wetland ecosystems.[8]

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (such as leaves), exuded and excreted substances and products of feeding.

Humus: the organic constituent of soil, usually formed by the decomposition of plants and leaves by soil bacteria

Peat: partially decayed organic matter, mainly of plant origin

Anoxic: deficiency or absence of oxygen

Carbon forms part of wetland soils

In wetlands with a water column, the less soluble compounds in the water column often aggregate into larger particles and settle out from the water column, and along with larger plant and animal debris, form part of the soil material of a wetland. This soil material also develops in waterlogged wetlands, through the breakdown and 'sedimentation' of plant and animal **detritus**, although generally to a lesser extent. This material may form soil such as carbonate muds or calcilutite, or **humus** or **peat**, depending on the pattern of wetting and drying in the wetland (its hydroperiod) and various other processes and conditions, such as acidity. Some plants contribute a lot of litter that forms part of the organic sediment fraction, such as the common Perth sedge, *Baumea articulata*.[9] Once the sedimented organic material becomes covered by further sediment and forms part of the **anoxic** zone, its breakdown is extremely slow.[3] If a wetland's sediments dry, the exposure of the organic carbon to oxygen speeds up its decomposition by microbes, and as a result, much less organic soil material tends to accumulate in regularly-drying wetlands.[10] Associated factors that may affect the rate of decomposition of organic material are the pH of the detritus itself and the buffer capacity of the surrounding water.[11]

extra information

Carbon rich soils of the Becher wetlands

Wetland scientist Dr Christine Semeniuk undertook a detailed study of the Becher wetlands, located on the coast between Rockingham and Mandurah on the Swan Coastal Plain.[7] Dr Semeniuk found these wetlands to be carbon rich, with some of the carbon derived from beach shell material, and fossil shell material from the freshwater gastropods *Gyraula* sp. and *Glyptophysa* sp. which in the past inhabited many of these wetlands. Shells and shell fragments were found either scattered in the wetland soils or forming shell laminae beds. Highly disintegrated shell material was also present in the form of small grains, forming part of the wetland sediment, along with other sources of carbon from fragments of algae (charophytes), molluscs and crustaceans including seed shrimp (ostracods). Plant material was also found to contribute significantly to the carbon content of the wetland sediment, in particular, the remains of the grass tree (*Xanthorrhoea preissii*), coast sword-sedge (*Lepidosperma gladiatum*), jointed rush (*Baumea articulata*), *Typha* sp. and coast saw-sedge (*Gahnia trifida*). Trees including banbar (*Melaleuca teretifolia*) and swamp paperbark (*Melaleuca rhaphiophylla*) and the herb *Centella asiatica* were also found to contribute to the carbon content of the sediment.

What are the main forms of carbon in wetlands?

Table 8 outlines the main forms of carbon in wetlands. The table shows carbon in two main groups: organic and inorganic. The cycling of these two types of carbon compounds directly represents the way that energy and living material is moving through the wetland ecosystem.

There are two main sources of carbon in wetlands:

- allochthonous carbon, that is, carbon originating outside the wetland, for example, leaf litter from vegetation in the catchment
- autochthonous carbon, originating from within the wetland, for example, vegetation and algae growing within the wetland.

Table 8. Forms of carbon and implications for wetland management

Name	Chemical form	Description	Implications for management
Carbon dioxide	CO_2	A gas that dissolves in water. It is ten times more soluble in water than oxygen, and is derived from the atmosphere and respiration by wetland organisms.[2] Carbon dioxide is able to be 'fixed' (used) by plants, algae and microbes to create organic materials via photosynthesis or chemosynthesis.[2,8] It is the major source of inorganic carbon to wetlands.	A critical component of wetlands as it is needed for photosynthesis. However it rarely limits plant growth as it is freely available from the atmosphere.[12]
Carbonic acid	H_2CO_3	The 'hydrated' form of CO_2 (i.e. water has been added). As a weak acid, it lowers the pH of wetland water by dissociation (breaking up) into H^+ and HCO_3^- ions (see 'pH' section). Carbonic acid is not directly utilised by organisms, although its component ions are.[2]	Lowers the pH of wetland waters.
Bicarbonate	HCO_3^-	One of the ions resulting from the dissociation (breaking up) of carbonic acid, and is most abundant in neutral to slightly alkaline waters (pH 7–9). Bicarbonate is utilised by some aquatic plants and macroalgae as a carbon source for photosynthesis.[2]	Used by some aquatic plants and macroalgae for photosynthesis.
Carbonate	CO_3^{2-}	A further dissociated form of HCO_3^-, which occurs most abundantly at alkaline pH.[2] At high pH (often resulting from photosynthesis), carbonate reacts with calcium ion (Ca^{2+}) and precipitates out of the water (becomes an insoluble solid) as calcium carbonate (calcite, $CaCO_3$).[8] Where abundant, carbonate has an important role as a chemical 'buffer' of wetland waters; preventing them from changing pH too rapidly.[13]	Important in providing buffering capacity to wetlands. Knowledge of a wetland's buffering capacity is useful if there is the potential for threatening processes or restoration activities to alter the pH.
Methane	CH_4	Methane is produced by one type of bacteria and used by a different type of bacteria. Methane is produced by bacteria known as 'methanogens'. They are prevalent in the sediments of freshwater wetlands. Methanogens produce methane by decomposing organic material in anaerobic conditions (that is, in the absence of oxygen). This process is called 'methanogenesis'. It is not as prevalent in saline wetlands, where it tends to be out-competed by sulfate reduction. Sulfate is more abundant in saline wetlands and its reduction yields more energy for sulfate-reducing bacteria than carbon dioxide does for methanogens.[10] Together with CO_2, methane is a significant greenhouse gas.[10] Freshwater wetlands that have large stores of organic carbon in their sediments (such as peat-containing wetlands along the south coast of WA) tend to contribute more methane to the atmosphere. The methane-using bacteria are known as 'methanotrophs'. They require oxygen and as such are limited to areas where oxygen is available, such as around plant roots in inundated soils. Methanotrophs limit the transfer of methane to the atmosphere (for example, a study in Florida found that half of the methane produced was oxidised by methanotrophs).[10]	Important for the production of energy by methanogens in anoxic conditions. Used by methanotrophic bacteria for chemosynthesis in aerobic conditions.

Name	Chemical form	Description	Implications for management
Biological molecules		Includes carbohydrates, lipids, proteins and nucleic acids. These are carbon-containing chemicals manufactured by plants and microbes. These biological molecules are included broadly in the categories of dissolved and particulate organic carbon. Used by plants, animals and microbes for a wide range of functions including the production of energy, cells and tissues, plant and animal hormones, enzymes and genetic material.[14] Animals often need to source theirs by eating living or dead biological material.	Essential food for animals (consumers) and microbes (decomposers).
Polyphenols (including tannins)		Are dissolved organic carbon chemicals produced during plant metabolism. Tannins are complex polyphenols, derived from plant material.[15] Dissolved organic matter (DOM) is the dominant form of organic carbon in almost all aquatic ecosystems with a water column.[16] May protect plants against grazers by making them toxic or unpalatable, and may also give plants colour.[15] Tannins contribute to the colour of wetland waters, and may also lower the pH.	Important for water colour and pH.
Humic substances (humic and fulvic acids)		Decomposition products of polyphenols.[15] Along with living plants, humic substances are often the dominant form of organic carbon in waterlogged systems. Dissolved humic substances impart colour and acidity to wetland waters and can be an important source of carbon to microbes.[17] Humic substances may also have inhibitory and regulatory roles in wetlands.[17]	Important for water colour, pH and microbial activity.

How is carbon transformed and transported?

Carbon in wetlands is converted into different forms, and can be transported into and out of wetlands. These transformations and sequences are part of the carbon cycle, with the wetland components of the cycle shown in Figure 28.

Key parts of the carbon cycle include:

- import
- dissolution
- dissociation
- photosynthesis and chemosynthesis
- consumption
- excretion/secretion
- degradation
- aerobic and anaerobic decomposition
- photodegradation
- precipitation
- adsorption
- storage

These are described below.

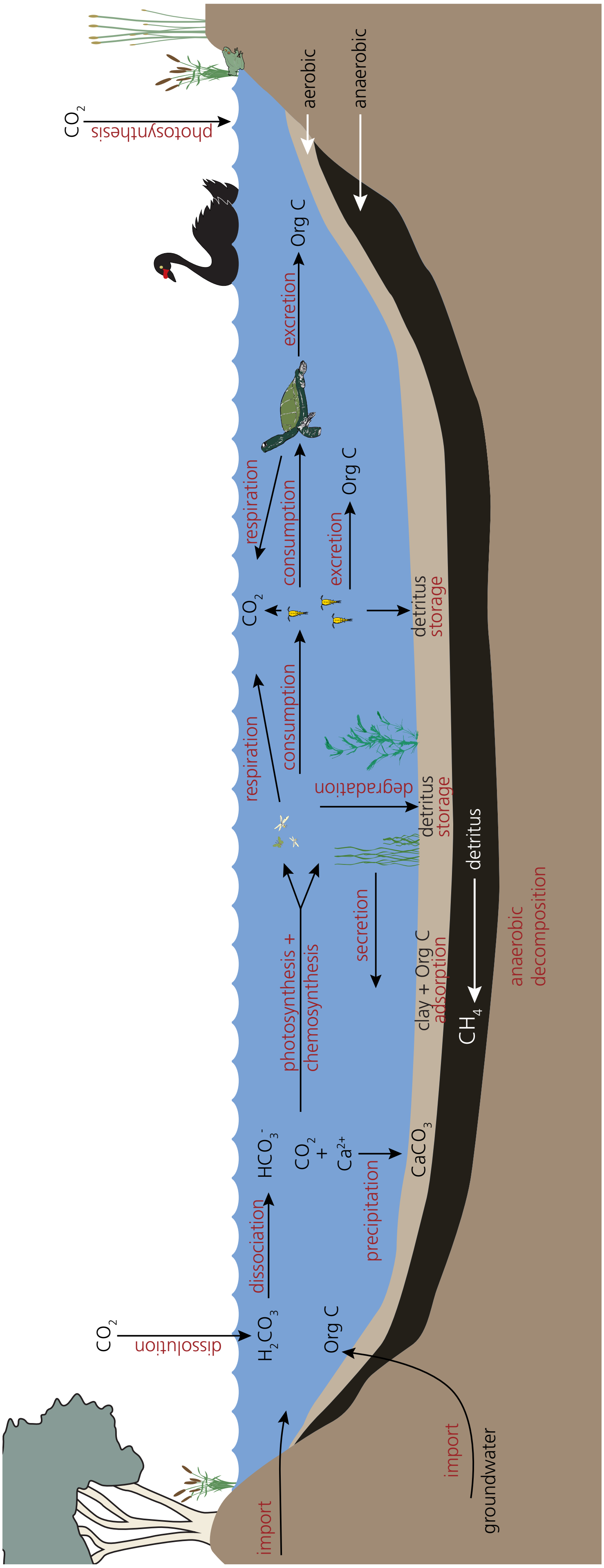

Figure 28. Simplified depiction of the wetland carbon cycle.

Import of inorganic carbon - dissolution

The major source of inorganic carbon to wetlands is atmospheric carbon dioxide (CO_2). Second to this is the CO_2 produced through plant, animal and microbial respiration. Carbon dioxide dissolves readily in water, and for this reason carbon is generally not a limiting factor in wetlands. A small amount of dissolved carbon dioxide joins with water to become carbonic acid.[2]

Global climate change may lead to alterations in the amount of dissolved organic matter in wetlands due to increased concentrations of atmospheric CO_2 and CH_4, and warmer temperatures encouraging algal growth.[18]

Import of organic carbon

Other than mobile animals, there are two sources of organic carbon in wetlands: carbon generated (fixed) by photosynthesis within the wetland, and carbon imported into the wetland by wind or water movement, including groundwater transporting leached humic substances. The movement of water can often be a major means of transporting organic material from one location to another. In practice, the carbon in most WA wetlands is a combination of both internal and external sources. The concentration of dissolved organic carbon (DOC) increases in direct proportion to decreasing water level (and vice versa) in wetlands.[19]

The timing, amount and quality of organic carbon imported into a wetland has a major driving influence on wetland metabolism. The origin of organic material determines the type of carbon input, which has significant flow-on consequences. For example, it influences the wetland's structure (such as the types of species present) and functions (such as the dominance of processes such as decomposition or methanogenesis).[15,3] Clearing of either wetland or dryland vegetation may lead to a decrease in the input of carbon to wetlands.[16]

Changes to species composition of near by terrestrial vegetation can alter the timing and quality of carbon inputs into wetlands. For example, in southern temperate areas *Eucalyptus* species have their main period of leaf fall in summer, while introduced deciduous species have theirs in autumn. As deciduous species drop most of their leaves in a very short period, this can produce a large 'spike' in carbon and nutrients in the wetland (and clog stormwater systems). The chemical and nutritional composition of these species also differs. While leaves from some introduced deciduous species are soft and easily decompose, a lot of native dryland plant material, and some wetland plants are very tough due to lignin, unpalatable due to antiseptic tannins[20], and of less nutritional value. These traits makes these plants less attractive foods for consumption and more resistant to decomposition.

These sorts of changes to the amount, timing and quality of carbon inputs can affect the rates at which organic carbon is converted to other forms, and may alter the relative dominance of ecological processes (such as the production of methane) or wetland species (such as insect larvae that rely on summer leaf litter inputs for their development).

Changes in the chemical form of carbon in solution - dissociation

Carbon dioxide dissolves readily in water, and for this reason carbon is generally not a limiting factor in wetlands. A small amount of dissolved carbon dioxide joins with water to become carbonic acid.[2] Carbonic acid (H_2CO_3) breaks up (dissociates) into bicarbonate (HCO_3^-) and hydrogen (H^+) ions, then bicarbonate breaks up further into carbonate

(CO_3^{2}) and hydrogen ions.[2] Depending on the pH of the water, different amounts of CO_2, H_2CO_3, HCO_3^- and CO_3^{2-} are present, with mostly carbonic acid at low pH and mostly bicarbonate ions at high pH.[2]

Photosynthesis and chemosynthesis – turning inorganic carbon into organic carbon

Plant, algae and microbes underpin the productivity of wetland ecosystems by converting carbon into organic form. Plants, algae and bacteria mostly use atmospheric or dissolved CO_2 for photosynthesis and chemosynthesis, although aquatic plants and macroalgae are also able to use bicarbonate (HCO_3^-) if CO_2 concentrations are low.[8] In areas where little detrital carbon is preserved in the sediments or water column, this autochthonous production is even more critical. The majority of CO_2 'fixed' (converted to biological materials) in wetlands is a result of photosynthesis rather than chemosynthesis.[8,3] The process of methane oxidation by methanotrophic bacteria is a form of chemosynthesis that can use large amounts of the greenhouse gas methane (CH_4).[21] Methanotrophic bacteria may therefore play an important role in carbon cycling, and influencing the release of greenhouse gases.[22]

Enrichment of wetlands with nitrogen and phosphorus may lead to increased growth of algae or wetland plants, and increase the importance of these sources of carbon within wetlands. Both algae and submerged aquatic wetland plants have strong influences on other aspects of water quality (such as dissolved oxygen concentration and light penetration), therefore multiple effects on carbon cycling may result.

Consumption of organic carbon

Animals, fungi and microbes that consume living or dead plant, algal and bacterial material take their carbon in organic form, for example, as carbohydrates, lipids and proteins.

Many forms of dissolved organic material are consumed by bacteria (the 'microbial loop').[23,8] The 'microbial loop' describes the way in which bacteria can decompose and incorporate matter (such as humic acids) that other organisms cannot; allowing these substances to enter the food chain.[23] Bacteria play an important role in consuming humic substances, thereby ensuring this carbon remains biologically available.

Excretion/secretion of organic carbon

Dissolved organic compounds such as carbohydrates and polyphenols may enter wetland waters as by-products of the metabolism of wetland plants, forming a food source for bacteria.[10,17] Other dissolved organic compounds such as urea [$(NH_2)_2CO$] are released as waste products excreted by animals. These all add to the total pool of dissolved organic carbon in wetlands.

Degradation of organic carbon

An extremely important part of the cycling of carbon is its breakdown from more complex to simpler physical and chemical forms. When organisms die and become detritus, both degradation and decomposition of the detrital material occur. 'Degradation' refers to the *physical* breakdown of organic matter.[10,2]

Organic carbon in the form of dead, excreted and secreted matter can undergo degradation, leaving smaller pieces. The breakdown of large pieces of detritus into small pieces can occur through physical processes such as wind or wave action or biological processes such as grazing for example, by invertebrates such as aquatic snails. Eventually the pieces become so small as to be close to the size of dissolved materials.

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Respiration (aerobic decomposition)

Like degradation, decomposition is an extremely important part of the carbon cycle as it results in the breakdown of matter from more complex to simpler physical and chemical forms. Decomposition is the chemical breakdown of organic matter mediated by bacteria and fungi. Decomposition occurs via several main processes in wetlands; aerobic (respiration) and anaerobic (methanogenesis and sulfate reduction) processes.[10] The chemical breakdown (decomposition) of organic matter into inorganic compounds is also known as 'mineralisation', as it results in the production of minerals.[10]

Animals, plants and microbes **respire**, that is, consume oxygen (O_2) and generate carbon dioxide (CO_2).[10] This process is known as aerobic (oxygenated) respiration and its purpose is to decompose of detrital organic matter by all animals and plants and many microbes. The carbon dioxide generated from aerobic respiration is a major source to wetland waters.

In wetlands with a water column (as compared to those in which the sediments are waterlogged), dissolved organic matter (DOM) is the dominant form of organic carbon, and are driven by detrital material.[16]

Decomposition is the major fate of organic matter in wetlands.[21,24] Changes to the water regime of a wetland and increases in nutrients can upset the natural rate of decomposition in the wetland[21] and ultimately change the way the wetland functions and the values it supports.

Anaerobic decomposition

The decomposition of organic material in the absence of oxygen carried out by specialised bacteria. The dominant processes of anaerobic decomposition of organic material in wetlands are methanogenesis and sulfate reduction. Methanogenesis generates methane gas (CH_4) and is the dominant process in freshwater wetlands, while sulfate (SO_4^{2-}) reduction is dominant in saline waters.

Anaerobic processes are much less dominant in waterlogged than inundated wetlands, because without a water column, the surface sediments are open to the air, and therefore oxygenated. However, anaerobic processes do take place in the deeper, anoxic portion of the sediments, trapping by-products such as methane, which are then only released to the atmosphere if the sediments are disturbed, or through emergent vegetation, such as sedges, which act as channels for gases.[10] In Western Australian wetlands that dry, anaerobic processes occur when they are wet (waterlogged or inundated) on either a seasonal or intermittent basis, since methanogens are obligate anaerobes (require anoxic conditions) making them very sensitive to exposure to air.[25] There is evidence to suggest that when seasonally-drying wetlands re-wet, they can produce methane at similar rates to permanently wet wetlands.[10]

Salinisation of wetlands can lead to a shift from methanogenesis to sulfate reduction, due to increased sulfate (SO_4^{2-}) concentration. This may cause an alteration in the dominant processes of organic matter breakdown in these wetlands.

Changes to wetland wetting and drying such as increased or decreased periods of inundation or waterlogging can affect bacterial processes by changing redox conditions and sediment characteristics.[26] This can affect factors such as phosphate (PO_4^{3-}) release from wetland sediments.

Global climate change may lead to increases in the methane generated by wetlands globally, due to increased ambient temperatures and increased microbial activity (especially in the northern hemisphere).[27]

Photodegradation

Humic and fulvic acids are subject to photodegradation, that is, decomposition by light.[8] If a wetland is to remain coloured, these acids must be continually replaced by the breakdown of decaying plant material. Increased light penetration (for example, through the removal of shading vegetation) can increase the rate of photodegradation. In these ways, the clearing of vegetation can significantly reduce wetland colour, which in turn can dramatically affect the ecological character of a wetland.

Precipitation of carbon

'Precipitation' occurs when solid (insoluble) substances form and settle out of solution. In the case of carbon, carbonate (CO_3^{2-}) often precipitates out of wetland waters as calcium carbonate ($CaCO_3$) at high pH (often due to photosynthesis).[8]

Adsorption (attaching to the surface of a particle)

Dissolved organic materials such as humic acids and fatty acids may come out of solution when they adsorb (attach) onto particles of clay or calcium carbonate ($CaCO_3$).[8]

Storage

Peat-containing wetlands such as peatlands contain large reserves of carbon.[28] They are not a predominant wetland type in WA, occurring most commonly in the wetter temperate regions such as the south coast. They occur mostly in the northern hemisphere. Factors such as altered water regime and fire can diminish carbon stores.

What affects the concentration of carbon in wetlands?

In general, Australian wetlands tend to be relatively rich in dissolved organic carbon, with the mass of dissolved organic matter being far greater than the mass of living organisms in many cases.[2,8] The type and quantity of both dissolved and particulate organic materials varies greatly between wetlands and is influenced by the following factors:

- degree of waterlogging or inundation and period when water is present (intermittently, seasonally or permanently)
- setting within the catchment; for example low-lying basin versus slope-side
- the amount of aquatic and other wetland vegetation
- connection with groundwater[2,8,3]

The flow of energy and carbon through wetlands can vary greatly between systems. For example, the food webs of some wetlands may be driven by allochthonous carbon sources (such as lakes that receive organic debris from surrounding terrestrial vegetation) while others by autochthonous carbon (such as arid zone saline wetlands driven by in-basin production by algae). In practice, there is rarely a distinct division of wetlands driven by either allochthonous or autochthonous carbon, and most receive a mixture of both types of sources.

How is carbon measured, and what units are used?

In wetland waters, inorganic forms of carbon are rarely measured; as such the following section focuses on the measurement of organic carbon.

Concentrations of dissolved and particulate organic carbon in surface waters are sometimes used as monitoring parameters for wetland condition, but not those of sediment pore waters. The organic carbon content of sediments, combining dissolved and particulate forms, is often measured. Total organic carbon in the water column is measured by laboratory analysis, and must be collected in a dark brown glass container to prevent photodegradation. Sediment organic carbon is determined by oven drying then combusting samples.

Both dissolved and particulate organic carbon are usually expressed as concentrations; mass (of carbon) per volume (for example, milligrams of carbon per litre; mg C/L) for surface waters or per weight (milligrams of carbon per gram; mg C/g) for sediments. These values include a whole range of substances and do not distinguish between compounds that break down readily and those that resist decomposition and become humus. The dissolved organic compounds that contribute to 'colour' (and affect the light climate of the water column) can also be measured using 'absorption spectrometry'. The measurement of gilvin concentration could be seen as a partial surrogate for dissolved organic carbon concentration, but it is really only used to infer changes to the light climate of a wetland (see the 'Light availability' section).

Information on organic matter content is often not collected as part of a routine monitoring program. It may provide valuable insight about the functioning of wetland food webs, but is relatively expensive to determine.

Sources of more information on carbon in wetlands

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Glossary

Anoxic: deficiency or absence of oxygen

Chemosynthesis: the process by which organisms such as certain bacteria and fungi produce carbohydrates and other compounds from simple compounds such as carbon dioxide, using the oxidation of chemical nutrients as a source of energy rather than sunlight

Dystrophic: wetlands that suppress increased algal and plant growth even at high nutrient levels due to light inhibition

Humus: the organic constituent of soil, usually formed by the decomposition of plants and leaves by soil bacteria

Inorganic carbon: (in a wetland) various forms of carbon in solution from non-organic sources including dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and carbonic acid (H_2CO_3)

Organic carbon: carbon existing in or derived from living organisms including all living and dead plant, animal and microbial material

Particulate: in the form of particles, which are very small portions of matter

Peat: partially decayed organic matter, mainly of plant origin

Photodegradation: chemical breakdown caused by UV light

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

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NITROGEN AND PHOSPHORUS

Contents of the 'Nitrogen and phosphorus' section

What are nitrogen and phosphorus?

A 'nutrient' is defined as 'any substance that provides essential nourishment for the maintenance of life'.[1] A whole range of substances are nutrients, but in wetlands nitrogen and phosphorus (with the chemical symbols 'N' and 'P'), are the two main nutrients of interest. The nutrients required by plant growth in aquatic systems in the greatest amounts are carbon, nitrogen, phosphorus, sulfur, magnesium, calcium and potassium.[2]

Why are nitrogen and phosphorus important in wetlands?

Nutrients are essential for life. Nitrogen and phosphorus are 'macronutrients', meaning that they are required in relatively large amounts by organisms to develop and maintain living tissue and for their **metabolic processes**. Nitrogen is needed by organisms to make amino acids, proteins and enzymes, which are essential for living cells. Nitrogen is also used to create genetic material (DNA and RNA), and even the photosynthetic pigment chlorophyll.[3] Phosphorus forms an important part of biological molecules such as DNA and RNA, and is used to generate energy.[3]

The availability of nutrients influences how suitable a wetland is as habitat for organisms, particularly plants, algae and some bacteria, and this has flow-on effects for the animals that rely on these **primary producers** for food. For example, Australia has relatively few native floating plants (that is, plants that do not have roots in the soil) and this has been linked to the limitations that naturally nutrient-poor water columns pose to these plants[4], as they do not have direct access to nutrients within sediments. Rooted wetland plants tend to get most of their nitrogen and phosphorus from **sediment pore water** rather than the water column, where the concentration of nutrients is, in general, naturally often much greater than that of the water column. Most aquatic plants have root 'hairs' or lateral root projections that increase their ability to take up nutrients from the sediment pore water.[5]

This is not to say nutrient-poor wetlands are poor habitats for all plants, algae and bacteria. Generally speaking, the soils of WA are relatively nutrient-poor compared to those in the northern hemisphere and even eastern Australia. This soil infertility is considered to be one of the strongest influences driving the evolutionary diversity of plants in its ancient soils[6], contributing to the extremely high biological diversity in regions such as the southwest Australian floristic region. An increase in the availability of nutrients can decrease the competitive ability of species that are adapted to severely impoverished sites[6] resulting in a loss of biodiversity and invasion of weeds.

In extremely nutrient-poor wetlands, such as those on granite outcrops, specialist plants have ways of overcoming a lack of nutrients in the soil and water. For example, carnivorous plants including sundews (*Drosera*) and bladderworts (Lentibulariaceae) consume small animals such as small insects and crustaceans.[4,7] Similarly, the Albany pitcher plant (*Cephalotus follicularis*) (Figure 29) is an insectivorous plant inhabiting peat wetlands of the south coast of WA, and its ability to acquire extra nutrients in this way confers it a competitive advantage over other plant species that rely entirely on soil and water mediums for nutrients.

Metabolic processes: the chemical reactions that occur within living things, including the digestion of food

Primary producer: a photosynthesising organism. Primary producers, through photosynthesis, harness the sun's energy and store it in carbohydrates built from carbon dioxide

Sediment pore water: water present in the spaces between wetland sediment grains at or just below the sediment surface. Also called interstitial waters.

Figure 29. The Albany pitcher plant, *Cephalotus follicularis*, makes up for a lack of nutrients in its environment by luring, trapping and digesting insects. It inhabits peat wetlands on the south coast of WA. Photo – A Matheson/DEC.

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

WA is also home to two species of *Azolla* (Figure 30). These floating aquatic ferns are reliant on nutrients in the water column. To supplement their nutrition, they support the **cyanobacterium** *Anabaena azollae* in their fronds. This bacterium is able to convert nitrogen present in the air into a form that can be used; this is referred to as 'fixing nitrogen'.[8]

Figure 30. The floating water fern *Azolla filiculoides* (a) and (b) close up in green and red varieties; (c) at a Kemerton wetland. Photos – C Prideaux/DEC.

Wetland plants adapted to low levels of nutrients tend to reinforce these conditions by producing leaf litter that is less degradable due to resistant compounds[7] whereas many weeds contribute large amounts of easily decomposable materials that create nutrient 'spikes' in wetlands.

Research also shows that there is a relationship between the nutrient availability in wetlands and species of algae and cyanobacteria. For example, in a study of wetlands in Perth, Wrigley et al.[9] found that diatoms, a common type of green algae, were dominant in relatively nutrient-poor wetlands (and coloured wetlands).

A large part of the reason that nitrogen and phosphorus are important in understanding wetlands and assessing wetland condition is because of the dramatic effects they can have on wetland ecosystems when they change, due to either natural or human-induced causes. If nitrogen or phosphorus are in short supply, or not present in a form that can be readily used, they can limit plant and algal growth and hence the primary productivity within a wetland.[10] However, human-induced changes to nutrient levels in Western Australian wetlands are almost always in the form of additional nutrients. Wetlands in coastal areas of the south west of WA are considered to be prone to increased nutrient levels.[11] When nitrogen and phosphorus are not limiting, growth of some algae, cyanobacteria and wetland plant species can occur unchecked, and this can lead to the overgrowth of one or several types of these organisms, such as in the development of algal or cyanobacterial blooms[10] (Figure 31a).

In addition to water column algal blooms, high nutrient levels can also lead to the development of:

- **flocculent** algal/bacterial layers above the sediments (Figure 31b)
- excessive amounts of **epiphytic** algae coating the leaves of submerged wetland vegetation and other surfaces such as logs and rocks (Figure 31c)
- large masses of **filamentous** cyanobacteria (Figure 31d).

All of these types of 'overgrowth', including algal blooms, tend to occur during warm, dry weather, due to the concentration of nutrients as water levels decrease, and warm conditions promoting their growth. Severe and sustained overgrowth of this nature can lead to serious associated impacts. In particular, it can cause a reduction in dissolved oxygen in the water column, and eventually **anoxia** as the algae start to decompose. This reduces the biodiversity and functionality of wetlands[2] and can be self-sustaining.

Flocculent: loosely massed

Epiphyte: a plant or algae that grows upon or attached to a larger, living plant

Filamentous: a very fine threadlike structure

Anoxic: deficiency or absence of oxygen

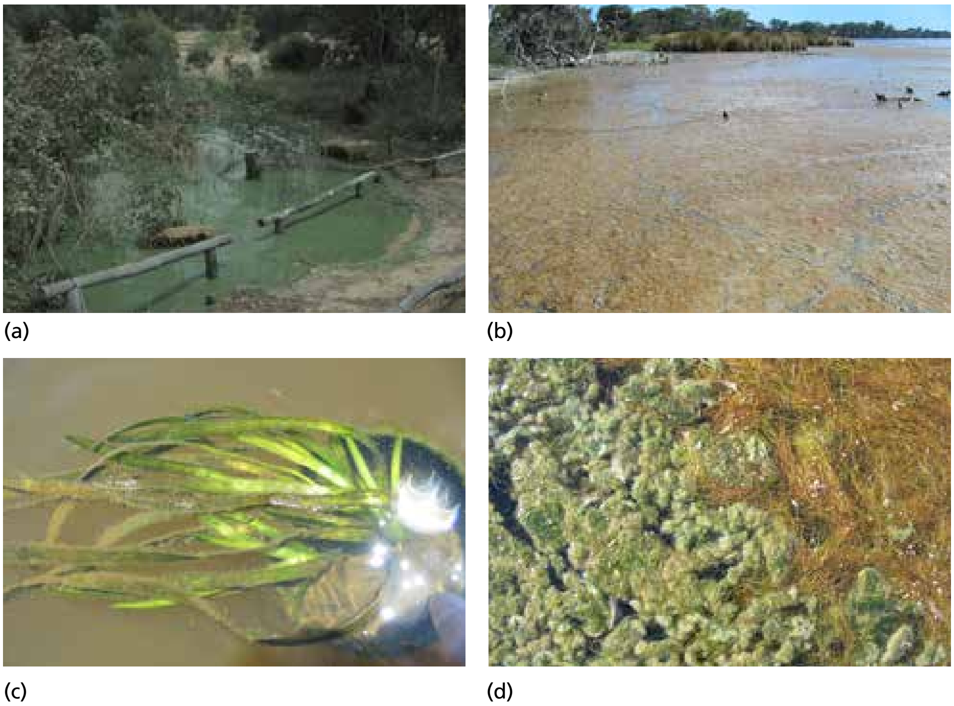

Figure 31. Examples of plant, algal and cyanobacterial 'overgrowth' caused by nutrient enrichment: (a) bloom (unidentified); (b) flocculent benthic microbial layer present in Lake Coogee, Munster; (c) epiphytes coating the leaves of the introduced species *Vallisneria americana*; (d) filamentous cyanobacteria (*Lyngbya* sp.) present in Lake Mount Brown, Henderson. Photos – (a) J Davis (b-d) L Sim.

What are the natural nitrogen and phosphorus levels of Western Australian wetlands?

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response, e.g. further investigation

In general, Australian wetlands are typically naturally low in nutrients compared to wetlands in other parts of the world.[5]

Guidelines on nutrients are provided by the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[5] (known as 'the ANZECC guidelines' in reference to the author institution). The ANZECC guidelines identify default '**trigger values**' which indicate when further investigations may be required to determine the possible causes for nitrogen and phosphorus being above guideline limits (Table 9).

In defining trigger values, the ANZECC guidelines distinguish between lakes and other types of wetlands (the WA government identifies lakes as one type of wetland). The guidelines indicate that [other] wetlands are likely to have higher natural nutrient loadings and therefore higher productivity than lakes. 'Wetlands' as used in this context probably includes shallower and more vegetated systems, which are likely to dry periodically.

Table 9. Default trigger values for nutrients and chlorophyll a (risk of adverse effects) from ANZECC and ARMCANZ.[5]

Ecosystem type	Chlorophyll *a*	Total P	Filterable Reactive Phosphate (FRP)	Total N	Oxides of nitrogen (NOx = (NO_3^- + NO_2^-)	NH_4^+
Unit of measurement	**Micrograms per litre (µg L⁻¹)**					
Tropical Australia						
Freshwater lakes and reservoirs	3	10	5	350[a]	10	10
[Other] Wetlands	10	10–50	5–25	350–1200	10	10
South-west Australia						
Freshwater lakes and reservoirs	3–5	10	5	350	10	10
[Other] Wetlands	30	60	30	1500	100	40

a: this value represents turbid lakes only. Clear lakes have much lower values.

The trigger values for the south-west of WA have been derived from a limited set of data (two years) collected at forty-one wetlands within and near Perth[10] and are representative of basin wetlands of this region that are permanently or seasonally inundated rather than wetlands across the entire south-west of the state.[6] The trigger values from the north-west of the state are derived from an even more restricted study (less than one year) in the Pilbara region.[6] All trigger values should therefore be used with caution.

It is important to consider how relevant these guidelines are for a particular wetland, and to identify, or have professional assistance to identify, an appropriate nutrient regime for the wetland, taking into consideration the natural factors affecting nutrient levels in wetlands outlined in this topic.

➤ The topic 'Water quality' in Chapter 3 provides guidance on establishing site-specific water quality objectives.

ANZECC guidelines under review

The Council of Australian Governments has announced that the ANZECC guidelines are under review. This review includes the revision of sediment water quality guidelines, nitrate trigger values and toxicant trigger values. For more information, see www.environment.gov.au/water/policy-programs/nwqms/index.html#revision.

Trophic status

Since the early twentieth century, lakes (permanently inundated basins) in the northern hemisphere have been classified according to their trophic state. The word 'trophic' is derived from the Greek word 'trophe' which means 'nourishment', and is used in reference to food or nutrition. **Trophic classifications** are used to describe the amount of productivity (usually algal) or nutrient richness occurring within lakes.[12,13] Productivity is usually measured through inferred **biomass** (via chlorophyll *a*, Secchi disk depth), whilst nutrient richness is measured through total nitrogen and total phosphorus. A eutrophic ("well-nourished") lake is rich in nutrients and plant growth. Eutrophic lakes are typically shallow. An oligotrophic lake is usually relatively deep, has low nutrient concentrations and low plant growth. Mesotrophic lakes fall in between eutrophic and oligotrophic lakes.[14] Lakes tend to progress to a more eutrophic state over geologic time due to infill.[2]

Trophic classification: the classification of an ecosystem on the basis of its productivity or nutrient enrichment

Biomass: the total quantity or weight of organisms in a given area or volume

A number of criteria have been developed to determine trophic status. A group of Western Australian researchers (Davis et al.[15]) suggested that the most suitable of these for the determination of the trophic status of WA wetlands is the Pan American Center for Sanitary Engineering and Environmental Sciences criteria[16], known as CEPIS criteria, developed for warm-water tropical lakes.[17] This system uses total phosphorus as the basis for classification. The mean and range (within two standard deviations) of annual mean total phosphorus concentrations are used to define trophic categories under the CEPIS scheme[16], shown in Table 10.

Table 10. CEPIS trophic state classification system based on total phosphorus[16]

	Oligotrophic	Mesotrophic	Eutrophic
Mean (average) annual total phosphorus (micrograms per litre; µg L^{-1})	21.3	39.6	118.7
Range ± 2 standard deviations	10–45	21–74	28–508

What affects nitrogen and phosphorus levels and availability in wetlands?

Nutrients entering from the catchment

Nutrients can be imported into wetlands from the surrounding catchment. The extent to which this occurs is influenced by factors such as the sources of water into a wetland, which dictate the amount and types of materials entering the wetland, for example, groundwater, floodplain and catchment runoff and debris. A wetland high and separate from other wetlands and waterways, such as many wetlands on granite rocks will have lower levels of incoming nutrients to one that is low in the catchment and part of a chain of wetlands connected by surface or groundwater.

Most natural, undisturbed ecosystems are very efficient in recycling nutrients provided by litter fall from vegetation through the activity of microbial communities in the soil and there is little 'leakage' of nutrients out of these systems. There are exceptions to this generalisation, which include periods following large fires or extreme weather events, which can release sudden and large pulses of nutrients that may then leak out of the system and into wetlands. For example, in a burnt catchment the surface water flows are much more unimpeded and these flows can carry nutrients within ash to wetlands that are low in the catchment, creating a pulse of nutrients.[18,19]

The amount of time water resides in a wetland (its residence time) and the nature of outflows of water are also very important. For example, whether water is 'flushed' out of a wetland by scouring floods or waterways, or flows out via groundwater; some forms of nitrogen, such as nitrate, can leach out of wetland soils.

Material imported into wetlands (that is, **allochthonous** material) links wetlands to terrestrial ecosystems, rivers and other wetlands through energy and nutrient flow. The **cycling** of nutrients and other substances into and out of wetlands is a way in which wetlands form an important part of the catchment and this understanding is crucial to their management and restoration.

The nutrient levels in many Western Australian wetlands were historically much lower than they are currently, due in part to nutrient pollution, predominantly from urban and agricultural sources. Nitrogen cycling in wetlands has been altered by changes to land use, mostly through increases in the inputs of nitrogen into wetlands from fertilisers (transported to wetlands via surface or groundwaters), and animal waste products.[20] This leads to an excess of nitrogen (and often also phosphorus), causing uncontrolled growth of some algae, cyanobacteria and wetland plants. In some parts of the world, wetlands are affected by acidic rainfall caused by nitrogen compounds such as nitric oxide (NO) and nitrogen dioxide (NO_2) dissolving in atmospheric water vapour. This is not currently a significant problem in WA. However, the prevalence of these nitrogen compounds in the atmosphere has increased through the widespread burning of fossil fuels such as coal and oil.[21] Similarly to nitrogen, changes to phosphorus cycling in wetlands are mostly related to increased inputs of phosphate from catchment sources, resulting in eutrophication. Because phosphorus is usually the main limiting nutrient in freshwaters, it is particularly important in the development of algal and cyanobacterial blooms.[10] Some of the sources of increased phosphorus to wetland waters include phosphate-based fertilisers, sewage, detergents, soil erosion[21] and the inflow of effluent from dairies or other livestock holdings.[22]

Secondary salinisation of wetland waters may affect phosphorus availability. Increases in the availability of either or both calcium and sulfate ions affect the binding or release of phosphate in the sediments.

➤ Human-induced nutrient enrichment is discussed in more detail in the topic 'Water quality' in Chapter 3.

Nitrogen and phosphorus transformations in wetlands

Nitrogen and phosphorus can be present in a wetland in a number of chemical forms. Importantly, not all of the chemical forms of nitrogen and phosphorus are able to be used by plants and animals as some are not 'biologically available' – often shortened to '**bioavailable**' – and others are even toxic. Specialised bacteria and fungi play an essential role in transforming nutrients from unavailable to available forms by driving the chemical transformations needed. Almost all nutrient cycling processes in wetlands are mediated by bacteria[23], and nutrient concentrations can alter very rapidly in response to microbial activity. These transformations are described in more detail below.

A wetland's **water regime**, especially the frequency and duration of wetting and drying, strongly influences the availability of nutrients in wetland waters[24,10], because of its influence on oxygen availability, **redox potential** and pH, all of which affect the chemical forms of nutrients in wetlands, as well as affecting the bacteria that drive many nutrient transformations. Human-induced changes can affect nutrient transformations in wetlands, particularly by altering the natural wetland water regime. Researchers in the Netherlands have found that even when wetlands receive no additional nutrients, for example, in pristine catchments, they may show signs of excess nutrients if their water regime is changed.[25]

In general, an understanding of nutrient dynamics at a particular wetland requires the collection of regular data.

Allochthonous: derived from outside a system, such as the leaves of terrestrial plants that are carried into a wetland

Nutrient cycling (wetlands): the transformation of nutrients between different chemical forms, and their transport into and out of wetlands

Bioavailable: in a chemical form that can be used by organisms

Water regime: (of a wetland) the specific pattern of when, where and to what extent water is present in a wetland, including the timing, duration, frequency, extent, depth and variability of water presence

Redox potential: the potential of chemical substances to undergo two (coupled) types of chemical change: the removal ('oxidation') or addition ('reduction') of electrons

Nitrogen in more detail

What are the main forms of nitrogen in wetlands?

Nitrogen can be found in a number of different chemical forms in wetlands, and can be converted between these forms and transported into and out of wetlands. These transformations and sequences are part of the 'nitrogen cycle'.

While nitrogen can be found in a number of different chemical forms in wetlands, only some are available to be taken up by wetland plants, animals and microbes as nutrients.[8] The sum of all chemical forms of nitrogen present in a water sample is referred to as 'total nitrogen' (TN). The fraction of the total that is actually available to be used by wetland organisms is known as the 'bioavailable' fraction. Under the right conditions, unavailable forms of nitrogen can rapidly be converted to bioavailable forms.

Measuring the bioavailable nitrogen concentration provides a snapshot of the conditions in a wetland at a point in time, and may provide insight into why and how specific events, such as algal blooms or fish kills, are triggered. Measuring the total nitrogen concentration provides an understanding of the total 'pool' of nitrogen in comparison with the proportion available under the current conditions, to guide longer term management actions.

Most animals and microbes consume or assimilate nitrogen as living or dead tissue or its by-products (the latter two are referred to as **detritus**). This nitrogen is in the form of **organic** molecules (that is, molecules containing carbon). Plants and algae generally take up **inorganic** forms of nitrogen from soil and water (although it is known that they also have capacity take up some organic forms under some circumstances), converting them to organic forms that are then available to consumers (animals) and **decomposers** (fungi and bacteria). Some bacteria can 'fix' nitrogen gas (N_2), which is not a form available to other organisms, and once it is converted to ammonia, it can enter the food chain.[8]

Breaking nitrogen down into its major organic and inorganic components provides an indication of what fraction of the total nitrogen is bioavailable (Table 11). Around 10–70 per cent of the nitrogen dissolved in freshwaters is organic, with the proportion often depending on catchment characteristics such as soil type and vegetation cover.[26] The inorganic fraction is what is used for plant growth.[2]

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (such as leaves), exuded and excreted substances and products of feeding.

Organic: compounds containing carbon and chiefly or ultimately of biological origin

Inorganic: compounds which are not organic (broadly, compounds that do not contain carbon)

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its physical breakdown.[23,10] Also known as mineralisation.

Table 11. Main forms of nitrogen in wetlands

Chemical form	Name(s)	Bioavailable?	Notes
Organic nitrogen			
Various	Dissolved and particulate organic nitrogen (DON, PON)	Yes, predominantly to animals and microbes.	It is a less common form of N.
$(NH_2)_2CO$	Urea	Yes.	It is a common form of nitrogen available for plant growth and assimilation by bacteria.[5]
Inorganic nitrogen			
NO_3^-	Nitrate. Often expressed together with nitrite (NO_2^-) as one chemical group called 'NOx', although nitrate (NO_3^-) usually occurs in much higher concentrations than nitrite.	Yes, it is readily taken up by plants and algae.[21]	Most commonly available form.[5]
NO_2^-	Nitrite	Yes, it is taken up by plants and algae.	It is a common bioavailable form of nitrogen.
NH_3	Ammonia	Yes, to bacteria[21]	
NH_4^+	Ammonium	Yes, it is the form most readily assimilated.[5,21] However it is also readily adsorbed onto clay particles.	It is a common bioavailable form of nitrogen.
N_2	Nitrogen gas, elemental nitrogen	Only to specialised cyanobacteria.	It is common in the atmosphere.

How is nitrogen transformed and transported?

Nitrogen in wetlands is converted into different chemical forms, and can be transported into and out of wetlands, making up part of the 'nitrogen cycle'. The wetland components of the cycle are shown in Figure 33.

A lot of the transformation of nitrogen between different chemical forms takes place at the sediment-water interface, the zone where surface waters and sediment pore waters meet (Figure 32). For this reason, both sediment and water column nutrients are often measured when assessing the nutrient status of a wetland, as this allows a better understanding of both the actual and potential (stored) nutrient pools. The presence of an oxidised zone at this interface is important for many reactions.

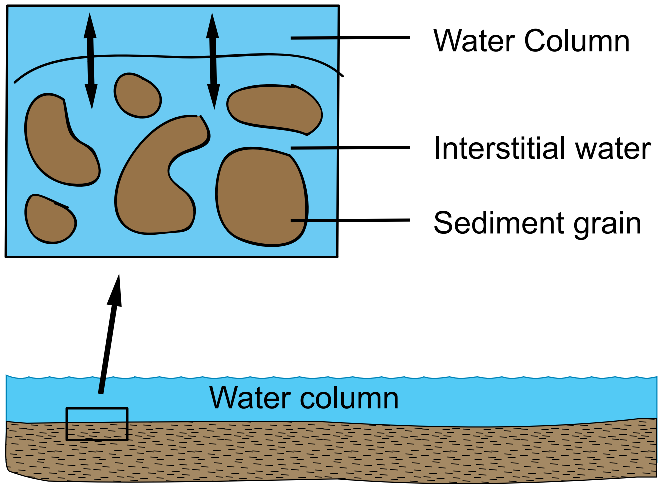

Figure 32. The sediment–water interface, where surface waters and pore waters meet, is where a lot of transformations of nitrogen take place. Image – J Higbid/DEC.

Bacteria are largely responsible for these transformations. The type of reaction that takes place depends on whether conditions in the surface sediments are oxygenated or deoxygenated. The cycling of nitrogen is closely tied to carbon cycling, as most of the conversions between different forms of nitrogen are facilitated by living organisms. In addition, chemical conditions (such as redox potential) determine which of these organisms can survive and which forms of nitrogen are chemically dominant, and therefore influence the main nitrogen cycling processes in wetlands. Assimilatory or dissimilatory processes may be favoured (assimilatory reduction results in a compound being incorporated into new organic compounds while dissimilatory reduction results in organic compounds being chemically broken down).

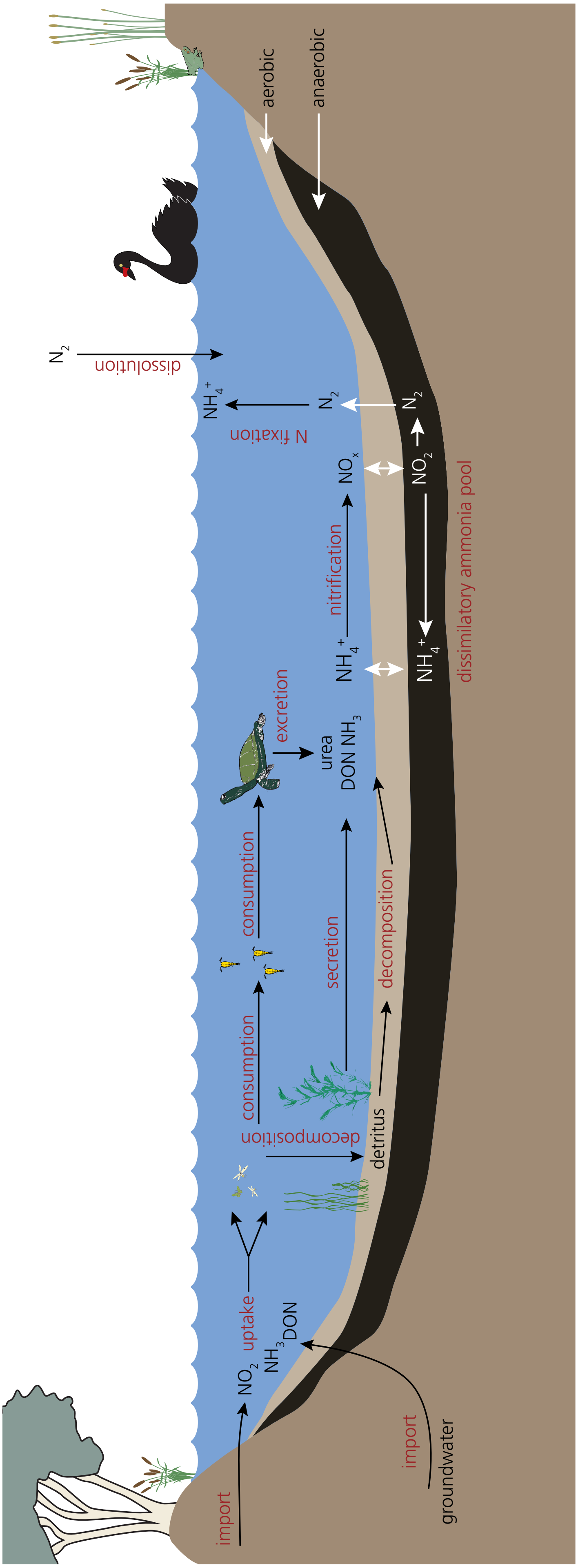

Figure 33. The wetland nitrogen cycle.

extra information

Nitrogen cycling in wetlands: a summary

Table 12. Key components of nitrogen cycling in wetlands

Process	Potential implications for wetland management
Import Organic forms of nitrogen can enter wetlands in surface water originating from animal wastes, detritus and fertilisers applied in the catchment, and it can enter via groundwater sources (inorganic forms).[21] Fire in a vegetated catchment can also result in a flush of nitrogen into wetlands low in the catchment, particularly when the fire is followed by rain.[18,19] The conversion of elemental nitrogen to ammonium by 'nitrogen fixing' bacteria is referred to as nitrogen fixation[27] and can take place under low oxygen conditions. This conversion is the main way in which atmospheric nitrogen is able to enter ecosystems.[27] Atmospheric nitrogen only dissolves into wetland waters in small amounts, as it is not very soluble in water.[28,27] Nitrite can originate from dissolved atmospheric sources. [21]	• Influx of nitrogen from surface and groundwater catchments can be a major contributor of nitrogen in a wetland. • Agricultural and urban land uses import nitrogen (for example, in fertilisers and sewage) into catchments. • Fire in vegetated catchments may create a pulse of nitrogen in wetlands low in the catchment. • Nitrogen fixation is more prevalent in tropical wetlands. • 'Nitrogen fixing' bacteria can have a competitive advantage when nitrogen is limiting. • Some plants, including *Azolla* and *Casuarina* species, have a symbiotic relationship with a nitrogen-fixing bacterium of the genus *Rhizobium*. • Unlike nitrogen, phosphorus cannot be fixed, so strategies to manage eutrophication often focus on the control of phosphorus because the forms of its entry into a wetland can be more easily managed.[2] • Nitrogen-fixing bacteria are virtually absent from the low-pH peat of northern bogs (in the northern hemisphere). [29] • Nitrogen fixation may have an important function in wetlands where benthic microbial communities are the dominant producers. • Nitrogen fixation can be inhibited at high salinities.
Uptake by primary producers Dissolved inorganic nitrogen, particularly as nitrate and ammonium, is taken up by plants, algae and some bacteria and is used to manufacture nitrogen-containing chemicals such as proteins and nucleic acids.[30] This organic nitrogen then flows through food webs. Plants rooted in sediments obtain most of their nitrogen from the soil pore water in the form of ammonium.	• Uptake by primary producers is critical in transforming inorganic nitrogen to organic nitrogen that consumers (animals) can use. • Competition between plants and the microbial community for uptake of available nitrogen can be altered by the physical conditions in the surface soil, particularly moisture and temperature and the ratio of nitrogen to carbon in the organic source. • High levels of nitrogen, in inorganic form, can promote algal blooms in warm weather. • Regeneration and revegetation of cleared/grazed wetlands can accelerate inorganic nitrogen uptake, reducing problems associated with excess bioavailable nitrogen such as algal blooms. • Harvesting and removal of weeds exports nitrogen from wetlands. • Most weeds can respond rapidly to increases in nutrients. However some weeds, such as those with corms, bulbs and tubers, can flourish in nutrient-deficient soils. • Saline conditions can inhibit the uptake of ammonium.[31]
Consumption Animals, fungi and bacteria consume/assimilate living or dead plant, algal and microbial material, taking in nitrogen in organic form, for example, as proteins, enzymes, amino acids and nucleic acids. The dead material may be in the form of dissolved organic nitrogen (DON) or particulate organic nitrogen (PON). Almost all proteins in organisms are made up of the same twenty amino acids (which all contain nitrogen), nine of which can only be manufactured by plants (the 'essential' amino acids), meaning that animals must eat other organisms in order to obtain them.[30,3]	• Plants, algae and bacteria directly provide food/energy for animals, fungi and (other) bacteria. • Evidence suggests that the nitrogen consumed by microbes and stored as microbial biomass can be a significant store of nitrogen in the soil.
Excretion/secretion Excretion by animals results in ammonia, urea and other dissolved organic nitrogen compounds entering wetland waters and sediments.[3] Organic nitrogen compounds may also be secreted by plants and algae as metabolic by-products.	• Large populations of animals may contribute high levels of urea, promoting plant growth. • An influx of migratory waterbirds can alter nitrogen dynamics in a wetland, both during and after their stay. Some birds, such as ibis, feed outside wetlands but roost in wetlands, and as such may import nitrogen. Exclusion of over-abundant populations of animals (for example, kangaroos, ibis) may help to reduce nitrogen import.

extra information

Nitrogen cycling in wetlands: a summary (cont'd)

Process	Potential implications for wetland management
Decomposition and ammonification Decomposition is the microbially-assisted chemical breakdown of organic materials. It results in the conversion of nitrogen from organic to inorganic forms, which mostly takes place through the process of 'ammonification' (production of ammonium/ammonia).[27] Ammonification is the main source of ammonia generation in wetlands and can take place under either aerobic or anaerobic conditions.[27] Under high pH (>8), oxygenated conditions, ammonia is released to the atmosphere in gaseous form.[28,32]	• Microbes (including fungi) are essential for the transformation of organic nitrogen into inorganic forms that can be used by plants and algae. • Mass deaths, such as fish kills or widespread botulism in birds, may result in a sudden spike in nitrogen converted from organic to inorganic forms. • Mass deaths of microbes can also result in a spike of nitrogen. This can occur, for example, in wetlands that dry; air-drying can kill up to 75 per cent of microbial biomass. A 'flush' of nitrogen and phosphorus is then available on re-wetting.[33,32] • The leaves of some plants, such as *Eucalyptus* species, have low levels of nitrogen relative to carbon, so to decompose these leaves bacteria need to take up very large amounts of external nitrogen.[23] • Ammonia levels are in equilibrium (balance) with ammonium levels; ammonia is more common at high pH. Ammonia is highly toxic and can kill fish.[10] • High pH, oxygenated conditions can promote the export of nitrogen from wetlands in gaseous form. • The conversion of ammonium to ammonia at high pH limits the nitrogen available to plants and animals. • If the wetland sediments do not have an oxygenated surface layer, levels of ammonia may build up to toxic levels in the sediments.[29]
Adsorption, sedimentation Ammonium is readily adsorbed onto charged clay particles.[23] This is most likely to occur in anaerobic conditions. Organic nitrogen from dead organisms can be incorporated into wetland sediments.[21]	• Sediments can be a significant sink/source of nitrogen. • High concentrations of ammonium in the sediment pore waters may signal adsorption of ammonium (i.e. converting bioavailable nitrogen to inaccessible forms).[23] • Disturbance of sediments can lead to the re-suspension of organic nitrogen in the water column.[23, 21]
Nitrification (oxygenated conditions) Nitrification, the conversion of ammonia (NH_3) or ammonium (NH_4^+) to nitrate (NO_3^-) (via nitrite, NO_2^-) occurs in freshwater wetlands under oxygenated conditions.[28] Aerobic nitrifying bacteria including *Nitrosomonas* and *Nitrobacter*[2,29] facilitate nitrification to obtain energy. The conversion of ammonium to nitrate is also controlled by pH, temperature and organic carbon availability, and is regulated by competition for organic carbon with heterotrophic bacteria.[34] When the wetland is re-wet after a drying phase, there may be a lag in the production of nitrate because most or all of the nitrifying bacteria are killed on drying.[32]	• Even in low-oxygen conditions, nitrification can occur in pockets of sediment pore waters where oxygen is leaked from plant roots (the rhizosphere). The nitrate produced can then be assimilated by plants or microbes. • Nitrite is toxic to fish in high concentrations.[35] • Nutrient enrichment can increase aerobic decomposition. If this leads to a sufficient decline in oxygen levels, nitrification can be prevented, blocking the subsequent process of denitrification. If this occurs, ammonium can build up until it is released from the sediments, further exacerbating nutrient enrichment. • In downwards-percolating waters (such as groundwater recharge wetlands), nitrate and nitrite are easily leached from wetland soils.[23]
Denitrification (deoxygenated conditions) Under deoxygenated conditions nitrate gets converted to elemental nitrogen (N_2) by denitrification, another process facilitated by specialised bacteria.[32] Elemental nitrogen generated through the process of denitrification may subsequently be released to the atmosphere. Partial drying of the sediments allows nitrification (NH_4^+ to NO_3^-) and denitrification (NO_3^- to N_2) to occur in quick succession, as deoxygenated and oxygenated areas are in close physical proximity, and the low water level means that the nitrogen gas does not have far to diffuse to reach the atmosphere.[28] This linking of the two processes can cause more rapid loss of nitrogen from wetland systems as N_2.[28]	• Deoxygenated conditions can promote the export (loss) of nitrogen from a wetland in gaseous form. • Partial drying of wetland sediments can also promote the export of nitrogen from a wetland in gaseous form. • Denitrification is inhibited in acid soils and peat.[29]
Dissimilatory ammonia production Nitrate can also be converted to ammonia/ammonium via a process of reduction called 'dissimilatory ammonia production', which occurs under anaerobic conditions.[28,27]	If the wetland sediments do not have an oxygenated surface layer, ammonia (NH_3) in sediments may build up to toxic levels.[29]

Phosphorus in more detail

What are the main forms of phosphorus in wetlands?

Phosphorus can both be found in a number of different chemical forms in aquatic ecosystems, and, as with nitrogen, only some are actually available as nutrients to be taken up by wetland plants, animals and microbes.[8] However, unavailable forms of phosphorus can rapidly be converted to bioavailable forms under the right conditions.

Breaking phosphorus down into its major organic and inorganic components gives a better idea of how much of the 'total phosphorus' (TP) is actually available to be used by wetland plants and algae.

Phosphorus is present in large amounts in natural wetland ecosystems, but naturally occurs mostly in inaccessible mineral forms[21], while biologically-available phosphorus (PO_4^{3-} and organic P) tends to be the nutrient that limits primary production.[10] Phosphorus is not present in the atmosphere as it reacts easily with other chemicals and instead tends to become bound up in mineral form.[21] It has an affinity for calcium, iron and aluminium, forming complexes with them when they are available.[29] As phosphorus is usually the main limiting nutrient in freshwaters, it is particularly important in the development of algal blooms.[10] However, nitrogen can limit algal growth in some wetlands, especially those in arid areas.[10]

Wetland plants and algae can obtain phosphorus in dissolved inorganic form (as phosphate, PO_4^{3-}) from wetland waters, and incorporate it into their tissues.[27] In contrast, fauna and microbes must take up phosphorus in organic form, either as living plant or animal tissue or as detritus.[27]

Table 13. Main forms of phosphorus in wetlands

Chemical form	Name(s)	Bioavailable?	Common?
Organic phosphorus			
Org-P	Organic phosphorus (in dissolved and particulate forms as molecules such as nucleic acids and phospholipids, or as part of organisms).[27]	Yes, but it is quickly mineralised to inorganic P by microbes.	Organic phosphorus constitutes a large proportion of the total phosphorus found in wetlands.[27]
Inorganic phosphorus			
PO_4^{3-}, HPO_4^{2-} and $H_2PO_4^-$	Phosphate, orthophosphates, soluble reactive phosphorus (SRP), dissolved inorganic phosphorus (DIP) and filterable reactive phosphorus (FRP).	Yes, when dissolved, it is biologically available to plants and algae.	Orthophosphate is the most common soluble inorganic form of phosphorus.
Various	Insoluble phosphorus minerals including apatite $Ca_5(PO_4)_3(F,Cl,OH)$ and clays.	No, they are inaccessible (as nutrition) to biota.	Mineral forms are the largest pool of phosphorus in the environment.

How is phosphorus transformed and transported?

As with nitrogen, phosphorus in wetlands is converted into different forms, and can be transported into and out of wetlands, forming the part of the 'phosphorus cycle', as shown in Figure 34. The characteristics of phosphorus cycling differ between calcareous (calcium-containing) and non-calcareous wetlands. As mentioned, phosphorus has an affinity for calcium, forming complexes with it when it is available. The cycling of phosphorus in non-calcareous wetlands depends on the substrate type and water conditions, for example, whether it is saline; whether water is intermittent, seasonal or permanent; and the pH.

As with nitrogen, much of the transformation of phosphorus between different chemical forms takes place at the 'sediment-water interface', which is the zone where surface waters and sediment pore waters meet (Figure 32). Sediments may act as a 'sink' (endpoint) for phosphorus, which often becomes bound up in insoluble forms that are unavailable for use by plants and animals. Nutrients in these unavailable forms are actually bound to sediment particles.[8] The binding or release of phosphorus in wetland sediments is linked indirectly to the redox state[36] because of its association with other elements that are affected, particularly iron. Its state in wetlands is also linked to other chemical conditions such as pH, oxygen concentration and salinity[21,37] as outlined on the next page.

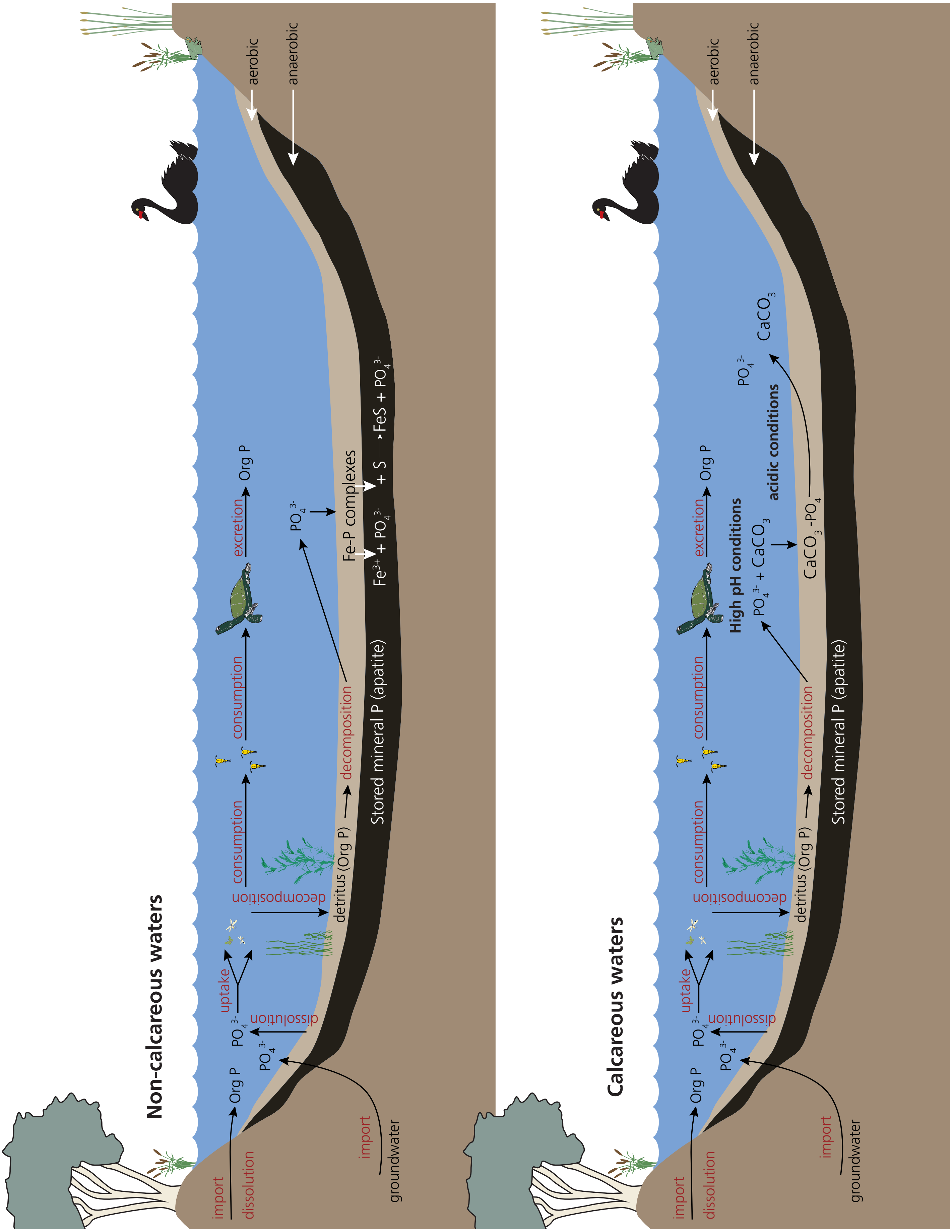

Figure 34. Diagram of the wetland phosphorus cycle.

extra information

Phosphorus cycling in wetlands: a summary

Table 14. Key components of phosphorus cycling in wetlands

Process	Implications for wetland management
Dissolution (dissolving) Chemical weathering of rocks releases phosphate.[21]	• Chemical weathering over long periods releases phosphate, which can be utilised by wetland vegetation and enter the food web.
Import Phosphorus can enter wetlands in surface water and groundwater from various sources including animal wastes, soil particles from soil erosion and the leaching of fertilisers, septics and natural sources, particularly in sandy soils[21], in particulate and dissolved organic form as well as phosphate.	• Influx of phosphorus from surface and groundwater catchments can be a major contributor of phosphorus in a wetland. • Agricultural and urban land uses import phosphorus into catchments (such as in fertilisers).
Uptake (assimilation) Phosphorus is taken up by plants and algae and some bacteria as phosphate and is then incorporated into the cells of wetland organisms, becoming organic phosphorus.[21]	• Flowering plants, ferns and structurally complex algae such as charophytes primarily absorb nutrients from sediments, limiting the availability of nutrients in the water column and thereby limiting phytoplankton.[2] • Some plants are also able to take up more phosphorus than they require and this 'luxury uptake' can reduce levels during their spring/summer growth periods. • High levels of phosphorus, in inorganic form, can promote algal blooms in warm weather. • Significant phosphorus may be stored in the microbial biomass of wetlands. • Revegetation of cleared/grazed wetlands can accelerate phosphate uptake, reducing problems associated with excess phosphate. • Harvesting of plants exports organic phosphorus from wetlands. • Most weeds can respond rapidly to increases in nutrients. However some weeds, such as those with corms, bulbs and tubers, can flourish in nutrient-deficient soils.
Consumption Animals and microbes that consume living or dead plant, algal and bacterial material take in their some of their phosphorus in organic form, similarly to the uptake of nitrogen and carbon.	• Plant, algal and bacterial material provides sources of phosphorus needed by animals and many microbes. • Bacteria are critical in the uptake of phosphorus in leaves that fall into wetlands.
Excretion Dissolved organic phosphorus compounds can enter wetland waters and sediments via excretion by animals.[3]	• Large populations of animals may contribute high levels of organic phosphorus. • An influx of migratory waterbirds can alter phosphorus dynamics in a wetland, both during and after their stay. Some birds, such as ibis, feed outside wetlands but roost in wetlands, and as such may import phosphorus.[23]
Aerobic decomposition (mineralisation) When detrital organic phosphorus is decomposed by microbes (under aerobic conditions), phosphorus is released in the form of phosphate or dissolved organic phosphorus.[37]	• Microbes (including fungi) are essential for the transformation of organic phosphorus into phosphate for use by plants and algae. • Mass fish deaths (fish kills) may result in a flush of phosphorus. • When sediments dry out, the subsequent death of a large proportion of bacteria (up to 75 per cent) may release a big flush of phosphorus available on re-wetting of the wetland soils.[23]
Adsorption, sedimentation Under oxygenated conditions in non-calcareous waters, phosphate is bound in the sediments (especially clays, peats and minerals) in complexes with the ferric ion (Fe^{3+}) [36, 37] or aluminium.[21] This adsorption of phosphate to iron complexes is highest at pH 3–7, increases with increased temperature, and decreases with increasing salinity.[38] Organic and particulate phosphorus can fall to the wetland sediments and be buried, temporarily or permanently.	• Phosphorus is most bioavailable at slightly acidic to neutral pH. • Sediments are a very important sink of phosphorus in many wetlands, particularly those freshwater wetlands with a neutral to low pH.

extra information

Phosphorus cycling in wetlands: a summary (cont'd)

Process	Implications for wetland management
Release from sediments (desorption, sediment flux, resuspension) In deeper anoxic sediments of non-calcareous wetlands, or surface sediments if the water column is stratified and anoxic, phosphate is released through the reduction of Fe^{3+} to Fe^{2+} by bacteria.[37] Alternatively, phosphate can also be displaced by sulfur, also under anaerobic conditions, as sulfur facilitates the reduction of iron to form a new compound, FeS.[36] Drying of these wetland sediments and exposure to air leads to the oxidation of iron and increased binding of phosphate, but this affinity of the sediments for phosphorus tends to decrease over time, since there is an initial increase in aerobic processes with drying, then a decrease as the microbes die from lack of water.[36] Ultimately, the likelihood that phosphate will be released from sediments appears to increase if sediment is air-dried, as there is a flush of phosphorus resulting largely from killed microbial biomass.[24]	• A sufficient decline in oxygen in the water column through events such as stratification, high temperatures, high rates of bacterial consumption, algal blooms and fish kills, can release phosphorus bound to sediment into the water column as phosphate. • Under saline conditions, sulfur is likely to be more prevalent and will facilitate phosphate release[35], increasing phosphate concentrations in the water column. • When these sediments dry out, more phosphate will originally be bound to it, but over time phosphorus is likely to be released. • Disturbance of sediments can lead to the re-suspension of phosphorus in the water column. [21]
Precipitation, remobilisation In aerobic, calcareous (calcium-containing) waters, phosphorus precipitates out of the water column in a complex with (insoluble) calcium carbonate ($CaCO_3$). Calcium carbonate tends to form under the high pH conditions resulting from high rates of photosynthesis.[37] The precipitation process is not redox-dependent, meaning that the phosphorus is not re-released from the sediments when they change from oxic to anoxic or vice versa.[37] However, some of the precipitate will re-dissolve under acidic conditions. It has been suggested that it may be possible for phosphorus to precipitate and remobilise alternately in response to diel fluctuations in pH of the water column.[23]	• Phosphorus is removed from the water column in wetland waters that are calcareous and high pH, but can be re-dissolved into the water column under acidic conditions; therefore the diurnal and seasonal changes in pH may be an influence on phosphorus levels. • Phosphorus is most bioavailable at slightly acidic to neutral pH.[29]
Flushing In wetlands with an outflow, flood events that scour the wetland sediments and carry it downstream can export phosphorus from wetlands.	Periodic flooding and flushing of sediments downstream can potentially reduce phosphorus from wetlands.

How are nutrients measured, and what units are used?

Water column nutrients are regularly measured to monitor wetland condition. Nutrients are measured by laboratory analysis. Sediment pore water sampling does not have the same usefulness, since pore water nutrients are more difficult to sample, and require extraction in an oxygen-free environment to prevent chemical changes due to oxygenation from occurring. It is difficult to separate the nutrients in pore waters from those bound to sediment grains. Therefore, nutrients are usually measured in sediments rather than pore waters (although 'sediment' values include pore waters); enabling the inclusion of both bound and unbound fractions of nitrogen and phosphorus.

Nitrogen and phosphorus in water columns are all measured as concentrations; amount of substance per unit volume of water, or per unit weight in sediments. Water concentrations are expressed as milligrams per litre (mg/L or mg L^{-1}), which is equivalent to parts per million (ppm), or micrograms per litre (µg/L or µg L^{-1}), which is equivalent to parts per billion (ppb), and sediment concentrations as mg/g (mg g^{-1}).

As nutrient analyses are relatively expensive, total nitrogen (TN) and total phosphorus (TP) are often used as surrogates for the suite of nutrients that includes both organic and inorganic compounds but these 'total' measurements are less informative than measuring a suite of chemical forms, as TN and TP do not actually indicate how much of each nutrient is bioavailable.

➤ For detailed information about sampling nutrients in wetland waters refer to the topic 'Monitoring wetlands' in Chapter 4.

extra information

Chlorophyll *a*

Chlorophyll *a* concentration is the other water quality parameter that is often recorded along with nitrogen and phosphorus. Chlorophyll *a* is a light-capturing pigment found in plant and algal cells.[39] Plants and algae use this pigment to absorb light for use in the process of photosynthesis, which provides them with energy, and this energy ultimately flows through the food webs of wetlands (refer to the topic 'Wetland ecology' in Chapter 2 for more information on food webs).

The concentration of chlorophyll *a*, which is common to all photosynthetic plants and algae, is used as an estimate of the amount of microalgae in the water column or on the sediment surface[40,41], and as such it is an indicator of a wetland's productivity. Chlorophyll *a* itself is used as a surrogate (substitute) for cell counts of algae (biomass estimates), as it is simpler and much less time consuming to measure. If the amount of algae in a wetland is high, the nutrient levels may be high. As such, the presence of high concentrations of chlorophyll a can indicate nutrient enrichment.

Concentrations of chlorophyll *a* are often measured at the same time as measuring nutrient concentrations, as this gives a picture of how the nutrients in the system are influencing the amount of phytoplankton (photosynthetic plankton including algae and cyanobacteria)[10]. Phytoplankton growth rates change in response to nutrient availability but they are also affected by the light availability and temperature (over days or weeks, rather than each day) among other factors.[39] For example, shade-adapted species of wetland plants tend to have higher concentrations of chlorophyll a in their cells, introducing some natural variability into the chlorophyll *a* measure.[39]

Chlorophyll *a* in water columns is measured as a concentration; amount of substance per unit volume of water, or per unit weight in sediments. Water concentrations are expressed as milligrams per litre (mg/L or mg L^{-1}), which is equivalent to parts per million (ppm), or micrograms per litre (µg/L or µg L^{-1}), which is equivalent to parts per billion (ppb), and sediment concentrations as mg/g (mg g^{-1}).

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Glossary

Allochthonous: derived from outside a system, such as the leaves of terrestrial plants that are carried into a wetland

Bioavailable: in a chemical form that can be used by organisms

Biomass: the total quantity or weight of organisms in a given area or volume

Chlorophyll *a*: a light-capturing pigment found in plant and algal cells. Measurement of chlorophyll ***a*** is used as a surrogate for cell counts of algae.

Detritus: organic material from decomposing plants or animals

Epiphyte: a plant or algae that grows upon or attached to a larger, living plant

Filamentous: a very fine threadlike structure

Flocculent: loosely massed

Inorganic: compounds which are not organic (broadly, compounds that do not contain carbon)

Metabolic processes: the chemical reactions that occur within living things, including the digestion of food

Nutrient cycling (wetlands): the transformation of nutrients between different chemical forms, and their transport into and out of wetlands

Organic: compounds containing carbon and chiefly or ultimately of biological origin

Total nitrogen (TN): the sum of all chemical forms of nitrogen

Trophic classification: the classification of an ecosystem on the basis of its productivity or nutrient enrichment

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SULFUR

Contents of the 'Sulfur' section

What is sulfur?

Sulfur is a key chemical element. It is often referred to by its chemical symbol 'S'.

As well as being present within organisms, sulfur is present in the environment in the atmosphere, soil and water. It is also spelt 'sulphur'.

Why is sulfur important?

Sulfur is an important nutrient for all living organisms. It forms an essential part of several amino acids (for example, methionine, cysteine) required for the construction of proteins.[1] The amount of sulfur found in living organisms varies depending on the species, physico-chemical conditions and the season.[1] Unlike nitrogen and phosphorus, sulfur is rarely limiting for organisms, especially in saline wetlands, where it tends to be present in large amounts.[1,2]

Sulfate (SO_4^{2-}), a form of sulfur, is also ecologically significant because of its influence on phosphorus cycling in non-calcareous wetlands (that is, wetlands without relatively large amounts of calcium). The activity of sulfate-reducing bacteria in wetland sediments interacts directly with the phosphorus cycle, since sulfate reduction leads to the formation of iron sulfides, freeing phosphate from its complexes with iron compounds.[3]

Sulfur is also very important because of the role it plays in forming acid sulfate soils. This is a natural phenomenon that can influence conditions in wetlands, but its major significance is when disturbed, as has occurred on a large scale due to human-induced changes, when significant impacts to wetlands can occur.

extra information

Sulfur as a resource: mining of wetlands for gypsum

Dihydrous calcium sulfate ($CaSO_4 2H_2O$), or gypsum as it is commonly known, is found in many wetlands in WA, particularly in the Wheatbelt, the south-west and Goldfields region. The origin of this sulfur is believed to be ocean-derived, carried inland as an aerosol on prevailing winds. As wetlands dry out and the water evaporates, gypsum deposits on the dry bed and is often then blown on to the south and south-east shores, forming gypsum dunes. These dunes can reach more than 20 metres in height and several kilometres in length. It is estimated that gypsum deposits have been forming up to 35,000 years ago in some WA wetlands.[4] Gypsum is mined for a multitude of uses, including drywalls, plasters, fertilisers and soil conditioners and in WA it has been mined since 1921 using methods such as excavators (dry excavation) and sub-aqueous dredges.

What are the main forms of sulfur in wetlands?

Sulfur occurs in many gaseous, solid and dissolved forms in wetlands.[2] In sediments, the main forms tend to be reduced sulfur minerals (including pyrite or elemental sulfur) and dissolved forms such as sulfate.[2] In wetland waters, the dominant form is sulfate. In general saline wetlands have much higher sulfur concentrations in their waters and sediments than freshwater wetlands[2] because sulfate is one of the component salts contributing to salinity. Because there is such a wide range of chemicals containing sulfur in wetlands, only those of most ecological significance are described in Table 15 on the next page.

Table 15. Important forms of sulfur and implications for wetland management

Name	Chemical form	Description
Sulfate	SO_4^{2-}	A very important form of sulfur in wetland waters and sediments. It is used by sulfate-reducing bacteria in the decomposition of organic matter (especially in saline wetlands) and is also the form of sulfur readily taken up as a nutrient by wetland vegetation and microbes.[5] Wetland plants and algae, and many bacteria have the ability to take up sulfate directly for use in the manufacture of amino acids[1], while animals need to incorporate living or dead biological material in order to fulfil their requirements for sulfur.
Pyrite	(FeS_2) (a metal sulfide)	The most common reduced sulfur compound in wetland sediments.[6] When exposed to air or the ferric ion (Fe^{3+}) it is oxidised to form sulfuric acid (H_2SO_4), and can lead to the development of acid sulfate soils[7,8], creating conditions toxic to many wetland organisms.
Sulfide (or hydrogen sulfide)	(H_2S)	Another commonly occurring reduced sulfur compound in wetland sediments, found in gaseous form, which gives off the 'rotten egg' smell characteristic of many wetlands. It is toxic to many organisms, but can be used by photosynthetic and chemosynthetic bacteria to fix carbon.
Organic sulfur compounds	(Org-S)	A wide range of organic sulfur compounds occur in wetlands, including amino acids, proteins, vitamins and hormones. The formation and interaction between different types of Org-S is not well understood.[6] Some of the most important biological compounds include amino acids such as cysteine and methionine.[6] Organic sulfur is the only form of sulfur that can be taken up by animals, and it is decomposed by microbes into sulfate and sulfide.

How is sulfur transformed and transported?

Like nitrogen, the transformations of sulfur in the wetland sulfur cycle are driven by microbes, particularly sulfur-reducing and autotrophic sulfur (oxidising) bacteria, and controlled by the prevailing redox conditions in wetland waters and sediments.[5] The wetland components of the sulfur cycle are shown in Figure 35.

There are several main ways in which wetland sulfur cycling has been altered by changes to land use and climate. Most of these involve increases in the amount of sulfur entering wetlands from the surrounding landscape, including burning of fossil fuels causing acid rain; inflow of wastewater containing sulfates and acid mine drainage; and seawater intrusion.[9] Another important change to sulfur cycling relevant to Western Australian wetlands is changed hydrology (increased drying), leading to acidification of pyrite-containing soils.[10]

Key

1 dissolution
2 gaseous release
3 sulfate reduction
4 oxidation of sulfur
5 photosynthesis and chemosynthesis
6 consumption

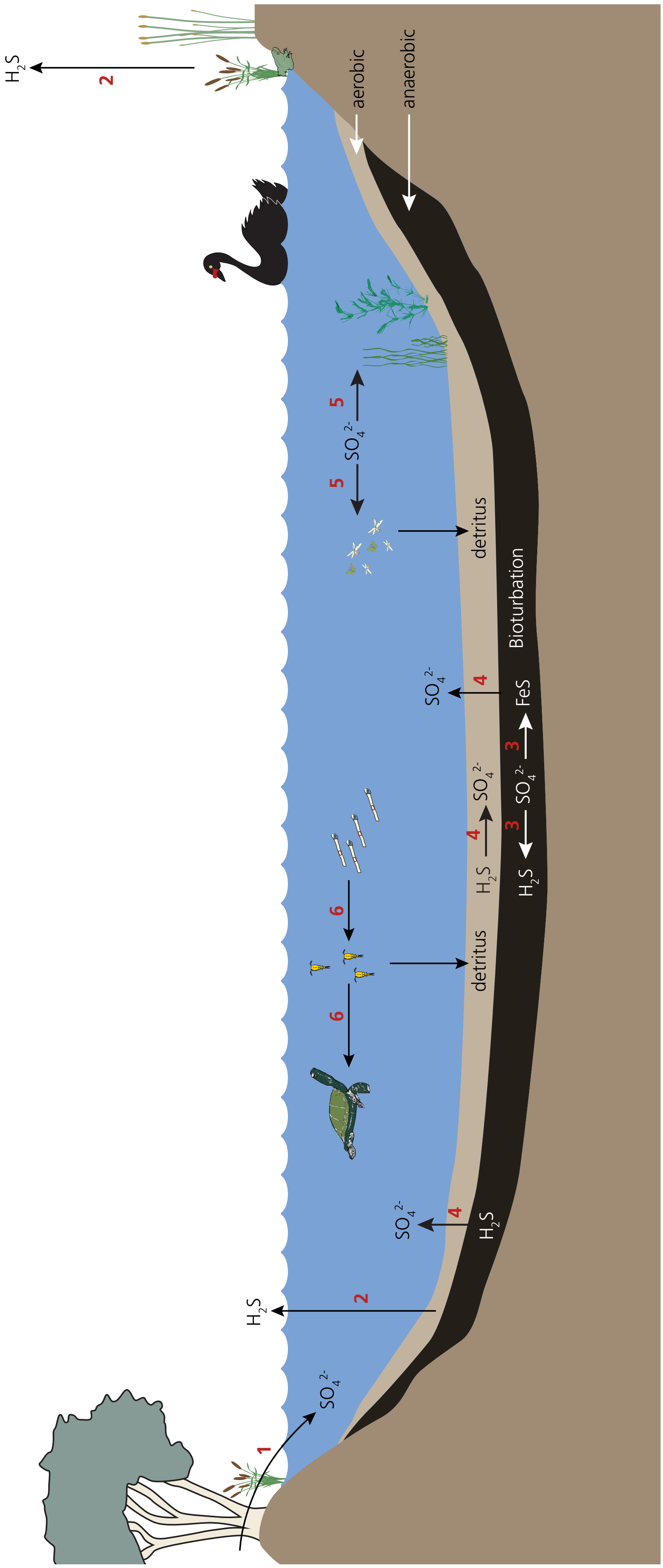

Figure 35. Diagram of the wetland sulfur cycle.

Key components of sulfur cycling in wetlands include:

- dissolution
- sulfate reduction
- oxidation of sulfur
- photosynthesis and chemosynthesis
- consumption
- gaseous release

Anoxic: deficiency or absence of oxygen

Dissolution (dissolving)

Most of the sulfur found in natural wetlands originates from external sources; either the weathering of rocks or the oxidation of organic sulfur.[9] Sulfur stored in mineral form in rocks is mostly in the form of metal sulfides which become oxidised to sulfate on exposure to air.

Sulfate reduction - decomposition of organic matter

A major process involving sulfur in wetlands is the 'dissimilatory' reduction of sulfate (SO_4^{2-}), which takes place under **anoxic** conditions and is facilitated by 'sulfate-reducing bacteria'.[1] Dissimilatory reduction means that when sulfate is reduced, organic compounds are chemically broken down.[1] In contrast, 'assimilatory' sulfate reduction results in the sulfate being incorporated into new organic compounds (org-S) such as amino acids.[1] Dissimilatory sulfate reduction is more prevalent in saline waters, where sulfate concentrations are generally much higher than in fresh waters.

The majority of sulfate reduction occurs in the top 10 centimetres of wetland sediments.[9] The rate at which sulfate is supplied to the sediments (the anoxic zone) is usually controlled by diffusion of sulfate from the water column into sediment pore waters, and this can be sped up by 'bioturbation' of sediments by animals in the sediment.[1]

The main product of sulfate reduction in wetland sediments is pyrite (FeS_2).[6] The bicarbonate ion (HCO_3^-) is also produced during the reduction of sulfate. It has a buffering effect on wetland waters which may prevent the pH of sediment pore waters from changing too rapidly.[1,2]

Sulfide is also produced in wetland sediments through sulfate reduction or the decomposition of organic sulfur compounds. Sulfide is toxic to a range of plants and animals, making its concentrations in wetlands important.[1,2] In high concentrations it may slow the rate of primary production.[2] Sulfide tends to accumulate in anoxic waters, especially under eutrophic conditions.[9]

The rate at which sulfate reduction takes place is often regulated by the availability of organic carbon compounds, rather than the amount of sulfate[1] although it can be limiting in some fresh waters.[2] Eutrophication of wetland waters and its stimulation of primary producer biomass tends to stimulate sulfate reduction, due to the increased availability of carbon for microbial decomposition[1], and lowered re-oxidation of sediments due to a lack of bioturbation by animals, and the absence of macrophyte roots.[2] Under these conditions, and high sulfate reduction rates, sulfate may become limiting.[9] Therefore, there are very close links between the carbon and sulfur cycles.[1]

Under high sulfate concentrations, nitrogen-fixing bacteria take up less essential nutrients, which decreases the rate of nitrogen fixation that can occur.[1] This may limit nitrogen fixation in saline systems such as salt lakes.

Another anaerobic process that also involves the decomposition of organic material in wetlands is methanogenesis (the production of methane, CH_4). The bacteria that drive this process, methanogens, directly compete for organic matter with sulfate-reducing bacteria.[1] In general, methanogenesis is more prevalent in fresh waters, where concentrations of sulfate are very low, and dissimilatory sulfate reduction takes place in saline waters, where sulfate concentrations are generally much higher.[1,2] In addition to inhibiting methanogenesis, the presence of sulfate may also increase the rate at which methane is broken down by methanotrophic bacteria, further decreasing its release to the atmosphere.[1]

Oxidation of sulfur

The oxidation of reduced sulfur compounds such as sulfide (H_2S) and pyrite (FeS_2) results in the generation of sulfuric acid (H_2SO_4).

Sulfide (H_2S) is oxidised when oxygen is present (to produce elemental sulfur or other compounds including sulfate).[1] Oxidation may occur slowly, especially at low pH.[1] It occurs much more quickly in waterlogged wetlands where the sediments are open to the atmosphere.[6] Sulfide remaining in the sediments may be incorporated into metal sulfides (for example, pyrite), or organic sulfur compounds.[1] A small amount of sulfide is lost in gaseous form to the atmosphere.[2]

Pyrite may quickly be oxidised to form other compounds such as thiosulfate and sulfate.[6]

The generation of sulfuric acid can cause acid conditions in drained or disturbed wetland soils (that is, exposed to the atmosphere).[2] This is a significant risk in areas where wetlands are likely to contain significant amounts of sulfur (for example, naturally saline lakes) and in those with low buffering capacity. If sulfuric acid causes a drop in the pH of wetland waters, this acidification can inhibit the microbial decomposition of organic substances.[1] Acidic conditions can cause the inhibition of nitrification, causing a build-up of ammonium as it cannot be converted to nitrate.[1] For information on the prevention and management of acid sulfate soils in wetlands, see the topic ‘Water quality’ in Chapter 3.

Photosynthesis and chemosynthesis

Some types of bacteria are able to use reduced sulfur compounds to fix carbon dioxide (CO_2).[2] Examples are the photosynthetic purple sulfur bacteria, which oxidise H_2S rather than water (H_2O), usually under anoxic conditions[6] and chemosynthetic bacteria that use H_2S rather than light (under oxic conditions).[11]

Consumption

Animals are only able take up sulfur in organic form, that is, as living or dead plant or animal material, and they require it for important molecules such as amino acids.

Gaseous release

The flow of sulfur-containing gases from wetland waters to the atmosphere is a relatively minor part of the total wetland sulfur cycle[1,2] however the amounts of gas generation may contribute significantly to acid rain in some regions (mostly Northern Hemisphere).[2] Fluxes of sulfur gases are greater from saline than freshwater wetlands.[2] Some gases such as sulfide (H_2S) are transported directly from the sediments to the atmosphere via the gas transport mechanisms of emergent vegetation.[6]

Sources of more information on sulfur cycling in wetlands

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Glossary

Anoxic: deficiency or absence of oxygen

Gypsum: dihydrous calcium sulfate ($CaSO_4 2H_2O$)

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A guide to managing and restoring wetlands in Western Australia

Wetland ecology

In Chapter 2: **Understanding wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Wetland ecology' topic

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Disclaimer

While every effort has been made to ensure that the information contained in this publication is correct, the information is only provided as a guide to management and restoration activities. DEC does not guarantee, and accepts no liability whatsoever arising from, or connected to, the accuracy, reliability, currency or completeness of any material contained in this guide. Sections of this topic were drafted by November 2009 therefore new information that may have come to light between the completion date and publication date may not have been captured in this topic.

Contents

Ecosystem: a community of interdependent organisms together with their non-living environment

Organism: any living thing

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'. Note that the collection of flora and fauna, even for conservation purposes, must be consistent with State laws, and is likely to require a license. More detail is provided in this topic.

Introduction

Wetlands, by virtue of the presence of water, are distinctive **ecosystems** that are important for the life they sustain. The remarkable diversity of wetland types in Western Australia, from those that are seasonally waterlogged or intermittently inundated to those that are always inundated, mirrors the diverse and unique range of **organisms** they sustain. Some organisms rely entirely on these wetlands for their survival, including a range of wetland plants, fish, frogs, turtles, reptiles, birds, mammals, crustaceans, insects and other animals. Some rare plants, animals and other living things are known from as little as one or a handful of WA wetlands. At the other end of the spectrum, WA's wetlands provide sustenance and refuge for large populations of mammals, reptiles and birds that visit them at times in their life, including migratory birds that span continents to reach WA.

The diversity and wealth of life that WA wetlands directly and indirectly support is truly amazing, and forms an important part of Australia's rich biological diversity. Managing wetlands to sustain this life requires an understanding of the wetland ecology: the living things, and the relationships between these living things and with the non-living parts of the wetland. This topic provides an overview of the groups of organisms present in wetlands in WA and important ecological roles each group fulfil (Part 1), and what requirements these organisms have that explain why they are found where they are found (Part 2).

➤ More detailed descriptions of the physical factors (such as water, wind, light and temperature) and chemical factors (such as the availability and cycling of nutrients, carbon, salts and so on) that affect wetland organisms are provided in the topics 'Wetland hydrology' and 'Conditions in wetland waters' in Chapter 2.

- Introduced plant and animals are covered in the topics 'Wetland weeds' and 'Introduced and nuisance animals' in Chapter 3.
- Information on how to monitor plants and animals is provided in Chapter 4.

PART 1: WETLAND ORGANISMS

The plants, algae, bacteria, fungi and animals that inhabit or regularly visit WA's wetlands are outlined in this section. Although usually very inconspicuous, algae, bacteria and fungi are included because of their importance within wetland ecosystems. Although it is not always possible to see them or directly manage populations of these organisms, it is important to understand them and their role when managing and restoring wetlands.

extra information

A note on terminology used in this topic

Scientific names

In this topic, organisms are referred to by common names (for example 'human') and by their scientific names (for example '*Homo sapiens*').

Scientific names are assigned to living things in accordance with a long-standing naming system that groups them into 'kingdoms' of life. The original two kingdom system recognised only plants and animals. The six kingdom system is now widely used; this recognises the plant, animal, bacteria, fungi, protozoa and chromista kingdoms. Within each of these kingdoms, how closely related each life form is to one another, in terms of common ancestry, is reflected by whether they belong to the same taxonomic groups, starting with phylum and becoming more and more related if they belong to the same class, order, family and genus. Finally, within each genus are species, which are organisms capable of interbreeding and producing fertile offspring. The scientific name for the species is in Latin and in italics and in this topic it is often included along with the common name, for example: black swans, *Cygnus atratus.* Figure 1 shows the taxonomic groups that black swans belong to.

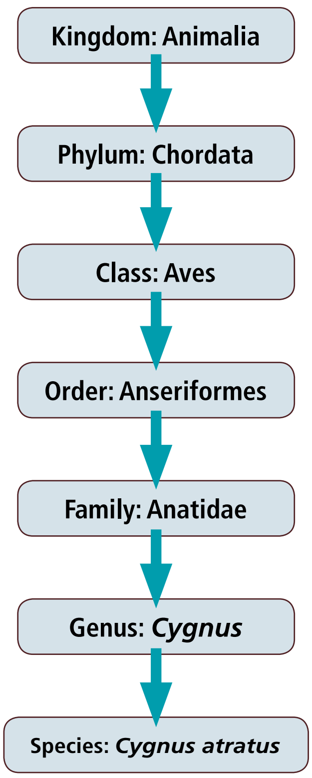

Figure 1. The taxonomic groups that the black swan (*Cygnus atratus*) belongs to.

extra information

The term taxon (plural 'taxa') is often used when referring to a specific type of organism or group of organisms. Depending on the context, this may be a species, genus or higher group.

For more information on the six kingdoms of life, see the Tree of Life website[1] or search under 'biological classification' on the Wikipedia website.

Threatened and priority wetland flora, fauna and communities

A number of wetland species are formally listed as 'threatened species' under the *Wildlife Conservation Act 1950* because they are under identifiable threat of extinction, are rare, or otherwise in need of special protection.

A relatively large proportion of wetland plants are threatened. As of 2011, forty-six of the 402 declared rare flora in WA occur in wetlands.[2] Additionally, a number of wetland plant taxa are listed as 'priority species'. Because of the large Western Australian flora, there are many species that are known from only a few collections, or a few sites, but which have not been adequately surveyed. Such flora may be rare or threatened, but cannot be considered for declaration as rare flora until targeted survey has been undertaken. These flora are included on a supplementary conservation list called the priority flora list. This list is dynamic—as new information comes to light the species' conservation status is reviewed and changes to the listing may result. Of the 2,704 priority species identified in 2011, 270 are known to occur in wetlands.[2] More information on these flora are provided in the topic 'Wetland vegetation and flora', also in Chapter 2 of this guide.

Listed threatened wetland fauna include the bilby, quokka, Australasian bittern, Australian painted snipe, fairy tern, western swamp tortoise, white-bellied frog, orange-bellied frog, sunset frog, western trout minnow, western mud minnow, Balston's pygmy perch, Cape Leeuwin freshwater snail, Minnivale trapdoor spider, Margaret River burrowing crayfish, Dunsborough burrowing crayfish, Walpole burrowing crayfish, megamouth bee and another native bee.[3]

Listed priority wetland fauna include rakali, quenda, western brush wallaby, the Nornalup frog, marbled toadlet, small toadlet, the black-striped minnow, the black bittern, little bittern, Carter's freshwater mussel, Poorginup Swamp watermite and Doeg's watermite.[4]

Similarly, a significant number of wetland communities are listed as threatened ecological communities (TECs). The Minister for Environment may list an ecological community (the sum of species within an ecosystem) as being threatened if the community is presumed to be totally destroyed, or is considered to be at risk of becoming totally destroyed. As of 2009, 316 threatened or priority ecological communities have been formally identified. Sixty-nine of these have been endorsed by the Environment Minister as follows: twenty-one as critically endangered, seventeen as endangered, twenty-eight as vulnerable, and three as presumed totally destroyed. Significantly, thirty-seven of Western Australia's sixty-nine[5] threatened ecological communities are wetland communities. These are listed in Appendix 1. Ecological communities with insufficient information available to be considered a TEC, or which are rare but not currently threatened, are placed on the priority list and referred to as priority ecological communities (PECs), of which there are five categories.

Lists of threatened flora, fauna and ecological communities are updated each year and are available on the DEC website: see the 'Threatened flora, fauna and ecological communities' webpage.[6] Information can also be accessed through the online mapping tool *NatureMap* (naturemap.dec.wa.gov.au) which can be used to produce maps, lists and reports of WA's flora and fauna diversity. It is constantly being updated or added to so the data is the most up-to-date available.

Other significant flora and fauna

Other significant wetland flora and fauna includes but are not necessarily limited to:

- species protected by international agreements or treaties such as migratory bird species[3]
- short range endemic species
- species with declining populations or declining distributions
- species at the extremes of their range
- isolated outlying populations
- undescribed species.

For more information regarding the protection of the state's flora, fauna and ecological communities, see the topic 'Wetland legislation and policy' in Chapter 5.

Wetland plants

Note

The following information is a very brief summary of the characteristics of Western Australia's wetland plants. A whole topic is dedicated to them: 'Wetland vegetation and flora', also in Chapter 2, while algae are included in this topic. For introduced wetland plants, see the 'Wetland weeds' topic in Chapter 3.

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Obligate wetland plants: plants that are generally restricted to wetlands under natural conditions in a given setting

Facultative plants: plants that can occur in both wetlands and dryland in a given setting

Wetland plants include all plant growth forms including trees, shrubs, sedges, ferns, herbs and grasses. There are a variety of Western Australian wetland trees, including paperbarks (*Melaleuca* species), eucalypts (*Eucalyptus* species), sheoaks (*Casuarina* species), and acacias (*Acacia* species). Shrubs, herbs and grasses are from a very broad range of families and genera. **Sedges** are common in Western Australia's wetlands. Sedges are members of the Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Typhaceae and Xyridaceae families. The Restionaceae and Juncaceae are often called rushes while the Typhaceae are usually called bulrushes. Some grasses (Poaceae family) are known as reeds but only the tropical reed *Phragmites karka* is native to Western Australia. Other reed species, that is, other species in the genera *Phragmites* and *Arundo*, are not native to Western Australia.

Figure 2. Vegetation of a Kemerton wetland that is waterlogged in winter and spring and dry in summer and autumn (a dampland). Photo – J Lawn/DEC.

Wetland plants differ from dryland plants in their ability to grow in water, or alternatively in soils that are waterlogged either intermittently, seasonally or permanently. Wetland plants may be submerged or floating in water, or emergent from water or soil. It is a common misconception that only plants that grow in inundated areas are wetland plants, and that plants growing in areas that are only waterlogged or that are dry for a period (that is, seasonally or intermittently inundated) are dryland plants (Figure 2). It is also a common misperception that wetland plants always 'fringe' a waterbody. Wetlands that are completely vegetated throughout are common in Western Australia, and it is these wetlands that often have the greatest diversity of vegetation units and often flora.

Some plant species only grow in wetlands; these are called **obligate wetland plants**. Other plant species can grow in dryland ecosystems as well as wetlands; these are called **facultative plants**. Facultative and obligate wetland species are from a range of plant families.

More than 3,000 taxa in WA are thought to be wetland flora.[2] This is over 20 per cent of Western Australia's 12,500 flora. Some areas of the state, particularly the south-west, support a remarkable diversity of wetland plants, including a relatively large proportion of locally and regionally **endemic** species. This is in keeping with the large proportion of endemic species in Australian ecosystems more generally, due partly to the continent's long geographic isolation.

It has been often reported that Australian freshwater wetlands display remarkably low levels of endemism, with many genera and some species being almost **cosmopolitan** (for example, Commonwealth of Australia[7]). There are many wetland flora which have a cosmopolitan distribution, occurring in wetlands worldwide. This is primarily because of the worldwide migration of waterbirds, carrying seeds and other propagules between habitats with similar environmental conditions. In WA these genera are more prevalent in large, permanently inundated wetlands (lakes). These wetland ecosystems often do not support such high levels of endemism as their dryland counterparts. However, in the broader context of all wetland types in WA, generalisations regarding endemism are inaccurate. For example, high levels of local and regional flora endemism are found in nearly all **perched** wetlands in the south-west, regardless of substrate (granite, clay, ironstone). The south-west is the world centre of diversity for a range of wetland-centred groups including the families Droseraceae, Restionaceae, Juncaginaceae, Centrolepidaceae[8] and Hydatellaceae and the samphire genus *Tecticornia*.[2]

New discoveries are still common across WA, in both remote and populated areas. The Southern Swan Coastal Plain Survey (1992–1994) alone resulted in ten plants new to science being recognised in the wetlands of the Pinjarra Plain east of Perth[9], including the swamp devil (*Eryngium pinnatifidum* subsp. *palustre*) (Figure 3). A range of wetland weeds also occur in WA.

Figure 3. The swamp devil (*Eryngium pinnatifidum* subsp. *palustre*) is one of ten plants new to science identified in a single study of the Pinjarra Plain east of Perth. Photo – B Keighery/ OEPA. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

A relatively large proportion of wetland plants are of conservation significance. Forty-six of the 402 declared rare flora in WA occur in wetlands, while 270 of the 2,704 priority species occur in wetlands.[2] Significantly, thirty-seven of Western Australia's sixty-nine threatened ecological communities are wetland communities; of these thirty-three are defined or reliant on **vascular plant** taxa.[2]

It is thought that the earliest vascular land plants on Earth were wetland plants, growing on the water's edge, some 410 million years ago.[10] Primitive flowering plants such as waterlilies are found in the Kimberley, and researchers have recently used DNA studies to discover that tiny wetland plants found in southern Western Australia—members of the Centrolepidaceae, Hydatellaceae and Juncaginaceae families—also have an ancient lineage, stemming from the time when Australia was part of the supercontinent Gondwana. They are thought to have some characteristics similar to those of waterlilies and conifers.[11]

Endemic: naturally occurring only in a restricted geographic area

Cosmopolitan: can be found almost anywhere in the world

Perched: not connected to groundwater

Vascular plants: plants with defined tubular transport systems. Non-vascular 'plants' include algae, liverworts and mosses.

A licence to take samples

Picking or harvesting of native plants on crown land in Western Australia is illegal unless authorised. This applies to conservation-related activities such as taking flora for the purposes of identification or inclusion in a herbarium. People who wish to take flora for scientific study, education, hobby, propagation or other non-commercial purposes must hold a Scientific or Other Prescribed Purposes Licence. Flora that is declared rare cannot be taken without written consent of the Minister for the Environment. For more information, see the flora licensing webpage on DEC's website.[12]

Rhizome: a horizontal, underground stem which bears roots and leaves and can usually persist, even if above-ground parts die back

The role of wetland plants

Providing food

Being an abundant resource in most wetlands, it is reasonable to assume that vascular wetland plants are an important food source. Yet although they do provide food for other organisms, their relative importance as a food source in wetlands is still the subject of research and debate, much of it based on studies conducted in the northern hemisphere.

Different plants and plant parts provide different resources. Many waterbirds in particular feed on grasses, the **rhizomes** of sedges and leaves of submerged plants (Figure 4). Kangaroos and wallabies enjoy grasses, shrubs and herbs, and while rakali are predominantly carnivorous, they also feed upon plant material. Pollen and nectar produced by a range of wetland plants is a food resource for a number of animals. For example, *Melaleuca* and *Barringtonia* species in north-western WA provide sustenance for the northern blossom bat *Macroglossus minimus*, which is a major pollinator of a number of plant species including within its range. Dead, submerged wood is of low nutritional value and is only eaten by a few specialised invertebrates. However, it tends to be coated by microorganisms including algae, bacteria, fungi and protozoans, which are a rich food source for invertebrates (small animals).[13]

Figure 4. Waterbirds such as Eurasian coots (*Fulica atra*) consume wetland plants. Photo – © W Eddy.

Some researchers propose that the consumption of living wetland plants is on par with that of terrestrial plants (such as Wetzel[14]). However, some attribute the majority of this consumption to terrestrial insects[15], concluding that vascular wetland plants contribute little to the food webs of many wetlands (although, in turn, it should be noted that fish of south-west WA have a higher reliance on terrestrial insects than fish of other regions of Australia[16]). Sophisticated analysis techniques, such as stable isotope analysis, appear to support the theory that wetland plants contribute little to the food webs of many wetlands. The reason put forward for the apparent lack of consumption of what can be a very abundant resource in wetlands is that many vascular wetland plants are too tough (due to **lignin**) or unpalatable (due to antiseptic **tannins**) for many wetland animals to consume (for example, Boulton and Brock[17], Chambers et al.[18]). In Australian wetlands, this is generally thought to be the case for fish, frogs, reptiles and mammals[19], with some invertebrates and waterbirds thought to be the main exceptions.[17],[19] High lignin content and polyphenolic concentration are common adaptations of plants in acidic, nutrient poor environments[13], such as many WA wetlands.

Many factors make this a complex field of study. In addition, studies differ as to whether they take into account only submerged plants or a broader range of wetland plants. Some differences are also attributable to regional variations in ecosystems. For example, in the northern hemisphere nutria (or coypu), muskrats, snow geese, voles, boars, capybaras, and some fish can consume significant amounts of wetland plants[14,20] and freezing of dead plant tissue during winter can break down tough plant cell walls and encourage herbivory.[13]

Species introduced to WA (weeds) vary in their palatability. *Typha orientalis* leaves are higher in structural carbohydrates than some other common wetland plants, making them particularly fibrous and not very palatable. Herbivory by invertebrates is said to be virtually unknown, although kangaroos do eat young shoots. In contrast, leaves from introduced **deciduous** species are soft and tend to easily decompose (Figure 5).[21]

Figure 5. Leaves of deciduous species tend to be softer and decompose easily. Photo – J Lawn.

Wetland plants are, indirectly, an important source of food once dead, as **detritus**[22,13], at which point they are consumed by detrital feeders such as midge (chironomid) larvae, crustaceans (ostracods, amphipods and isopods), worms (oligochaetes) and insects such as mayflies and caddisflies[18] and assimilated by fungi and bacteria. Some scientists take

Lignin: a material (a complex organic polymer) deposited in the cell walls of many plants, making them rigid and woody

Tannins: complex organic compounds (polyphenols) occurring in various plants

Deciduous: a plant that sheds its leaves annually

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

an alternative point of view, citing studies that provide little evidence that wetlands plants contribute significantly to aquatic food webs, either directly or indirectly.[17,15] A common view point is that the evidence to date indicates that algae serve as the primary base of wetland food webs, with a few exceptions such as heavily shaded forested wetlands.[15]

Providing habitat

Wetland plants are the dominant structure in many wetlands, and along with soil, sediment and the water column (if present), their surfaces, structures and microclimates create habitats for other organisms, both when alive and dead. For example:

- Wetland plants play a critical role in sheltering the adults, larvae and nymphs of wetland animals from predators. For example, dense understorey provides quenda with safe foraging and burrowing habitat; surface and partly submerged vegetation including hollow logs provide protection, feeding platforms, nesting areas and nesting material for rakali; vegetation and litter are important for reptiles, including lizards, snakes and nesting turtles; and submerged and emergent plant beds harbour very small aquatic animals and the larvae of a range of native fish from predators.
- Birds and bats roost and nest in wetland vegetation, including trees and tree hollows, shrubs, sedges and grass, and many birds use plant materials to form nests on the ground (Figure 6), in vegetation, or floating or anchored in water. Trees in water can provide bird chicks with refuge from foxes, cats and native predators.
- Microalgae, bacteria, fungi and very small animals live on plants and dead plant material such as logs, and sponges grow on submerged logs. These organisms play a very important role in wetlands and so, by extension, wetland plants are a critical part of most wetland ecosystems.
- Some frogs and many insects lay their eggs on submerged and emergent wetland vegetation (Figure 7).
- The larvae of aquatic weevils (a type of beetle) live on the inside of, and feed on, the air-filled stems of sedges.
- Some caddisfly larvae species (an important food source for fish) live in water, but build protective cases formed from plant material and spun with silk, which they live in until they change into adults.
- Many sediment-dwelling species can only live in the sediment within the rhizosphere, the area around the roots of plants that leak oxygen into sediment, making it habitable.

Figure 6. A red-necked avocet nest constructed from woody material. Photo – DEC.

Figure 7. The pupa case of a praying mantid constructed on a wetland plant at Lightning Swamp in the Perth suburb of Noranda. Photo – J. Lawn.

Figure 8. Wetland plants help to camouflage and stabilise this entrance. Photo – DEC.

Turbid: the cloudy appearance of water due to suspended material

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Sediment pore water: water present in the spaces between wetland sediment grains at or just below the sediment surface. Also called interstitial waters.

Inorganic: compounds that are not organic (broadly, compounds that do not contain carbon)

Stabilising sediment

Wetland plants stabilise sediments by binding them with their roots. By creating areas of slow moving or still water where sediments drop out of the water column, plants help to maintain a wetland's shape and flow paths and reduce **turbid** conditions in wetland waters.

Rain, stormwater, channelised flows and wave energy erodes sediments in areas around wetlands as well as in wetlands themselves. Wetland plants moderate this. For example, powerful rainfall events can erode soil. Plant leaves intercept raindrops and reduce their erosive power, while roots and fallen plant litter bind soil, reducing the rate of erosion. Similarly, wave energy is baffled by plants. This is evident in wetlands with a body of water fringed by plants, where the plants along the water's margin considerably reduce wave power. The plants, particularly sedges, allow water to pass through them but water is slowed, energy dissipated and suspended particles in the water lose energy and drop, depositing sediment and organic matter in the substrate amongst the plants. By preventing erosion and settling out incoming material, intact vegetation reduces **turbidity** in wetland waters[18] and helps to build wetland sediments.

Moderating nutrient levels

Nutrients are needed by all living things. A reduction or increase in nutrients outside of the natural range of a wetland can disadvantage some species and favour others. Up to a certain point, plants help to moderate nutrient levels within wetlands. However if nutrient levels increase too much, many plants will also be disadvantaged by the altered nutrient regime. Algae tend to be favoured by these conditions and may out-compete plants, which may ultimately be lost from a wetland (for more information see the section 'Alternate stable states' in Part 2 of this topic).

Wetland plants tend to get most of their nitrogen and phosphorus, two key nutrients, from **sediment pore water** (also known as interstitial waters) rather than the water column. The concentration of nutrients in sediments is often much greater than that of the water column. Most aquatic plants have root 'hairs' or lateral root projections that increase their ability to take up nutrients from the sediment pore water.[14] Plants are able to take up nutrients if they are in an **inorganic** form that plants can use, known as '**bioavailable**' forms (under some circumstances they may be able to take up organic forms). When plants are consumed or decomposed, these nutrients are transferred to animals and other organisms. This allows a proportion of nutrients to cycle through wetlands instead of it all being locked away in the sediment.

Under low nutrient conditions, many wetland plant species form mutually beneficial relationships with fungi (known as mycorrhizae, described further in the 'Fungi' section) to enhance their growth.

On the other hand, in high nutrient conditions, some plants such as sedges and some submerged plants can act as nutrient 'sponges'. When nutrient availability is high, they are capable of taking up more nutrients than they need for current growth and storing them for future growth. The name of this process is '**luxury uptake**' (or luxury consumption). This is why harvesting sedge leaves is sometimes proposed as a way to remove excess nutrients from a wetland. They can also internally recycle nutrients by withdrawing them from senescing leaves and stems for use in new growth.[23] This recycling ability also allows them to survive in naturally low nutrient level conditions. Trees provide long-term storage of nutrients while herbs have shorter life cycles and their nutrients are returned to the system more rapidly.

Organisms living in the oxygenated root zones (the rhizosphere) of stands of sedges also take up nutrients, further increasing the nutrient buffering occurring in wetlands. Within these oxygenated pockets nutrient binding with iron or organic complexes in the sediment also occurs. This moderates **eutrophication**. In this way, healthy stands of sedges can help to reduce potentially harmful algal blooms.[18]

Some plants, such as duckweed (*Lemna*) absorb nutrients directly from the water via pendulant (suspended) roots. By shading the water column, they inhabit the growth of algae and submerged aquatic plants.

Building sediment

Plants help to build up the organic material of wetland sediments. As noted above, not all plant material within a wetland is consumed. A proportion falls to the wetland floor and is neither consumed nor fully decomposed. In wetlands that dry, most of this material will get consumed, but in permanently inundated wetlands the build up of wetland plant material over time can result in the development of sediment with high levels of organic matter, and ultimately the development of **peat** (the reason for this is outlined in the 'Bacteria' section).

The introduced species *Typha orientalis*, for example, will initially be rapidly decomposed, but the remaining leaf material can take up to eight years to completely break down.[21]

The sediment is habitat for a range of wetland species, and its composition (particularly the organic/mineral fraction) has a bearing on what species inhabit it and its water-holding capacity. Importantly, the sediment is also where many chemical reactions occur which govern nutrient and carbon cycles in wetlands, and the composition of the sediment strongly influences these reactions.

Influencing wetland hydrology

Wetland vegetation, like dryland vegetation, uses water and loses it to the atmosphere by the process of **transpiration**, leading to the loss of water from wetlands. The water lost to the atmosphere by emergent and floating wetland plants is reported to be greater than evaporation from an equivalent area of water.[14] On the other hand, dense growth of wetland plants can block flow paths, retaining more water in wetlands. Similarly shading of water can reduce the evaporation rate in a wetland.

Bioavailable: in a chemical form that can be used by organisms

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plants, algae and cyanobacteria. May occur naturally over geologic time or may be human-induced

Peat: partially decayed organic matter, mainly of plant origin

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour

Moderating light and temperature

The presence of wetland vegetation also moderates light and temperature. Some wetlands naturally have tea-coloured water due to staining with tannin, a dark-coloured chemical produced by plants. This tannin staining limits the amount of light that penetrates the water column, which in turn limits the activity of organisms in the water that need light in order to photosynthesise (such as submerged plants, cyanobacteria and algae) or to fix nitrogen (such as cyanobacteria). In this way, tannin staining is thought to play a role in keeping harmful algal and cyanobacterial blooms at bay, and in turn, moderating the populations of organisms that consume algae, such as midges and mosquitoes. Shading from vegetation also keeps wetland waters cool, and may contribute to controlling the populations of species which proliferate in warmer waters, such as some species of nuisance midges.[24]

Providing oxygen

One of the biggest challenges for organisms in wetlands is that oxygen can be limited in water. This affects organisms that inhabit waterlogged soil or water columns. While plants can help by generating oxygen during the day via the process of **photosynthesis**, they also use oxygen at night to **respire**.

Some wetland plants can store oxygen from photosynthesis in specialised air-filled spaces called **aerenchyma**. This allows them to pass oxygen from above-ground parts to their roots to allow them to live and grow. Some of the air leaks out of the roots into the surrounding soil, which is known as the **rhizosphere**, creating an oxygen-rich environment in the substrate. This creates an environment suitable for organisms that could not otherwise survive there[18], supporting high levels of microbial activity and facilitating many important chemical reactions.

Moderating toxic compounds

Wetland plants can reduce the levels of compounds such as ammonia and nitrite. In high concentrations ammonia is toxic to some animals including fish and frogs. Some plants can remove some metals in dissolved forms from the water column.[19]

Sources of information on wetland plants

- For detailed information on the state's wetland plants, and how to identify them, see the topic 'Wetland vegetation and flora' in Chapter 2.
- For information on the state's wetland weeds and how to control them, see the topic 'Wetland weeds' in Chapter 3.
- For information on how to revegetate wetlands, see the topic 'Managing wetland vegetation' in Chapter 3.
- For information on how to survey or monitor wetland vegetation, see 'Monitoring wetlands' in Chapter 4.

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Aerenchyma: interconnected air-filled spaces within plant tissue that transport air from plant parts above the water or saturated soils to the roots

Rhizosphere: the area of soil immediately surrounding plant roots, which is altered by their growth, respiration, exchange of nutrients etc

Wetland algae

Without algae, all freshwater bodies would be effectively dead.[25] Yet, as leading Australian algae researchers put it, 'algae have an image problem'.[26] Despite being a very important and dominant component of most wetland ecosystems, **algae** in wetlands are widely perceived as purely problem species.

While algae are found in virtually all habitats, the marine algae known as seaweed are probably the most well-known. Although all of WA's wetlands typically contain algae[27], it is a small number of problem species that tend to be the most well studied. There are approximately 2,800 species (and another 1,300 subspecies) of non-marine algae in Australia[28]; at least 12,000 marine, freshwater and terrestrial species in Australia, and world wide 27,000 species of algae are described.[25] Like vascular plants, there are some species that are widespread, and a large number that are restricted in their distribution and their habitat requirements. Knowledge of the taxonomy, ecology and distribution of most algae groups in Western Australia is still rudimentary. In particular, the north-west of the state is inadequately surveyed.[28] While studies confirm that a variety of algal species occur even in central Australia[29], the reality in Australia is that algal habitat is being destroyed or altered at a far greater rate than species are being discovered.[25] The *Wildlife Conservation Act 1950* allows for algae to be listed as rare, but the lack of comprehensive distributional data presents an impediment. Like vascular plant weeds, introduced algae can alter the ecology of a wetland. This is an important consideration in the developing industry of commercial algal production for biofuels, carotenoids, lipids, fatty acids, pharmaceuticals and pelletised stock fodder.

Algae vary significantly in size. **Macroalgae** is the term applied to multicellular algae that are individually visible to the unaided eye. **Microalgae** refer to single-celled algae visible under a microscope. 'Alga' is singular and 'algae' is plural.

Algae: a general term referring to the mostly photosynthetic, unicellular or simply constructed, non-vascular, plant-like organisms that are usually aquatic and reproduce without antheridia and oogonia that are jacketed by sterile cells derived from the reproductive cell primordium. It includes a number of divisions, many of which are only remotely related to one another[30]

extra information

Algae: more like friends than family

Algae are organisms that share a number of traits: most photosynthesise; have relatively simple physical structure, unlike vascular plants; and have similar reproductive characteristics. But despite these similarities, algae did not evolve from a common ancestor (unlike flowering plants, for example), instead deriving from a number of ancestral lineages, meaning many groups of algae are not closely related to one another.[30]

Some groups are thought to be related to vascular plants, in particular red and green algae, and are classified as belonging to the plant kingdom, and this is consistent with the traditional view of algae. On the other hand, many algae have traits that are traditionally considered characteristic of animals, such as being capable of motion (that is, they are **motile**). Dinoflagellates and euglenoids are two groups of algae that use whip-like appendages called flagella for locomotion (they are assigned to the protozoa kingdom).

Because the term algae relates to an artificial cluster of unrelated or distantly related groups of organisms[30], when reading literature it is important to understand which organisms are considered to be 'algae' for the purpose of that document. For example, cyanobacteria were previously known as 'blue-green algae', and because they function in a similar way to other organisms described

extra information

Algae: more like friends than family (cont'd)

as algae, they may be listed as either or both bacteria or algae in texts, scientific articles and studies. Similarly, dinoflagellates (Dinophyta) are treated as algae by some and not by others. Table 1 shows examples of groups that are treated as algae for the purposes of this publication.

Table 1: Examples of algae found in different kingdoms (source: adapted from DEC[31])

Kingdom of life	Groups within kingdoms, with algae in italics
Animals	Animals.
Plants	Angiosperms, conifers and cycads, ferns and fern allies, mosses, liverworts, hornworts, *green algae, red algae, glaucophytes*.
Chromista	*Diatoms, brown algae*
Protozoa	*Dinoflagellates*, excavata (*euglenoids*), rhizaria, amoeba, slime moulds.
Fungi	Fungi and lichen.
Bacteria	Cyanobacteria, archaea, bacteria.

Algae inhabit both inundated and waterlogged wetlands, with many species inhabiting saturated soils of waterlogged wetlands. Many species live in wetlands that are subject to periods of drying, by forming spores that can survive in dry conditions. This allows them to quickly recolonise a wetland upon wetting. Others rely on air, water or animals (for example, birds) to transfer **spores** from permanently inundated wetlands to those wetlands that dry out. Algae can be found free-floating in the water column (**phytoplankton**) and, typically to a much greater extent[14], attached to surfaces (collectively known as **periphyton**) including the surface layers of sediments (**benthos**) and to plants (**epiphyton**). Some single-celled algae form **colonies**. Species composition and abundance in a wetland is influenced by a wide range of factors including water regime, nutrient regime, salinity and pH, and seasonal trends are often observable.[14,32] Some species inhabit freshwater wetlands, others saline wetlands, while other algal species can tolerate fluctuating salinities.[33] Coloured wetlands tend to be **desmid**-rich habitats[25] and most types of green algae are not common in saline wetlands.[32]

Like plants, algae are able to photosynthesise, but they can get the nutrients they need directly from the water column.[34] Because they produce energy from this process they are a nutritious food source for many other wetland species[15], both when alive and following their death, and are referred to as **primary producers**. Their role as producers is critically important in wetland ecosystems, particularly the productive and palatable periphytic and planktonic algae, while floating beds of filamentous green macroalgae called metaphyton are thought to be less important.[15] Most frog larvae are considered to feed on algae (algivores).[15] Other algivores include bacteria, microcrustaceans and rotifers.

In addition to being important primary producers, algae can significantly influence the physical conditions in wetlands; even microalgae are a force to be reckoned with in sufficient numbers. When conditions are right, including sufficient sunlight and nutrients,

Spore: a reproductive structure that is adapted for dispersal and surviving for extended periods of time in unfavourable conditions

Phytoplankton: aquatic organisms that photosynthesise and which float or are suspended in water, drifting with water movements and generally having minimal ability to control their location, such as algae

Plankton: aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location, such as phytoplankton (photosynthetic plankton including algae and cyanobacteria) and zooplankton (animals)

Periphyton: organisms such as bacteria, fungi, algae and invertebrates that are attached to underwater surfaces including sediment, rocks, logs and plants

Benthic: the substrate of a wetland; the organisms inhabiting it are known as benthos

Epiphyton: organisms such as bacteria, algae and plants that grow attached to plants

Colony (algal): a closely associated cluster of cells, joined together or enclosed within a common sheath or mucilage.[26] A colony may incorporate thousands of cells.[17]

Desmid: a member of the Desmidialies (Zygnemophyceae) within the Division Chlorophyta (green algae)

Primary producers: organisms which produce food (by photosynthesis or chemosynthesis) rapid and excessive growth of algae can lead to densities sufficient to be identified as an **algal bloom** (the density of algae required to be identified as a bloom is outlined in *Algal blooms*[35]). The natural balance of life in the wetland can be significantly affected. For example, blooms can shade submerged plants and populations of other algae species to the extent that they cannot get enough sunlight to photosynthesise, and they can weaken and die. Algal blooms can also shade out threatened benthic microbial communities, with catastrophic consequences (see 'Bacteria' for more information). They can also favour algae consumers, such as the crustacean *Daphnia*, which increase in population in response to greater food resources. Some algal species are toxic and can be harmful to people and animals to come into contact with or to ingest, either directly or via the consumption of shellfish or fish. For example, about thirty species of dinoflagellates produce powerful nerve toxins (neurotoxins). However reports of toxic algae are almost exclusively cyanobacteria, commonly called blue-green algae. These organisms are a special group of bacteria (division Cyanophyta), discussed in the 'Bacteria' section later in this topic.

When conditions become unsuitable for the algae (for example, once they consume all of the nutrients in the water column), the algal blooms collapse and the decomposition process depletes the water column of oxygen. This can lead to many changes in a wetland ranging from noxious smells (due to the proliferation of certain bacteria) to the death of fish and other organisms from a lack of oxygen, to **botulism** in birds. Crusting of algae on the surface of lake beds and seedlings can also inhibit plant germination by smothering emerging seedlings. This occurred at Lake Toolibin between 1986 and1992, contributing to the death of *Casuarina obesa* seedlings.[36] Yet not all blooms are bad: for some species a bloom may, in fact, be a part of its natural cycle[37] (in fact, Captain Cook recorded an algal bloom in 1770![35]), and may not impact upon a wetland system to the extent described above. The distinction is that human activities are increasing the frequency, duration and magnitude of algal blooms.[38] Some wetlands, such as Yangebup Lake in Perth's southern suburbs, are now afflicted by algal blooms almost year-round.[39] The excellent local guide, *Scum book*[37], identifies common 'blooming' species as well as those that are typically only found in patches in undisturbed wetlands. Blooms typically comprise only one or two species.

➤ For additional detail on the prevention and management of algal blooms, see the topic 'Water quality' in Chapter 3.

➤ For more information on botulism, see the topic 'Water quality' in Chapter 3.

Macroalgae

Some types of macroalgae form mats of long, green, multi-celled thread or strands known as **filaments** that may be attached to sediment, plants and other surfaces, in the water column and at the water's surface (Figure 9). Filamentous algae that occur in Western Australian wetlands include the red algae *Compsogon* and green algae including *Spirogyra, Enteromorpha, Cladophora, Zygnema, Mougeotia, Oedogonium, Sirogonium*. Many filamentous algae bloom in nutrient-enriched waters, but there are notable exceptions including *Zygnema, Mougeotia* and *Oedogonium*.[37]

The main type of macroalgae attached to wetland sediments are the **charophytes**, a group of green algae of the Characeae family.[17] The charophytes, chiefly the genera *Chara, Nitella* and *Lamprothamnium* are very beneficial to wetlands (outlined under the heading 'The role of charophytes'). Superficially they look more like submerged flowering plants (such as some species of *Myriophyllum*), with stem-like and leaf-like parts, than other types of algae (Figure 10). Charophytes are amongst the most complex of algae; they are, in fact, close relatives of vascular plants. In many text books and studies they are grouped with submerged plants, often included in the term 'submerged macrophytes'.

Algal bloom: the rapid, excessive growth of algae, generally caused by high nutrient levels and favourable conditions

Botulism: a paralytic disease caused by ingestion or exposure to a toxin produced by the bacterium *Clostridium botulinum*

Filament: cells in a linear series, usually abutting one another, creating threads or strands

Charophytes: green algae of the Characeae family; complex algae that superficially look like submerged flowering plants

Figure 9. Algae at Lake Goollelal, Kingsley, in Perth's northern suburbs.

They occur in a wide range of intermittently, seasonally and permanently inundated wetlands including those with fresh, brackish, saline and turbid water, and across a broad phosphorous regime.[33] Charophytes include both **annuals** and **perennials**. Chara is typically found in alkaline wetlands while *Nitella* is typically found in wetlands with mildly acidic conditions, although there are exceptions[40], while *Lamprothamnium* is found in brackish to saline waters.[41] Although many charophytes are considered cosmopolitan species, current research indicates there are many endemic species in Australia, for example, Australia is home to a large number of endemic species of *Nitella*.[42] Although charophytes need free water for phases of their life, the spores of charophytes can be found in dry wetlands, surviving for many years until the right conditions for germination occur. Charophytes have root-like structures known as 'rhizoids' but are able to absorb nutrients such as phosphorous equally from all parts of the plant.[14]

Figure 10. ***Chara*** species can look similar to many aquatic plants. Photo – J Chambers/ Murdoch University.

Some *Chara* **precipitate** calcium carbonate ($CaCO_3$) from wetland water and deposit it onto their surfaces, becoming encrusted with it to the extent that they are known as **stoneworts** and when they die, a plant-like stone may remain, or it may desiccate to create a 'carpet fibre' look. The precipitate contributes to wetland sediment. In some wetlands, it creates marl[17], a material often mined from wetlands.

Macroalgae are thought to absorb nutrients through their foliage rather than from their rhizoidal (root-like) structures.[14]

In *Algae of Australia: Introduction*[33], it is reported that the few studies of macroalgal **species richness** in Australian wetlands suggest that, similarly to vascular wetland vegetation patterns, wetlands that are not permanently inundated tend to have a higher

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Perennial: a plant that normally completes its life cycle in two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Precipitate: cause a substance to be deposited in solid form from a solution

Stonewort: a term applied to *Chara* species that precipitate and deposit calcium carbonate on their surfaces

Marl: fine-grained calcareous material (often the biologically-precipitated calcium carbonate remains of charophyte algae)[17]

Species richness: the total number of species (in a defined area) macroalgal species richness. Wetlands that experience perturbations in water quantity (for example, drought and inundation) on an intermediate scale can be expected to have a higher diversity than wetlands that are not subject to these events.

Diatomite, diatomaceous earth: siliceous deposits made up of the sedimentary build up of diatom shells (frustules)30

Microalgae

Microalgae are tiny single-celled organisms, and a microscope is needed to see individuals. However when they occur in high concentrations in the water column or form a scum on a wetland's surface they can be very visible! Single-celled (or unicellular) algae are extremely simple life forms. Cells are the basic unit of life; the smallest unit of life to be classified as a living thing. Yet microalgae are vitally important food sources in wetlands. The concentration of microalgae in a water column is often gauged by measuring the concentration of chlorophyll *a.* Chlorophyll *a* is a green pigment used by plants, algae and cyanobacteria to photosynthesise.

➤ For more information on measuring the concentration of microalgae, see 'Wetland monitoring' in Chapter 4.

There is a diverse range of microscopic algae in wetlands. Microalgae include green algae (Chlorophyta), diatoms (Bacillariophyta), euglenoids or flagellates (Euglenophyta), cryptophytes (Chryptophyta), dinoflagellates (Dinophyta) and golden algae (Chrysophyta).[30,17,37,43] They may be planktonic, benthic or periphytic. Different conditions favour different species.

Periphytic microalgae tend to live in close association with bacteria, with each supplying the other with compounds needed for survival. Microalgae are also important components of benthic microbial communities. Bacteria, algae and other organisms, collectively make up these communities. They are responsible for creating structures such as living mats known as benthic mats or microbial mats, and fascinating 'living rocks' known variously as microbialites, stromatolites and thrombolites. These are described in more detail under the heading 'Bacteria'.

Diatoms are a group of single-celled algae with intricately patterned glass-like cell walls made of silica, belonging to the class Bacillariophyceae (Figure 11). Wetland diatoms have a marine ancestry. Diatoms are typically present in WA's wetlands, and they are thought to be very similar to in the eastern states[44] and elsewhere in the world. They form the majority of free-floating algae (phytoplankton) in wetlands[45] but are also commonly attached to sediment and plant surfaces. There is evidence that land uses that influence pH, salinity and phosphorus levels are a determinant of which diatom communities will be present in a wetland. However even hypersaline, acidic Wheatbelt wetlands have been found to support tolerant diatom species such as *Navicula minuscula* var. *muralis* and *Pinnularia divergentissa* var. *subrostrata*.[44] When diatoms die, their siliceous cases are deposited on the sediment and build up, sometimes forming **diatomaceous earth** (also known as **diatomite**). Over time these individual skeletons can deposit in such volumes that they form vast layers, as has occurred at Lake Gnangara north of Perth. Diatomaceous earth has many commercial uses including abrasives, polishes and even in toothpaste. Large deposits are often mined, as was the case at Lake Gnangara in the 1940s, where several hundred tonnes was dredged.[45] Due to the persistence of diatomite in wetlands over extremely long time periods, it is often used by researchers (palaeolimnologists) to interpret historic conditions in wetlands and surrounds. At Lake Monger, for example, the marine diatom cells buried deep in the sediment confirm the area was previously under the ocean.[35]

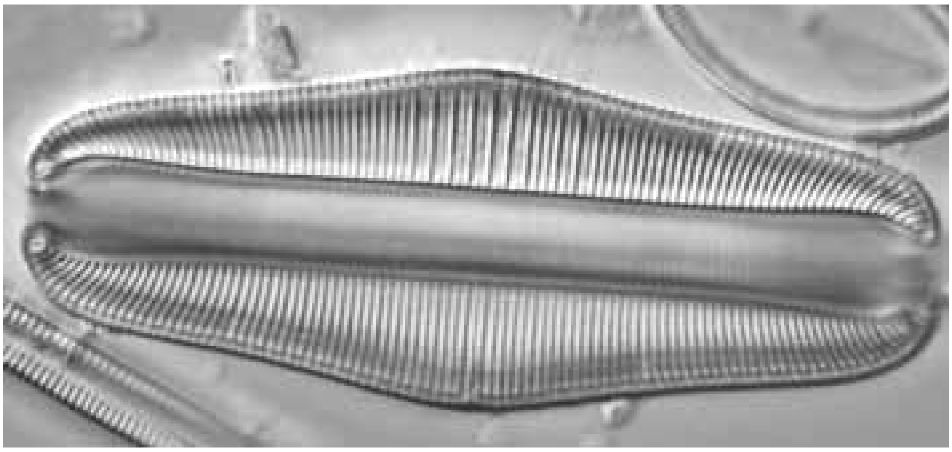

Figure 11. ***Rhopalodia gibba***, a diatom that is common in wetlands. Photo – courtesy of Monash University.

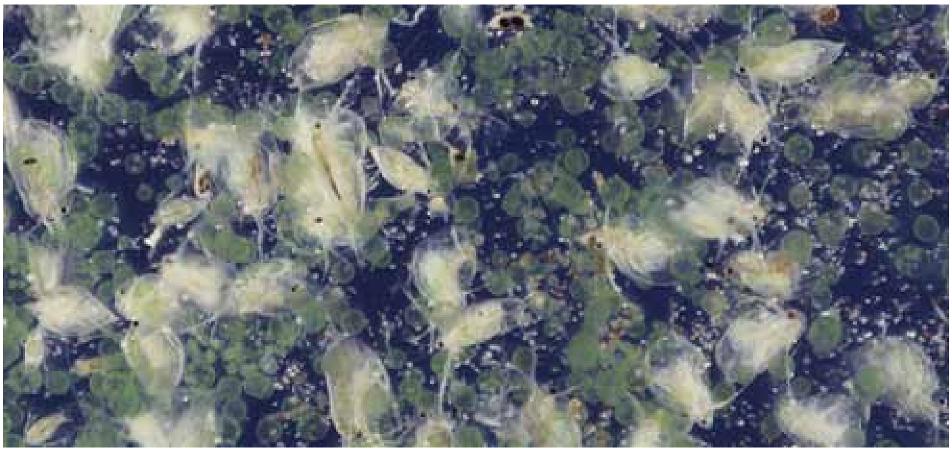

Figure 12. The green alga *Volvox*, with the water flea, *Daphnia*, in a water sample from Jualbup Lake, Shenton Park. Photo – J Davis.

extra information

Didymo: an alarming invasive alga

The freshwater diatom *Didymosphenia geminata,* commonly known as 'didymo' and 'rock snot', is an invasive algae species from the northern hemisphere. It could have devastating effects if it is introduced into Australia because it can completely alter ecosystems. It has been spread to many parts of the world, including New Zealand. It takes only one diatom in a single drop of water for the alga to spread between waterways.[46] The Tasmanian government has adopted the 'check, clean, dry' campaign to educate people to minimise the risk of introducing didymo to Tasmania via fishing gear or other equipment. For more information, or to report possible sightings, contact the Australian Quarantine and Inspection Service.

Pink Lake near Esperance gets its pink waters from *Dunaliella salina*, a green alga that accumulates pigments (carotenoids) that give it a red colour, and when abundant, give water a pink or red colour. *Dunaliella salina* is responsible for most of the primary production in hypersaline environments worldwide.[47] However over the past ten years the wetland's pink colouring has faded. This is due to a number of processes that are changing the water chemistry of the wetland, leading to declining salinity and nutrient enrichment, resulting in changes to the dominance of organisms in the wetland, including a decline in *D. salina*. The Department of Environment and Conservation is working with local landholders to minimise water quality changes in the wetland. A number of other WA wetlands also support considerable densities of *D. salina* including Lake Hillier on Middle Island, on the Recherche Archipelago off the south coast, and Hutt Lagoon, northeast of Port Gregory. In fact, Hutt Lagoon contains the world's largest microalgae production plant, a 250 hectare series of artificial ponds used to farm *Dunaliella salina*. This microalga gives Hutt Lagoon its colouring (Figure 13) and is used to produce beta-carotene, a source of vitamin A used in vitamin supplements, and a food-colouring agent used in products such as margarine, noodles and soft drinks.[10]

Figure 13. The waters of Hutt Lagoon, coloured pink by the alga ***Dunalliela salina***.
Photo – S Kern/DEC.

The role of algae

Algae have a significant role in the functioning and productivity of wetlands.[33]

- Algal photosynthesis a significant source of primary productivity[33], with phytoplankton and periphyton in particular forming the base of many wetland food chains[25], providing a valuable food source for algivores including bacteria and other microbes; and animals such as tadpoles, invertebrates including crustaceans such as cladocerans and copepods, molluscs such as mussels and birds such as black swans (*Cygnus atratus*).
- Both macro and microalgae help to make wetland environments suitable for a range of organisms by adding oxygen to (oxygenating) wetlands by photosynthesis, a process which creates oxygen as a by-product.
- Algae provide habitat, with macroalgal surfaces inhabited by smaller algae and other epiphytic organisms, and providing other organisms with refuge from predators and shade and shelter from unfavourable conditions.
- Diatoms develop diatomaceous wetland soils, which can significantly influence wetland water chemistry and hydrology, and can be used to interpret environmental conditions in much earlier time periods.
- Benthic communities formed between algae, bacteria and other organisms are ecologically significant components of some WA wetlands (outlined in the 'Bacteria' section below).

The role of charophytes

Charophytes are important in wetlands because they:

- are often pioneer colonisers of shallow waters of recently inundated wetlands.[48]
- inhabit niche areas including deeper waters of clear-water lakes that are too dark for flowering plants.
- keep the water clear of sediments by rooting into and stabilising sediment and, in dense populations, creating areas of slow-moving or still water where sediments drop out of the water column (with studies suggesting this function is provided by charophytes even more effectively than plants.[33])
- trap nutrients and minerals in a gelatinous mucilage, removing it from the water column.[37] Their high biomass means that they accumulate and retain large concentrations of nutrients for long periods due to their slow rate of decomposition.[49]
- provide habitat for insects, crustaceans, fish and other animals at various life stages, as well as smaller algae (such as diatoms[50]), especially in saline systems.
- provide an important food source for some invertebrates and birds. *Lamprothamnium* is an important primary producer in saline wetlands. It can grow in water with up to twice the salinity of sea water and is a food source for waterbirds, including black swans.[33] For example, at Lake Pollard south of Mandurah, growth of extensive areas of *Lamprothamnium papulosum* in summer months has been linked to the influx of black swans (*Cygnus atratus*), with numbers of grazing swans as high as 3000 in a single month.[51]
- potentially purify the water column and sediments of heavy metals. Research undertaken in Capel in WA's south-west suggests that some species, such as *Nitella congesta*, hyper-accumulate metals.[52]
- potentially provide an indicator of a wetland's water quality in respect of nutrients, although species may disappear due to other factors such as alteration of wetland water regime.
- develop wetland soils via the precipitation of calcium carbonate, which contributes to wetland sediment. In some wetlands, it creates marl[17], a material often mined from wetlands.
- potentially help to control nuisance insect populations. Several species of *Chara* have been found to have sulphur-releasing compounds that are thought to be harmful to mosquito larvae.[14]

Sources of more information on wetland algae

The following resources provide more information on wetland algae:

- *Scumbook: a guide to common algae and aquatic plants in wetlands and estuaries of south-western Australia*[37]
- *Freshwater algae in Australia: a guide to conspicuous genera*[26]
- *Australian Freshwater Algae*[53] website – provides a key, pictures, census, guides on how to collect and examine freshwater algae, and links to a number of other algae-related websites
- *Algal blooms (Water Facts series)*[35]
- *Waterplants in Australia: A field guide*[40] for information on charophytes

- *Algae of Australia: introduction*[30]
- *A phytoplankton methods manual for Australian freshwaters*[54]
- *Algaebase*[55]
- *Charophytes* journal and website www.charophytes.com

extra information

Identifying algae

The WA Herbarium provides a public reference herbarium, a public access collection of typical specimens of all known vascular plant species in the State. It is used widely by consultants, researchers and the public to help identify wildflowers and other vascular plants. The WA Herbarium and associated regional herbaria do not specialise in the identification of algae (including charophytes) and do not maintain algae collections. Various private industry and university specialists provide identification services, for example, the algae and seagrass research group at Murdoch University. A number of the references cited above provide information on the collection, storage, preservation and identification of algae. A guide to the collection of charophyte specimens for identification purposes is provided by www.charophytes.com.

Bacteria

Although invisible to the unaided eye, bacteria are nutrient recyclers and primary producers vital to wetland function and they are an important part of the food web. They are single-celled microscopic organisms that are neither plants nor animals, and, along with other very small organisms, are often referred to as **microbes**. At 0.3 to 0.6 microns in length[17], powerful microscopes are needed to study bacteria (one micron is one thousandth of a millimetre and the symbol for the unit of measurement is 'µm'). Bacteria are now usually identified using DNA analysis. Bacteria (and viruses) are the most abundant organisms in wetlands and occur in the water column (bacterioplankton), attached to surfaces such as plants, logs and animals (periphyton) and in the sediment (benthos). It was not until the 1970s that new techniques to count bacteria shed light on their abundance.[17] Bacteria can be dispersed by animals such as birds, as well as on winds and via dust storms as 'bioaerosols'.

Some bacteria are able to photosynthesise while others get nutrition from **organic** matter. These bacteria don't ingest food in the way animals do, nor do they have digestive tracts to consume food. Instead, they secrete chemicals to the outside of their cells ('extracellular enzymes') to decompose the adjacent material and break it into smaller materials. They can then transport these smaller materials into the cell and use the carbon and energy they contain. So, rather than eating and digesting food, bacteria are said to 'assimilate' carbon and other nutrients. Similarly, bacteria don't breathe, and don't have lungs or complex respiratory systems. They are so small and consist of only one cell, meaning that gas can diffuse into and out of their bodies.

Bacteria are not unique to wetland environments; they provide nutrient recycling and are a food source in all environments. However, particularly in inundated wetlands, the way in which bacteria overcome the lack of oxygen has a defining role in how wetlands function. Many do not require oxygen to survive, allowing them to inhabit **anoxic** (oxygen-poor) conditions in all areas of the wetland, but particularly the sediment. These are often called '**anaerobic** bacteria' and rather than using oxygen, they are capable of

Microbe: an organism that can be seen only with the help of a microscope for example, bacteria, some algae (also referred to as microorganisms)

Organic: compounds containing carbon and chiefly or ultimately of biological origin

Anoxic: deficiency or absence of oxygen

Anaerobic: without air (organisms that live in these conditions are anaerobes)

anaerobic respiration. **Aerobic** bacteria are also plentiful, floating in water and present in the **biofilm** found on all underwater surfaces: in or on wetland sediment and its rhizosphere, or on surfaces such as rocks and vegetation.[17] Some bacteria are also able to inhabit extreme environments, including extremely saline conditions (halobacteria), extremely high temperatures (thermophiles) and extremely acidic conditions (acidophiles).

Oxygen is required by the majority of living organisms. Bacteria that do not require oxygen instead use other materials in order to extract what they need from organic matter. These materials include metals in the case of iron-reducing and manganese-reducing bacteria, nitrate in the case of denitrifiers, and sulfate in the case of sulfate-reducing bacteria.[22] The conditions in a wetland will dictate which type of bacteria will predominate. Some, such as denitrifying bacteria, preferentially use oxygen when it is available then switch to nitrate when it is not. Methanogens are those bacteria present in anaerobic zones of freshwater wetlands that are responsible for breaking down organic matter that remains once other bacteria have extracted what they can from it. They are known as such because they produce methane (not to be confused with methanotrophs, which use methane). In saline wetlands, where sulfate is more abundant, sulfate-reducing bacteria are much more abundant than methanogens. When these bacteria are very active, they can be noticeable, especially when the sediment is disturbed, because their activity produces hydrogen sulfide (a gas also emitted by rotten eggs) giving off a characteristic odour.

This diverse use and manipulation of chemical compounds in wetlands means that bacteria have significant ecological roles, distinct from that of plants, animals, algae and fungi. Although microscopic, the cumulative effect of a population of bacteria in a wetland can have a significant effect on the chemical conditions in the wetland, which in turn affects all other organisms inhabiting it.

Bacteria populations can fluctuate in wetlands that wet and dry. Anaerobic bacteria such as sulphate-reducing bacteria and methanogens die when exposed to oxygen[22]; in wetlands that follow a wetting and drying pattern a large proportion of these bacteria die during the drying phase.[56] However, in wetlands that are only inundated seasonally or intermittently, deeper sediments may still remain anoxic for long periods and thus support anaerobic bacteria.

One particular bacterium, *Clostridium botulinum*, produces a potent nerve toxin that, if ingested or wounds are exposed to it, can make birds and mammals including humans very sick, and can be fatal. This form of bacterial poisoning is known as botulism, and more specifically avian botulism in bird populations. One outbreak at Toolibin Lake in 1993 caused the death of 450 birds.[57] Inhabiting soil and sediments, it can occur throughout WA at any time of the year. Temperature, oxygen and a suitable energy source are thought to be the factors that determine whether an outbreak of *C. botulinum* will occur. In wetlands, warm weather and anoxic conditions are optimal conditions for an outbreak. This is why avian botulism is commonly associated with algal or cyanobacterial blooms. The spores of *C. botulinum* can lie dormant for many years, germinating and multiplying when conditions are right.[58] Sick native birds should be reported to the Wildcare Helpline on 08 9474 9055, which operates 24 hours a day.

➤ For more information on botulism, refer to the topic ‘Water quality’ in Chapter 3.

Cyanobacteria

Cyanobacteria is one of the groups of bacteria (specifically, a phylum) that, like plants, are able to photosynthesise. They are a large and varied group of bacteria that were formerly known as **blue-green algae**. Cyanobacteria are an ancient form of life, at least three billion years old, and are thought to have been the first oxygen-producing organisms. Their activity is thought to have produced the oxygen-rich atmosphere which

Anaerobic respiration: respiration without oxygen (O_2). Respiration is the process by which organisms convert the energy stored in molecules into a useable form. In most organisms, respiration requires oxygen, which is why breathing by animals is referred to as respiration. However, some bacteria are capable of anaerobic respiration, in which other inorganic molecules (such as sulfur, metal ions, methane or hydrogen) are used instead of oxygen

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Biofilm: bacteria, microalgae, fungi and unicellular microorganisms enmeshed in a hydrated mucopolysaccharide secretion that sequesters ions and isolates microorganisms from the water column.[14] May be present on living and non-living surfaces and substrates.

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Blue-green algae: an older term for cyanobacteria today's life forms are adapted to, increasing it from about 1 per cent to about 21 per cent.[59] In effect, humans are alive today because of cyanobacteria.

Cyanobacterial bloom: the rapid, excessive growth of cyanobacteria, generally caused by high nutrient levels and favourable conditions

Many cyanobacteria also have the ability to secure their own nitrogen by 'fixing' atmospheric nitrogen (some other bacteria also have this ability but generally fix less nitrogen than cyanobacteria). This gives them a competitive advantage over plants and algae that rely on the nitrogen available to them in the soil or water column. Nitrogen fixation by cyanobacteria can be an important source of nitrogen for the wetland, and as such can influence productivity, particularly when phosphorus is also available.

The cells of cyanobacteria are much smaller than algal cells.[37] Some species appear as a scum on the water surface of wetlands, including *Anabaena*, *Nodularia* and *Oscillatoria* (although long filaments are visible under a microscope). Other species such as *Microcystis* also float at the surface but are colonial (a closely associated cluster of cells, joined together or enclosed within a common sheath or mucilage), with clumps of cells visible under the microscope. Others again inhabit sediment. Not all cyanobacteria blooms are blue or blue-green; *Oscillatoria* form brown scum and *Trichodesmium* pinkish scums, leading to it being known as 'red tide'.[37] *Cylindrospermopsis* on the other hand occurs throughout the water column, and may colour it brown or red.[37]

These cyanobacteria may proliferate in wetlands with high nutrient levels, causing water to become toxic to come into contact with or to ingest.[17] At a certain density, this proliferation is classified as a **cyanobacterial bloom** (the density required to be identified as a bloom is outlined in *Algal blooms*[35]) (Figure 14). Although cyanobacteria are found in almost any environment, ranging from hot springs to Antarctic soils, known toxic members mostly inhabit water and can occupy wetlands that range from fresh water to saline. Cyanobacterial blooms can cause severe illness and death in animals, including fish kills and cattle deaths. In humans, cyanobacterial toxins can cause nerve and liver damage, gastroenteritis and severe skin and eye irritations. For this reason, protective clothing should be worn and extreme caution should always be taken when sampling waters and when conducting associated management activities, even in what appears to be cyanobacteria-free wetlands. Damage caused by cyanobacteria blooms are estimated to cost $200 million yearly in Australia, and blooms are predicted to worsen with climate change.[60] However, they are not new, with anecdotal evidence to suggest that Aboriginal people were aware of toxic outbreaks in wetlands before European settlement.[35,60]

Figure 14. A cyanobacterial bloom at North Lake, in Perth's southern suburbs. Photo – J Davis.

Cyanobacteria can use gas-filled bags, known as vacuoles, to stay buoyant in the area of the water column with optimal light and nutrients in order to photosynthesise. The sugar-heavy cells then sink following photosynthesis. However, in optimal conditions, the water surface can be densely populated, meaning that the cells on the surface cannot sink, and the cells below them cannot rise. The surface cells die due to prolonged UV exposure, creating the toxins and leading to a loss of oxygen in the wetland.[60]

It is thought that part of the reason why these blooms can occur is that cyanobacteria may be unpalatable to zooplankton.[61,14] During blooms, cyanobacteria can also suppress population growth of algae by releasing allelopathic compounds[14] (chemicals that inhibit other species). They can also have a competitive advantage over algae when conditions are still. Planktonic algae tend to be heavier than water and use water turbulence to stay suspended in the water column. In contrast, cyanobacteria use gas vacuoles to remain in the optimal zone of light and nutrients. This is why artificially mixing the water column, referred to as thermal destratification, is thought to be one of the ways to tackle serious cyanobacteria blooms.

Cyanobacteria produce resistant spores when a wetland dries.[17] Upon wetting the wetland is repopulated by a new generation of cyanobacteria from this propagule bank.

Cyanobacteria are an important part of the microbial communities that form microbial mats and stromatolites in a number of Western Australian wetlands (described below in more detail).

The role of bacteria

Decomposing and recycling materials

Particularly in very productive wetlands, the organic matter produced within the wetland and transported in from the surrounding catchment would build up rapidly, in some circumstances to the point where the basin would fill completely and then cease to exist as a wetland, if not for the action of bacteria and fungi.[14] Bacteria, along with fungi, play an important role in the **decomposition** of organic matter in wetlands[61]

Their reason for doing so is to gain energy and nutrients. They secrete chemicals (extracellular enzymes) to break down organic matter present in large, fine or dissolved forms in and on the soil and the water. This organic matter, commonly referred to as detritus, comes from a variety of plant, animal and microbial sources including dead organisms, substances exuded by algae, animal excretion and feeding and microbial decomposition. Depending on the substance, it may be decomposed relatively easily or fairly resistant to decomposition. Many terrestrial plants and sedges, for example, have a lot of structural material (that is, cellulose and lignin), and this tissue and humic substances from it are relatively resistant to decomposition and tend to accumulate in wetlands.

In the process of decomposing organic matter, nutrients are released and returned back into circulation in wetlands in **inorganic** forms, which are the favoured forms of nutrients that plants and algae can use for growth and survival. This is one reason why text books talk about almost all nutrient-cycling processes in wetlands being 'mediated' by bacteria.[22] This is covered in more detail below.

Providing food

It has been known for a long time that many bacteria decompose detritus in order to obtain energy and in doing so liberate nutrients, but until the 1980s it was not suspected that bacteria were in fact eaten by other single-celled organisms, including rotifers, which are tiny microscopic animals; protozoans, which are organisms that are neither plants nor animals (also sometimes called protists), such as small flagellates and ciliates,

Decomposition: the *chemical* breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its *physical* breakdown.[22,17] Also known as mineralisation.

Inorganic: compounds that are not organic (broadly, compounds that do not contain carbon) that occur in abundance in aquatic and damp environments; and a range of larger bactivorous animals such as chironomids (midges) and mussels.[17,22] It is now widely accepted that bacteria are an extremely nutritious food source, forming a vital food source for organisms further up the food chain.[17] Only bacteria are able to assimilate carbon when it is the form of dissolved organic carbon, which is the most abundant form in wetlands.[22] This makes bacteria essential in wetlands because carbon is needed for growth and survival of all life in wetlands. Much of the nutritious value of detritus, such as dead leaves, is not in the detritus itself, but rather in its coating of microbes that are decomposing it, that provides an energy-rich food source. This concept of the 'microbial loop' has revolutionised understanding of how energy cycles through wetlands.

Affecting nitrogen availability in wetlands

Nitrogen is a nutrient, meaning it is essential for living things. Bacteria are responsible for three key processes that have a significant effect on nitrogen availability in wetlands.

Firstly, some bacteria mediate a process known as *denitrification*, which reduces overall nitrogen levels in wetlands by converting nitrate to gaseous nitrogen, leading to its export from the wetland to the atmosphere. Denitrification occurs under anoxic conditions, however, it is much more prevalent in wetlands that wet and dry[22], because it is then coupled with the process of nitrification (production of nitrate) during the dry, aerobic phase. It is largely the result of the microbes and conditions within wetland sediments. This export of nitrogen is a contributing factor to the typically lower nutrient levels of these wetlands.

A second set of processes, known as *dissimilatory nitrate reduction to ammonium and nitrate-nitrite respiration*, retain nitrogen in a wetland. The nitrogen is retained in the form of ammonium and nitrite respectively, forms that are readily taken up by plants and algae. These typically take place in wetlands that hold water permanently and again are driven by the bacteria (anaerobic, aerobic and facultative) and conditions within wetland sediments.

Figure 15. The floating water fern ***Azolla filiculoides*** is a host to the cyanobacterium ***Anabaena azollae***, which provides it with nitrogen in return. (a) and (b) green and red varieties of ***A. filiculoides***; (c) in a Kemerton wetland. Photos – C Prideaux/DEC.

Finally, some bacteria are able to 'fix' atmospheric nitrogen under oxygenated conditions. They effectively import nitrogen into wetlands. Well-developed cyanobacteria mats are able to fix relatively high amounts of nitrogen, for example.[34] Some also have **symbiotic** partnerships with plants, including *Azolla* and some species of *Casuarina*. The floating water fern Azolla is fed nitrogen fixed from the air by its partner, the cyanobacterium *Anabaena azollae* (Figure 15). The cyanobacterium can meet the fern's total nitrogen requirements (in fact, it will continue to fix nitrogen even if the fern assimilates ammonium or nitrate from the water). Unlike many other cyanobacteria, this one is not toxic. This relationship plays a major role in fertilising rice fields in Asia, so much so that as much as a quarter of the total human nitrogen consumption is obtained from the *Azolla-Anabaena* source assimilated by rice.[14] Tropical wetlands are responsible for two-thirds of the biological fixation of nitrogen on Earth.[34]

Symbiosis: a relationship in which dissimilar organisms live in close association, and which is mutually beneficial to both organisms

Bioremediation: the use of microorganisms to break down environmental pollutants

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

➤ For more information on microbial processes and the nitrogen cycle, see the topic 'Conditions in wetland waters' in Chapter 2.

Affecting phosphorous availability in wetlands

Phosphorus, like nitrogen, is a nutrient required by living organisms. Bacteria can make phosphorus available to other organisms in wetlands, through the process of decomposition which releases phosphorus from detritus in phosphate, a bioavailable form of phosphorus.

Bacteria are also responsible for the release of phosphorus from sediments into the water column in the form of phosphate. This happens under anoxic conditions in wetlands with low levels of calcium carbonate.

➤ For additional detail on microbial processes and the phosphorus cycle, see the topic 'Conditions in wetland waters' in Chapter 2.

Altering the toxicity of metals, hydrocarbons and pesticides in wetlands

Sometimes called 'nature's janitors', bacteria are capable of degrading complex chlorinated solvents, diesel fuel, hydrocarbons and pesticides under certain conditions[22] and so are the focus of many **bioremediation** studies. They can also alter the toxicity of heavy metals in aquatic systems. For instance, the hydrogen sulfide produced by bacteria in anoxic environments can react with a range of metals, making them insoluble and therefore biologically inactive. Other bacteria and fungi can produce organic compounds (such as citric, oxalic and humic acid) which can bind metal ions and render them inactive, and still others bind toxic metal ions to their cell walls, or within extracellular slimes, thereby removing them from the water column.[62] This prevents them from being toxic to other organisms. However, bacteria are not a simple solution for wetland pollution; and in some circumstances, they may increase toxicity of pollutants. For example, some evidence suggests that the solubility, toxicity and availability of mercury may be increased by sulfate-reducing bacteria in estuarine wetlands.[22]

Creating benthic mats and other microbial structures

Benthic mats

Some types of cyanobacteria are dominant parts of microbial communities that create living mats on the surface of wetland sediments. These dense living mats are often visible as pink or purple mats, and vary in characteristics from rubbery, cohesive mats, such as those found in Pink Lake in Esperance, to loosely mucilaginous mats, or thin films, as can be found in the Yarra Yarra salt lake system of the northern agricultural region.[63] These mats are often called microbial mats, benthic mats or sometimes algal mats. They are created by cyanobacteria and other types of bacteria, algae and other organisms, collectively known as **benthic microbial communities** (BMCs) and include both the organisms themselves as well as non-living material. For example, at Lake Clifton the mat has been found to be composed of two species of cyanobacteria and fifteen species of diatoms (a type of algae) embedded in a matrix formed by mucilage secretion of the organisms.

Conditions suitable for the establishment and survival of BMCs are variable, but permanently inundated, high salinity, low nutrient wetland conditions are favoured.[64] Upon wetting, some wetlands are initially dominated by BMCs but over time become phytoplankton dominated, while others, such as Lake Coogee, retain mats over time as do those at Rottnest (Government House Lake, Herschell Lake and Serpentine Lake).[59] They grow very slowly; a footprint in a mat may last hundreds of years.[59] Higher species diversity and thicker, cohesive mats are typical in wetlands that hold surface water for sustained periods. Lake Thetis in Cervantes contains a variety of much less cohesive BMCs, each producing a distinctive mat. These include crenulate mats, nodular mats, filamentous mats, flocculent mats and diatomaceous mats (Figure 16); flocculent mats are thought to be 50–60 centimetres thick.[65] BMCs have also been recorded from Lake Cowan, Lake McLeod and Salmon Swamp (on Rottnest Island).[66]

Figure 16. Benthic microbial mats are visible (a) in the shallows of Lake Thetis in the forefront of the rock-like thrombolites and (b) in closer detail. Photos – W Chow/DEC.

Benthic microbial mats can significantly influence the ecology of some wetlands. They are often the predominant primary producers. In the Yalgorup Lakes, the BMC is thought to be the main source of food for thousands of migrating and local birds.[51] They also produce oxygen; often visible as bubbles beading the mat in the middle of the day when photosynthesis is highest.[67] In fact, their photosynthetic activity can supersaturate the bottom waters with dissolved oxygen.[68] In many permanently inundated saline wetlands, a thick mat of BMCs may reduce or almost stop water exchange between groundwater and surface water.[69] This means that the wetland waters become increasingly saline over time, as the surface water evaporates and is not diluted by an inflow of fresher (although still saline) groundwater. In Lake Clifton where the mat is 1 centimetre thick the inflowing groundwater can be intercepted and calcium removed.[51]

A change in conditions, such as secondary salinisation, may promote the loss of plants and an increasing dominance of BMCs in a wetland. In this situation, invertebrates, amphibians, reptiles and waterbirds reliant on plant-dominated wetland ecosystems may be lost.[70]

However, if conditions do not favour BMCs they can easily be outcompeted by submerged plants and charophytes, and they have low resistance to physical disturbance.[64]

Stromatolites and thrombolites

Mats are one type of microbial structure; the other types, **stromatolites** and **thrombolites**, are structures formed by the microbial communities by precipitating calcium carbonate (the key component of limestone) out from wetland water. These structures often look like stone domes, reaching up to 1 metre in diameter (Figure 17 and Figure 18). Their plain exterior belies the fact that they are representatives of ecological communities that have existed for three-quarters of the Earth's existence[59], known to have existed 3.5 billion years ago, while other early life forms did not develop in the Earth's ocean until 635 million years before present.

They house a complex assemblage of other bacteria and algae, as well as other aquatic fauna. Worldwide, these structures are limited to very few locations, predominantly Bermuda, the Bahamas and WA.71 WA contains the oldest microbialite fossils, at 3.5 billion years.[59] The state also contains the greatest number and most varied occurrences of living microbialites in the world59, including both marine (stromatolite) and wetland (thrombolites) occurrences, and a number of fossil sites including one just north of Kalgoorlie. Perhaps the best known microbialites in Western Australia occur at Hamelin Pool, Shark Bay.

Living and fossilised thrombolites in the south west of the state occur at Pink Lake in Esperance, Lake Clifton, Pamelup Pond at Lake Preston in Yalgorup; Government House Lake in Rottnest Island; Lake Thetis in Cervantes, Lake Richmond in Rockingham and Lake Walyungup southwest of Rockingham.[72,59] Each of these constitutes a distinct and very significant community in terms of history, structure, and morphology.[73] The extensive 'reef' of thrombolites at Lake Clifton provide a home for the microbial association itself, as well as a range of other organisms. Twenty-five species of aquatic animals were found inhabiting the thrombolites at Lake Clifton, including crustaceans and worms.[73]

It is thought that light and fresh water rich in calcium carbonate and low in nutrients is required for the survival of these thrombolitic communities. Despite having existed in wetlands for thousands of years, these internationally significant biological wonders are showing a decline in condition. A worldwide decline 1,000 million years ago is attributable to increased nutrients associated with plant and animal evolution. However, the recent decline in modern communities is the result of human activity within their catchments. The communities at Lake Thetis, Lake Clifton and Lake Richmond are now listed as threatened ecological communities by both the state and Australian governments and interim recovery plans are in place for the latter two (for more information see the 'Threatened ecological communities' webpage of DEC's website[6]).

Figure 17. Incredible structures: thrombolites of Lake Clifton, within the Peel-Yalgorup wetland system near Mandurah. Photos - M Forbes/DEC.

Figure 18. Incredible structures: thrombolites of Lake Thetis, Cervantes. Photo – R Jenkins/robertjenkinsphotography.

Creating crusts on wetland soils

In arid and semi-arid regions, dense plant growth is limited by the hot, dry conditions and variable rainfall. In wetlands and their surrounding drylands, large open spaces between plants often have a hard crust of soil a few millimetres thick, which is actually constructed by living organisms binding together soil particles to form biological soil crusts. Biological soil crusts can be formed by cyanobacteria, algae, lichens, fungi and bryophytes (that is, mosses, hornworts and liverworts). The crust stabilises the soil, protecting it from blowing or washing away, as well as retaining moisture and adding nutrients to the soil. The retained moisture can be essential for the survival of animals such as burrowing frogs. Biological soil crusts are common at the edges of many salt lakes in Australian inland regions, and are critical to the maintenance of wetland condition in these fragile systems.[74] They are also often present on the wetland bed once a salt lake has dried, containing the drought-surviving spores, seeds and eggs of organisms which spring to life when the wetland is next inundated.[17]

Producing sulfide that generates potential acid sulfate soils

Under anaerobic conditions, sulfate-reducing bacteria produce sulfide which can react with iron present in the sediment to form iron sulfides, most commonly pyrite.[22] When these soils are exposed to air, the sulfides are oxidised, creating sulfuric acid.[75] The resulting acid can dramatically alter the chemistry of the area, releasing other substances, including heavy metals, from the soil and into the surrounding environment. Significant areas of Western Australia, including a large number of wetlands, contain either potential or actual acid sulfate soils.

➤ For more information on sulfur cycles, see the topic ‘Conditions in wetland waters’ in Chapter 2. For more information about the cause and management of acid sulfate soils, see the topic ‘Water quality’ in Chapter 3.

Sources of more information on wetland bacteria

Stromatolites[59] provides an account of stromatolites, focussing on Western Australian occurrences.

Ecology of freshwater and estuarine wetlands[76] contains an excellent, though relatively advanced chapter on bacteria by Paul I. Boon: 'Chapter 5: Biogeochemistry and bacterial ecology of hydrologically dynamic wetlands'.

The chapter 'Benthic microbial communities of Australian salt lakes' by J. Bauld, in the book *Limnology in Australia*.[66]

The chapter 'Bacterial biodiversity in wetlands' by Paul I. Boon in the book *Biodiversity in wetlands: assessment, function and conservation*.[77]

extra information

Identifying bacteria

Bacteria are not typically monitored in wetlands, with the exception being cyanobacteria and those species that are indicators of faecal pollution (for example, from septic tanks and overflowing sewage pumping stations). Sometimes the activity of bacteria are obvious; the activity of sulfate-reducing bacteria produces hydrogen sulfide, a gas also emitted by rotten eggs, giving a characteristic odour sometimes noticeable in inundated saline wetlands, especially when the sediment is disturbed. Where warranted, biofilms can be sampled; specialists can measure the algal and microbial biodiversity of a biofilm and the functions it is performing, such as nutrient recycling, oxygen production or food production for bugs. The potential for in-depth bacteria studies to provide information about the state of a wetland has been highlighted[61], but due to the expertise needed it is unlikely to be a feasible option in the majority of cases.

Fungi

Fungi are multi-celled organisms that are neither plants nor animals (fungi is the plural, fungus singular). Fungi include an extremely wide range of organisms including macrofungi such as mushrooms, toadstools, puffballs, coral fungi, earthstars and truffles, and an even broader range of microfungi.

Fungi occur in most environments, however, some fungi species are much more prevalent in wetlands than other areas, such as certain species of macrofungi that fruit most abundantly on paperbark (*Melaleuca*) trees, and the predominantly microscopic aquatic fungi, which rely on free water for some part of their life cycle. The total number of fungi worldwide is estimated at between one and half to five million species. While the number of fungi species that occur in Western Australia is not known, it is estimated to be approximately 140,000 species.[78] Six hundred species of macrofungi have been recorded in the Perth region alone to date.[78] The Perth Urban Bushland Fungi Project has significantly increased the knowledge of this region. More than sixty urban bushlands have been surveyed and 600 fungi species recorded, of which forty are new records for Western Australia and several are new to science. Among their discoveries, participants of the Perth Urban Bushland Fungi Project found the first Perth occurrence of a fascinating mushroom: the volvate cortinar, *Cortinarius phalarus*. This mushroom was found at Forrestdale Lake growing under a thick layer of *Astartea* shrubs with an overstorey of *Eucalyptus rudis* and *Melaleuca preissiana*, with which it is considered likely to form a mycorrhizal partnership (explained below). This mushroom is a member of a small group also found in South America, giving rise to the theory that it is a relic from the time when what is now Australia and South America were part of the Gondwanan supercontinent (between 510 and 180 million years ago).[78]

Although fungi are not plants, they are considered to be plants for the purposes of the *Wildlife Conservation Act 1950*. This means that a flora license is required to collect fungi. For more information see the flora licensing webpage of the DEC website.[12]

Saprotroph: an organism that absorbs soluble organic nutrients from inanimate objects (e.g. from dead plant or animal matter, from dung etc)

The role of fungi

Although much research is still needed to understand the diversity and role of fungi in WA's wetlands, their role in a range of processes provide some insight into their importance in the function of wetland ecosystems. For example, truffle fungi are a favoured food of quendas and a range of soil-dwelling animals. Quendas return the favour by ingesting and then dispersing truffle spores in other locations in their dung.

Decomposing materials

Unlike plants which can secure energy from the sun through photosynthesis, many fungi gain their energy by decomposing organic materials.[17] Litter, dung, wood and dead organisms are all decomposed by these **saprotrophic** fungi. Their ability to decompose major plant components—particularly lignin and cellulose (the major components of plant cell walls)—means that we are not buried in debris (Figure 19).

Figure 19. Fungi decompose organic materials.

Recycling nutrients

The decomposition of dead materials also means that carbon and nutrients such as phosphorus, nitrogen, sulphur and copper are recycled, and bioavailable for plants, which is extremely important given the state's infertile soils.[79] Fungal networks capture soil nutrients, help prevent leaching, and retain nutrients in a plant available form. The importance of these functions has led scientists to conclude that 'it is difficult to conceive of any bar the simplest ecosystem surviving in the complete absence of fungi'.[31]

Supporting wetland plants

Many fungi form a close association with plants in which both parties benefit from an exchange of nutrients and sugars. This relationship is known as **mycorrhiza** and the roots of these plants are referred to as mycorrhizal roots. These fungi-plant roots are connected to networks of microscopic thread-like structures developed by the fungi known as hyphae or mycelia, which explore and exploit a far greater area of the soil than 'uninfected' roots alone. These networks take up nutrients, such as phosphorus, and transport the nutrients back to the plant. Two main types of mycorrhiza occur: endomycorrhiza, where the fungi penetrate the plant's cell wall, and ectomycorrhiza, where the fungi are external to the plant cells. Endomycorrhiza are formed mainly by microfungi and can be present in permanently flooded soils, while ectomycorrhiza are formed by many macrofungi and appear to be sensitive to inundation.[80]

Mycorrhiza: a symbiotic association between a fungus and the roots of a plant, from which both fungus and plant usually benefit

Lichen: a composite organism consisting of a fungus and a cyanobacterium or alga living in symbiotic association

Studies worldwide show that a large number of wetland plants are partnered with mycorrhizal fungi[14,81] and WA is no exception—including but not limited to *Melaleuca, Astartea, Isoetes, Cotula, Viminaria, Myriophyllum, Nymphoides, Nymphaea, Pericalymma, Livistona, Pandanus, Ruppia* and *Eucalyptus*.[82] In recent decades there has been developments in the understanding of mycorrhizal associations with sedges, and the major role they play in phosphorus dynamics.[81]

The significance of these beneficial plant-fungi partnerships needs to be considered when planning wetland revegetation. Research has found that healthy natural woodlands have a greater diversity of native fungi than degraded woodlands or revegetated agricultural lands, and that most native fungi are not self re-establishing in degraded or cultivated land, at least in the short to medium term.[79]

It has also been proposed that these fungi have a protective role for some plants rooted in soils with high metal concentrations. Similarly the truffle fungi that are the favoured food of quendas and other animals are mycorrhizal.

Stabilising soil and creating soil crusts

Networks of fungi hyphae (mycelia) stabilise soil. **Lichens** are associations between fungi and cyanobacteria or algae. Usually the partners comprising a lichen are unable to live apart. Lichens help form biological soil crusts along with algae, bryophytes (that is, mosses, hornworts and liverworts) and stand-alone fungi and cyanobacteria. These biological soils crusts stabilise and protect the soil in arid and semi-arid regions, where dense plant growth is limited by the hot, dry conditions and variable rainfall. In wetlands and their surrounding drylands, large open spaces between plants often have a hard crust of soil a few millimetres thick, which is actually constructed by living organisms binding together soil particles to form biological soil crusts. The crust stabilises the soil, protecting it from blowing or washing away, as well as retaining moisture and adding nutrients to the soil. The retained moisture can be essential for the survival of animals such as burrowing frogs. Biological soil crusts are common at the edges of many salt lakes in Australian inland regions, and are critical to the maintenance of wetland condition in these fragile systems.[74] They are also often present on the wetland bed once a salt lake has dried, containing the drought-surviving spores, seeds and eggs of organisms which spring to life when the wetland is next inundated.[17]

Providing food and habitat

Fungi are an important food source for many animals. Notably, fungi form an important part of the diet of a number of mammals including the quenda, bilby and western bush rat.

The hyphal networks (mycelia) of fungi provide nutrients for myriads of microorganisms and soil fauna. Fruit bodies of macrofungi provided habitat and food for many invertebrates, particularly during the cooler/wetter months.

Moderating populations

Some fungi are pathogenic, that is, they derive energy from living organisms by invading and often killing them. A notable example is the chytrid fungus *Batrachochytrium dendrobatidis*, which infects frogs with the chytridiomycosis disease, which has decimated many frog populations. Aquatic fungi are typically microscopic and predominantly saprotrophic or pathogenic, or both.

Sources of information on wetland fungi

Key databases

NatureMap is a collaborative website of DEC and the Western Australian Museum, available at naturemap.dec.wa.gov.au. It presents the most comprehensive and authoritative source of information on the distribution of Western Australia's flora and fauna. *NatureMap* is an interactive tool designed to provide users with comprehensive and up to date information on plants, animals, fungi and other groups of biodiversity. It can be used to produce maps, lists and reports of WA's flora and fauna diversity.

Key websites

Perth Urban Bushland Fungi www.fungiperth.org.au

Fungibank www.fungibank.csiro.au

Fungimap www.rbg.vic.gov.au/fungimap

Fungigroup, Western Australian Naturalists Club www.wanats.iinet.net.au/fungigroup.html

Mycorrhizal associations: the web resource www.mycorrhizas.info

Key literature

The field guide *Fungi of the Perth region and beyond: a self-managed field book*[83] available from the Perth Urban Bushland Fungi website www.fungiperth.org.au

Working with mycorrhizas in forestry and agriculture[84] available from http://aciar.gov.au/publication/mn032

Animals

Sources of information on wetland animals

Key databases

NatureMap is a collaborative website of DEC and the Western Australian Museum, available at naturemap.dec.wa.gov.au. It presents the most comprehensive and authoritative source of information on the distribution of Western Australia's flora and fauna. *NatureMap* is an interactive tool designed to provide users with comprehensive and up to date information on plants, animals, fungi and other groups of biodiversity. It can be used to produce maps, lists and reports of WA's flora and fauna diversity.

WetlandBase is an interactive database by DEC, with web hosting by the Department of Agriculture and Food WA, available via http://spatial.agric.wa.gov.au/wetlands. *WetlandBase* provides a comprehensive online resource of information and data about Western Australian wetlands. It provides spatial data, such as wetland mapping, and point data, such as water chemistry, waterbirds, aquatic invertebrates and vegetation sampling results. DEC is preparing an alternative to *WetlandBase*, scheduled for release in 2013, that will continue to make this data publicly available.

Freshwater fish distribution in Western Australia database is a spatial dataset by the Department of Fisheries, available at http://freshwater.fish.wa.gov.au. It is an interactive online tool that enables users to search all available information on the distribution of native and introduced freshwater fish and crustaceans in Western Australia. The dataset also contains historical records of freshwater fish collected in WA. It is constantly updated with new records of native and feral fish distribution provided by Department of Fisheries researchers, universities and other agencies.

Key websites

DEC's online library catalogue: www.dec.wa.gov.au/content/view/123/2122/

The Australian Museum: www.australianmuseum.net.au

DEC's biological surveys: www.dec.wa.gov.au/content/category/41/834/1814/

Animal conservation research: www.dec.wa.gov.au/content/category/41/829/1813/

Legislation relating to the protection of native animals: www.dec.wa.gov.au/content/section/43/1979/

The Australian Faunal Directory[85] provides information and a comprehensive list of references on mammals.

Environmental impact assessment reports prepared under the *Environmental Protection Act 1986* generally include fauna investigations on local fauna: www.epa.wa.gov.au

Key literature

Note: field guides to particular groups of animals are listed in text.

Fauna of Australia[86] (multiple volumes, available online).

A biodiversity audit of Western Australia's 53 biogeographical subregions in 2002[87]

A biodiversity survey of the Western Australian agricultural zone[88]

A biodiversity survey of the Pilbara region of Western Australia, 2002 – 2007[89] and the associated database (available at http://science.dec.wa.gov.au/projects/pilbaradb/).

Surveying fauna

A licence from the Department of Environment and Conservation is required if native fauna is to be caught or interfered with in any way. Catch and release surveys should not be undertaken without instruction from DEC. For more information, see the 'Fauna licensing' webpage of the DEC website.[90] A licence from the Department of Fisheries is required to survey fish.

Reporting fauna

Sick or orphaned native animals should be reported to the Wildcare Helpline on 08 9474 9055, which operates 24 hours a day.

Opportunistic native fauna sightings can be reported to DEC using the fauna report form available from the 'Standard report forms' webpage of DEC's website.[91] The report form is used for recording observations of threatened or priority fauna species but it may also be used to record unusual observations of common fauna (for example, where an animal is found outside of its usual range, such as a specimen washed up on a beach after a storm, or a migratory bird etc). Survey observations are to be submitted to the fauna survey database as per the conditions of the licence to take/collect fauna.

Introduced animals can be reported to the Pest and Disease Information Service, Department of Agriculture, phone number 1800 084 881; introduced fish, crayfish and other aquatic species to the FISHWATCH service, Department of Fisheries, phone number 1800 815 507.

Animals: vertebrates

Vertebrates are animals with backbones, including fish, frogs, reptiles, birds and mammals. Some live all or most of their life at wetlands but many are wetland visitors, such as dingos, emus and kangaroos. The following is a summary of vertebrate animals that are known to inhabit or often make use of Western Australian wetlands. This list is certainly not exhaustive. This is, in part, because we still do not have a comprehensive understanding of the habitat use of many species, particularly those of remote or under-surveyed areas of the state. Additionally, biologists may identify a species as occurring in 'moist habitats' or 'riparian habitats' without specifying whether these are in wetlands.

Fish

Native fish species in inland waters of Western Australia are few, and they tend to be more prevalent in waterways than in wetlands. In a global context, Australia is considered to be depauperate (deficient) of freshwater fish, with less than 200 species. This is thought to be because of the relative scarcity of rivers and the seasonal nature of inland waters. In particular, the freshwater fish of south-western Australia is considered to be far more depauperate than that of south-eastern Australia, attributable to the long isolation of south-west WA, a long history of aridity, and an extremely low level of primary productivity.[92] No fish species have been recorded from the Great Sandy, Gibson or Great Victoria Deserts.[92]

The Kimberley supports at least forty-nine species of freshwater fish.[93] Researchers consider it likely that there will be future discoveries. The Kimberley is an endemic hotspot for freshwater fishes, with around forty per cent of the species found nowhere else. It is encouraging that there are currently no introduced fishes found in any major catchments of the Kimberley; however there are records of eastern mosquitofish (*Gambusia holbrooki*) from Cape Leveque and redclaw crayfish (*Cherax quadquicarinatus*) within the Ord River basin.[94]

The Pilbara region supports thirteen native species of freshwater fish, including two that are restricted to caves.[95] Five of these are endemic, with the rest also occurring in the Kimberley. Four introduced species are also present. Importantly, they are presently restricted to the southern half of the Pilbara Drainage Division, with no records of them north of the Lyndon River.[94]

With only eleven native freshwater fish species, the south-western region of Western Australia has a remarkably small number of freshwater fish. Notwithstanding this, they are considered a unique assemblage of freshwater fishes. Nine are endemic, meaning the south-west region has the highest percentage of endemic fishes in Australia, that is, over 80 per cent of the freshwater fish are found nowhere else on Earth.[96] This is thought to be due to the long period of isolation (approximately 15 million years). They are small bodied, generally less than 140 millimetres with the exception of the freshwater cobbler *Tandanus bostocki*. They are all well adapted to life in the variable aquatic environment of the south-west, which is characterised by a long dry summer and a cool wet winter. Research indicates that the south-west freshwater fishes have a higher reliance on terrestrial insects than fishes in other regions of Australia.[16] Inundated vegetation is thought to be important habitat for the larvae of the salamanderfish, black-stripe minnow, western mud minnow and Balston's pygmy perch (Figure 20).[92] Acidic (pH 3.9–6.0), tannin-stained waters are important for Balston's pygmy perch.[97]

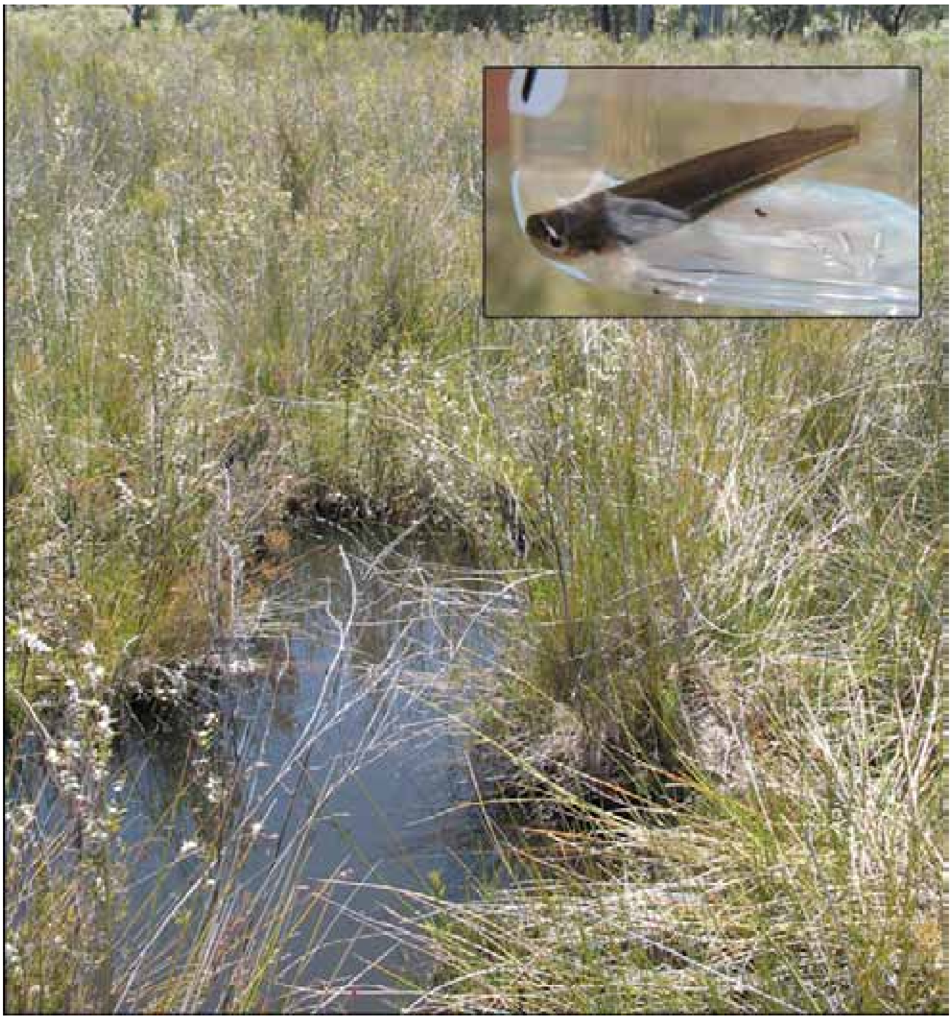

Figure 20. Inundated vegetation is important habitat for native fish in WA's wetlands, such as this western mud minnow, *Galaxiella munda,* found during water sampling in a densely vegetated wetland east of Margaret River. Photos – M Bastow/DEC.

In 2009–2010, a study by the Department of Fisheries found native fish in only fifty of 114 wetlands surveyed in the south west and Midwest.[98] Concern has been expressed that native fish habitat in the southwest is being lost due to development and altered regime (drying) of wetlands. Introduced fish are also implicated; 66 per cent of wetlands in the study were found to contain introduced species and only 9 per cent of the sites were populated exclusively with native freshwater fish. Previous studies (for example, Morgan et al. 1998[92] and Morgan et al. 2004[94]) show similar trends.

Aestivation: a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

The conservation status of WA's wetland fish is as follows:

- Threatened: western trout minnow *Galaxias truttaceus hesperius*
  western mud minnow *Galaxiella munda*
  Balston's pygmy perch *Nannatherina balstoni*[99]
- Priority three: black-stripe minnow *Galaxiella nigrostriata*

case study

Figure 21. The incredible salamanderfish, which reaches a maximum size of 5 centimetres (male) and 8 centimetres (female).[103] Photo – G Allen/Freshwater Fish Group and Fish Health Unit, Centre for Fish and Fisheries Research, Murdoch University.

Fish mystery solved by a water truck

Most fish inhabit permanent water sources or move to permanent water sources during the dry season. The salamanderfish *Lepidogalaxias salamandroides*, and the black-stripe minnow *Galaxiella nigrostriata* do not, puzzling researchers as to how they survive the hot, dry summers of the southwest.

The salamanderfish is of ancient lineage, described as looking a little like a "dark grub with fins and tail" (Figure 21). Its mystery appearance and disappearance from wetlands every year was solved by freshwater fish research Gerald Allen, co-author of *Field guide to the freshwater fishes of Australia*.[101] He borrowed a water truck one hot summer to flood a dried-up hole. He recalls "It was amazing. Within 10 or 15 minutes the pool was virtually teeming with fish".[102]

By following the dropping groundwater table down into the moist sandy soil and **aestivating** during the dry season, the salamanderfish and the black-stripe minnow display an extraordinary adaptation to the conditions of the south west. It is thought that there are only twenty four species worldwide that share this life cycle![104] Because the salamanderfish and black stripe minnow are reliant on the underlying substrate to remain waterlogged, the drying climate of the south west poses a major threat to the remaining populations, which have already contracted (considerably, in the case of the black-stripe minnow which is mostly confined to the Scott Coastal Plain). Burning of sediment poses another key threat.

Research into the ecology of the black-stripe minnow is shedding light on their habitat and diet preferences, aestivation requirements and population genetic structure. One investigation is looking at their burrowing capability as well as the commonly cited theory that the minnows inhabit the burrows of the koonac crayfish, *Cherax preissii*.[105,106]

A recovery plan is in place for the western trout minnow.[100] For more information, see the 'Recovery planning and implementation' webpage of the DEC website.

➤ For more information, see the following resources on freshwater fish:

- The *Field guide to the freshwater fishes of Australia*[101] provides photos and information to help guide identification.
- Introduced fish in WA's wetlands and their management is outlined in the topic 'Introduced and nuisance animals' in Chapter 3 of this guide.
- The website of the Freshwater Fish Group and Fish Health Unit, Centre for Fish and Fisheries Research, Murdoch University (http://freshwaterfishgroup-fishhealthunit.yolasite.com/) provides excellent information.
- The Department of Fisheries website www.fish.wa.gov.au provides information and the spatial dataset *Freshwater fish distribution in Western Australia database*, available from http://freshwater.fish.wa.gov.au/.
- An excellent film, *Native freshwater fishes of south-western Australia*[107], is available for viewing from the Envfusion films website: www.envfusion.com.au/Portfolio.htm

Amphibian: the class of animals to which frogs, toads and salamanders belong. They live on land but develop by a larval phase (tadpoles) in water.

Frogs

The ancestors of amphibians crawled from the water over 370 million years ago and were the first vertebrates to colonise the land.[108] Most are still dependent on water to complete their life cycle giving rise to the term '**amphibian**' meaning 'two lives' - one in water and one on land. Other present-day amphibians occur on other continents, including toads, salamanders, newts and caecilians.

There are about 216 frog species in Australia, with eighty-one known to occur in WA.[109] Over time, additional new species of frogs are being identified in WA. With over forty species, the Kimberley is home to the greatest diversity of frogs in the state, and is

Figure 22. Frog spawn in waterlogged soil of a wetland, in a depression created by animal pad. The lack of a protective shell renders frog eggs susceptible to pollutants and altered water quality. Photo – J Lawn.

considered to be a centre of frog endemism in Australia.[110] The south-west boasts thirty species[109] and the arid zone home to more than twelve. There are three threatened species of frog, all from the south-west. The cane toad *Bufo marinus* is the only introduced frog in WA.

Spawn: eggs surrounded by jelly; generally applied to a group of eggs

Wetlands are essential habitat for many of WA's frogs. As amphibians, the vast majority need water to breed, to keep eggs moist and to provide habitat for tadpoles.[111] There are exceptions, with the young of some species developing entirely within the egg, and upon hatching are miniatures of the adults, rather than tadpoles. Eggs are typically produced in a clump, referred to as **spawn**, kept together by the jelly encasing each egg. Wetland spawning sites include floating, submerged or at the bottom of open water, in 'foam rafts' on the water, on vegetation above water, in shallow depressions or a burrow in waterlogged soil (Figure 22), and in depressions or channels in peat. Adults of many species can travel significant distances from wetlands. In Perth, the moaning frog *Heleioporus eyrie* (Figure 23) and the pobblebonk *Limnodynastes dorsalis* rely on wetlands to breed but as adults are entirely terrestrial, living up to 4 kilometres from water.

Figure 23. The moaning frog, *Heleioporus eyrie*, breeds in wetlands in south-western Australia. Photo – C Mykytiuk/WWF.

All Kimberley species are known to breed in the wet season (November–March).[112] Arid zone frogs breed when water becomes available, typically following infrequent storms, especially when cyclones travel south from the Timor Sea during the wet season (November–March). The tadpoles complete development rapidly as ponds do not last long in the arid zone. The only exception is the northern sandhill frog (*Arenophryne rotunda*) near Shark Bay, which breeds in winter and spring and has direct-developing young (no tadpole stage). In the south-west, most species breed for a period between autumn and spring but there are exceptions, such as the motorbike frog (*Litoria moorei*), which breeds well into summer[112], and others, such as plonking frog (*Neobatrachus wilsmorei*) and the shoemaker frog (*Neobatrachus sutor*) which breed in response to summer rains.[112]

Frog species vary widely in their adult habitat requirements. Some frogs can live their adult lives in dryland habitats, seeking moisture from below ground or under surfaces, for example, the turtle frog (*Myobatrachus goldii*).[109] Some species, such as the moaning frog (*H. eyrei*), burrow into soil during the day in summer and forage at night to avoid dessication.[112] WA is considered to be rich in burrowing frogs by Australian standards, with burrowing being an important survival strategy employed by a large proportion of WA's frogs: over 70 per cent of Kimberley frogs, close to 75 per cent of arid region frogs, and over 60 per cent of south west frogs.[113] Some burrow extremely deep, such as the aptly named desert spadefoot, *Notaden nichollsi*, which can burrow to 1 metre.[112] Some, such as the water holding frog *Cyclorana platycephala* absorb large quantities of water through their skin and store it in their tissues and particularly in the bladder where it can be reabsorbed later.[114]

Frogs play a key role in many food webs, both as predators and as prey. Frogs are an essential part of the diets of many animals including snakes and birds.[114] Frogs are carnivores, and mostly eat insects and arthropods. Some eat other frogs, lizards and small mammals. Most tadpoles are considered to feed on algae (algivores).[15]

Amphibians are experiencing an unprecedented decline worldwide, with more than a third of species considered to be at risk of extinction. The decline in frogs has significant implications for food webs of wetland and dryland ecosystems globally. More than half of Australia's frog species are threatened by a disease called chytrid fungus *Batrachochytrium dendrobatidis*, which infects frogs with the chytridiomycosis disease.

Frogs are particularly good indicators of changes to water chemistry because they breathe primarily through their moist, semi-permeable skin, which is a poor barrier to pollutants, and their eggs lack a protective shell. Both of these factors make them highly susceptible to pollutants in the water and to changes in water chemistry. Frogs seem to be most vulnerable to pollutants when they are in the egg and tadpole stages.[114] Only limited information is available about the tolerances of frogs to salinity in Western Australian wetlands, however, anecdotal information suggests that frog declines are associated with an increase in salinity.[115] The effect of increased salinity on populations of the spotted burrowing frog (*Heleioporus albopunctatus*) has been investigated in the inland south-west agricultural area, and there is some indication that there may be a decline in its numbers correlated with salinisation of its habitats, possibly related to the effect of salinity on eggs and tadpoles. If this is the case, it is likely that other frog species in the region are also vulnerable.[116]

Much loved by children and adults alike for their charismatic tadpole and adult forms and their calls, native frogs are fantastic icon species for wetlands. Creating frog ponds is a popular way to interact with frogs, but moving tadpoles around can spread diseases and move frogs out of their natural range. The Alcoa Frog Watch website[112] facilitates a tadpole exchange program and provides tips on how to minimise potential adverse effects of moving frogs.

The conservation status of WA's frogs is as follows:

- Threatened: white-bellied frog *Geocrinia alba*
  yellow-bellied frog *Geocrinia vitellina*
  sunset frog *Spicospina flammocaerulea*[99]

Note: recovery plans are in place for each of these species. For more information, see the 'Recovery planning and implementation' webpage of the DEC website.[117]

- Priority one: marbled toadlet *Uperoleia marmorata*
  small toadlet *Uperoleia minima*

- Priority four: Nornalup frog *Geocrinia lutea*[4]

➤ Frog resources include:

- *Field Guide to Frogs of Western Australia*[109]
- the Alcoa Frog Watch website[112]
- the CD *Frog calls of southwest Australia*, available from the Western Australian Museum; for more information see the Alcoa Frog Watch website
- the Frogs Australia Network website[114]
- the website www.frogwatch.org.au, designed to provide information about frogs from across Northern Australia, including the Kimberly region. *The Northern Australian Frogs Database System* can be accessed from this website.
- the topic 'Monitoring wetlands' in Chapter 4, which provides a guide to monitoring frogs.

Reptiles

Western Australia's wetland reptiles include lizards, snakes, turtles and crocodiles.

Crocodiles

Crocodiles are an ancient group of reptiles who are well-adapted adapted to the warmer waters of northern Western Australia. They are of importance in Aboriginal culture, featuring in the rock art and stories of the traditional owners of the Kimberley. Freshwater crocodiles, *Crocodylus johnstoni*, and estuarine crocodiles, *Crocodylus porosus*, inhabit rivers and also some wetlands south to Exmouth. Freshwater crocodiles inhabit freshwater wetlands and occasionally tidal areas, with track marks indicating they can walk considerable distances at the end of the wet season in search of a dry season refuge.[118] During the dry season the crocodiles may lie dormant in areas where the water dries up, sheltering in burrows among the roots of trees fringing waterbodies or in shelters dug into creek banks. Adult crocodiles are the top of the food chain of many wetlands, feeding mainly on insects and fish, as well as crustaceans, spiders, frogs, turtles, lizards, snakes, birds and mammals. Although estuarine crocodiles are known as 'salties', they inhabit both freshwater and saline wetlands. Growing up to seven metres, this iconic species of the Kimberley is the largest reptile on earth. They feed on fish, waterbirds and occasionally large land mammals such as humans and wallabies.

Freshwater crocodiles excavate a hole in soil and lay 70 millimetre eggs in late August to early September, incubating them for three months. About three weeks before egg-laying starts the female begins excavating a number of 'test' holes at night, usually in a sandbank within 10 metres of water. In areas where there are limited suitable nesting sites, many females may choose the same area, resulting in a number of nests being accidentally dug up.[118] Estuarine crocodiles construct a nest of vegetation and soil and lay 85 millimetre eggs during the wet season from November to April, also incubating the eggs for three months.

Young crocodiles are often taken as food by birds of prey, goannas, dingoes and adult crocodiles. A study of freshwater crocodile nest egg predation at Lake Argyle found that dingoes were responsible for most predation.[119] Adult crocodiles have few predators besides other crocodiles, however the cane toad *Bufo marinus* is considered a threat to freshwater crocodiles after the discovery of many dead crocodiles with toads in their stomachs.[118]

Historically, unregulated commercial hunting for meat and skins drove the saltwater crocodile to the brink of extinction in WA while the numbers of freshwater crocodiles were considerably reduced in some areas. Today crocodiles are legally farmed for meat and skins but are not hunted in the wild. Farmed crocodile meat has been approved for human consumption in Western Australia since 1989 and crocodile meat products for human consumption are sold within Australia and exported overseas.[120]

Conservation status: Crocodiles have special protection under schedule 4 of the *Wildlife Conservation (Specially Protected Fauna) Notice 2010 (2)* as 'other specially protected fauna'.[3]

➤ For more information on crocodiles, see:

- DEC webpage 'Crocodile management in WA'[121]
- *Australian Crocodiles: a natural history*[122]; and
- The relevant chapters of *Fauna of Australia Volume 2A amphibia and reptilia*.[123]

Turtles

Western Australia supports seven of the twenty-six described species of Australian freshwater turtles (a number are yet to be described).[124,125] All of Western Australia's freshwater turtles live in water for the duration of their lives; feeding, courting and mating underwater. They emerge to bask in the sun to raise their body temperature (thermoregulation) and lay their eggs on land. Hatchlings are preyed upon by many other animals, for example, crayfish such as koonacs (*Cherax preissii*) and introduced yabbies (*Cherax destructor*) predate upon oblong turtles.[126] Foxes, cats and birds are known predators of adult turtles.

Figure 24. A turtle saved from the wheels of a four-wheel drive vehicle, Jurien Bay. Photo – A Shanahan/DEC.

Kuchling's long-necked turtle, *Chelodina kuchlingi*, is found in a very small area of north-east Kimberley, east of Kalumburu. The Kimberley is also home to the sandstone snake-necked turtle, *Chelodina burrungandjii, Elseya dentata* and *Emydura victoriae*, which occurs west across to the Fitzroy drainage.[125] *Chelodina kuchlingi* and *C. burrungandjii* are carnivorous while *E. dentata* and *E. victoriae* are omnivorous, eating a lot of plants, and fruit and algae, respectively.

The flat-shelled turtle, *Chelodina steindachneri*, is very hardy, inhabiting the most arid region of any Australian turtle. It inhabits seasonally and intermittently inundated wetlands from the Pilbara to the Midwest extending into the desert. When surface water dries up, it digs holes under vegetation surrounding wetlands and aestivates for periods up to years, until the next heavy rains arrive, or it undertakes lengthy overland migration to find surface water. It is adapted to hot, dry conditions, employing a range of techniques to survive including storing water in the urinary bladder. It is carnivorous, eating a variety of food such as fish, tadpoles, insects, frogs, small crayfish, freshwater prawns and carrion. Hatchlings have been known to eat aquatic plants, insects and mosquito larvae.

The oblong turtle (*Chelodina colliei,* formerly *C. oblonga*) is endemic to the south-west of WA, occurring from Hill River in the Midwest region to the Fitzgerald River on the south coast, and extending east into the Avon Wheatbelt. Also known as the long-necked turtle, it withdraws its long neck in a sideways motion into a groove in its shell, like all other turtles in the genera *Chelodina*. It is carnivorous, eating a variety of food such as fish, tadpoles, insects, frogs, small crayfish, freshwater prawns and carrion. Hatchlings have been known to eat aquatic plants, insects and mosquito larvae. It usually occurs in permanently inundated wetlands, but it is known to aestivate in mud or under leaves or logs for five to six months or migrate to nearby water during dry periods.[124] Recent research indicates that turtles are only likely to successfully aestivate or migrate if they are in good health. In urban environments such as Perth, where it is common, inadequate wetland buffers and poor management of humans, pets and introduced predators in and around wetlands take a serious toll on populations of the oblong turtle. Added to this is the tendency of well-meaning humans to thwart the migration and egg-laying processes, which can involve the females travelling considerable distances from the water to reach nesting sites, typically between September and January: *'It is a tough life for those turtles inhabiting lakes surrounded by busy roads and manicured lawns with little lakeside vegetation remaining…[but] during the warmer months, female turtles are best left alone to fulfil their motherhood duties. Imagine hauling yourself around for a considerable distance with a tummy full of eggs looking for a good egglaying site only to be returned to the water to start the journey all over again.'* - Bush *et al.*, 2007.[127] Interestingly, a study of two Perth wetlands found a preference amongst the oblong turtles for laying eggs on the southern aspect of these wetlands.[128] Hatchlings emerge at different times at different wetlands.

The species is known to tolerate estuarine level salinities if it has access to fresh water for breeding and long-term health.[129] It does not possess a salt excretory gland (J Giles 2009, pers. comm.).The habitat of the oblong turtle is likely to have contracted considerably with the widespread secondary salinisation of Wheatbelt wetlands.

Lastly, human poaching, including for the illegal pet and restaurant trade, has been implicated as the cause of population declines at some wetlands. In 2003, more than twenty females were poached from Lake Joondalup in an attempt to smuggle them out of the country, of which only four survived.[130]

For all these reasons, oblong turtles are assigned the status 'near threatened' by the IUCN, meaning that the species is close to qualifying for 'vulnerable' status (which applies to taxon facing a high risk of extinction in the wild in the medium-term future).[131] To assist with its conservation, people can record their observations of oblong turtles on the ClimateWatch website (www.climatewatch.org.au) or via Turtle Watch, which is run out of four environment centres in the Perth metropolitan region: Cockburn Wetlands Education Centre, Canning River Eco Education Centre, South East Regional Centre for Urban Landcare and Herdsman Lake Wildlife Centre.

Western swamp turtles (*Pseudemydura umbrina*) are considered Australia's most endangered reptiles. Their habitat has been cleared for agriculture, urbanisation and for extraction of clay for brick and tile manufacture. The remaining populations are now protected in two seasonally inundated wetlands in Ellenbrook Nature Reserve and Twin Swamps Nature Reserve in Bullsbrook, north of Perth.[127] Attempts to broaden their distribution are being progressed with translocations to other sites north of Perth. At a tiny 15 centimetres, the tortoises are vulnerable to predation by foxes, cats, dogs, rats and ravens. They are also reliant on rainfall to survive and reproduce successfully, so without intervention, successive dry years pose a considerable threat to the populations. Perth Zoo runs a breeding program for the tortoise with 700 successfully reared since 1989 and 500 returned to the wild. The Friends of the Western Swamp Tortoise actively support and promote the management of the turtles. It is carnivorous, eating a variety of food such as fish, tadpoles, insects, frogs, small crayfish, freshwater prawns and carrion. Hatchlings have been known to eat aquatic plants, insects and mosquito larvae.

The red-eared slider is the only introduced turtle in WA, where known occurrences in Perth wetlands have been removed. It is one of the top 100 'World's Worst' invaders as determined by the International Union for the Conservation of Nature and is considered a major threat to biodiversity. In Australia, they compete with native turtles for food, nesting areas and basking sites; and by eating hatchlings and carrying diseases that can infect native turtles.

The conservation status of WA's turtles is as follows:

- Threatened: western swamp tortoise *Pseudemydura umbrina*[3]

A recovery plan is in place for the western swamp tortoise. For more information, see the 'Recovery planning and implementation' webpage of the DEC website[117]

➤ For more information on turtles, see:

- *Australian freshwater turtles*[132]
- 'Management of the long-necked tortoise *Chelodina oblonga*' in *Managing your bushland*[129]
- The Friends of the Western Swamp Tortoise website www.westernswamptortoise.com[133]
- Perth Zoo and its website www.perthzoo.wa.gov.au

Lizards

While lizards are widespread in dryland habitats, wetlands may form part of the habitat of many species. Some lizards specialise in wetland habitats, such as the saltpan ground dragons, *Ctenophorus salinarum*, which are found amongst the glare, wind and salt of salt lakes of inland WA[127,88] and the painted ground dragon, which occurs in samphire of salt lakes of far south-eastern WA. The long-snouted water dragons (*Lophognathus longirostris*) are found in areas close to water from the Murchison to the Midwest. The purple arid dtella *Gehyra purpurascens* are a tree-climbing gecko that perch on trees in damp areas such as claypans in arid Western Australia.[127] The water monitor, *Varanus mertensi*, is a semi-aquatic monitor seldom seen far from water in the Kimberley. It is an accomplished climber and a strong swimmer. It mostly feeds on fish and frogs, but will also eat insects and small terrestrial vertebrates. It has an excellent sense of smell and may dig up prey when foraging, including freshwater turtle eggs. Mortalities from ingesting cane toads, *Bufo marinus*, have been recorded.

A number of skinks prefer cool, damp wetland habitats, such as the western glossy swamp skink (*Egernia luctuosa*) which is found in dense wetland vegetation from Perth to Albany. They are perfectly adapted for their wetland habitat; they can dive into shallow water and swim with ease, and have been reported sheltering down abandoned crayfish burrows.[127] Researchers have identified a dramatic decline in numbers of western glossy swamp skink in the Perth metropolitan region, and attribute this to the destruction of wetland habitats.[134] The south-western cool skink (*Acritoscincus trilineatum*) prefers thick vegetation and moist conditions between Gingin and Israelite Bay, including wetland habitats. Apparently the loud rustling noises often heard coming from leaf litter and dense vegetation of wetlands can often be attributed the south-western cool skink, despite its small size.[135] The loss of leaf litter associated with the vegetation decline is likely to impact upon this and other skinks.[136]

A number of mulch skinks inhabit wetlands. The south-western mulch skink, *Hemiergis gracilipes*, occurs in wetlands from Bunbury and Collie south to near Albany.[127] The two-toed mulch skink *Hemiergis quadrilineata* occurs in wetlands from Jurien south to Busselton. It inhabits leaf litter and forages for small prey such as termites and ants. The four-toed mulch skink *Hemiergis peronii peronii* occurs in wetlands of the south coast. The southern five-toed mulch skink, *Hemiergis initialis initialis,* prefers moist areas of the Darling Range and the south-eastern Wheatbelt.

Snakes

There are more than one hundred species of snake found in Western Australia and its oceans.[137] While most of WA's snakes are terrestrial, many do use or inhabit wetlands and some are aquatic (Figure 25). These are described below (estuarine and mangrove snakes are not included). Wetlands also indirectly support terrestrial snake populations because frogs and other wetland animals are an important part of the diet of many snake species.

Figure 25. An unidentified snake species in the water at Lake Hayward in the suburb of Preston Beach, south of Perth. Photo – Wetlands Section/DEC.

Northern Western Australia is home to a number of aquatic snakes that inhabit wetlands. The freshwater snake (also known as the 'Keelback') *Tropidonophis mairii* is a semi-aquatic snake that inhabits freshwater wetlands in the Kimberley, south to Kununurra. They may be seen basking on the surface of open, still water[137] and have the ability to remain submerged for 20 to 30 minutes.[138] They mainly feed on adult frogs (Figure 26), but also eat frog eggs, tadpoles, small fish and reptiles. It is reported that they can feed on cane toads, *Bufo marinus*, without ill-effect.[138]

Figure 26. A frog poses a hearty, if somewhat resistant, meal for this individual of the species known as the freshwater snake *Tropidonophis mairii*, which in WA can be found in the Kimberley, south to Kununurra. Photo – G Calvert/James Cook University.

The green tree snake *Dendrelaphis punctulatus* occurs in the Kimberly south to Lake Argyle. While they are at home in pandans and in trees as their name suggests, they are also excellent swimmers.[137] The threatened Pilbara olive python *Morelia olivacea barroni* are found close to[139] and in water.

The wetlands of the south-west (Gingin–Israelite Bay) are habitat of one of the world's most deadliest snakes, the tiger snake, *Notechis scutatus*. They are commonly observed amongst wetland vegetation, in animal burrows, under large boulders, in standing dead trees, and in water, being accomplished swimmers and readily searching underwater, where they can stay under for at least nine minutes.[140] Being relatively cold tolerant, they commonly emerge at night to prey on frogs[140], which make up the bulk of their diet, along with lizards, mammals, young birds, turtles and fish.[141] Tiger snakes mate in summer and bear live young in autumn. They are dangerously venomous, resulting in the second highest number of fatal bites by Australian snakes, after the brown snake group.[127] They display extreme colour and size variation, but get their name from the yellow stripes visible on some individuals.

Much more elusive is the large-eyed sedge snake, *Elapognathus minor*, which extends from Busselton to Two Peoples Bay. They inhabit wetlands dominated by sedges, tussocks and dense heath.[141] The related crowned snake, *Elapognathus coronatus*, also inhabits wetlands, and occurs mainly near the coast from Muchea to the Great Australian Bight.[127]

➤ A number of excellent guides to the reptiles of Western Australia are available. These include:

- *A complete guide to reptiles of Australia*[124]
- *Snakes of Western Australia*[137]
- *Reptiles and frogs in the bush: southwestern Australia*[127]
- *A guide to the reptiles and frogs of the Perth region*[141]
- *Lizards of Western Australia. 1. Skinks*[137]
- *Guide to the wildlife of the Perth region*[135]

Birds

Birds are usually the most visible of wetland animals, and can often be seen roosting, foraging and nesting even in urban wetlands. WA's wetlands provide habitat for a wealth of birds, too numerous to discuss here in any detail. Almost five hundred and fifty bird species are recorded from Western Australia, with sixteen occurring exclusively in the state.[142] Wetlands provide either important or sole habitat for a significant proportion of these, from a diverse range of bird groups including, but not limited to, quails, ducks, geese, swans, grebes, darters, pelicans, cormorants, herons, egrets, bitterns, ibis, spoonbills, storks, birds of prey, kingfishers, cranes, waterhens, button-quails, shorebirds, terns, scrub-birds, wrens, honeyeaters, robins, babblers, fantails, warblers, mistletoebirds, finches and pipits. Wetlands also provide an important drinking water source for birds such as Carnaby's cockatoo and emus (*Dromaius novaehollandiae*), which inhabit a wide range of habitats but remain within 20 kilometres of drinking water, favouring flats where fresh vegetation grows after rain.[143] Researchers estimate that approximately 150 waterbird species make use of WA wetlands.[144]

The importance of wetlands as habitat for many of the state's birds is reflected in the number of Important Bird Areas[145] (IBAs) that are wetlands. Similarly, two out of the nine criteria used to assess whether wetlands are listed as internationally significant under the Ramsar convention relates to waterbird habitat. Forrestdale and Thomsons Lakes, Lake Gore, Toolibin Lake, the Lake Warden system, Lakes Argyle and Kununurra, the Muir-Byenup system and the Peel-Yalgorup system are Ramsar sites in WA that meet one or both of these criteria.

Different wetland types provide different resources for wetland birds (Figure 27). Seasonally inundated wetlands, for example, are important bird habitat, with small, poorly defined wetlands inundated for a few months accounting for more than half of the breeding by ducks.[146] Saline wetlands, in particular, support an abundance of waterbirds.

Figure 27. The striking pink-eared duck, *Malacorhynchus membranaceus*, prefers shallow intermittently and seasonally inundated wetlands. Photo – S Halse/DEC.

A large proportion of birds that use wetlands are mobile[147], travelling between wetlands, waterways, estuaries and dryland and creating biological networks and connectivity between them. Bird species that are relatively sedentary, living locally for the duration of their life, are known as residents. Even residents may use one or more wetlands within a territory. They may visit several wetlands in a day, using each wetland for different purposes.[27] For example, they may feed at a saline wetland, drink at a freshwater wetland and roost at a third wetland.

Waterbirds are mobile and typically use many wetlands in a lifetime. Episodic migration between breeding territory in the south-west in winter and the north in the wet season is common. Movements of Australian waterbirds are considered to be largely unpredictable and complex.[38] Partial migration (where only part of the population migrates) south from the Kimberley during the dry season is undertaken by a number of wetland bird species, including the white-necked heron (Figure 28), plumed whistling duck and brolga.[147] The arid zone is an important nursery for waterbirds. Lake Gregory, Fortescue Marsh and Mandora Marsh in the north together support over a million waterbirds during the late dry season in some years and are important breeding sites for some species.[146] Irregular movement beyond the normal breeding range of a species also occurs in wetland bird populations. These irruptions are often a reflection of rainfall patterns. Many wetland birds can respond to rainfall by dispersing quickly and widely, and then contracting to

Figure 28. The white-faced heron, *Ardea novahollandiae*, occurs in many areas of WA. Photo – J Lawn/DEC.

a small number of sites during dry times.[146] Nomadism, where individuals of a species regularly move away from the breeding range to take advantage of favourable conditions to feed or breed, also occurs in many wetland birds. These include the Australian white ibis, straw-necked ibis, red-necked avocet, banded stilt, black-winged stilt and the black-tailed native-hen, to name a few.[147]

Some migratory shorebirds travel between continents, flying thousands of kilometres to reach Western Australian wetlands. These fly south from Asia or Alaska stopping first at the north-west tidal flats and then on to the wetlands and estuaries of southern Australia.[148] More than fifty million migratory waterbirds from fifty-four species[149] use the East Asian–Australasian **flyway**, which extends from the Russian Far East and Alaska in the north to Australia and New Zealand in the south, and incorporates eastern Asia and parts of south Asia (Figure 29). These birds make an annual round trip of up to 25,000 kilometres. Important WA wetland sites already recognised along this route include Lake MacLeod, Lake Cooloongup, Lake Gregory, Forrestdale Lake, Lake Preston, Thomsons Lake and Camballin. Beaches and waterways are also very important habitat, including Roebuck Bay, Eighty-Mile Beach and parts of the Swan River.

Flyway: a geographic region that supports a group of populations of migratory waterbirds throughout their annual cycle. Up to nine flyways are recognised worldwide.

Propagule: a unit or a piece of an organism that facilitates the organisms' reproduction. Plant propagules primarily include seeds, spores and plant parts capable of growing into new plants. Invertebrate propagules are usually eggs or, in the case of sponges, gemmules. Protist propagules are usually cysts. Bacteria and algae propagules are usually spores.

Figure 29. The East Asian–Australasian flyway. Image – © East Asian–Australasian flyway Partnership.[149]

Mobile birds can transport materials, nutrients and energy into and out of wetlands. In particular, they move **propagules** to and from wetlands[150] on their bodies (for example, stuck to feathers), in their gut, and in faeces. Long-distance dispersal by birds helps to explain major disjunctions (separations) between populations of a species, such as many sedge species. They can also transport adults; small animals such as water mites can hitch a ride while some, such as snails, may actually be ingested and survive inside a bird gut for hours before being excreted many kilometres away. In boom times, large populations can import significant amounts of nutrients into wetlands, via faeces.

Birds are often at the top of many wetland food chains. There are birds that eat almost every conceivable type of food in wetlands, including plants, fish, frogs, tortoises, small mammals such as mice, insects, gilgies, lizards, worms, leeches, snails, slugs, algae and other birds. Food is sourced from vegetation, water, the soil and soil litter, and organisms caught in flight. Colonies of breeding waterbirds may range some distance from wetlands to feed. Farmers sometimes consider them important in pest control in crops and pasture because they eat caterpillars, crickets and grasshoppers.[17] They can also reduce nuisance midge and mosquito populations. Bird diets range from extremely specialised to more generalist. For example, blue-billed ducks (*Oxyura australis*) are thought to rely on larvae of midges for about 25 per cent of their food[152], as well as caddis flies, dragonflies, flies and water beetle larvae. They may also eat the seeds, buds, stems, leaves and fruit of a wide variety of plants.[142] A waterbird's beak is usually a good guide to its preferred foods.

➤ For more information on inferring diet from bill morphology, see the feeding ecology information on Birds Australia's website www.birdlife.org.au/all-about-birds/australias-birds/biology-ecology

extra information

International agreements and treaties for the protection of migratory birds

Listed migratory species are those animals that migrate to Australia and its external territories, or pass through or over Australian waters during their annual migrations. Migratory species include species of birds, reptiles and mammals (such as whales).

The Australian Government maintains a list of migratory species, available online.[151,3] It includes those listed in the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention), China-Australia Migratory Bird Agreement (CAMBA), the Japan-Australia Migratory Bird Agreement (JAMBA) and the Republic of Korea-Australia Migratory Bird Agreement (RoKAMBA).

All species on the list of migratory species are 'matters of national environmental significance' under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. This means that any action that has, will have, or is likely to have, a significant impact on a listed migratory species will require referral to the Commonwealth Environment Minister and undergo an environmental assessment process.

For more information, see the topic 'Legislation and policy' in Chapter 5.

Similarly, birds make use of most wetland habitats to feed, nest and roost. Trees and tree hollows, shrubs, sedges and grass on land and in water are nesting sites for various species, as well as floating structures on water. A number of species nest on the ground, while the rainbow bee-eater (*Merops ornatus*) tunnels into sandy soil to nest underground. Caves and old rabbit burrows are also used by species including the Australian shelduck (*Tadorna tadornoides*).[152] Loss of wetland plants can have a major impact on many birds. For example, the whistling kite *Haliastur sphenurus* has suffered a major decline in population in many urban areas because of the loss of woodlands of flooded gum, *Eucalyptus rudis*, and the paperbark, *Melaleuca preissiana*, which are used for breeding.[134] Similarly, the Swan Coastal Plain Wetlands Study found that generally the wetland with the most complex vegetation structure had the most birds.[153,154] However, birds are not always a good indicator of the health of a wetland; the same study indicated that birds are often very abundant at nutrient enriched wetlands.

Waterbirds digging and probing wetland soils seeking underground plant parts (rhizomes) or wetland invertebrates mix air or oxygenated water into the sediment[155], and may also temporarily increase turbidity. In open water, diving waterbirds increase mixing and oxygenation of the water column, as does walking and probing in the shallows. Plants may be pollinated by nectar-feeding birds (this is less relevant to aquatic species).

The conservation status of WA's wetland birds is:

- Threatened: Australasian bittern *Botaurus poiciloptilus*
  Australian painted snipe *Rostratula benghalensis australis*
  fairy tern *Sterna nereis nereis* [3]
- Priority three: black bittern *Ixobrychus flavicollis australis*
- Priority four: little bittern *Ixobrychus minutus*[4]

➤ A number of excellent guides to the birds of Western Australia are available. These include:

- *The Michael Morcombe eguide to Australian birds*.[156] This application includes both images and recordings available for Apple iPhone and iTouch and Android phones and doesn't need internet access to function.
- *Handbook of Western Australian Birds* Volumes I and II[147,157]
- *Field guide to Australian birds*[158]
- *Field guide to the birds of Australia* 7th edition[159]
- *The Slater field guide to Australian birds*[160]

➤ Birdlife Australia (formerly Birds Australia and Bird Observation and Conservation Australia) have produced a number of resources, including:

- Guides, lists and other WA-specific resources, available online: www.birdlife.org.au/locations/birdlife-western-australia/bird-guides-wa
- *The Atlas of Australian Birds*, a database documenting the distribution and relative abundance of Australia's birds across the continent. It is available at www.birdata.com.au.
- *The state of Australia's birds 2004*[146], which provides a water-focussed overview of factors affecting birds, and in particular, birds that rely on wetland and waterway habitats.
- *Australia's important bird areas: key sites for bird conservation*[145]

➤ For more information on migratory birds, see:

- the Global Flyway Network at www.globalflywaynetwork.com.au
- Partnership for the East Asian–Australasian flyway: www.eaaflyway.net
- the International Waders Study Group at www.waderstudygroup.org
- Shorebirds 2020 at www.shorebirds.org.au
- DEC has published a number of reports and data detailing long-term monitoring of birds in south-west WA. For more information, see the 'Wetlands data' webpage on DEC's website[161]. Reports and publication links are provided.

Mammals

Mammals are warm-blooded vertebrates that suckle their young and have hair. Most mammals live a dryland existence, visiting wetlands because of the rich food sources they provide. A range of mammals including kangaroos and wallabies visit wetlands to graze and drink, while others such as dingoes drink and hunt for a variety of animals.

Relatively few of the mammals that inhabit WA rely solely on wetlands for survival. Of WA's 141 mammal species, the rakali is the sole mammal dependent on wetlands, waterways and coasts. A number of other mammals which use wetlands heavily include the quenda, the quokka, the western brush wallaby, the yellow-footed antechinus, bilbies and at least five species of bat. As with most of Western Australia's mammals, the populations of all of these species have been seriously impacted by clearing, habitat fragmentation, changes in fire and hydrological regimes and the introduction of cats, foxes and other predators and competitors. A number of these species are threatened, and this is stated below alongside their name. The Tanami desert populations of the rufous hare-wallaby (*Lagorchestes hirsutus*) inhabited salt lakes, but are now extinct.[162] While kangaroos do not rely solely on wetland habitats, they are included here because of their important role in wetlands.

- *The mammals of Australia* 3rd edition[162] is a comprehensive text on Australian mammals. More species-specific resources are listed below.

Rakali (*Hydromys chrysogaster*)

Rakali, also known as water rats, have been present in Australia for at least four million years.[163] They are variously described as iconic, cryptic, fascinating and 'our other platypus'. They require permanent water and are highly adapted to a semi-aquatic life. They have a broad muzzle, partially webbed hind feet, thick water-repellent fur and large, muscular white-tipped tail (Figure 30).[164] In WA water rats occur predominantly along the coast from Moore River in the Midwest region across to the Fitzgerald River National Park on the south coast, with isolated coastal populations in the Pilbara and Kimberley across to the Northern Territory. They depend on waterways and wetlands with fresh or brackish water and, on the Pilbara coastline and offshore islands, marine environments.[165] They live in dens or burrows hidden amongst vegetation alongside water, with a round entrance around 15 centimetres in diameter.[166] Steep banks are often a favoured location for burrows and nesting sometimes occurs in logs. They are typically nocturnal, being most active around sunset and sunrise, although they may be seen during the day. They predominantly hunt in water, with reports suggesting that they favour water less than 2 metres deep[167], but it is also thought that they forage in vegetated areas and occasionally climb trees in search of food.[168] A top-order predator, they mainly seek out large aquatic insects, fish, crustaceans and mussels from the water column, although frogs, lizards, young turtles, small mammals, fresh carrion, and birds are occasionally eaten.[165,17] Middens of food remains, such as crayfish and mussel shells, can signal their presence. Although predominantly carnivorous, they will also eat plants when other food is scarce. Rakali have significant home ranges; in Two Peoples Bay, in the South Coast region, they were found to be between 7 and 10 hectares. They also show preference for habitat with intact vegetation, better water quality and habitat complexity.[169] Rakali litters are between one and seven offspring, with three being average.[167]

Figure 30. (a) Rakali are cryptic mammals adapted to semi-aquatic lives; (b) occurring in low numbers across WA's western and northern coastal areas. Photo – R Jenkins © Australian Museum.

(a) (b)

During the 1930s and 1940s they were heavily hunted for their fur, until the practice was put to an end by protective legislation. Although the populations increased as a result, they have been slow to recover, and are thought to be once again in severe decline in south-west Western Australia, caused by loss of habitat; fragmentation and degradation of habitat via clearing, drying of suitable habitat, salinisation, acidification and potentially increasing turbidity; predation and competition with introduced species and by drowning in illegal marron and gilgie nets[163] (Figure 31). A 2009 study of thirty-nine wetlands in the Perth metropolitan region found evidence of rakali at only seven.[167] There have been many local extinctions on the Swan Coastal Plain (Jurien Bay – Dunsborough). Genetic studies are being undertaken to understand the relationships between populations, remote cameras are being employed to learn more about these very shy creatures. However there are still significant gaps in knowledge of their ecology.

Figure 31. A rakali found drowned in an illegally set opera house trap near Thompson Bridge, Roleystone on the Canning River in 2011. Photo – courtesy of P Mutton.

Conservation status: priority four[4]

➤ The following resources provide information on rakali:

- The Australian Platypus Conservancy website (www.platypus.asn.au/the_australian_water_rat.html);
- Journal articles including DEC[165]; Atkinson[168]; Smart[167].

Western bush rat (*Rattus fuscipes*)

Western bush rats, like water rats, are native rodents. They are seldom seen in their native habitat, which extends along the mid west coast to the south coast. They prefer dense vegetation and are common in wetlands and waterways and for this reason are sometimes referred to as the 'western swamp rat'. Fungi are a dominant part of their winter diet, along with fibrous stems and leaves of specific grasses and lilies, and in spring and summer fruits and seed are important.[162] They help to disperse fungi by ingesting and excreting fungal spores.

Conservation status: not listed as either a threatened or priority species.

➤ It can be tricky to distinguish between the western bush rat, the black rat and common mouse. 'Rodents – the good and the bad'[164] is a handy one-page guide to native and introduced rodents.

Quenda (*Isoodon obsesulus*)

Quendas or southern brown bandicoots are common in dense vegetation of wetlands of the south-west. They prey on insects, earthworms, plants[170] and fungi; and a tell-tale sign of their foraging is cone-shaped diggings. Being marsupials, they have a pouch. They live in nests, generally a slight bowl-shaped hollow constructed from grass, twigs and other plant material, under dense bush. If the nest gets saturated with surface water in winter they will move to drier areas to nest. They have large territories; for example, 2–7 hectares for an adult male. A study on the Darling Scarp east of the Swan Coastal Plain found that males travelled up to 800 metres in a night, and females 295 metres. They occur from Guilderton north of Perth inland to Hyden and east to Esperance.[171] In 1994, Perth Airport was recorded as having one of the most extensive and abundant populations of the quenda of any bushland remnant of the Swan Coastal Plain.[134] Both their distribution and their numbers are thought to have declined substantially since European settlement.[172] The results of a survey of quenda throughout greater Perth (Lancelin to Harvey, including the Perth Hills) by DEC in spring 2012 will be compared with an earlier 1984 survey to see how numbers have changed over the past thirty years.[173] Changes in their distribution and abundance have implications for species that prey on them as well as those they eat. Truffle fungi are a favoured food of quendas, which by ingesting truffles help to disperse truffle spores across their territories in their dung.

Figure 32. The quenda is an iconic wetland species of south west WA. Photo – B Glossop.

Conservation status: priority five.[4]

- The Wildlife Note *Encouraging quendas*[172], and the pamphlet *Living with quendas*[174] are good sources of information for landholders.

Quokka (*Setonix brachyurus*)

Quokkas need to live near permanent fresh water, and are therefore restricted to land near freshwater wetlands. They were once common throughout the south-west of WA, where they favoured swamps and coastal thickets.[139] Quokkas are now restricted to Rottnest and Bald Islands and a few isolated populations located predominantly in densely vegetated wetlands and creeks from Gingin to Albany.[139,171] In the northern Jarrah forest, quokkas are closely associated with the wetland plant *Taxandria linearifolia* and the presence of a complex structural mosaic as a result of the fire history. A reduction in the number of wetlands supporting this complex habitat mosaic and/or increasing distances between patches of suitable habitat are thought to have contributed to the decline in the number of populations at this northern limit.[162]

Conservation status: declared threatened fauna.[99]

Note: a recovery plan for quokkas is being drafted. For more information, see the 'Recovery planning and implementation' webpage of the DEC website.[117]

Western brush wallaby (*Macropus irma*)

The western brush wallaby lives in open forest or woodland in the south-west, but particularly favours open, seasonally wet flats with low grasses and open scrubby thickets, appearing to manage without free water.[162]

Conservation status: priority four.[4]

Figure 33. Open, seasonally wet flats with low grasses are favoured by the western brush wallaby for grazing. Photo – B & B Wells/DEC.

Kangaroos (grey, *Macropus fuliginosus* and red, *Macropus rufus*)

Kangaroos have large home ranges that can include wetlands. While they do not rely solely on wetlands, kangaroos can have a significant influence on them, because they are widespread across WA with the exception of the far north-east, abundant in many areas, and able to exert significant grazing pressure on a wetland. They will visit wetlands to graze, and where surface water is present, to drink. Red kangaroos (*Macropus rufus*) drink about every four to ten days in summer from available water sources and in the dry season they are found within 10–20 kilometres of a water point, often aggregating in moist or wet areas where short green pasture is available.[162] Kangaroos can create trails through wetland vegetation, import nutrients via droppings, and import and export seeds in their droppings and on their coats.

Conservation status: not listed as either a threatened or priority species.

Yellow-footed antechinus or mardo (*Antechinus flavipes*)

The yellow-footed antechinus is a very small (mouse-size), nocturnal marsupial that in WA is found only in the south-western corner. It exists in a broad spectrum of habitats, although the dense vegetation of wetlands and waterways are favoured.[134] In urban environments it is known to pilfer from the kitchen and build nests inside television sets and lounge chairs.[162] It has a varied diet including insects, flowers, nectar, small birds and house mice. The yellow-footed antechinus has declined markedly around Perth.[134]

Conservation status: not listed as either a threatened or priority species.

Bilbies (*Macrotis lagotis*)

Bilbies occur in the southern Kimberley and Pilbara, where salt lakes form part of their habitat.[175] They eat insects and their larvae, seeds, bulbs, fruit and fungi. They construct impressive burrows up to 1.8 metres deep and 3 metres long where they remain during the day. Bilbies can shift rapidly in response to changing food availability.[162]

Conservation status: declared threatened fauna.[99]

Figure 34. Salt lakes are used by hardy bilbies. Photo – B & B Wells/DEC.

Western ringtail possum (*Pseudocheirus occidentalis*)

The Western ringtail possum inhabits peppermint (*Agonis flexuosa*) tuart (*Eucalyptus gomphocephala*), jarrah (*E. marginata*), wandoo (*E. wandoo*) and marri (*Corymbia calophylla*) habitats, and is also known to also nest in rushes and blackberry thickets.[162]

Conservation status: declared threatened fauna.[99]

Bats (including flying foxes)

Bats are an important part of the Western Australian environment, with more than twenty species recorded, and a distribution across many areas of the state, particularly the Kimberley and Pilbara. Bats use a variety of habitats, and a number are known to use wetlands for foraging or camping. These include the echolocating, insect-eating microbats (of the suborder Microchiroptera) and the fruit and nectar-eating bats (of the suborder Megachiroptera). Species that forage at wetlands include the northern long-eared bat *Nyctophilus arnhemensis*, which eats mainly beetles, bugs, crickets and spiders; and the little north-western mastiff bat *Mormopterus loriae cobourgiana*. Many species catch their prey in flight, for example, by flying over wetland water to catch flying insects such as mosquitoes. The large-footed myotis *Myotis macropus* is adept at this technique, raking the surface of the water with sharp, curved claws to catch aquatic insects and small fish and excelling at downward spiralling flight as they search for flying insects.[162] They roost close to freshwater and make use of wetland trees such as *Pandanus* spp. Camps of other species can also be found in wetlands, including those of the northern blossom bat *Macroglossus minimus*; black flying fox *Pteropus alecto*; and the little red flying fox *Pteropus scapulatus*.[162] Some, such as the "small but characteristically feisty"[162]

Figure 35. The little broad-nosed bat *Scotorepens greyii* is just one of many bat species that use wetlands in WA. Photo – G Little © Australian Museum.

little broad-nosed bat *Scotorepens greyii* (Figure 35) skim over the water surface to drink.[176] Many species are not often sighted because they are nocturnal. The northern blossom bat is a major pollinator of a number of plant species including *Melaleuca* and *Barringtonia* species within its range in north-western WA. A high proportion of Australian bats are threatened with extinction. The main causes of decline in bats have been identified and include habitat clearing, disturbance of roosts, forest harvesting and the collapse, closure or re-working of old mines.

Conservation status of the above bats is as follows:

Priority one: little north-western mastiff bat, *Mormopterus loriae cobourgiana*.[99]

➤ *The action plan for Australian bats* reviews the conservation status of 90 taxa of Australian bats.

- A key to bat families and genera is provided in *A field guide to the mammals of Australia*.[177]
- The article, 'Capturing the call of the bat' in *LANDSCOPE* Volume 26 No. 4 outlines advances in bat monitoring.

The role of vertebrates

Transporting life, energy and nutrients and pollinating plants

Vertebrates are mobile, and some travel between wetlands, creating biological connectivity between them. They can be responsible for the transport of materials, nutrients and energy into and out of wetlands, and can also act as a means of transport for the import and export of propagules to and from wetlands. All vertebrates contribute nutrients and energy to wetlands in form of faeces. Kangaroos and emus eat plant material, often ingesting seeds that are deposited in faecal matter at other wetlands. Similarly, quendas, bilbies and western bush rats disperse fungal spores. As top-order predators, rakali and crocodiles are ecosystem regulators. Waterbirds are the ultimate wetland travellers, typically using many wetlands in a lifetime. They move between regions and continents, flying hundreds or even thousands of kilometres to reach a wetland when it fills. A waterbird can visit several wetlands in a day, using each wetland for different purposes.[27] They act as modes of transport between wetlands for the propagules of wetland algae, plants, animals and other life forms.[150] Bats such as the northern blossom bat *Macroglossus minimus* can also be major pollinators. Vertebrate pollination of aquatic plants appears to be rare compared to invertebrate pollination. However some shrub species that grow in waterlogged land may be pollinated by vertebrate visitors to wetlands such as nectar-feeding birds, possums and bats.

Mixing and oxygenating sediments

Digging by vertebrates disturbs wetland soils and sediments, a process often referred to as bioturbation. This physical soil turnover, oxygenation of soil, leaf litter disturbance and burial, movement of fungal spores and creation of fertile bare areas are all critical components of soil ecosystem processes provided by native vertebrate species in balance with the landscape. In inundated mud, digging and probing by waterbirds seeking rhizomes or wetland invertebrates mixes oxygenated water into the sediment[155], and may also temporarily increase turbidity. Activity of waterbirds diving and walking in the open water zone also increases mixing and oxygenation of the water column. Digging in soil by vertebrates such as bush rats, burrowing frogs and rakali also provides a pathway for aeration of the soil. Research undertaken at Lake Martin, Yalgorup National Park, found that an individual quenda can displace more than 3 cubic metres of soil per year– about the same size as a small spa.[178] Disturbance created by larger vertebrates such as kangaroos and emus may create spaces in the soil and vegetation and in doing so, create opportunities for colonisation by plants. In comparison, large, hoofed introduced species including camels, pigs, goats, horses and cows can often crowd into an area and create significant damage to soil structure. Species such as such cows pug and compact wetland soils, and pigs wallow in mud in warm weather.

Consuming

Like invertebrates, arguably the key role of vertebrates in wetland ecosystems is as consumers in the food chain, controlling populations of the organisms they eat. This role extends to the landscape surrounding wetlands too. Colonies of breeding waterbirds at wetlands may range some distance from wetlands to feed. They are sometimes considered by farmers important in pest control in crops and pasture because they eat caterpillars, crickets and grasshoppers.[17] Wetland vertebrates also provide food sources to predators that predominantly inhabit dryland.

Animals: invertebrates

Invertebrates are animals without backbones. While small, they are not inconsequential, as observed by E. O. Wilson in 1987: "If human beings were to disappear tomorrow, the world would go on with little change........ but if invertebrates were to disappear, I doubt that the human species could last more than a few months."

Invertebrates are categorised based on their size. Some groups, such as protozoans, rotifers, copepods, ostracods and cladocerans are usually smaller than 0.25 millimetres and often known as **microinvertebrates**, whilst most aquatic invertebrate groups are usually larger than 0.25 millimetres and known as **macroinvertebrates**. Microinvertebrates are unable to actively disperse.

Wetland invertebrates include worms, molluscs, leeches, water mites and spiders, shrimps, crayfish and many other crustaceans, bugs, beetles, dragonflies, damselflies, mayflies, caddisflies, sponges, midges and mosquitoes. Over 3000 species have been recorded in Western Australia. They are found in virtually all habitats in wetlands including in and on wetland sediments, in the water, on plants and on submerged rocks and logs. Some invertebrates are aquatic in their larval and adult phases, whilst others are only aquatic in their larval phase.[179]

To date, invertebrates that inhabit waterlogged wetlands have not attracted as much attention as those invertebrates that inhabit the water column either permanently or for some portion of their life cycle. This is now being addressed, with a range of specialised spiders, bees and other insects of waterlogged wetlands now being identified and studied.

The total number of wetland invertebrate species in Western Australia is extremely high. For example, more than 1000 species have been identified in the Pilbara and 1200 in the Wheatbelt (A. Pinder pers. comm.). Aquatic invertebrate sampling is used to get a snapshot of the aquatic invertebrate community at a point in time. Aquatic invertebrates are also a popular target for wetland monitoring programs because they are found in almost all wetlands, are found in the water column for at least part of their life cycle and many are relatively easy to survey (but often difficult to identify). Invertebrate monitoring can provide insight into a wetland's food web, for example, benthic sampling can indicate the benthic invertebrates that form part of the diet of many waterbirds, particularly waders.

Monitoring of aquatic invertebrates is sometimes also used as a surrogate to infer water quality, wetland condition or habitat. The diversity of invertebrate taxa usually provides a good indication of the conditions in a wetland, provided there is some reference level of diversity for the wetland in question, as some wetlands have naturally low diversity. Some invertebrate taxa have quite specific ecological requirements, for example, persisting only within a narrow range of environmental conditions (particularly salinity and pH), and for this reason these particular taxa are sometimes used as a surrogate measure to infer water quality, wetland condition or habitat. In general though, the direct measurement of water quality is always a more reliable and straightforward approach.

➤ The following resources provide guides to invertebrates:

- *A guide to wetland invertebrates of southwestern Australia*[179]
- *The waterbug book: a guide to the freshwater macroinvertebrates of temperate Australia*[180]
- *What bug is that? The guide to Australian insects website*[181]
- *The Bugwise website*[182]
- The Bug guide website: *Identification and ecology of Australian freshwater invertebrates*[183]
- *Critter catalogue: a guide to the aquatic invertebrates of South Australian inland waters*[184]

For technical taxonomic guides, including keys, see the Murray Darling Freshwater Research Centre's list of publications, available from www.mdfrc.org.au/bugguide/resources/taxonomy_guides.html

Freshwater sponges

Sponges are simple, primitive animals which as adults are sessile, or fixed to the spot (they disperse as gemmulae or through fragmentation and re-attachment as adults). Sponges exist in all different shapes, sizes and colours, and members of the same species can vary greatly depending upon where they live.[185] They consist of numerous cell types with special functions, but they lack tissues and organs like more complex animals. They are best known from marine environments, but one of the three classes of sponges, the Demosponges, also occur in freshwater wetlands. The skeleton of Demosponges is composed of spongin, a flexible material made of collagen, some with spicules of silica dioxide. Over time, **spicules** can build up in wetland sediments, forming a common component of sediment on the Swan Coastal Plain (Jurien Bay–Dunsborough), particularly of peats and diatomites, where they may constitute up to 10 per cent of the sediment.[186] Twenty-four species of freshwater sponges, all from the family Spongillidae, have been recorded in Australia.[180] They are referred to as 'freshwater' species to distinguish them from marine species; they do occur in brackish to saline wetlands.

The presence of Spongillidae in Western Australia has been recorded at wetlands from the south coast to the Pilbara (Figure 36). During a study of wetlands on the Swan Coastal Plain, researchers noted that encrusting sponges were commonly encountered on vegetation of permanently and seasonally inundated wetlands, noting that they were not abundant at any site[186]; this is thought to be the general pattern of occurrence in the Pilbara too.

Spicule: minute, needle-like body made of silica or calcium salts found in some invertebrates

Freshwater sponges are typically thin crusts or mats, found on the undersides and edges of solid surfaces such as submerged wood and can be confused with fungi. They are an irregular shape but sometimes with regular patterning and dull grey, brown, yellow or alternatively green if covered by algae, and may be spongy to touch. Sponges are fixed to the spot so they cannot escape from predators and instead produce strong chemicals and bristly textures to deter predators. Sponges belong to the Phylum Porifera, which means 'pore bearer'. They feed by pumping water into and out of their bodies through these pores, filtering out bacteria and other tiny organisms and dead plant and animal particles. This passage of water also brings in oxygen and takes out carbon dioxide and wastes. The (limited) literature suggests that sponges inhabit wetlands of reasonable water quality and that some pollutants may cause growth and developmental abnormalities in sponges.[184]

Figure 36. A Pilbara sponge. Photo – A Pinder/DEC.

Sponges are the main food sources for the larvae of sponge flies (Sisyridae), an aquatic family of lacewings.[180] Sponge flies lay their eggs on vegetation, and when the eggs hatch, larvae fall into the water and swim to a sponge by flexing their body.[181] They have specialised mouthparts that allow them to pierce and extract the contents of the sponge tissue.

Birds and floods transport the gemmules (resting bodies) of sponges to other wetlands; these gemmules are resistant to adverse conditions.[183]

Worms and leeches

Aquatic worms include segmented (Phylum Annelida) and unsegmented worms (various phyla). They are mostly sediment-dwelling but some crawl on the sediment surface, swim directly above it, or live amongst macrophytes or periphyton. They are either detritivores, grazers or predators. A few are predatory on other oligochaetes.[179]

Unsegmented worms include flatworms and roundworms, amongst others. Wetland flatworms (Platyhelminthes) vary in colour from transparent to bright green. They probably survive seasonal drying of wetlands as thick-shelled resting eggs that are resistant to desiccation. Their food comprises live or decomposing animal matter. They prefer wetlands with low to moderate nutrient levels, being sensitive to organic pollution.[184]

Roundworms (Nematoda) are long, thing and cylindrical with a cuticular body wall. They are present in almost all wetlands other than the most saline ones. Roundworms feed on a variety of organisms, dead and alive. They are usually found in or near sediment at the wetland bed. Many species tolerate low concentrations of oxygen and can even remain inactive for weeks at a time if oxygen levels are very low, or go into a state of hibernation if dehydration is a threat.[184]

There are two main groups of segmented worms (Annelida) in WA wetlands. These are Clitellata (which includes all earthworms and leeches) and Polychaeta (bristle worms – mostly marine). Aquatic earthworms (oligochaetes) are numerous in Australia, with more than 119 recorded species (with nearly as many known but undescribed). Most aquatic earthworms are much smaller (generally 1 to 20 millimetres) than their terrestrial counterparts. A few cosmopolitan species are known to be very tolerant of poor water quality, though their presence does not necessarily indicate pollution. However, most endemic species have been collected in wetlands and rivers with good water quality and their tolerance to pollution is unknown. They are highly sensitive to salinity, with a few exceptions. Bacteria and algae in the sediments are their main source of food, though some live above the sediments and some of those are grazers or are predators, such as the genus *Chaetogaster*).

Genetic research has shown that leeches are simply highly modified oligochaetes so they are no longer classed separately (instead being grouped along with oligochaetes with the combined group now known as the Class Clitellata). Leeches occur in a wide range of freshwater habitats but are intolerant of salinity.[187] Most have suckers at each end of the body, and are predators or parasites, feeding on blood of worms, molluscs, midge larvae, frogs, turtles, waterbirds, cattle[180], or predators, eating invertebrates.[184] They can have several pairs of eyes. Leeches are not well studied in Australia.[179] They are able to survive in wetlands that dry by burrowing into the sediment and constructing a mucus-lined cell where they lie dormant.[184]

Most bristle worms (Polychaeta) are found in marine or estuarine environments, but one *Manayunkia* species is found in WA salt lakes, where it inhabits gelatinous tubes in the sediment.[187] Several species of *Aeolosomatidae* are also known from Australian freshwater wetlands and species of other marine families may be found in near coastal saline wetlands such as Lake MacLeod near Carnarvon.

Molluscs

Wetland molluscs include snails, limpets, mussels and clams.

Snails and limpets form the class Gastropoda (derived from Greek, meaning 'stomach-footed'). Snails typically have a coiled shell while limpets have simple shells that lack coiling and are cap-shaped. There are twelve native and one alien families of non-marine gastropods in Australia, which are comprised of forty-six valid genera and around 220 valid species[188], many of which are represented in the wetlands of Western Australia.[189]

Most notable is the critically endangered Cape Leeuwin freshwater snail *Austroassiminea letha* which occurs in stream systems and swamps fed by springs at Ellensbrook and Cape Leeuwin.[190] Introduced species include the infamous liver fluke snail, *Physa acuta*, which is an intermediate host for the sheep liver fluke (*Fasciola hepatica*), which can seriously damage the internal organs of their host (such as kangaroos, wallabies and sheep).

Snails and limpets have a pair of tentacles with eyes at the tips or bases. Some lay their eggs in characteristic cylindrical masses of jelly, while others bear live young. Most snails and limpets are grazers, feeding on plant material, particularly the algal film coating submerged plants; but some gastropods are omnivores. Snails and limpets tend to be rare in waterbodies of high nutrient concentration or low pH.[179] Gastropods tend to fossilise well[191], hence they are used in palaentological studies.

The attractive *Coxiella* snails inhabit salt lakes and are easily recognised by their colourful banded spires which are often broken off at the tip (Figure 37). The superficially similar hydrobiid snail *Ascorhis occidua* occurs in salt lakes along the south coast. Many arid zone species can survive for periods without water by sealing off the opening of their shell, either closing their 'door' (opercula) if they have one, or secreting calcified mucus plugs.[184]

Mussels, clams and basket shells are also molluscs and belong to the class Bivalvia. The name bivalvia refers to their shells, made of two valves. There are three recognised families in Western Australia: freshwater mussels (Hyriidae), basket shells (Corbiculidae) and pea clams (Sphaeriidae), each with their own anatomy and method of reproduction and dispersal.

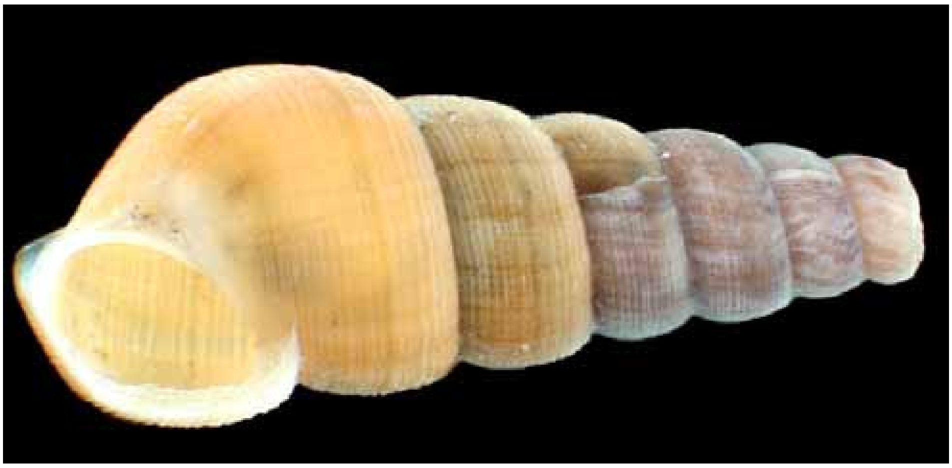

Figure 37. A close up photo of *Coxiella* snails, recognisable by their colourful banded spires which are often broken off at the tip. Photo – A Pinder/DEC.

Figure 38. *Coxiella* snails are often numerous in salt lakes. Photo – J Lawn/DEC.

Freshwater bivalves are generally filter feeders, taking in water through an inhalant siphon and moving food into their mouth and stomach for digestion using mucus and by moving microscopic hairlike cilia. The undigestible material is pushed out from between the shells and the filtered water continues out the exhalant siphon. This filtering function reduces fine **particulate** matter in the water column, improving water clarity and quality. Filtration capacity and diets of freshwater bivalves in WA are largely unknown and in need of further research. Oxygen exchange takes place in the gills. All organs

Particulate: in the form of particles (small objects)

in freshwater bivalves are internal, although they can extend a muscular foot to move themselves through the sediment and their inhalant and exhalant siphons can extend out beyond their shells. During drought, mussels can seal their shells tight until water returns.[180]

Five of the eighteen Australian freshwater mussels are known to occur in Western Australia.[192] As well as being the only mussel in the south-west of WA, Carter's freshwater mussel *Westralunio carteri* is endemic to the south-west, occurring between Moore River and the Frankland River (Figure 39). They occur in waterways and wetlands, most commonly in areas with muddy, silty and sandy bottoms and permanent water.[193] Unlike their marine and estuarine cousins, they do not attach to structures. This allows them to move with receding water levels and position themselves to the best feeding spots, so tracks can sometimes be an indication they are present. They have a complex life cycle involving a parasitic stage in which larva known as 'glochidia' use hooks on the edges of their shells to attach to passing fish. The glochidia live on the fish host for weeks to months, metamorphosing into juveniles, before dropping off the fish. The fish enable the mussels to disperse to new areas. Therefore the fate of Carter's mussel is closely tied to fish. Fishes responsible for supporting the life cycle of Carter's mussel include native species such as the freshwater cobbler, Swan River goby, southwestern goby, western pygmy perch, western minnow, western hardyhead and nightfish. Although the introduced eastern gambusia has been found to be a suitable host, goldfish and pearl cichlids were not.[194,195] There is also a new theory that freshwater shrimp, *Palaemonetes australis*, may be involved in the release of the glochidia from mussels.[196] This reliance on other animals leaves them susceptible to changes in environments that affect the other species; added to this is their intolerance to salinity greater than 3 parts per thousand.[197] These factors have lead to a decline in Carter's mussel, and it is now listed as a priority four species (taxa in need of monitoring).[4] Recent research is assisting conservation efforts.

➤ New resources are increasing awareness of the importance of Carter's freshwater mussel, including:

- Mussel Watch Western Australia website: www.musselwatchwa.com.[193] A comprehensive list of research papers is provided on the 'Resources and links' page.
- *A field guide to freshwater fishes, crayfishes and mussels of south-western Australia*[96]
- An excellent film, *Native freshwater fishes of south-western Australia film no. 3: Carter's freshwater mussel*[107], is available for viewing from the Envfusion website: www.envfusion.com.au/Portfolio.htm

The conservation status of WA's wetland molluscs is as follows:

Threatened: Cape Leeuwin freshwater snail *Austroassiminea letha*[3]

Priority two: *Glacidorbis occidentalis*

Priority four: Carter's freshwater mussel *Westralunio carteri*[4]

➤ Technical identification guides for molluscs include:

- *Identification keys to the families and genera of bivalve and gastropod molluscs found in Australian inland waters*.[198]
- *A guide to provisional identification of the freshwater mussels (Unionoida) of Australasia*.[199]

Insects

All adult insects have three pairs of legs, one pair of antennae and typically one or two pairs of wings. Wetland insects include, but are not limited to: bees, dragonflies, damselflies, mayflies, caddisflies, beetles, bugs, midges and mosquitoes. Insects are generally the dominant invertebrate group in terms of species number, **biomass** and productivity in freshwater wetlands, while crustaceans are usually dominant in biomass and productivity in salt lakes.[179]

Invertebrates that disperse from wetlands during adult phases, such as dragonflies, damselflies, and a wide range of true flies such as midges, all provide food for wetland and dryland animals such as bats, birds, reptiles and spiders.

Biomass: the total mass of biological material (living or dead), usually expressed as live or dry weight per unit area or volume

Nymph: a juvenile insect that resembles the adult, but has poorly developed wings

Dragonflies and damselflies

Dragonflies and damselflies (in the order Odonata) are well-known wetland insects because the adults are often colourful and visible flying around wetlands. Their grace and beauty has inspired the fields of art and literature in many cultures, but their physical attributes also enable them to be one of the most efficient aerial predators of the insect world. They have almost 360 degree vision, and are even able to fly backwards at speeds of 25–35 kilometres per hour.[184] Research suggests that there are relatively few pollution-tolerant dragonflies and damselflies.[179] Adult damselflies are usually smaller and more delicate than dragonflies and tend to hold their wings together over their backs when resting (Figure 41), rather than flat on either side of their body like dragonflies. Dragonflies and damselflies are all predators, feeding on other aquatic insects.[179] Vegetation plays an important role in harbouring eggs and nymphs. Some groups lay their eggs on submerged plant stems, others in the water column. The **nymphs** are commonly found amongst submerged plants or within the wetland sediment where they feed on aquatic earthworms and other food sources, and in many species they crawl up vegetation out of the water prior to emerging from their larval cases. Nymphal cases may be found attached to the vegetation for some time afterwards.[179] With more 300 hundred species of Odonata in Australia, they are a diverse group in terms of physiology, habitat and ecology.

➤ *The complete field guide to dragonflies of Australia*[201] covers both damselflies and dragonflies.

- Resources for the southwest include *Dragonflies and damselflies of southwest Australia: a photographic guide* and the website http://museum.wa.gov.au/waiss/dragonflies/

Figure 41. Damselfly at Ewans Lake, east of Esperance. Photo – S. Kern/DEC

Bees

Approximately 800 native bees occur in WA, and many of these are endemic. In 2010, a new and as yet unnamed species of bee (*Leioproctus* sp.), was discovered by a WA Museum volunteer and a WA Museum curator in seasonally waterlogged/inundated wetlands in Jandakot, south of Perth (Figure 40). The megamouth, named after the remarkably large jaws of the males, has been found to pollinate paperbarks (*Melaleuca* sp.) and spearwood (*Kunzea glabrescens*). Surprisingly, they nest in the ground, in an area subject to inundation during winter, and the entrances to their burrows are extremely inconspicuous. It is not known if the Jandakot Regional Park is their only or last remaining habitat. It is thought that, with the exception of very shallow nests, ground-dwelling bee larvae/pupae can survive fire.

The short-tongued bee, *Leioproctus douglasiellus* is a threatened bee.[3] It is thought to be dependent on the flowers of the thread-leaved goodenia, *Goodenia filiformis* (a priority three species), and *Anthotium junciforme*, both found in wetlands of the south west.[139]

Another threatened native bee, *Neopasiphae simplicior*, has been found only from two Perth locations—Cannington and Forrestdale Lake—and is also associated with wetlands, as it has been collected on flowers of wetland species including the thread-leaved goodenia, *Goodenia filiformis*, slender lobelia *Lobelia tenuior* and *Agianthus preissianus*.[139,151,3]

➤ For more information on native bees, see the WA Museum website and its native bees information factsheet.[200]

Figure 40. The charismatic megamouth bee, discovered in a Perth wetland in 2010. Photo - T Houston/WA Museum. Image copyright of WA Museum.

True bugs

The true bugs (of the order Hemiptera) usually have two wings and all have piercing and sucking mouthparts to suck body fluids from their prey. The majority are terrestrial but the aquatic and semi-aquatic true bugs include a range of charismatic species whose entertaining antics captivate children and adults alike. These include the water striders and pond skaters (Gerromorpha), which are able to skim or skate across the surface film of the water. Water boatmen (Corixidae) are up to 10 millimetres in size and are so-called because they use their oar-like middle legs to propel them through the water in a motion similar to a rowboat. They are excellent fliers, enabling them to move to other wetlands. They feed on plants and insects such as mosquito **larvae**. Backswimmers (Notonectidae) swim on their backs. They also have long oar-like middle legs with hairs on them that help them swim 'backstroke' quickly. Water scorpions (Nepidae) are also Hemipterans. They have a breathing tube that can be as long as their body. This allows them to hold the breathing tube to the water surface like a snorkel rather than having to surface for air.

Larvae: juvenile insects (the singular being 'larva')

Beetles

Beetles (of the order Coleoptera) inhabit a range of habitats available in WA's wetlands. Some require a water column in order to survive, while others favour wetlands that are only wet seasonally or intermittently, for example, those beetles found on the lake beds of dry salt lakes in the Wheatbelt.[202]

Western Australian wetlands support a range of aquatic beetles, including weevils, whirligig beetles, crawling water beetles and diving beetles. After living on dry land for millions of years[180], aquatic beetles have adapted to life underwater, most living in water both as larvae and adults but with terrestrial pupae.

Diving beetles (Dytiscidae) are the most diverse beetle group and are most common in freshwater wetlands and less common in fast flowing streams, saline lakes and waterbodies where fish are present.[179] Their diving behaviour is driven by the need to surface for air; they store air bubbles on the body before diving. Eggs are usually laid beneath the water surface, attached to aquatic plants. Both larvae and adults are carnivorous, and prey commonly include water fleas, larval mosquitoes and midges[179] and sometimes small fish and tadpoles.[180] It is thought that, because they breathe air from the atmosphere, they can tolerate poorer water quality, especially low oxygen levels.[38]

Beetles have hardened wing cases to protect the wings when they are folded. Most have retained their ability to fly, meaning that they can disperse to new habitats.

True flies

The true flies (Diptera) are a large and diverse group that encompasses mosquitoes, midges, hover flies, horse flies, sand flies, crane flies, march flies, marsh flies, black flies, moth flies and soldier flies. They have a single pair of flying wings, with the second pair modified into halteres used as stabilizers or wind speed detectors. The family Chironomidae (non-biting midges) is one of the most diverse aquatic invertebrate families.

All true flies live their adult lives in dryland ecosystems, but some have aquatic larval forms. Some adults can skate on the water surface to scavenge for food. They have a very short adult lifespan (rarely longer than a month) and can lay hundreds of eggs at a time. Some midge species have drought-resistant adaptations and survive as larvae in a partly hydrated state.[203]

➤ Nuisance midge and mosquitoes pose a particular challenge for wetland managers. The topic 'Managing nuisance midge and mosquitoes' in Chapter 3 provides guidance on possible approaches to their management.

- A photographic guide and keys to the larvae of Chironomidae (Diptera) of south-west WA is available from DEC's website.[204]

Mayflies

Australian species of mayfly (Ephemeroptera) nymphs are not tolerant of saline waters, but are found in most freshwater habitats, except for those with poor water quality, as most are not very tolerant of pollution.[184] They have three long thin 'tails'. Most are herbivorous, grazing on diatoms and other algae, or are detritivores. The adult flies are very short-lived, most only living a day but some up to several days.[179] Mayflies are the most primitive living winged insects: their fossils date to as far back as 300 million years ago.[184] Some species have desiccation resistant eggs, which allow them to colonise temporary water bodies.[184].

Caddisflies

Caddisflies (Trichoptera) are well-known because the larvae of some species build protective cases in which to live. They often appear to be a moving stick. Many use plant material, sticks, gravel and/or sand to construct their cases, which means that some species can't be identified by the look of their cases alone. Others spin cases from silk and some families do not construct cases at all. They live just about anywhere in wetlands and are detritivores. One species, *Symphitoneuria wheeleri*, inhabits saline waters along the south coast of Australia and some species require running water.

Moths and butterflies

Adults of all moths and butterflies (Lepidoptera) are terrestrial, but the moth family Pyralidae have aquatic larvae. They have a similar appearance to dryland caterpillars but most have gills and are often found on plants or rocks, feeding on plants and algae. They inhabit fresh to moderately saline wetlands across WA.

Springtails

Springtails (Class Collembola) are tiny animals with six legs and one pair of antennae. However, they are regarded as being distinct from insects. They rarely grow larger than 3 millimetres, and most of the 6000 species (including 1630 from Australia) are not aquatic[184] but do have an affinity for moist areas so they may be found at many wetlands. They burrow and remain underground during hot, dry weather. Those that do live in inundated wetlands live on the surface of the water using water-repellent hairs, often amongst vegetation. Despite their small size, they can jump over 30 centimetres. They feed on algae, fungi and plankton and can live in polluted wetlands. In turn, they are eaten by bugs, beetles and fish.

Spiders and water mites

Water mites, like spiders, have eight legs, but they are usually easy to distinguish from spiders; they have very simple, rounded bodies and only reach a maximum of 5 millimetres (most are less than 2 millimetres). Water mites are often highly visible, despite their small size, because of their spectacular red, orange, blue, green or yellow colouration and sometimes distinctive patterning. Water mites occur in a wide variety of freshwater habitats, including the interstitial waters of waterlogged wetlands, but are thought to be most abundant in shallow, heavily vegetated wetlands[179] including seasonally inundated wetlands. The Muir-Byenup system is known to support eleven water mites, including many of considerable zoogeographic interest.[190] The adults swim and/or crawl. Water mite larvae overcome their inability to move between wetlands when they dry up by simply taking a ride on another animal, such as dragonflies. Being parasites, their prey offers them food, board and transport! They typically parasitise insects and microcrustaceans, feeding on their body fluids, while some are known to feed mainly on midge eggs.[179] Most water mites have low salt tolerance, although *Acercella falcipes* and *Koenikea verrucosa* are found in slightly saline wetlands of the Wheatbelt.[88]

Aquatic spiders, like water mites, are thought to occur in shallow wetlands with dense overhanging vegetation. There is one family of truly aquatic spiders, the Pisauridae, which live underwater. In addition, many spiders are recorded from WA wetlands that are only seasonally or intermittently inundated. Lake Minigal, east of Kalgoorlie in the Goldfields, for example, is reported to be covered in spider webs at times. This intermittently inundated wetland is reported to be habitat for millions of spiders, which in turn are thought to be prey for dunnarts (*Sminthopsis* sp.), salt lake lizards and birds.[205,206]

Spider assemblages at salt lakes in the Wheatbelt are often distinct from those in surrounding dryland[202], due to the occurrence of salt flat specialists.[207] Some of the burrowing spiders are able to build burrows that can withstand flooding, using mud plugs, palisades or other physical barriers to water.[202] Some wolf spiders, such as those in the genus *Tetralycosa* (Lycosidae) are known to inhabit salt lakes[208] and claypans, while others are specially adapted to, and as a result particularly abundant in, many environments prone to inundation (including sandy beaches) because in the event of rising water levels, the mother spider can carry spiderlings to safety.[208] *Lycosa salifodina* is a known salt lake specialist occurring across arid salt lake systems in a number of Australian states.[202] The threatened Minnivale trapdoor spider (*Teyl* sp.) is a fascinating Wheatbelt spider that inhabits perched wetlands on high terrain.[139] Several undescribed species occur further to the east of the Minnivale trapdoor spider in salt lakes of the eastern Wheatbelt.[139] The christmas or jewel spider *Austracantha minax* is a colourful and highly visible species in many wetlands.

The conservation status of wetland spiders and water mites is:

- Threatened: Minnivale trapdoor spider *Teyl* sp.[3]
- Priority two: Poorginup Swamp watermite *Acercella poorginup*
  Doeg's watermite *Pseudohydraphantes doegi*[4]

Crustaceans

Crustaceans include large, well-known species such as freshwater crayfish and crabs, generally the largest of the wetland invertebrates. There are also many much smaller species called microcrustaceans, which are no less fascinating. All crustaceans have an external carapace; sometimes this is a hard casing (as in crayfish and crabs) but for some microcrustacea it is softer. Some clam shrimp (Conchostraca) have their carapace formed into a bivalve-like shell.

Crayfish

There are many non-marine crayfish in WA. While some species (such as koonacs) tolerate brackish conditions, none are tolerant of high salinities. Interestingly, freshwater crayfish do not naturally occur in either the Kimberley, Pilbara[103] or arid interior, with the Queensland redclaw *Cherax quadricarinatus* introduced to Lake Kununurra.[209] There are thirteen species of freshwater crayfish native to south-western Western Australia, belonging to two genera. The seven *Engaewa* species are rarely seen, being small, burrowing crayfish that are confined to small areas along the south west and south coast, a number of which are considered endangered or critically endangered by the IUCN (Figure 42).[131] *Cherax* species are found throughout the south-west.

Figure 42. (a) the endangered Dunsborough burrowing crayfish, *Engaewa reducta* (b) a 'chimney' of soil pellets at the entrance of a crayfish burrow. Photos – (a) K Rogerson/DEC (b) M Podesta/DEC.

(a)

(b)

Gilgies (*Cherax quinquecarinatus*) are widespread between Hill River and Denmark. They reach a maximum size of 140 millimetres, and are found in wetlands with sandy or peaty sediments. They inhabit both permanently and seasonally inundated wetlands. They survive drying of seasonally inundated wetlands by burrowing into the soil. A much less common species, the restricted gilgie *Cherax crassimanus* is found between Margaret River and Denmark.

In the southwest the glossy koonac *Cherax glaber* are found on the coast between Dunsborough and Windy Harbour, while the better known koonac (*Cherax preisii*) are found inland in wetlands with clay and organic sediments from Moore River to Albany. Both species can burrow well, which allows them to inhabit seasonally inundated wetlands and burrow into the soil when they dry.

The smooth marron *Cherax cainii* is native to south-western WA, but its range has been extended both north and south, occupying only permanent waterbodies. In contrast, the hairy marron *Cherax tenuimanus* is restricted to the upper reaches of the Margaret River. The smooth marron is the third-largest freshwater marron in the world (with the two largest being eastern Australian species).[210]

The yabby *Cherax destructor* has been introduced from south-eastern Australia and now occupies south-western wetlands between Kalbarri and Esperance. It is able to inhabit seasonally inundated wetlands, burrowing into the soils as the wetlands dry. They carry diseases which affect other freshwater crayfish and, if caught, following positive identification, should be destroyed. Sightings should be reported to the Department of Fisheries' FISHWATCH service on 1800 815 507.

The conservation status of WA's wetland crayfish is:

Threatened: Margaret River burrowing crayfish *Engaewa pseudoreducta*
Dunsborough burrowing crayfish *Engaewa reducta*
Walpole burrowing crayfish *Engaewa walpolea* [3]

A recovery plan is in place for these three crayfish. For more information, see the 'Recovery planning and implementation' webpage of the DEC website.[117]

➤ *A field guide to freshwater fishes, crayfishes and mussels of south-western Australia*[96] provides an excellent summary of the crayfish of the south-west.

- The pamphlet *Identifying freshwater crayfish in the south west of WA*[211] is an easy to use guide.

Other crustaceans

The south-west of Western Australia is one of the global hotspots for inland aquatic crustacean diversity[212]. Smaller crustaceans include water fleas (Cladocera), seed shrimps (Ostracoda), copepods (Copepoda), water slaters (Isopoda), side swimmers (Amphipoda), brine shrimp and fairy shrimp (Anostraca), shield shrimp (Notostraca) and clam shrimp (Laevicaudata and Spinicaudata).

These smaller crustaceans are highly abundant and diverse, inhabiting a range of fresh and saline Western Australian wetlands. Most are well adapted to drying that is a feature of most of WA's wetlands. Many produce desiccation-resistant eggs that lie dormant in the sediment, remaining viable during prolonged dry periods. Others survive drought as encysted embryos. They are usually the dominant invertebrate group in intermittently inundated salt lakes in terms of biomass and productivity, although species richness is often low.[179]

Very small crustaceans, namely the water fleas and copepods have limited powers of locomotion to overcome currents and wave action, and along with other organisms such as rotifers and protozoans, are known as **zooplankton**.

Zooplankton: tiny invertebrates and protozoans floating or suspended in the water that drift with water movements, generally having little or minimal ability to control their location

The transparency of the south-west glass shrimps, *Palaemonetes australis*, makes them an easily identifiable crustacean. They are benthic inhabitants of fresh and estuarine waters[179] across south-western Australia,[213] scavenging on decaying plant and animal material. Research suggests they may be a potential bioindicator of crustacean health in relation to hydrocarbons.[214] It has also been suggested that they may be involved in the lifecycle of Carter's freshwater mussel, *Westraluno carteri*, a threatened endemic mussel of south-west Western Australia.[196] At a total body length of up to 35 millimetres, they are dwarfed by the cherabin *Macrobrachium rosenbergii*, a freshwater prawn native to the Kimberley that grows up to 300 millimetres.

Shield shrimp are a particularly fascinating crustacean of ancient origin. They have not changed physically in almost 300 million years[184] (Figure 43). They are typically found in wetlands that dry out and which do not support fish, surviving in the form of desiccation-resistant resting eggs, which are so small they can be carried by wind to other wetlands.[184] They are mostly found in wetlands with naturally high turbidity, protecting them from predation by waterbirds.[187] They feed on algae, bacteria, protozoa, rotifers, aquatic worms, fairy shrimp, frog eggs, tadpoles, rotting leaves and other detritus.[184]

Figure 43. The fascinating shield shrimp (*Notostraca*). Photo - W Chow/DEC.

Brine shrimp inhabit naturally saline wetlands while fairy shrimp tend to inhabit freshwater wetlands. Fairy shrimp eat bacteria, protozoa, rotifers, algae and detritus.[184] The brine shrimp *Parartemia* are an important component of many of Western Australia's primary saline wetlands, particularly in terms of their role in the food web supporting waterbirds, but they are rarely found in secondarily saline wetlands.[187] *Parartemia contracta* is uniquely restricted to acidic wetlands with a pH of between 2 and 6.[187] Despite being quintessential components of saline wetlands, little is known of the distribution, abundance and habitat requirements of brine shrimp.[215] Some appear to be quite rare. The introduced genus of brine shrimp, *Artemia*, were introduced as fish food and to control algae in salt production ponds but are now found in natural wetlands[187] and their distribution appears to be spreading. They are also sold as pets, commonly called 'sea monkeys'. Both the native and introduced species can inhabit wetlands that dry out, occurring as cysts during dry periods. It is thought that *Artemia* are less likely to occur in wetlands that dry regularly.

Clam shrimps (Laevicaudata and Spinicaudata), water fleas (Cladocera) and seed shrimps (Ostracoda) live within a two-halved shell, and move around using legs and/or antennae that can be protruded from the shell. The shells of Laevicaudata and Ostracoda can be closed shut whereas those of Spinicaudata and Cladocerans are permanently open.

Clam shrimp look a lot like molluscs such as mussels and clams because they are entirely enclosed in a shell. They usually inhabit seasonally to intermittently inundated wetlands, with their desiccation-resistant eggs remaining viable during prolonged dry periods.

The common name of 'water flea' given to Cladocera is due to their jerky swimming style, resembling a jumping flea. Visually they can be very interesting; for example, in some water fleas a green digestive tract, due to their algal diet, is visible, while in others, multitudes of eggs are visible in or on the female. Many aspects of their life are also fascinating, including the fact that while conditions are favourable, populations usually consist of female clones. When a wetland begins to dry, males are produced and sexual reproduction occurs, producing drought-resistant eggs.[187] Their ability to withstand drying, freezing and digestive juices as eggs allows them to disperse widely and survive in harsh conditions. Invertebrate specialists Gooderham and Tsyrlin[180] note that water flea eggs have been hatched from sediments that have been dry for 200 years! Water fleas of the genus *Daphnia* are familiar to many Western Australians, being common and abundant in many wetlands. They graze significant numbers of bacteria and phytoplankton as well as detritus and are food for many animals themselves. One species is largely restricted to granite outcrop pools (*Daphnia jollyi*) and some others occur only in salt lakes.

More than 150 species of surface water seed shrimps (ostracods) are known from Western Australia, although fewer than half are described.[216] Most inhabit wetland substrates (that is, benthic habitat). They can be important in wetlands, both when alive and dead, for example, their skeletons have been found to contribute to wetland sediments.[217] They fossilise well[218], so they are often used in palaeontological studies.

Copepods (Copepoda), water slaters (Isopoda) and side swimmers (Amphipoda) do not have shells. Copepods are very small crustaceans (most less than 2 millimetres) and inhabit all types of wetlands and are often extremely abundant. They vary in their habitat requirements. Water slaters are common in inland wetlands and waterways, with *Paramphisopus palustris* being the most common in south-western Australian wetlands and *Haloniscus* species the only ones to occur in saline wetlands. Water slaters and side swimmers don't produce drought-resistant eggs so are more common in permanently inundated wetlands, although they also take refuge in waterlogged soils.[187] The most common inland water amphipod of south-western Australia, *Austrochiltonia subtenuis*, is moderately salt tolerant. In inland Australia, amphipods and isopods are largely restricted to groundwater or groundwater fed wetlands.

➤ A key to and checklist of amphipods is available from the Australian Museum.[219]

Rotifers

Rotifers are microscopic to near-microscopic animals, with most being less than 1 millimetre in size. Close to 700 species are known from Australian inland waters[220], with over 300 known from WA. They can be extremely diverse and very abundant in almost all types of wetlands. Rotifers form part of wetland zooplankton communities, although some are sessile and are more common in submerged plant communities. Despite their size, their often high abundance means they can significantly contribute to nutrient cycling by eating small particles including particulate organic detritus, bacteria, algae, protozoans and other rotifers, mostly by filter feeding although some are active predators. Some live on the surface of other animals (epizoic) while others parasitise algae and zooplankton. Rotifers affect the species composition of algae in ecosystems through their choice in grazing.[221] In turn, they are eaten by some crustaceans and insect larvae. Many aspects of rotifers are fascinating, not least that most are female[19] and that some rotifers, such as bdelloids, can change from an inert state to normal activities within hours of a dry wetland flooding.[187]

The south-west is a biodiversity hotspot for rotifers, with more than one hundred species recorded in the Avon region alone.[187] They are readily dispersed as resting eggs by wind, birds and people, which helps to explain the widespread distribution of many species, though there is some regional endemism. Due to their small size, rotifers are sometimes omitted from sampling even though they can have extremely important ecological roles in wetlands.[221]

➤ For more information on rotifers, see the chapter 'Australian rotifera' in *Limnology in Australia*.[220]

➤ *A guide to the identification of rotifers, cladocerans and copepods from Australian inland waters*[222] contains a range of information including keys and general ecological and life history information.

The role of wetland invertebrates

- Invertebrates play a pivotal role in wetland food chains and nutrient cycling. They are a particularly important food source for wetland vertebrates such as fish, frogs, turtles, lizards, mammals, birds and bats. Moreover, many insects leave wetlands as adults, providing a very important source of food for a wide range of terrestrial animals. In seasonally inundated wetlands, remains of dead invertebrates on the dry bed provide a food source for terrestrial communities.
- Invertebrates that feed on algae, such as small crustaceans, molluscs and rotifers, improve water clarity by removing particulate matter from the water column. Water clarity is an important determinant of aquatic biota.
- Burrowing invertebrates (such as freshwater crayfish and oligochaetes) turn over and oxygenate wetland sediments. Oxygen in the sediment has a critical influence on the organisms that will inhabit it, as well as affecting other aspects of sediment and water chemistry.
- Molluscs and crustaceans such as seed shrimp create calcium carbonate in the form of calcite for their shells and this accumulates as a component of wetland sediments once these organisms die (Figure 44).
- Insects that leave wetlands as adults export nutrients, material and energy.

Figure 44. Mollusc shells are part of the sediment of the Mandora Marsh
Photo – M Coote/DEC.

PART 2: WETLAND ECOLOGY

Water, whether it is present permanently, seasonally or intermittently, is common to all wetlands. But what makes a wetland suitable for a particular plant or animal is a much more complex tangle of factors, as can be seen in Figure 45. Part 2 outlines major drivers of habitat. These include climate, and requirements for water, salinity, oxygen, light and food.

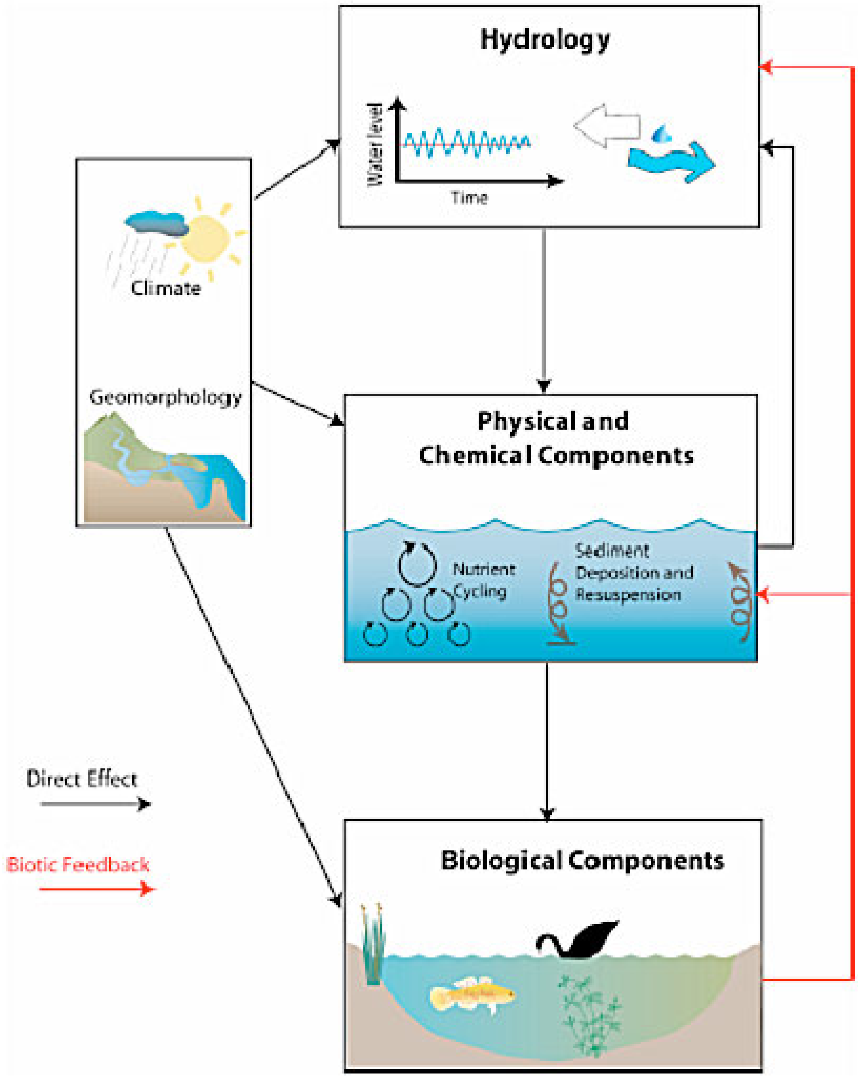

Figure 45. Connectivity between living and non-living parts of wetlands: linkages between physical, chemical and biological aspects. Adapted from Mitsch and Gosselink (2007).[223]

Regional climate and ability to disperse

Like dryland organisms, there are wetland species that occur widely across WA and beyond (**cosmopolitan** species). Other wetland species only occur in a particular region or subregion of Western Australia. The reason for this is the extreme regional differences in current and historical climates across WA, from tropical, to arid, to Mediterranean; and the environmental heterogeneity (diversity) produced by the evolution of landscapes, soils, aquifers and fire regimes over thousands of years in response to climatic variability.

Over geological time, species have had to adapt to changing conditions driven by rising and falling sea levels, aridity and ice ages; most of those that did not change significantly have become extinct or remain only in **refugia** including mound springs, permanently inundated wetlands in arid areas and damplands in wetter regions retaining Gwondanic elements.[224] For example, the ancient sedge species, *Reedia spathacea* (Figure 46), occurs in the Walpole region and the Blackwood Plateau. *Reedia* is considered to be a Gondwanan relict species, that is, a relict from the time when Australia, India and Antarctica were one landmass. It is found in wetlands with constantly high groundwater levels. Its current distribution is suspected to be the remains of a wider distribution during wetter conditions during the early and middle Tertiary period.[225] It is declared rare under the state *Wildlife Conservation Act 1950* and listed as critically endangered under the national *Environment Protection and Biodiversity Conservation Act 1999.*

Refugia: restricted environments that have been isolated for extended periods of time, or are the last remnants of such areas

Generalist: a species that can live in many different habitats and can feed on a variety of different organisms

Figure 46. The ancient sedge species, *Reedia spathacea*, occurs in the Walpole region and the Blackwood Plateau. Reedia is considered to be a Gondwanan relict species. Photos – main: J Liddelow/DEC; inset: S Kern/DEC.

The distribution of a species is also determined by its ability to disperse, either because it is mobile or it can make use of an alternative mode of 'transport'. This can be a lift on another animal (in a variety of forms including as an adult, larvae, egg, seed, cyst or spore) or via wind or water. Dispersal ability is very important in landscapes with variability in wetting and drying regimes. For example, studies of the Mandora Marshes in the northwest show that the macroinvertebrate fauna is dominated by highly vagile predators (species with a strong ability to move about).[216] Once a species disperses, it will only survive if it can either cope with different conditions (**generalists**) or adapt to them. Geographic barriers to dispersal can have a very strong influence on the occurrence and persistence of a species.

Western Australia's wetland plants are distinctive to three zones: the Kimberley, the deserts and the south west (Figure 47). These three zones are identified as distinct regions by both climatologists and biogeographers (who study the relationships between plants, animals, soils, water, climate and humans). The wetland flora and vegetation characteristics of each zone is described in detail in the topic 'Wetland vegetation and flora' in Chapter 2.

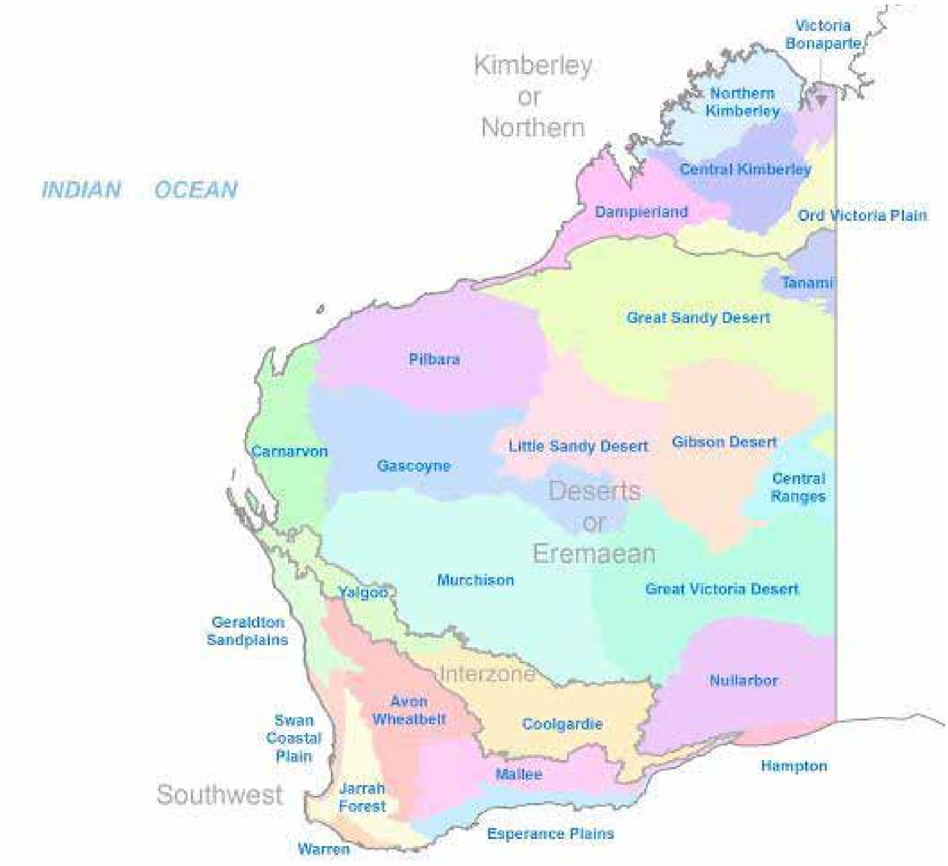

Figure 47. The three zones of wetland vegetation: the Kimberley, the deserts and the south west. Image - C Aurícht/Auricht Projects

Niche: the role of an organism in a community, in terms of its presence, activity, habitat and the resources it uses

Many vertebrate animal species also show similar distribution patterns, including many wetland species. For example, researchers identify three unique fish provinces in Western Australia: the Kimberley, the Pilbara and the south west.[103] These provinces support different species, with very little overlap between the Kimberley and Pilbara, and no overlap with the south west region. Frog researchers also identify three Western Australian regions that define frog fauna (the Kimberley, arid zone and south west).[109] Distributions of turtle species are also extremely well defined, with little overlap in species composition between these broad areas.

Distribution patterns are also evident amongst invertebrates; for example, there are no crayfish species native to the deserts, while the Kimberley supports only one freshwater prawn (also of the Decapoda order), the cherabin *Macrobrachium rosenbergii*. However, due to the sheer number of species within many invertebrate groups such an analysis is complex.

Species water requirements

Water is the defining feature of all wetlands and influences the composition, richness and abundance of organisms in a wetland.

Water is naturally variable across the Earth, but especially so in Australia, a land 'of droughts and flooding rains'.[226] Its variability in terms of presence and absence, timing, duration, frequency, extent and depth is what makes each wetland unique. The flux of water drives many physical and chemical fluctuations in wetlands, such as the amount of oxygen, light, salts and nutrients. This creates a myriad of habitats and resources, and wetland organisms are adapted to these **niches**. Therefore, in managing wetlands, it is important to maintain the natural water variability of wetlands, in order to conserve the biological, physical and chemical diversity they support.

Most of Western Australia's wetlands are not permanently wet. In response to this transience of water, wetland organisms have many adaptations for surviving or avoiding drought, and this is part of the reason for the uniqueness of our wetland flora and fauna.

At a basic level, WA's wetland organisms can be grouped into one of four extremely broad groups:

1. those that inhabit, or need permanent access to a water column
2. those that inhabit, or need access to a water column for a period sufficient to fulfil part of their annual cycle or life cycle
3. those that inhabit, or need permanent access to saturated soils (without an overlying water column)
4. those that inhabit, or need access to saturated soils for a period sufficient to fulfil part of their annual cycle or life cycle

Many organisms may not fit neatly into one of these groups; they are useful as broad generalisations only. In reality, each wetland species has specific **water requirements** that determine where and how it lives and reproduces. If the **water regime** of its habitat changes beyond its tolerance, an organism must move to a new habitat on either a temporary, seasonal or permanent basis, or it will die; many smaller animals and annual plants do, typically reproducing first.

'Boom and bust' cycles are a natural part of the population dynamics of many wetland species in Western Australia. When a dry wetland wets, water seeps through the soil and soaks the resting eggs, seeds, spores and cysts, which begin to develop.[227] The influx of water releases a pulse of nutrients from the soil that, together with light and water, provide the resources for germination and growth of algae and plants. Algae and bacteria proliferate, providing food for consumers. A succession of small animals hatch, grow, reproduce and die. Emergent plants flourish, and in inundated wetlands, aquatic plants grow in submerged or floating habits, and both types of plant provide habitats for other organisms. As water recedes, new plants germinate on the exposed soil, flourishing on the nutrients released by anaerobic bacteria on drying. If water recedes through evaporation, concentration of the salts may result in increases in salinity. The smaller water volume may also lead to increases in temperature. These types of cues trigger plants, algae, bacteria and animals to prepare for another dry period.[227] Those that cannot tolerate dryness leave, burrow down, or die, first replenishing seed or egg banks.

Water requirements helps to explain why, for example, fish are not as prevalent in Western Australia's wetlands as some of the eastern states: with the exception of two species, all fish need to inhabit inundated wetlands or waterways for all parts of their life cycle, and a relatively small proportion of the state's wetlands are permanently inundated. It also helps to explain why annually renewed plant species that renew from seed, underground or above-ground storage organs on an annual basis, tend to be much more prevalent in wetlands than drylands. In the southern Swan Coastal Plain, for example, annually renewed species are twice as prevalent in wetlands than drylands.

As well as explaining the presence of species, water requirements provide an insight into the patterning of species over space and time. For example, why the same species of plants can be found at similar water levels in different wetlands, and why events such as a particularly wet season can result in a mass germination of tree seedlings in a given area of a wetland, or a larger than usual frog population. Wetland managers can use

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence.

Water regime: (of a wetland) the specific pattern of when, where and to what extent water is present in a wetland, including the timing, duration, frequency, extent, depth and variability of water presence this knowledge for a variety of purposes, from planning revegetation to predicting how a long term change in a wetland's water regime to a wetter or drier state will affect the organisms that inhabit it.

Hydroecology: the study of the water regimes required to maintain and enhance conservation values of ecosystems

The study of water requirements of native species and ecosystems (known as **hydroecology**, and sometimes ecohydrology) has been driven by the widespread alteration of water in wetlands, waterways and terrestrial environments. In Western Australia, research into the water requirements of wetland organisms has focused on the Gnangara and Jandakot groundwater mounds in the greater Perth region[228,229,230], the Blackwood and Scott Coastal Plain groundwater areas[231], and Ramsar wetlands. Riparian studies that include wetland species in the Pilbara and Kimberley have also been the subject of a number of studies (for example, Loomes[232,233,234]).

Water requirements of plants

Given its optimum water regime, a wetland plant has the ability to grow, maintain new growth, periodically flower and set seed, and maintain resilience to disease and other factors.[234]

The study of the water requirements of wetland plants is instructive, because they are not mobile and can provide an insight into the water regime of a wetland, potentially over a long period. Trees in particular must become established at the right location in the landscape to meet their water requirements in order to survive. They will only germinate if the right conditions, including water regime, occur. These conditions must also prevail while the seedlings become established. Recruitment of some species, such as the moonah *Melaleuca preissiana*, has been found to be predominantly episodic rather than common, with particular events resulting in mass recruitment.[235] This is why it is common to see stands of these trees of the same age (height) and structured age sequences up and down elevational gradients in basin wetlands.

Once the trees are mature they are more likely to be able to cope with conditions outside of their optimum water requirements (this is sometimes referred to as 'plasticity'). In particular, if a seasonally inundated wetland is mainly groundwater fed and the groundwater level steadily falls further below the level of the wetland in the dry season over the course of an extended drought, some wetland trees will attempt to 'follow' the water down with their roots.[235] This is only possible, however, if the rate of decline is slow. The energy required for the tree to do this can be substantial, particularly for a tree experiencing water stress (often evident as yellowing, browning, wilting or dead foliage in vegetation). Rapid and prolonged alteration of water regime to wetter or drier conditions can result in the death of individuals, and potentially the whole population at a wetland. This is because in a time of rapid change, the conditions suitable for recruitment may not occur. For this reason mature wetland trees tend to be a good indication of the water trends in a wetland over their lifespan.

Wetland sedges, on the other hand, are typically capable of responding more rapidly to water fluctuations, because they can alter their distribution in the landscape using new recruits from seed, or using vegetative reproduction to produce clones. Clonal growth is more common and rapid than reproduction by seed. A below-ground rhizome grows parallel to the ground, producing a clone of its parent a short distance away.[236] This means that if the current position of a stand of sedges becomes unsuitably wetter or drier, the stand may use rhizomes to extend into an area more suited to their water requirements. But, as with wetland trees, if a change is too rapid or too extreme for the population to respond to, it will decline and lead to death. For this reason, sedges can be a good indication of short-term water conditions. A useful guide to the optimum water depths for a number of south-west sedges is the handbook *A guide to emergent plants of south-western Australia*[237].

Submerged plants and charophytes usually persist for up to four to five months at seasonally inundated wetlands in southwest WA.[238] Within the time that surface water is present, they must germinate, grow and reproduce. The persistence of a population at a wetland is therefore very dependent upon particular aspects of water regime including depth and drying time, as well as salinity and nutrient levels. The interplay of these factors can determine whether individuals and populations germinate, survive and reproduce.[239]

Thresholds: points at which a marked effect or change occurs

In 2000, a study was carried out on the water levels and duration of inundation or waterlogging being experienced by sixty wetland species at wetlands on the Swan Coastal Plain.[228] The results of this study have been used to inform the management of a number of wetlands in the greater Perth area. For example, the common wetland tree *Melaleuca rhaphiophylla* was found, on average, to exist at a maximum water depth of 0.006 metres above the ground and minimum water depths of 2.14 metres below the ground. However, the maximum water depth at which the tree was found during the study was 1.03 metres, while the minimum water level at which it was found was 4.49 metres below the ground. It was found to live in wetlands that are inundated on average 2.15 months of every year, but the longest period was 9.4 months of every year. This information is useful in that it provides wetland managers with a coarse indication of the maximum and minimum **thresholds** for the species' survival. Of equal importance, it shows that there is a great deal of variation amongst a species. However, identifying the water regime that supports a species is not as simple as defining the extreme measures (maximum and minimum). Simply maintaining the water level between a maximum and minimum height is a simplistic approach, because variability in water level is important for plant reproduction and other aspects that determine the ecological character of the site. Since this study, further studies have been undertaken across the broader south-west, resulting in updates to this water range data.

When managing a wetland of conservation value that is at threat of altered water regime, the physiological tolerances of the plants should be determined using information and measurements taken at the site (that is, empirical data). Knowledge of their physiological responses, morphological plasticity and reproductive flexibility is invaluable. Sophisticated on-site measurement techniques, such as sapflow sensors and water potential, are now available to quantify a plant's use of water. However, there are still limitations with extrapolating this data to stands, populations and communities.

Water requirements of animals

The water requirements of wetland animals is often considered in broad-brush terms, particularly those that require permanent surface water, such as almost all fish, rakali, waterbirds, and many aquatic worms, insects and crustaceans. Their requirements can be relatively simple in comparison to other wetland animals which have complex water requirements because they vary with life stages. Animals that require surface water for some of their life cycle include burrowing fish, tortoises, frogs, crocodiles, and many worms, insects and crustaceans (Table 2). The requirements of species that use seasonally waterlogged wetlands are even less well understood.

Table 2. Adaptations to wetland drying.

Strategy	Which organisms	Examples
Disperse to other wetlands/ waterways	Many waterbirds; freshwater crocodiles, some turtles, many invertebrates, such as true bugs and water mites	Movements of all waterbirds are closely tied to the availability of water and associated habitat conditions
Aestivation, hibernation, dormancy or burrowing	Some turtles, some crayfish, some fish, many frogs, mussels, snails, roundworms, leeches, rotifers	In response to dehydration, some roundworms enter a state of hibernation called 'cryptobiosis' that they can maintain for months or years.[184] Midge larvae in wetlands on granite outcrops are also known to do this[17]
Skin adaptations	Frogs	Specialised skin secretes mucus to help stop frog skin from drying out
Water holding capacity	Frogs	The water holding frog *Cyclorana platycephala* absorbs large quantities of water through their skin and store it in their tissues and particularly in the bladder where it can be reabsorbed later[114]
Drought-resistant larvae	Some midge species	Some midge species have drought-resistant adaptations and survive as larvae in a partly hydrated state[203]
Desiccation-resistant eggs	Many crustaceans, many insects such as some may flies, true flies and beetles	Water fleas (Cladocerans) have been recorded hatching from eggs that have been dry for 200 years[174]
Drought tolerant spores, cysts	Algae and bacteria, protozoans	Some advanced colonies of cyanobacteria are able to produce akinetes, thick-walled dormant cells that allow them to resist drought
Drought tolerant seeds	Plants	Nardoo sporocarps are resistant to desiccation and can survive for up to 20 years when wetlands dry out[10]

Mobile animals can move in response to changing water availability. If habitat is subject to changes in water regime, and changes to vegetation occur in response to this, it may no longer be suitable habitat for a particular animal, and might prompt it to move to other areas of a wetland, or to new wetlands. For example, if a waterbird's usual nesting sites are no longer inundated, they may seek a new nesting site. Human land uses can create barriers and fatal hazards to migration, particularly for land-based animals such as frogs, tortoises, quendas, rakali, snakes and lizards. These barriers and fatal hazards can coincide with a bust cycle of a population with catastrophic consequences for that population.

Water requirements of wetlands

Water managers and wetland managers often infer the water requirements of a particular wetland on the basis of data about the water requirements of a number of key species.

In WA, when water is being allocated to users in the community and to the environment by the Department of Water, two key concepts are used: EWRs and EWPs. An **ecological water requirement** (EWR) is defined as the water regime needed to maintain the ecological values of a water dependent ecosystem at a low level of risk. The EWR is typically expressed as measurable hydrological variables and their limits of acceptable change for key components and processes of the water dependent ecosystem (for example, Table 3). Managers can then determine the social and cultural (traditional owners) water requirements. Once these are known, the **environmental water provisions** (EWP) can be decided upon. This is defined as the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements.

Aerenchyma: interconnected air-filled spaces within plant tissue that transport air from plant parts above the water or saturated soils to the roots

Table 3. Environmental water requirements expressed as measurable hydrological variables and their limits of acceptable change. Adapted from material drafted by the Department of Water.

Environmental objective	Baseline condition/ range of natural variation	Water regime attributes	Ecological water requirement	Interim limits of acceptable change (based on water regime)	
				Short-term (1–2 years)	Long-term (5–20 years)
Fringing sedge community	Area: 2 ha	Water level	Range: x m AHD	Observed range +/- x %	Observed range +/- x %
	Condition: excellent		Timing: Max levels in x ; min levels in x	Observed range +/- x %	Observed range +/- x %
	Trend: successful recruitment		Rate of change: x	+/- x %	+/- x %
		Hydrologic events	Magnitude: receives overflow in events exceeding x ARI	X events exceeding x ARI	X events exceeding x ARI

➤ The Department of Water is preparing guidelines on ecological water requirements for urban water management.

➤ *Statewide policy no. 5: Environmental water provisions policy for Western Australia*[240] provides a policy position on protecting wetland ecological water requirements.

Species oxygen and carbon dioxide requirements

Oxygen is needed by most living things. Oxygen exists in much lower proportions in water (about 1 per cent) than in air (about 21 per cent).[241] This affects which organisms can inhabit waterlogged sediments and wetland water columns. Wetland waters that are saline, warm, coloured, turbid, stratified, nutrient-rich or plagued by algal blooms tend to have even lower oxygen levels than other wetlands.

The sediments of wetlands that dry are subject to large variations in oxygen levels. This exposure of sediments to air between inundation or waterlogging events typically causes a shift in the suite of organisms present.

Many wetland plants, and particularly shrubs and trees, need the soil around their roots to dry out periodically, to let in air. This is because plants evolved on land, where oxygen is abundant and can be accessed from the soil by plant roots. The plants that we now know as wetland plants have, over time, developed a variety of adaptations in order to colonise wetland habitats where the waterlogged or inundated conditions mean that oxygen levels are low or completely absent due to waterlogging of the soils. The adaptations include:

- Fine, shallow root systems that avoid the need to transport gases a long way, for example, *Melaleuca* species.[242]
- Air spaces known as **aerenchyma** in their roots and stems, that act like straws,

moving air from aerial parts of the plant to the root tissues where it is needed. In sedges, this is often visible as spongy or hollow tissue in the leaves and stems.[43] Genera which display this adaptation include *Viminaria, Melaleuca, Juncus, Typha, Sesbania, Eucalyptus* and *Marsilea*[243] including local species such as *Melaleuca cuticularis*[244], *Melaleuca cajuputi*[245] and *Typha domingensis*.[246] This can have implications for plants such as *Typha*, which can decline in health when cut or grazed to below the water line, as this seriously impedes oxygen access.

- Pressurised gas flow from the surface to the roots. A study of a number of southwestern WA sedges demonstrated that those species that produced more pressure are able to survive deeper water than those that produce low pressure. Amongst others, this study found this link occurred in *Typha domingensis, Typha orientalis, Eleocharis sphacelata, Schoenoplectus validus, Baumea articulata* and *Cyperus involucratus*.[223]

- Specialised roots known as **adventitious** roots that grow from the plant trunk, just above the water line in order to access the air. *Melaleuca* trees (Figure 48) and river gums (*Eucalyptus camaldulensis*) are known to employ adventitious roots.[244]

- Loss of pores in leaves used for gas exchange (**stomata**) in submerged plants.[43] This waxy layer on the outside of the leaf that functions to reduce water loss in land plants is not required. Instead, the cell walls are very thin, to allow absorption of gases from the water column.[242,38] Unfortunately this also means submerged plants can absorb herbicides quickly, directly from the water.[43]

- Similarly, algae and cyanobacteria have very thin cell walls, making it easier to absorb dissolved gases and nutrients from the water column.

- Floating leaves, both on plants rooted to the sediments and those that are floating, unattached to sediment. Floating leaves with stomata on the upper surface can take up gases from the atmosphere. These often have a large surface area, for example, *Nardoo* and waterlilies such as *Nymphaea* species. Duckweed *Lemna* is an unattached, floating plant.

Figure 48. The adventitious roots of a *Melaleuca* tree at Manning Lake, in the suburb of Hamilton Hill. Photo – J Lawn/DEC.

The diffusion of oxygen from plants into wetland soil is often evident in the areas around plant roots or rhizomes. The presence of narrow, orange or brown-coloured areas along roots, known as 'oxidised root channels' indicates oxidised conditions due to radial oxygen loss.[247,242] The oxidised area, known as the rhizosphere, also supports types of bacteria and other organisms that are not found in surrounding areas with low oxygen levels.

Low-oxygen conditions pose a problem for large animals; for example, fish cannot survive in water with less than 30 per cent oxygen saturation.[67] They employ gills to maximise oxygen intake, as do larval insects (for example, dragonfly larvae), crustaceans, and tadpoles. The phenomenon of 'fish kills', when large numbers of fish perish, is often caused by low oxygen levels. Animals that don't have gills instead have

Adventitious roots: roots that arise from mature plant tissue such as stems or trunks and which take up oxygen and nutrients in inundated conditions

Stomata (plural of stomate): pores in leaves and stems used for gas exchange other interesting ways of accessing oxygen. Diving beetles and some of the true bugs (Hemipterans) capture bubbles of air from the surface, and carry them underwater to breathe. Crocodiles and turtles also surface to breathe. Frogs have specialised skin that absorbs oxygen and releases carbon dioxide.

Some snails have gills, while others such as pond snails (Lymnaeidae) have lungs, allowing them to better survive in oxygen-poor conditions. These snails can be seen just under the surface of the water, refilling their lungs. Mussels and clams continually pump water through their bodies, supplying their gills with a constant supply of oxygen. Some larvae of moths and butterflies (Lepidoptera) use a cylindrical case constructed of plant material, which they use like a scuba tank to stay underwater for prolonged periods.[180] The larvae of aquatic weevils (Curculionidae) live inside air-filled stems of aquatic plants.[180] Some animals move to another area of the wetland if conditions become anoxic. In deeper wetlands, invertebrates inhabiting the deepest area of the water column move into shallower waters when oxygen levels decline.

Many species of midges, worms and mosquitoes are well adapted to low-oxygen conditions. The distinctive red colour of the larvae of some midge (*Chironomus*) is due to their blood pigment (haemoglobin), which makes them efficient at breathing dissolved oxygen. Segmented worms (oligochaetes) can be common in low oxygen conditions.[18] In fact, some segmented worms can live in waters with an oxygen concentration close to zero.[180] Mosquito larvae and water scorpions breathe air from above the water surface through structures on their abdomens. Mosquitoes will either return to the surface, or they will often float with their snorkel-like siphons puncturing the water surface, which provides them with a constant supply of oxygen. Similarly, the unpleasantly named rat-tailed maggot (Syrphidae) survives in putrid, anoxic water by using their extendable snorkel (the so-called rat-tail) to take in air from the surface.

A range of bacteria do not require oxygen to survive, making them an important part of wetlands which support anoxic conditions. Some use oxygen when it is available but switch to other chemicals when it is not.

The oxygen level in water also affects the decomposition of organic matter. The process of decomposing organic matter in low oxygen conditions is less efficient and for example, freshwater wetlands with consistently low oxygen levels (and low pH) tend to build up peat.

➤ For more information on the conditions that influence oxygen levels in wetlands, see the topic 'Conditions in wetland waters' in Chapter 2.

Species light requirements

Light availability in wetlands with a water column is quite different to that of drylands, because once sunlight reaches wetland waters it is rapidly altered and reduced, so that both the quality and quantity of light available is quite different to what first reached the surface of the water. This affects which organisms can inhabit wetland water columns. Wetland waters that are deep, heavily shaded, turbid or coloured (for example, tannin stained) tend to have reduced light levels compared to other wetlands.

➤ For more information on the conditions that influence light levels in wetlands, see the topic 'Conditions in wetland waters' in Chapter 2.

Plants and algae are particularly affected by light availability. All plants and algae need light for photosynthesis and in wetlands with a water column they need to remain within the euphotic zone (also known as the photic zone). Put simply, this is the area of the water column penetrated by light of sufficient intensity and of suitable wavelength to enable photosynthesis by aquatic plants.

Aquatic plants with their roots in the sediment are almost always restricted to relatively shallow water. Their need for light means that they can be greatly affected by sudden declines in water clarity or changes in water level. A reduction in light availability tends to favour phytoplankton over plants (Figure 49). Therefore, plants use a number of strategies to maximise their access to light and to disadvantage phytoplankton. These 'self-stabilising mechanisms' include providing refuges for phytoplankton grazers, removing nutrients from the water column and using their surface area to reduce sediment re-suspension.

Figure 49. Plants and algae compete for light in wetlands, particularly those with a water column. Photos – (a) G Keighery/DEC (b) J Lawn/DEC (c) M Lyons/DEC.

(a) aquatic plants prevail in clear water with good light

(b) phytoplankton can completely block out light

(c) abiotic turbidity can affect both plant and phytoplankton growth

To maximise both light and nutrient absorption submerged plants maximise the surface area of the leaves; often forming very dissected or fine leaves especially in deeper waters. Examples include water milfoils (*Myriophyllum species*) and fennel pondweed (*Potamogeton pectinatus*). Other species form whorls or spirals of leaves down the stem to increase their access to light, such as curly pondweed (*Potamogeton crispus*).[43]

Water milfoils, *Myriophyllum*, are typically adaptable species, able to grow as a submerged plant or an emergent plant. Water milfoil is very common in coloured (tannin-stained) wetlands where having aerial shoots enables it to cope with the severe light limitation in these wetlands.[43]

Some plants get the best of the light, oxygen and nutrients by having their roots in the sediment where nutrients are concentrated, long stems that span the water column, and leaves floating on the surface where light is available. Because their stems must span the water column, sudden increases in water depth is a potential problem for these plants. Waterlilies have this growth form. The tropical climates and nutrient-rich sediments in which they grow allow them to have a high growth rate, and the stems elongate rapidly with rising water levels.[43,242]

In comparison to submerged and emergent plants, phytoplankton and floating aquatic plants are not restricted to shallow water. To cope with low light conditions in deep and/or turbid water, some algae and cyanobacteria can adjust their buoyancy to stay in the euphotic zone. Floating aquatic macrophytes can also live in wetland zones where water is deep, because at the surface they have easy access to light and oxygen. Some floating plants make use of the water's surface tension, laying their leaves flat on the water surface (for example, duckweeds, *Lemna*). Other larger floating plants have air-filled tissue that assists them to float (for example, the introduced aquatic pest plant, water hyacinth, *Eichhornia crassipes*). However, they trade off the ability to access nutrient-rich sediments.

Halophile: a species that shows a preference for saline habitat such as salt lakes

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia, Halosarcia, Sarcocornia, Sclerostegia, Tegicornia* and *Pachycornia*, belonging to the family Chenopodiaceae

Species salinity requirements

All wetland species are adapted to particular ranges and types of salts in their environment. Species range from very intolerant of salinity, through to **halophiles**, named after the Greek term for 'salt-loving'. Many of the ions dissolved in wetland water columns and pore waters are essential to life and play important roles in the functioning of particular species and the ecosystem.

Saline wetlands are inhabited by very different species than freshwater wetlands. This applies both to organisms in wetland water columns, and also to those in the sediments that are bathed in saline pore waters and/or ingesting salt associated with waters and sediments. To a much lesser degree, species salinity requirements are also evident in wetlands that are seasonally fresh but which become increasingly saline following seasonal evaporation.

Importantly, juvenile plants and animals are often much more susceptible to increased salinity levels than adults of the same species[248], therefore in order for a species to persist, salinities must be low enough during their development, as well as during reproductive phases, for recruitment to occur.

Organisms adapted to either naturally saline or freshwater conditions usually cannot tolerate large changes in the timing, duration, seasonality or range of salinities.[249,248] Although plants require some salts for development and growth, when grown in saline conditions, most plants (both wetland and dryland) suffer from stress. Osmotic stress occurs when saline conditions inhibit plants from taking up water, so that they become water-stressed. Ionic stress occurs because the dominant ions of salty water (often sodium and chloride ions) can disrupt proper functioning of cells, and can also inhibit the uptake of nutrients important for plant growth.

In the overstorey, some species of sheoaks (*Casuarina*) and even some paperbarks (*Melaleuca*) can be relatively salt-tolerant, such as *Casuarina obesa* and *Melaleuca cuticularis* respectively. Sedges such as *Gahnia trifida* are also salt-tolerant. However, more extremely salty environments are the domain of true saltmarsh plants, the **samphires**. Samphires include plants such as *Halosarcia* and *Sarcocornia* which are succulent in order to dilute the salt. For example, *Sarcocornia quinqueflora* accumulates salt in swollen leaf bases which fall off, thus removing excess salt.[43,76]

Some plants have roots with surfaces that exclude salt. Other plants have salt glands in which salt taken up is gathered and then excreted from plant leaves. Salt crystals, formed from very salty water excreted by salt glands, can often be seen on leaf surfaces in these species, such as in the grass Marine couch (*Sporobolus virginicus*) which grows at inland as well as coastal wetlands.[43]

Compartmentalising salt in a **vacuole** (package) within the cell is another method some plants use to keep salt from damaging the cell. However, compartmentalisation must be accompanied by osmotic adjustment, in which the cell must produce organic solutes to be kept outside the vacuole, to ensure that water from the cell does not flow into the vacuole through osmosis.[43]

➤ For more information on salinity thresholds for submerged plants and charophytes of south-west WA, see Sim (2006).[239]

The adults of many vertebrate species found in Western Australian wetlands are highly mobile, and can tolerate salinity if they can access alternative sources of fresh drinking water.[250,251,129] An example is the Australian shelduck (*Tadorna tadornoides*), which feeds at saline wetlands and is able to rid itself of excess salt it ingests through specially-adapted nasal glands.[250] However, when breeding, Australian shelducks are dependent of fresh waters until their young develop an ability to rid their bodies of salt.[250] Another example of a moderately salt-adapted freshwater vertebrate is the oblong turtle (*Chelodina colliei*), which is known to be able to tolerate estuarine level salinities if it has access to fresh water for breeding and long term health (J Giles 2009, pers. comm.).[129] It does not possess a salt excretory gland (J Giles 2009, pers. comm.).

Some species, such as the brine shrimp *Parartemia*, are able to regulate the concentration of their internal fluids in relation to the environment (osmoregulators), while others have no ability to do this, and their internal concentrations reflect that of the solution they are immersed in (osmoconformers).[252]

Species food/energy requirements

Much is made of the productivity of wetlands worldwide, but wetlands are not wet islands; most are very connected to the surrounding dryland, and often to waterways. Wetlands import and export energy and nutrients in two main ways: through the movement of water, which carries with it energy and nutrients in the form of particulate and dissolved matter; and the movement of animals. WA's wetlands vary widely in the amount of food and energy they contain, and this is a major influence on the amount and types of life they sustain.

Food chains and food webs are concepts to help describe how food and energy moves. **Food chains** describe who eats whom, in a simple linear order. They represent the flow of energy or nutrients in ecosystems. Vertebrate animals are usually at the 'top' of the chain. **Food webs** are comprised of two or more interconnected food chains, because many species can eat (or be eaten by) a range of organisms; these can be extremely complex. Understanding these **trophic** relationships can be very important to understanding a wetland's ecology.

In particular, food webs assist in explaining how nutrients, energy and biomass cycle through a wetland as well as what comes in and goes out. When one organism consumes another, nutrients and energy are transferred. Food webs shed light on a variety of natural processes, from why wetlands that wet and dry experience pulses of energy and life, to why some wetlands build up peat. It can also explain why alterations to the catchment of a wetland can affect wetland species. Alterations to the amount of nutrients and energy in a wetland are one of the most common challenges for Western Australia's wetland managers, resulting in booms in some populations of algae, nuisance midge and mosquitoes, weeds and other opportunists, at the expense of other species, as well as leading to problems such as botulism in waterbirds. On the other hand, high levels of nutrients and energy are the reason why some ecosystems support high numbers of birds (such as the Vasse-Wonnerup estuary in the south west).

Vacuole: A storage compartment found within a cell

Food chain: a diagram of who eats whom in a simple linear order, representing the flow of energy or nutrients in ecosystems. Two basic food chains are the grazing and detrital food chains.

Food web: a diagram that represents the feeding relationships of organisms within an ecosystem. It consists of a series of interconnecting food chains

Trophic: relating to nutrition, food or feeding

Along with other factors, food webs can assist in explaining why a species is present or absent at a wetland, and also a species' population dynamics. For example, foxes, which eat turtles, may act as a population control on turtles. If foxes decline, turtle numbers may return to natural levels, or alternatively, the cat population may instead flourish. Either scenario can have flow-on effects on an ecosystem. Wetland managers can use this information to understand how to maintain or restore natural populations and minimise unintended effects of management actions.

The concept of food webs is useful, but managers rarely construct anything but the most conceptual of food webs as management tools. Knowing what a species eats can vary according to the resources available in a region, site and season, and according to the phase of an individual in its life cycle. Scientists use inference, observation, confirmation of gut contents and isotopic analysis techniques to establish eating patterns.

At the beginning of every food chain on Earth are the **primary producers**: plants, macro and microscopic algae and cyanobacteria. Primary producers may be eaten alive or dead. They are called primary producers because they are able to produce their own energy for growth and survival. Via the process of photosynthesis, they harness the sun's energy and store it as carbohydrates built from carbon dioxide. As well as carbon dioxide, they need nutrients, such as nitrogen and phosphorus for growth and survival. Western Australian soils (and by extension waters) are some of the most nutrient-poor in the world, and in undisturbed wetlands, the plants and algae are in balance with levels of nutrients available. Nutrient cycling in wetland soils is very active and there is competition between plants and microbes occupying the soil for available nutrients.[253]

Organisms that consume other organisms, either dead or alive, are called **consumers**. These include herbivores (plant-eaters), carnivores (meat-eaters) and omnivores (plant and meat eaters); and they may be either specialists, with very specific diets or generalists, such as water boatmen, which eat a range of prey. Animals are sometimes described according to feeding **guilds**, particularly waterbirds. Usually the consumers at the top of the food chain in Western Australia's wetlands are large predators, including fish, tortoises, snakes, lizards, crocodiles, water rats and waterbirds. Predators such as birds of prey have large hunting territories including wetlands, and may consume the top wetland predators and, along with mammals such as kangaroos and wallabies, export nutrients and other material from wetlands.

Those consumers that predominantly eat decaying organisms are known as detritivores. Large **detritivores** such as crayfish fragment detritus, feeding on the larger pieces and creating smaller pieces that smaller detritivores eat with the help of bacteria and fungi that 'condition' the material. Very fine particulates are eaten by near-microscopic detritivores such as rotifers. Where oxygen levels are high, such as when wetland soils are dry, detritivores including earthworms, millipedes, isopods, mites, springtails, beetles and true flies may occur.[13] In saturated soils, where oxygen levels are low, insects such as midge (chironomid) larvae, craneflies, mayflies and caddisflies, worms (Oligochaetes and Platyhelminthes) and crustaceans such as seed shrimps (Ostracoda), water slaters (Isopoda) and side swimmers (Amphipoda), and sometimes sponges, prevail.[18,13] Many inhabit the sediment of wetlands where much of the detrital material settles. Although this can be a challenging environment because of the low oxygen conditions that can occur (particularly in deep, permanently inundated wetlands), many species employ a strategies to overcome the low oxygen in order to take advantage of the relatively abundant nutrient and food supply that settles at the bottom of a wetland. This trade-off seems to work, as the biomass of detritivores can be high.

Decomposers complete the cycle of life, with their ability to make use of carbon and nutrients that primary producers, consumers and detritivores are not able to take up. These fungi and bacteria perform most of the chemical breakdown of dead organisms, unlocking carbon and nutrients from complex molecules from this organic matter, with

Primary producer: a photosynthesising organism. Primary producers, through photosynthesis, harness the sun's energy, store it in carbohydrates built from carbon dioxide

Consumer: an organism that feeds on other organisms, either dead or alive

Guild: a group of species that exploit similar resources in a similar fashion

Detritivore: an animal that feeds on detritus

Decomposer: organisms, mainly bacteria and fungi, which break down complex organic molecules from detritus, liberating nutrients and assimilating carbon their armoury of chemicals known as enzymes. These enzymes enable them to assimilate dissolved and particulate organic matter that originates from dead microbes, animal faeces and algal secretions. This chemical decomposition of organic matter releases nitrogen in inorganic forms, which are then available for uptake by plants and algae. It also allows bacteria to assimilate carbon in the form of dissolved organic carbon, which is the most abundant form in wetlands.[22] This makes them a nutritious food source, forming a vital food source for organisms further up the food chain.[17] Much of the nutritious value of detritus (such as dead leaves) is not in the detritus itself, but rather in its coating of microbes that are decomposing it, that provides an energy-rich food source. They are efficient at assimilating the carbon they consume, converting 20–50 per cent of the carbon they consume into new bacterial biomass. This makes bacteria essential in wetlands because carbon is needed for growth and survival of all life in wetlands. Decomposers are fundamental to the nutrient, carbon and energy cycling of wetland ecosystems[17,18]

Wetland ecosystems

An ecosystem is a community of interdependent organisms together with their non-living environment. How wetlands function at the ecosystem level is a reflection of their physical, chemical and biological characteristics.

Wetland scientists use a number of tools to describe wetland ecosystems, including conceptual models, the alternate stable states model, and ecological character descriptions. These are outlined briefly below.

Conceptual models

A popular way to understand and communicate important influences and relationships in wetlands is to use simple diagram often called 'conceptual wetland models'. They typically depict how a wetland functions or how a change to a wetland may drive a series of further changes within the wetland. They may be basic, somewhat generic or stylised

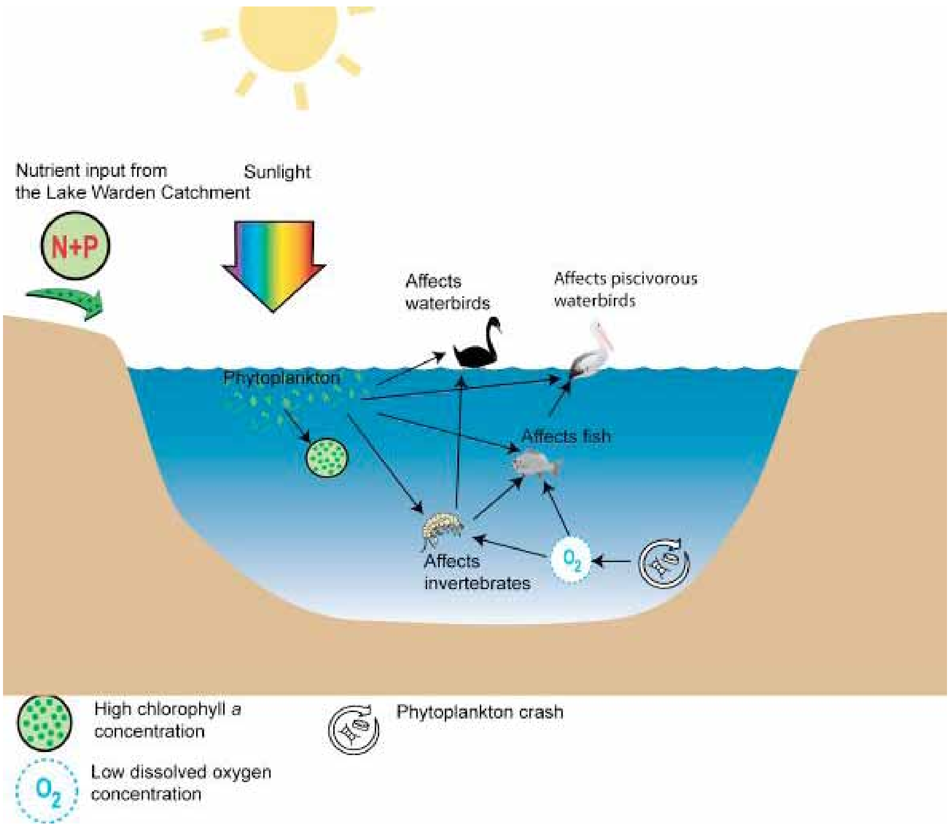

Figure 50. A stylised conceptual model of the potential effect of nutrient enrichment from the catchment at the Lake Warden System Ramsar Site, Esperance. Image - G Watkins.

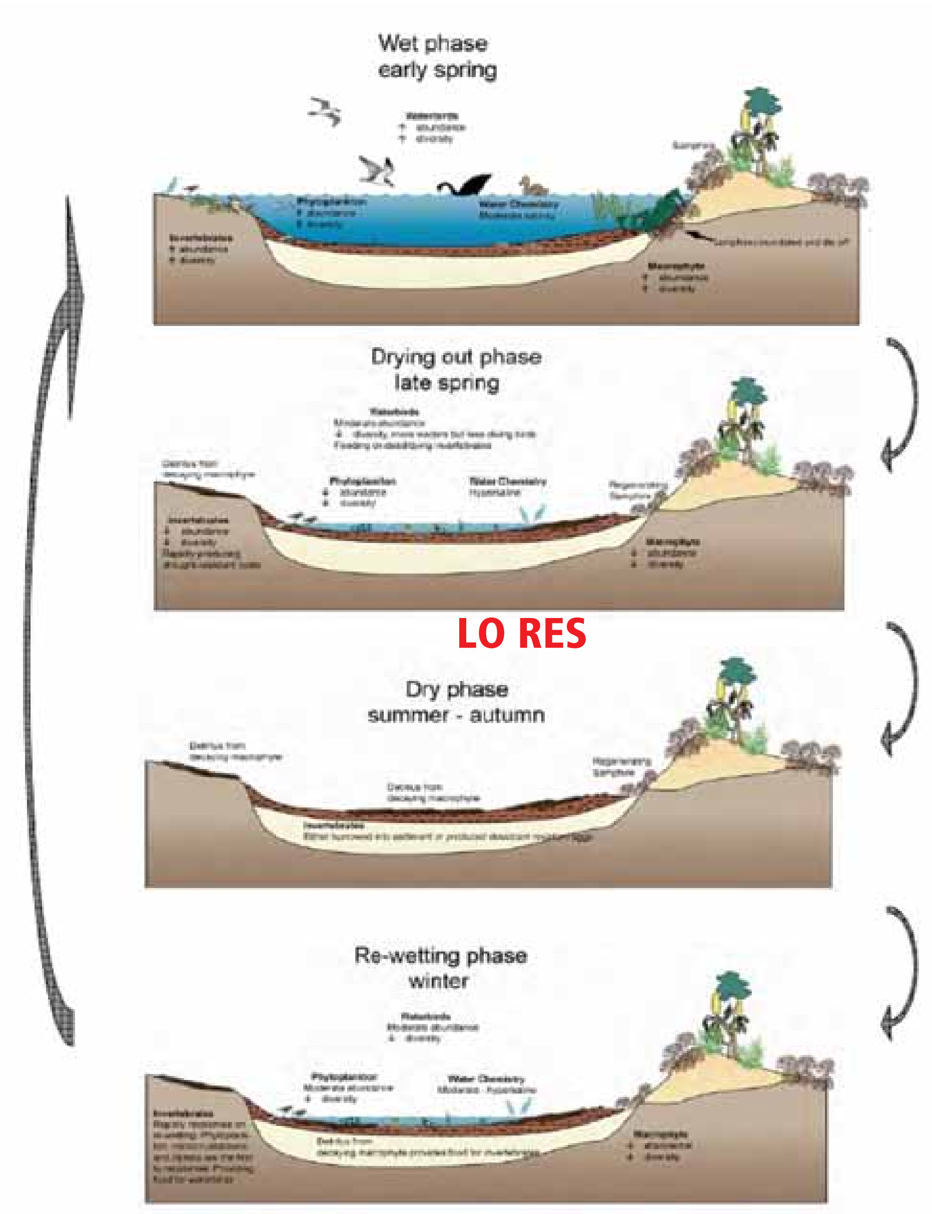

Figure 51. A conceptual model of a naturally saline playa, showing changes in wetland organisms over the course of a year. Image – Jones et al.[32]

models, such as Figure 50, or more detailed models, such as Figure 51. Conceptual models can also help wetland managers to identify important elements of a wetland that should be monitored.

➤ The Queensland State government is developing conceptual models for most of their wetland types. They provide a lot of resources online to assist individuals create conceptual models, available from the Queensland Department of Environment and Resource Management website.[254]

Alternate stable states

The alternate (or multiple) stable states model accounts for the combined effect of light, nutrients, salinity and water regime in wetlands with a permanent, seasonal or intermittent water column. It is based on the concept that within an ecosystem there may be two or more stable states that can exist at any one time depending on the influence of a determining factor or factors. A stable state is one where the ecosystem tends to remain the same (that is, comprises the same species in the same relative abundances) over a certain period of time (for example, a season or a year). Often a positive feedback system is present with a particular state creating conditions that will favour its persistence. Between the stable states is an unstable equilibrium. The change in the ecosystem between the alternate states often occurs very rapidly and with little warning. Hysteresis is also likely to occur, that is, the condition that caused a shift from one state to another does not necessarily result in a shift back to the first state when the condition is simply reversed. For shallow European lakes undergoing nutrient enrichment, the concept of two states has been described: clear water dominated by aquatic macrophytes (aquatic plants) and turbid (cloudy) water dominated by phytoplankton. For Australian lakes, this model has been extended to describe five 'states' or ecological regimes recognised by Davis et al. [255], Strehlow et al.[238], and Sim et al.[256] for southern Australian wetlands:

I Clear, submerged macrophyte-dominated;

II Clear, benthic microbial community-dominated;

III Turbid, sediment-dominated;

IV Turbid, phytoplankton-dominated; and

V Free-floating plant dominated.

Regime I is defined as clear water with aquatic plants (submerged, floating and emergent species). Regimes I, II, and III all represent regimes found in undisturbed wetlands and may often be the baseline state. The first regime represents undisturbed wetlands of fresh or low salinities and low to moderate enrichment. The second regime represents naturally hypersaline or acidic lakes. The third occurs naturally in shallow wetlands with clay substrates, for example, claypans, or under the low water levels associated with naturally occurring drying or wetting phases in seasonal wetlands. It is usually produced by wind driven re-suspension of bed sediments. The fourth and fifth regimes occur at high phosphorus levels, often more than 150 micrograms per litre, and usually represent a shift from Regime I driven by eutrophication. The submerged macrophyte-dominated regime demonstrates some resilience to increased nutrient loading before reaching a threshold. Secondary salinisation or acidification can drive a shift from Regime I to II. Drawdown of water levels as a result of surface water or groundwater abstraction can result in a shift from Regime I to III.

Text sourced from Department of Environment[70] and Maher and Davis.[257]

Ecological character descriptions

Wetlands that are recognised as internationally significant under the Ramsar Convention are now described by scientists using a report type known as an 'ecological character description'. This report describes the key aspects of the wetland that result in its **ecological character**, that is, the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region.

These characteristics form a benchmark against which any future change in condition is measured. In particular, the primary determinants of ecological character must be monitored. These are the features of the wetland that make it special or unique. In the case of a Ramsar listed site, these include the **wetland components, wetland processes** and **ecosystem services** that support the relevant nomination criteria. For example, if a site is internationally significant because it supports large numbers of waterbirds, it is important to protect these birds and the habitat that they utilise. This may include maintaining the water level and the water quality to ensure that the birds' food source persists, as well as maintaining vegetation that is used for nesting. At a minimum, monitoring must determine if the site continues to meet the Ramsar criteria under which it was nominated. Ideally, a monitoring program will include elements of the ecosystem that will provide early warning of any pending deterioration in ecological character.

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Wetland components: the physical, chemical and biological parts of a wetland (from large scale to very small scale, e.g. habitat, species and genes)

Wetland processes: the dynamic physical, chemical and biological forces within a wetland, including interactions that occur between wetland organisms, within the physical/chemical environment, and the interactions of these

Ecosystem services: benefits that people receive or obtain from an ecosystem, including provisioning services (such as food, fuel and fresh water), regulating services (such as ecosystem processes such as climate regulation, water regulation and natural hazard regulation), cultural services (such as spiritual enrichment, recreation, education and aesthetics) and supporting services (such as the services necessary for the production of all other ecosystem services such as water cycling, nutrient cycling and habitat for biota)

➤ To view the ecological character descriptions for each of WA's Ramsar sites, see the wetlands webpage of the DEC website www.dec.wa.gov.au/wetlands.[258]

- For information on the Ramsar ecological character description template, see the report and checklist available online from the Department of Sustainability, Environment, Water, Population and Communities.[259]

GLOSSARY

Adventitious roots: roots that arise from mature plant tissue such as stems or trunks and which take up oxygen and nutrients in inundated conditions

Aerenchyma: interconnected air-filled spaces within plant tissue that transport air from plant parts above the water or saturated soils to the roots.

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Aestivation: a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Algae: a general term referring to the mostly photosynthetic, unicellular or simply constructed, non-vascular, plant-like organisms that are usually aquatic and reproduce without antheridia and oogonia that are jacketed by sterile cells derived from the reproductive cell primordium; includes a number of divisions, many of which are only remotely related to one another[30]

Algal bloom: the rapid, excessive growth of algae, generally caused by high nutrient levels and favourable conditions

Amphibian: the class of animal to which frogs, toads and salamanders belong. They live on land but develop by a larval phase (tadpoles) in water.

Anaerobic: without air (organisms that live in these conditions are anaerobes)

Anaerobic respiration: respiration without oxygen (O_2). Respiration is the process by which organisms convert the energy stored in molecules into a useable form. In most organisms, respiration requires oxygen, which is why breathing by animals is referred to as respiration. However, some bacteria are capable of anaerobic respiration, in which other inorganic molecules (such as sulfur, metal ions, methane or hydrogen) are used instead of oxygen

Anoxic: deficiency or absence of oxygen

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Benthic: the substrate of a wetland; the organisms inhabiting it are known as benthos

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Benthos: organisms living in or on the wetland substrate

Bioavailable: in a chemical form that can be used by organisms

Biofilm: bacteria, microalgae, fungi and unicellular microorganisms enmeshed in a hydrated mucopolysaccharide secretion that sequesters ions and isolates microorganisms from the water column[14]. May be present on living and non-living surfaces and substrates.

Biomass: the total mass of biological material (living or dead), usually expressed as live or dry weight per unit area or volume

Bioremediation: the use of microorganisms to break down environmental pollutants

Blue-green algae: an older term for cyanobacteria

Botulism: a paralytic disease caused by ingestion or exposure to a toxin produced by the bacteria *Clostridium botulinum*

Charophytes: green algae of the Characeae family; complex algae that superficially look like submerged flowering plants

Colony (algal): a closely associated cluster of cells, joined together or enclosed within a common sheath or mucilage.[26] A colony may incorporate thousands of cells.[17]

Consumer: an organism that feeds on other organisms, either dead or alive

Cosmopolitan: can be found almost anywhere in the world

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Cyanobacterial bloom: the rapid, excessive growth of cyanobacteria, generally caused by high nutrient levels and favourable conditions

Deciduous: a plant that sheds its leaves annually

Decomposer: organisms, mainly bacteria and fungi, which break down complex organic molecules from detritus, liberating nutrients and assimilating carbon

Decomposition: the *chemical* breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its *physical* breakdown.[22,17] Also known as mineralisation.

Desmid: a member of the Desmidialies (Zygnemophyceae) within the Division Chlorophyta (green algae)

Detritivore: an animal that feeds on detritus

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, freely moving in the open water and forming fossil deposits

Diatomite, diatomaceous earth: siliceous deposits made up of the sedimentary build up of diatom shells (frustules)[30]

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Ecosystem: a community of interdependent organisms together with their non-living environment

Endemic: naturally occurring only in a restricted geographic area

Environmental water provisions (EWPs): the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social and economic impacts. They may meet in part or in full the ecological water requirements.

Ecological water requirements (EWRs): the water regime needed to maintain the ecological values of a water dependent ecosystem at a low level of risk

Ecosystem services: benefits that people receive or obtain from an ecosystem, including provisioning services (such as food, fuel and fresh water), regulating services (such as ecosystem processes such as climate regulation, water regulation and natural hazard regulation), cultural services (such as spiritual enrichment, recreation, education and aesthetics) and supporting services (such as the services necessary for the production of all other ecosystem services such as water cycling, nutrient cycling and habitat for biota)

Epiphyte: organisms such as bacteria, algae and plants that grow attached to plants

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plants, algae and cyanobacteria. May occur naturally over geologic time or may be human-induced.

Facultative plants: plants that can occur in both wetlands and dryland under natural conditions in a given setting

Filament: cells in a linear series, usually abutting one another, creating threads or strands

Flyway: a geographic region that supports a group of populations of migratory waterbirds throughout their annual cycle. Up to nine flyways are recognised worldwide.

Food chain: a diagram of who eats whom in a simple linear order, representing the flow of energy or nutrients in ecosystems. Two basic food chains are the grazing and detrital food chains.

Food web: a diagram that represents the feeding relationships of organisms within an ecosystem. It consists of a series of interconnecting food chains

Generalist: a species that can live in many different habitats and can feed on a variety of different organisms

Guild: a group of species that exploit similar resources in a similar fashion

Halophile: a species that shows a preference for saline habitat such as salt lakes

Hydroecology: the study of the water regimes required to maintain and enhance conservation values of ecosystems

Inorganic: compounds that are not organic (broadly, compounds that do not contain carbon)

Invertebrate: animal without a backbone

Larvae: juvenile insects (the singular being 'larva')

Lichen: a composite organism consisting of a fungus and a cyanobacterium living in symbiotic association

Lignin: a material (a complex organic polymer) deposited in the cell walls of many plants, making them rigid and woody

Luxury uptake: the process by which some organisms take up more nutrients than they need for current growth, instead storing them for future growth

Macroalgae: algae large enough to be seen with the unaided eye

Macroinvertebrate: an invertebrate that, when fully grown, is large enough to see with the naked eye (larger than 0.25 millimetres)

Marl: fine-grained calcareous material (usually from dead charophyte algae that are able to biogenically precipitate calcium carbonate)[17]

Microalgae: microscopic algae

Microbe: an organism that can be seen only with the help of a microscope for example, bacteria, some algae (also referred to as microorganisms)

Microinvertebrate: an invertebrate that is too small to see with the naked eye (smaller than 0.25 millimetres)

Migratory species: those animals that migrate to Australia and its external territories, or pass through or over Australian waters during their annual migrations

Motile: capable of motion

Mycorrhiza: a symbiotic association between a fungus and the roots of a plant, from which both fungus and plant usually benefit

Niche: the role of an organism in a community, in terms of its presence, activity, habitat and the resources it uses

Nymph: a juvenile insect that resembles the adult, but has poorly developed wings[180]

Obligate wetland plants: plants that are generally restricted to wetlands under natural conditions in a given setting

Organic: compounds containing carbon and chiefly or ultimately of biological origin

Organism: any living thing

Particulate: in the form of particles (small objects)

Peat: partially decayed organic matter, mainly of plant origin

Perched: not connected to groundwater

Perennial: a plant that normally completes its life cycle in two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Periphyton: organisms such as bacteria, fungi, algae and invertebrates that are attached to underwater surfaces including sediment, rocks, logs and plants

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Phytoplankton: aquatic organisms that photosynthesise and which float or are suspended in water, drifting with water movements and generally having minimal ability to control their location, such as algae

Plankton: aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location, such as phytoplankton (photosynthetic plankton including algae and cyanobacteria) and zooplankton (animals)

Precipitate: cause a substance to be deposited in solid form from a solution

Primary producer: a photosynthesising organism. Primary producers, through photosynthesis, harness the sun’s energy and store it in carbohydrates built from carbon dioxide

Propagule: a unit or a piece of an organism that facilitates the organisms' reproduction. Plant propagules primarily include seeds, spores and plant parts capable of growing into new plants. Invertebrate propagules are usually eggs or, in the case of sponges, gemmules. Protist propagules are usually cysts. Bacteria and algae propagules are usually spores.

Refugia: restricted environments that have been isolated for extended periods of time, or are the last remnants of such areas

Respiration: the process in which oxygen is taken up by a plant, animal or microbe, and carbon dioxide is released

Rhizome: a horizontal, underground stem which bears roots and leaves and can usually persist, even if above-ground parts die back

Rhizosphere: the area of soil immediately surrounding plant roots, which is altered by their growth, respiration, exchange of nutrients etc

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia, Halosarcia, Sarcocornia, Sclerostegia, Tegicornia* and *Pachycornia*, belonging to the family Chenopodiaceae

Saprotroph: an organism that absorbs soluble organic nutrients from inanimate objects (e.g. from dead plant or animal matter, from dung etc)

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Sediment pore water: water present in the spaces between wetland sediment grains at or just below the sediment surface. Also called interstitial waters.

Spawn: eggs surrounded by jelly; generally applied to a group of eggs

Species richness: the total number of species (in a defined area)

Spicule: minute, needle-like body made of silica or calcium salts found in some invertebrates

Spore: a reproductive structure that is adapted for dispersal and surviving for extended periods of time in unfavourable conditions

Stomata (plural of stomate): pores in leaves and stems used for gas exchange

Stonewort: a term applied to *Chara* species that precipitate and deposit calcium carbonate on their surfaces

Stromatolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate (see also 'thrombolite')

Symbiosis: a relationship in which dissimilar organisms live in close association, and which is mutually beneficial to both organisms

Tannins: complex organic compounds (polyphenols) occurring in various plants

Thrombolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate (see also 'stromatolite')

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour

Trophic: relating to nutrition, food or feeding

Turbid: the cloudy appearance of water due to suspended material

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Vacuole: a storage compartment found within a cell

Vascular plants: plants with defined tubular transport systems. Non-vascular 'plants' include algae, liverworts and mosses.

Vertebrate: animal with a backbone

Water column: the vertical section of water between the surface and the wetland bed

Wetland components: the physical, chemical and biological parts of a wetland (from large scale to very small scale, e.g. habitat, species and genes)

Wetland processes: the dynamic physical, chemical and biological forces within a wetland, including interactions that occur between wetland organisms, within the physical/chemical environment, and the interactions of these

Zooplankton: tiny invertebrates and protozoans floating or suspended in the water that drift with water movements, generally having little or minimal ability to control their location

APPENDIX 1

Table 4. WA's wetland threatened ecological communities

Source: the Department of Environment and Conservation's Threatened Ecological Community Database endorsed by the Minister for the Environment (DEC, sourced April 2012)

Community identifier	Community name	General location (IBRA regions)
2. Toolibin	Perched wetlands of the Wheatbelt region with extensive stands of living Swamp Sheoak (*Casuarina obesa)* and Paperbark (*Melaleuca strobophylla*) across the lake floor.	Avon Wheatbelt
3. SCP10b	Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)	Swan Coastal Plain
4. SCP19	Sedgelands in Holocene dune swales of the southern Swan Coastal Plain	Swan Coastal Plain
5. Clifton-microbialite	Stromatolite like freshwater microbialite community of coastal brackish lakes	Swan Coastal Plain
6. Richmond-microbial	Stromatolite like microbialite community of coastal freshwater lakes	Swan Coastal Plain
7. Mound Springs SCP	Communities of Tumulus Springs (Organic Mound Springs, Swan Coastal Plain)	Swan Coastal Plain
10. Nthiron	Perth to Gingin Ironstone Association	Swan Coastal Plain
11. Muchea Limestone	Shrublands and woodlands on Muchea Limestone	Swan Coastal Plain
14. SCP18	Shrublands on calcareous silts of the Swan Coastal Plain	Swan Coastal Plain
15. SCP02	Southern wet shrublands, Swan Coastal Plain	Swan Coastal Plain
16. SCP3a	*Eucalyptus calophylla - Kingia australis* woodlands on heavy soils, Swan Coastal Plain	Swan Coastal Plain
17. SCP3c	*Eucalyptus calophylla - Xanthorrhoea preissii* woodlands and shrublands, Swan Coastal Plain	Swan Coastal Plain
18. Thetis-microbialite	Stromatolite community of stratified hypersaline coastal lakes	Geraldton Sandplain
19. Scott Ironstone	Scott River Ironstone Association	Warren
21. SCP15	Forests and woodlands of deep seasonal wetlands of the Swan Coastal Plain	Swan Coastal Plain
32. SCP07	Herb rich saline shrublands in clay pans	Swan Coastal Plain
33. SCP08	Herb rich shrublands in clay pans	Swan Coastal Plain
34. SCP09	Dense shrublands on clay flats	Swan Coastal Plain
35. SCP10a	Shrublands on dry clay flats	Swan Coastal Plain
38. Morilla swamp	Perched fresh-water wetlands of the northern Wheatbelt dominated by extensive stands of living *Eucalyptus camaldulensis* (River Red Gum) across the lake floor.	Avon Wheatbelt
40. Bryde	Unwooded freshwater wetlands of the southern Wheatbelt of Western Australia, dominated by *Muehlenbeckia horrida* subsp. *abdita* and *Tecticornia verrucosa* across the lake floor	Avon Wheatbelt
42. Greenough River Flats	*Acacia rostellifera* low forest with scattered *Eucalyptus camaldulensis* on Greenough Alluvial Flats.	Geraldton Sandplain
46. Themeda Grasslands	Themeda grasslands on cracking clays (Hamersley Station, Pilbara). Grassland plains dominated by the perennial Themeda (kangaroo grass) and many annual herbs and grasses.	Pilbara

49. Bentonite Lakes	Herbaceous plant assemblages on Bentonite Lakes	Avon Wheatbelt
63. Irwin River Clay Flats	Clay flats assemblages of the Irwin River: Sedgelands and grasslands with patches of *Eucalyptus loxophleba* and scattered *E. camaldulensis* over *Acacia acuminata* and *A. rostellifera* shrubland on brown sand/loam over clay flats of the Irwin River.	Avon Wheatbelt
72. Ferricrete	Ferricrete floristic community (Rocky Springs type)	Geraldton Sandplain
74. Herblands and Bunch Grasslands	Herblands and Bunch Grasslands on gypsum lunette dunes alongside saline playa lakes	Esperance Sandplain
80. Theda Soak	Assemblages of Theda Soak rainforest swamp	North Kimberley
81. Walcott Inlet	Assemblages of Walcott Inlet rainforest swamps	North Kimberley
82. Roe River	Assemblages of Roe River rainforest swamp	North Kimberley
84. Dragon Tree Soak	Assemblages of Dragon Tree Soak organic mound spring	Kimberley Region, Great Sandy Desert Bioregion
85. Bunda Bunda	Assemblages of Bunda Bunda organic mound spring	West Kimberley, Dampierland Bioregion
86. Big Springs	Assemblages of Big Springs organic mound springs	West Kimberley, Dampierland Bioregion
89. North Kimberley mounds	Organic mound spring sedgeland community of the North Kimberley Bioregion	North Kimberley
92. Black Spring	Black Spring organic mound spring community	North Kimberley
95. Mandora Mounds	Assemblages of the organic springs and mound springs of the Mandora Marsh area	West Kimberley, Dampierland and Greats Sandy Desert Bioregions
97. Mound Springs (Three Springs area)	Assemblages of the organic mound springs of the Three Springs area	Avon Wheatbelt

Personal communications

Name	Date	Position	Organisation
Dr Jacqueline Giles	3/05/2009	Wetland Ecologist	Department for Environment and Heritage, South Australia
Adrian Pinder	05/10/2012	Research Scientist	Department of Environment and Conservation

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A guide to managing and restoring wetlands in Western Australia

Wetland vegetation and flora, part 1: Overview

In Chapter 2: **Understanding wetlands**

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Wetland vegetation and flora' topic

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FloraBase images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation (florabase.dec.wa.gov.au/help/copyright).

Recommended reference

When referring to the guide in its entirety, the recommended reference is: Department of Environment and Conservation (2012). *A guide to managing and restoring wetlands in Western Australia*. Department of Environment and Conservation, Perth, Western Australia.

When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Wetland vegetation and flora', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by G Keighery, B Keighery and V Longman, Department of Environment and Conservation, Perth, Western Australia.

Contents

Part 1: Overview – this PDF

Wetland profiles

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. Note that the collection of flora, even for conservation purposes, must be consistent with state laws, and is likely to require a license from DEC. For more guidance, see the topic 'Introduction to the guide'.

Vegetation: the combinations of plant species within a given area, and the nature and extent of each area[1]

Flora: the plant species, subspecies and varieties in a given area[1]

Community: a general term applied to any grouping of populations of different organisms found living together in a particular environment

Introduction to wetland vegetation and flora

Wetland plants are plants that inhabit wetlands. Wetlands are, in summary, areas subject to permanent, seasonal or intermittent inundation or seasonal waterlogging (Figure 1, Figure 2).

Wetland **vegetation** refers more broadly to the *combinations* of wetland plants in a given area, while wetland **flora** refers more specifically to the wetland plant species, subspecies and varieties in a given area.

Vegetated wetland ecosystems are characteristic of Western Australia. This is despite the perceived and actual dryness of most of the state, of which more than 40 per cent is desert receiving less than 250 millimetres of annual rainfall. WA's environment supports a diverse range of wetland plants and plant **communities**. The reasons for this include the diverse ancient flora (a product of old landscapes and diverse geologies and soils) and the huge diversity among wetlands across the state.

Figure 1. Wetland plants in two contrasting wetlands on the Swan Coastal Plain.

(a) A claypan in the inundated phase with emergent *Melaleuca rhaphiophylla* trees and aquatics. Photo – G Keighery/DEC.

(b) A seasonally waterlogged wetland with *Melaleuca preissiana* tree. Photo – B Keighery/OEPA.

Figure 2. The highly diverse saline and freshwater wetlands and wetland plant communities of Leeman Lagoons, east of Leeman (Geraldton Sandplain). This complex of mostly saline wetlands supports *Casuarina obesa* forest, *Melaleuca cuticularis* forest and samphire shrublands. Freshwater seepages form patches of freshwater wetlands within the complex. Photo – B Keighery/OEPA.

What is covered in this topic?

This topic describes the nature, characteristics and distribution of **vascular** vegetation and flora of WA's natural, non-flowing wetlands.

There are five parts to this topic. The first part introduces wetland vegetation and flora in a Western Australian context; and broadly describes the characteristics of WA's wetland vegetation and flora respectively (part 1). The second, third and fourth parts describe in detail the wetland vegetation and flora features of three zones: the Kimberley (part 2), the Deserts (part 3) and the Southwest (part 4). The fifth part of this topic provides more detailed information on the wetland vegetation and flora of the southern Swan Coastal Plain (part 5).

More than 500 wetland native vascular plant **taxa** are referred to in this topic. All 500 taxa are listed in Appendix 1 (in part 1) along with their family, common name, state and federal conservation ranking and which wetland zone (Kimberley/Desert/Southwest) they are discussed in within this topic (some taxa are found in more than one zone). Only widely used common names are used in the text for this topic.

This topic also includes photographs of more than 200 wetland taxa. Appendix 1 can be used to look up the figure numbers for the relevant photos for each taxon.

Wetland vegetation is highly variable, both within and between wetlands, and WA is a very large place, so while this topic can serve as a guide, any wetland-specific management should be supported by specific information on the wetland's vegetation and flora.[2] In most cases this will require a survey to be done, once informed by existing information on similar wetlands. Keighery[3], together with Lyons et al.[4], are useful guides to conducting a quadrat-based vegetation and flora survey of a wetland.

Vascular plants: plants with defined tubular transport systems. Non-vascular plants include algae, liverworts and mosses.

Taxa: a taxonomic group (the singular being taxon). Depending on the context, this may be a species or their subdivisions (subspecies, varieties etc), genus or higher group.[1]

What is not covered in this topic?

Non-vascular flora including algae, mosses and liverworts are not covered in this topic, nor are cyanobacteria, fungi and freshwater sponges. Similarly, the ecological roles, adaptations and ecological water requirements of vascular wetland plants are not covered in this topic.

The guide does not cover marine and coastal zone wetlands (marine waters, coral reefs, estuarine, intertidal mud or sand flats, intertidal marshes and forests), human made wetlands (dams, ponds, waste-water treatment plants, canals, irrigated land) and channel wetlands such as rivers and streams. However, in many locations estuarine and riverine vegetation merges with other wetland systems and these are considered here. Some of the characteristics and management considerations outlined in this topic may also be common to these systems.

- ➤ For information on cyanobacteria, freshwater sponges and algae; and on the ecological roles, adaptations and ecological water requirements of wetland plants, see the topic 'Wetland ecology' in Chapter 2.
- ➤ See the topic 'Wetland weeds' in Chapter 3 for details on weeds and their control.
- ➤ For information on waterway vegetation, see the Department of Water's website, which provides resources such as the *River restoration manual: a guide to the nature, protection, rehabilitation and long-term management of waterways in Western Australia*.[5]

What is the current knowledge of WA's wetland vegetation and flora?

To date, no comprehensive state, regional or sub-regional review of wetland vegetation and flora in WA has been published. This first review of the state's wetland vegetation and flora has been compiled by reviewing published and unpublished literature and using this, together with more than forty years of field experience working on the vegetation and flora of WA. The literature reviewed includes regional floras and reports on individual wetlands and wetland groups. Only those sources from which information is directly cited are referenced. A large number of other sources have been perused but, as much of this information is of a general nature, these are not given. Examples of these sources include Halse et al.[6], Ground Water Consulting Services Pty. Ltd.[7] and Henry-Hall et al.[8]

No comprehensive list of WA's wetland flora currently exists. WA has a huge diversity of wetland plants and plant communities, and many of these require better documentation of their flora and vegetation. It is estimated that more than twenty per cent (3,000 taxa) of the currently known 12,500 flora for WA are wetland taxa, compared to the 2,000 estimated in 2001.[9] From the work done on wetlands on the Swan Coastal Plain over the past twenty years, it is certain that a large number of plants and plant communities are yet to be located and described from WA's saline and freshwater wetlands. An unusual wetland at Point Ann in Fitzgerald River National Park (Figure 3), first noted in 2010, well illustrates this.

Figure 3. A hillside wetland community in Fitzgerald River National Park (Esperance Sandplains) at Point Ann, dominated by wind-shaped prostrate *Melaleuca cuticularis*. It is unusual, being a coastal saline paluslope. Photos – B Keighery/OEPA.

(a) View of headland and community. (b) and (c) *Melaleuca cuticularis* fruit and plant.

As with dryland flora, the scientific documentation and study of wetland flora across the state's 2.5 million square kilometres continues. With WA recognised as possessing one of the most diverse and unique floras in the world, this is not a simple task. In particular, the isolated south-western corner of WA, with its Mediterranean climate, is considered among the world's thirty-four plant biodiversity hot spots.[10] Remote areas also present many new discoveries as well as challenges for researchers. There has been a steady growth in the scientific discovery of new vascular (i.e. families other than those of the algae, liverworts, mosses etc) plant taxa over the last century; from 4,166 recorded in 1912, to 5,802 in 1969, and in 2011, an amazing 11,034 – of which more than 60 per cent of the species are **endemic** to WA, indicating the unique nature of WA's flora.[11]

Endemic: naturally occurring only in a restricted geographic area

➤ For more information on flora research, see the web page of the WA Herbarium.[12]

Statistics

- It is estimated that wetland taxa form more than 20 per cent, or 3,000 of WA's approximate 12,500 flora.
- Forty-six of the 402[13] declared rare flora in WA occur in wetlands.
- More than 270 of the 2,704[13] priority species in WA occur in wetlands.
- Thirty-seven of WA's sixty-nine[14] threatened ecological communities (TECs) are wetland communities; of these thirty-three are defined or reliant on vascular plant taxa (see Table 2 for more information).

How is wetland vegetation and flora identified?

Wetland plants can be discussed in terms of whether or not they are aquatic. Aquatic plants tend to be widely recognised as wetland plants, while non-aquatic wetland plants, because they do not grow in inundated areas, tend to be less well recognised.

While there is no comprehensive list of all of WA's aquatic plant species, there is general agreement as to what constitutes an **aquatic plant**, being a plant that grows for some period of time in inundated conditions and is dependent on a given inundation regime to grow and flower (including species that flower in waterlogged soils following inundation) (Figure 4 and Figure 5). Wetlands that are inundated for a period of time—whether permanently, seasonally or intermittently—provide suitable habitat for aquatic plants. All aquatic wetland plants are considered to be wetland **obligate**, that is, they are generally restricted to wetlands under natural conditions in a particular setting. Common descriptions of aquatic plants include 'submerged', 'floating' and 'emergent'; these terms refer to the position of the plant relative to the water's surface. 'Macrophyte' is another common term, referring to aquatic vascular plants as distinct from other aquatic organisms including algae, cyanobacteria, mosses, liverworts and fungi.

Figure 4. Claypan (sumpland) in the Tuart Forest on the Swan Coastal Plain with fringing *Melaleuca rhaphiophylla* trees. Photos – B Keighery/OEPA.

(a) Filled with rainwater in winter (growing in the water are the grass *Amphibromus nervosus* and the sedge *Eleocharis keigheryi*).

(b) Summer view of dry claypan and exposed clay base that forms the water impeding layer.

Figure 5. Aquatic taxa in a Swan Coastal Plain claypan. Aquatic taxa form 61 per cent of the southern Swan Coastal Plain's wetland flora.

(a) Inundated claypan emergent *Melaleuca rhaphiophylla* trees. Photo – G Keighery/DEC.

(b) *Aponogeton hexatepalus* flowers. Photo – B Keighery/OEPA.

(c) *Aponogeton hexatepalus* (long leaves) and **Hydrocotyle lemnoides** (kidney-shaped leaves). Photo – G Keighery/DEC.

Wetland plants that are not aquatic are sometimes mistakenly identified as dryland plants. Non-aquatic wetland plants grow in wetland areas that are seasonally waterlogged rather than inundated. These areas may be on the outer edges of, or higher areas within, a wetland that holds surface water permanently, seasonally or intermittently. Alternatively, the waterlogged area may be a stand-alone wetland, one that is entirely waterlogged on a seasonal basis, such as a dampland or palusplain. Many of WA's non-aquatic wetland plants are wetland obligate, that is, only found in wetlands in a given setting. However, some non-aquatic wetland plants are considered to be **facultative**, that is, they occur in both wetlands and dryland under natural conditions in a given setting.

Again, there is no comprehensive list of WA's non-aquatic wetland plants. However, this topic does refer to more than 500 wetland native vascular plant taxa (aquatic and non-aquatic), and these are listed in Appendix 1 for ease of reference. The wetland species described in this topic have been identified using a combination of field observations, *FloraBase*[11] and an ongoing literature review as primary sources. While *FloraBase* is a useful guide to what flora may be associated with wetlands, it is not designed to be used to establish conclusively if a species is a wetland species.

Field botanists develop a working set of wetland plants from field observations of plants that regularly occur together in vegetation in wetlands. This requires good field knowledge of the vegetation and flora of a zone/region/area and a sound understanding of what constitutes a wetland, if need be with reference to wetland mapping, wetland scientists or other diagnostic tools such as soils and hydrology. A series of characteristics of wetlands in WA contribute to numerous complexities in this determination:

- gradational boundaries from inundated areas, through waterlogged soils to dry soils (where soils are only wet immediately following rainfall) (Figure 6)
- inundation/waterlogging/wetting caused by groundwater, surface water and combinations of these (Figure 7)
- wetlands that exist due to the seasonal waterlogging of soils, that is, rarely, if at all, associated with inundation (Figure 8)
- seasonal or intermittent nature of soil inundation/waterlogging/wetting (Figure 4)
- persistence of wetland plant species that were established in wetter conditions which no longer appear to prevail.

These complexities are to be expected in a dynamic natural system, especially one such as WA's with a very old flora that has been subject to a changing climate, the current patterns of seasonal and intermittent rainfall and increasingly rapid climate change.

Because of these complexities, the expertise of suitably qualified and experienced field botanists is usually required to identify the wetland and dryland vegetation and flora of a site definitively (for example, for land planning or other legal matters). Similarly, defining wetland boundaries requires expertise, with wetland scientists typically working in liaison with field botanists to establish wetland boundaries, taking into account the hydrological and soil characteristics of the site.

➤ For more information on the delineation of wetland boundaries, see the wetlands webpage on DEC's website.[15]

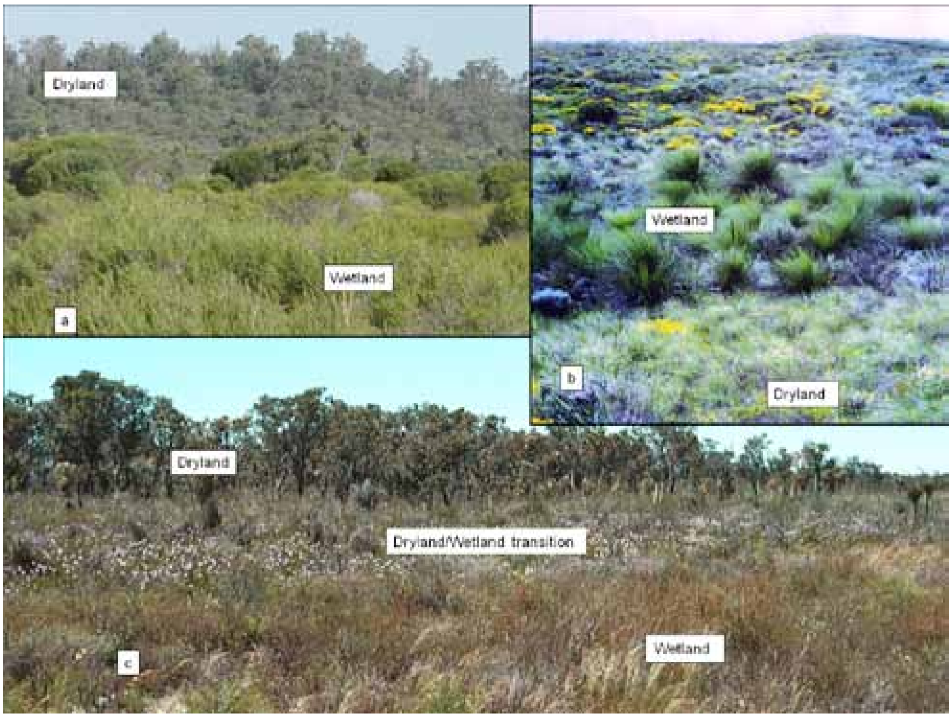


Figure 6. Three fully vegetated wetlands of the Swan Coastal Plain with a variety of wetland habitats and wetland/dryland boundaries.

(a) Defined boundary at Hay Swamp in Bunbury dominated by *Melaleuca* trees (mid-ground, palusplain) and shrubs (foreground) and tuart (*Eucalyptus gomphocephala*) and *Banksia* woodland (background) on dryland. The *Melaleuca* shrubland (foreground) is the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain'. Photo – B Keighery/OEPA.

(b) Defined boundary at the TEC 'Sedgelands in Holocene dune swales of the southern Swan Coastal Plain' in the Point Becher wetlands dominated by *Xanthorrhoea preissii*. Photo – G Keighery/DEC.

(c) Gradational boundary and a portion of the Cannington or Kenwick Swamp (palusplain) in the Greater Brixton Street wetlands. The wetland in the foreground is dominated by shrubs, herbs and sedges (the grass seen in this area is only dominant after fire), and merges through a shrub-dominated band to *Banksia* woodland on dryland. The shrub-dominated band contains wetland and dryland species. The foreground wetland community is the TEC 'Shrublands on dry clay flats'. Photo – G Keighery/DEC.

Figure 7. Two Swan Coastal Plain sumplands fed by water from different sources.

(a) Lake Mount Brown just south of Perth is a groundwater-fed wetland. Photo – K Clarke/ Western Australian Local Government Association.

(b) A claypan filled with rainwater (a perched wetland) in the Tuart Forest just north of Busselton. Photo – B Keighery/OEPA.

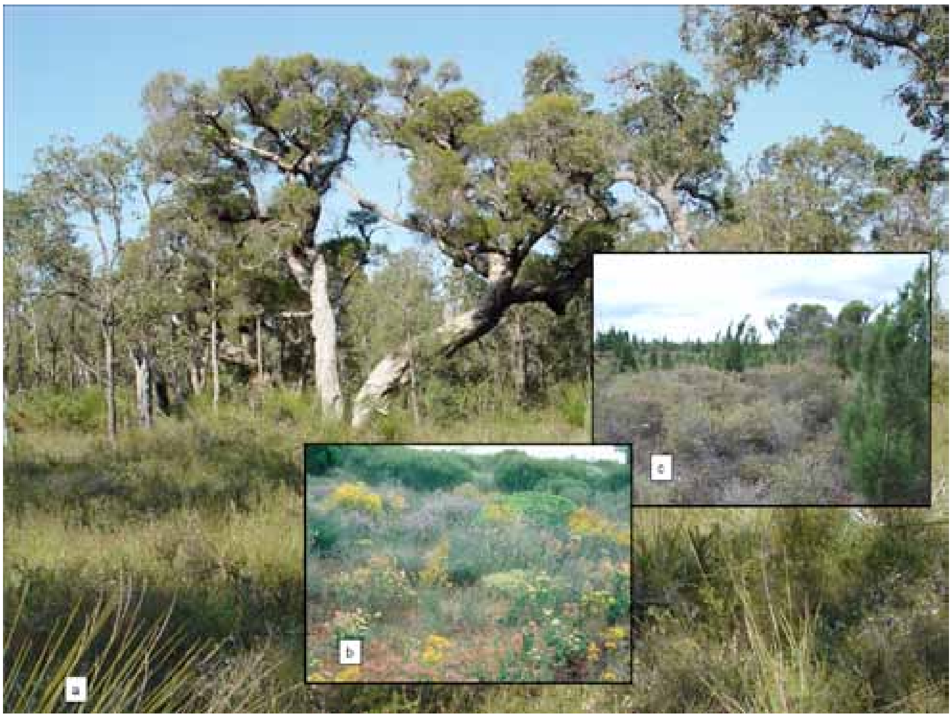


Figure 8. Vegetation of three Swan Coastal Plain seasonally waterlogged wetlands.

(a) *Melaleuca preissiana* woodland. Photo – B Keighery/OEPA.

(b) Shrubland dominated by *Verticordia* species including *V. plumosa* var. *pleiobotrya* (pink), *V. chrysantha* (yellow) and *V. huegelii* (white). Photo – G Keighery/DEC.

(c) Shrublands dominated by *Actinostrobus pyramidalis* and *Melaleuca scabra*. Photo – B Keighery/OEPA.

Botanists and wetland scientists also use field observations to identify wetland flora as either obligate (restricted to wetlands) or facultative species (found in wetlands and drylands) within a particular setting. The setting is an important factor. A species may grow in wetlands in one region/area and in drylands in another (Figure 9). At other times, what appears to be a single species is capable of growing in both drylands and wetlands in the same region (for example *Xanthorrhoea preissii* and tuart in Figure 10 and Figure 11 respectively). Many of these taxa do have distinctive wetland and dryland **ecotypes** and a number of these ecotypes are proving to be valid taxa (Figure 12 and Figure 13).

Ecotypes: a genetically distinct geographic variety, population or race within a species which is adapted to specific environmental conditions. Typically ecotypes exhibit differences in morphology or physiology stemming from this adaptation, but are still capable of breeding with adjacent ecotypes without loss of fertility or vigour.

Figure 9. The shrub *Hypocalymma angustifolium* is found in a variety of habitats including wetlands at the west of its range (Swan Coastal Plain) and drylands in the eastern part of its range (Jarrah Forest). Photos – B Keighery/OEPA.

(a) *Hypocalymma angustifolium* in a seasonally waterlogged wetland on the Swan Coastal Plain.

(b) *Hypocalymma angustifolium* flowers.

Figure 10. *Xanthorrhoea preissii* may be a wetland or dryland species (Swan Coastal Plain).

(a) *X. preissii* dominates some occurrences of the TEC 'Sedgelands in Holocene dune swales of the southern Swan Coastal Plain'. Photo – G Keighery/DEC.

(b) *X. preissii* shrubs from the wetland. Photo – B Keighery/OEPA.

Figure 11. Tuart (*Eucalyptus gomphocephala*) may be a wetland or dryland species (Swan Coastal Plain). Photos – B Keighery/OEPA.

(a) Tuart in the wetlands beside the Moore River; *Melaleuca rhaphiophylla* forest fringes the river.

(b) Tuart in the freshwater seepages around Lake Walyungup (this is likely to be the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain').

Figure 12. Members of the family Myrtaceae, such as *Melaleuca* and many other genera, are common in wetlands. A shrub of a restricted taxon from the Busselton Ironstones is illustrated here. *Calothamnus quadrifidus* shows a great deal of variation across its range; *Calothamnus quadrifidus* subsp. *teretifolius* is a newly described wetland subspecies. Photos – B Keighery/ OEPA.

(a) *Calothamnus quadrifidus* subsp. *teretifolius* shrub.

(b) Flowers.

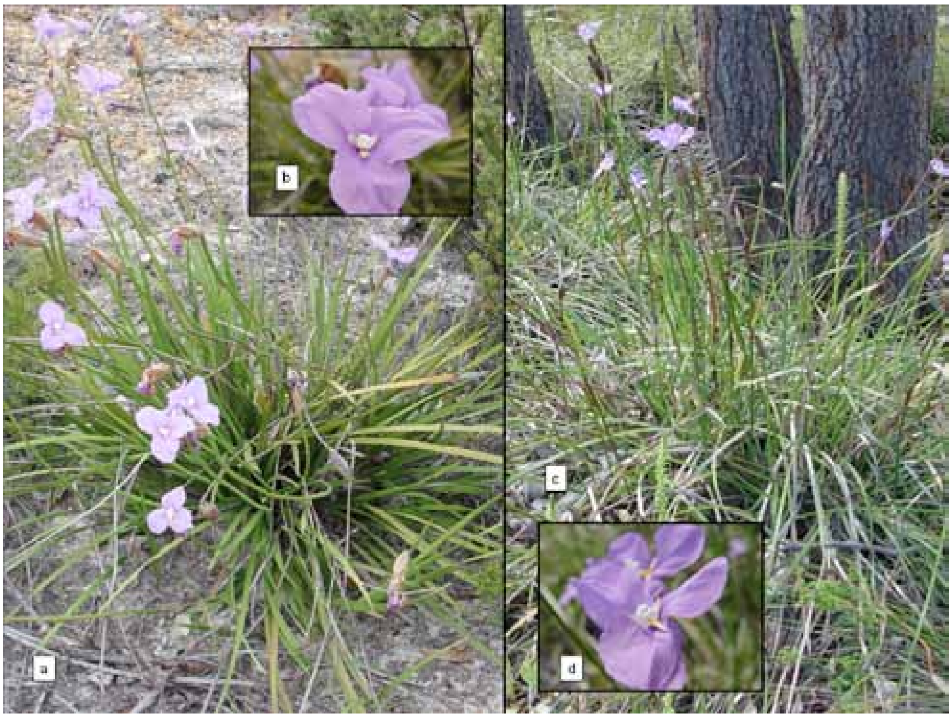


Figure 13. Dryland and wetland varieties of *Patersonia occidentalis* in the Southwest. These two photos were taken in two habitats in the same bushland patch, north-east of Perth on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) Plant and (b) flower of *P. occidentalis* var. *occidentalis* with short thick leaves and scapes in dryland.

(c) Plant and (d) flower of *P. occidentalis* var. *angustifolia*, with longer thinner leaves and scapes in wetland.

As would be expected, water plays an important role in determining the presence/absence of species in wetlands, and the study of wetland **water regimes** and the ecological water requirements of plants helps to explain wetland plant patterning, and informs the management of vegetation in areas subject to drying or wetting that is outside of natural water regimes.

Water regime: the pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, duration, frequency, extent and depth, and variability of water presence.

➤ For more information on ecological water requirements, refer to the 'Wetland ecology' topic in Chapter 2.

Despite the potential complexity surrounding the identification of non-aquatic wetland species, wetland managers can develop a sound understanding of the wetland vegetation and flora of a site with the help of good resources (such as those listed in the following section) and the invaluable understanding that comes with closely observing the nature of a wetland over many seasons.

Sources of information on wetland vegetation and flora

When using the below databases and literature to research wetland flora, it is important to be mindful that numerous terms are used to refer to wetlands, including moist places, damp areas, swamps, winter-wet swamps, moist swales and semi-permanent lakes.

Databases

FloraBase is a website of the Western Australian Herbarium available at florabase.dec.wa.gov.au.[11] It delivers the latest authoritative information about the Western Australian flora in an accessible and interactive manner, allowing users to browse or search for information on vascular flora, including descriptions, conservation status, photos, distribution maps and, in the case of weeds, control methods. A partner database is *Australia's Virtual Herbarium*, available at www.chah.gov.au/avh/.

NatureMap is a collaborative website of DEC and the Western Australian Museum, available at naturemap.dec.wa.gov.au. It presents the most comprehensive and authoritative source of information on the distribution of Western Australia's flora and fauna. *NatureMap* is an interactive tool designed to provide users with comprehensive and up-to-date information on plants, animals, fungi and other groups of biodiversity. It can be used to produce maps, lists and reports of WA's flora and fauna diversity.

WetlandBase is an interactive database produced by DEC, with web hosting by the Department of Agriculture and Food WA, available at spatial.agric.wa.gov.au/wetlands. *WetlandBase* provides a comprehensive online resource of information and data about Western Australian wetlands. It provides spatial data, such as wetland mapping, and point data, such as water chemistry, waterbirds, aquatic invertebrates and vegetation sampling results.

Some useful literature on wetland vegetation and flora

WA has such a diverse flora that there are no guides to the entire flora of the state. Some useful references are listed below; those listed can be used to find illustrations of wetland vegetation and flora. Those out of print are denoted by an asterisk (*), but they are available in libraries.

General

Vegetation

- * *Plant life of Western Australia*[16]
- * *A directory of important wetlands in Australia*, Third Edition[17]
- * JS Beard's *Vegetation Survey of Western Australia* series, containing maps and explanatory notes (published in the 1970s and 1980s by Vegmap Publications, Sydney)

Flora

- * *The Western Australian flora – A descriptive catalogue*[18]
- Australian rushes: biology, identification and conservation of Restionaceae and allied families[19]
- *Waterplants of Australia*[20]
- *Western Australia's threatened flora*[21]
- *Aquatic and wetland plants: a field guide for non-tropical Australia*[22]
- *Samphires in Western Australia: A field guide to* Chenopodiaceae *tribe* Salicornieae[23]

Kimberley

- *Flora of the Kimberley Region*[24]
- *Floodplain flora*[25]

Deserts

- *A guide to plants of inland Australia*[26,25]
- * *Flora of central Australia*[27]

Southwest

- * *Flora of the Perth Region*, Parts One and Two[28,29]
- *Flora of the south west: Bunbury–Augusta–Denmark*, Volumes 1 and 2[30,31]
- *Field guide to wildflowers of Australia's south west: Augusta–Margaret River Region*[32]

Reports on vegetation and flora of specific areas

These are just some examples of the region-specific vegetation and flora reports available:

- *Albany regional vegetation survey: extent, type and status*[33]
- *Flora and vegetation of the Byenup–Muir reserve system, south-west Western Australia*[34]
- *Flora and vegetation of Watheroo bentonite lakes*[35]
- *A vegetation survey of Yenyening Lakes Nature Reserve and adjoining vegetation: shires of Beverley, Brookton and Quairading for the Yenyening Lakes Management Committee*[36]
- *The remnant vegetation of the eastern side of the Swan Coastal Plain*[37]
- *A floristic survey of the southern Swan Coastal Plain*[38]
- *Bush Forever Volume 2: Directory of Bush Forever sites*[39]

Herbaria

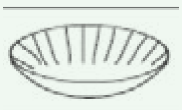
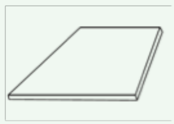
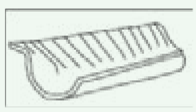
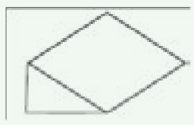
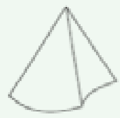
The WA Herbarium provides a public reference herbarium, a public access collection of typical specimens of all known plant species in the state. It is used widely by consultants, researchers and the public to help identify wildflowers and other plants. The WA Herbarium and associated regional herbaria can help community, industry and researchers understand and identify plants, algae and fungi. Information on services, fees and specimen collection requirements are available from the herbarium's webpage on DEC's website.[12]

Some notes on terminology used in this topic

Wetland descriptions

There are many terms used to describe groups of wetlands with similar characteristics. For example, descriptions may focus on the sediment (such as 'peatland'), the chemistry (such as 'salt lake') or the vegetation (such as 'Yate swamp'). Some terms, such as marsh and swamp, can have different meanings to different people, while some terms such as 'lake' seem to be applied to just about any wetland. WA has adopted the geomorphic classification system (Semeniuk[40] and Semeniuk and Semeniuk[41]) for use when mapping wetlands. This system groups inland (non-marine) wetlands into one of thirteen wetlands types, on the basis of their landform and hydroperiod, as shown in Table 1.

Table 1. Wetland types according to the global geomorphic classification system, adapted from Semeniuk[40] and Semeniuk and Semeniuk[41]

Water periodicity	**Landform**				
	 **Basin**	 **Flat**	 **Channel**	 **Slope**	 **Highland**
Permanently inundated	Lake	-	River	-	-
Seasonally inundated	Sumpland	Floodplain	Creek	-	-
Intermittently inundated	Playa	Barlkarra	Wadi	-	-
Seasonally waterlogged	Dampland	Palusplain	Trough	Paluslope	Palusmont

This topic does make reference to these wetland types where possible, but most of the time a much wider variety of names for wetlands is used, because the numerous studies used to compile this topic use a wide variety of descriptions for the wetlands.

Flora: names and groups

This topic employs terminology used by botanists and ecologists to describe flora. In particular, it refers to plants by their scientific names, and it compares broad trends of wetland plants of each region of WA, according to whether they are ferns and fern allies, gymnosperms, monocotyledons or dicotyledons. This terminology is briefly described below.

Plant names

Scientific (or botanical) names are used in this topic. For example *Calothamnus quadrifidus* is the scientific name of the most common one-sided bottlebrush found in the Southwest (Figure 12). Scientific names are established in accordance with the International Code of Botanical Nomenclature, and identify a plant's family; for example in the case of *Calothamnus quadrifidus* it is in the family Myrtaceae, the genus *Calothamnus* and the species *Calothamnus quadrifidus* (here you need both names).

Plants within a family share features; for example the Myrtaceae, or the myrtle family, has about 5,500 species, all with a set of common features including oil-glands in their leaves.[42] It is standard for botanical family names to end in '-aceae'. Within each family are one or more genera (or singularly 'genus') which share additional features in common, for example within the Myrtaceae family, is the *Calothamnus*, or one-sided bottlebrush genus, within which there are about forty-one species and all of these are only found in WA. Within each genus is one or more species. Although there are complexities as to what defines a species, it is commonly defined as a group of organisms capable of interbreeding and producing fertile offspring. In accordance with the International Code of Botanical Nomenclature, scientific names of plants are latinised (written in the language of Latin as a universal standard) and italicised (although in formats such as tables this may not always be observed, for example, Appendices 1 and 2).

At times species are divided into named subspecies (subsp.) and varieties (var.). For example the Ironstone Calothamnus (Figure 12) is a subspecies of *Calothamnus quadrifidus*: *Calothamnus quadrifidus* subsp. *teretifolius* (here you need all three names). If a new species, subspecies or variety is recognised, it is initially designated by a phrase name until formally named, for example, *Calothamnus* sp. Whicher, and the particular specimen to which it is referenced is stated in brackets, for example, *Calothamnus* sp. Whicher (B.J. Keighery and N. Gibson 230). Species can also be divided into unnamed categories, generally called 'forms'. For example *Kunzea recurva* has two colour forms as shown in Figure 27.

Plant groups

Vascular plant families are grouped into two broad groups: plants that flower, and plants that do not flower. These groups and their subdivisions are used in this topic. Appendix 1 lists the group in which each taxon belongs. Information on the characteristics of each plant group is outlined below.

Vascular plants without flowers

Plants that do not flower are divided into two groups: ferns and fern allies, and gymnosperms.

Ferns and fern allies

These are plants with stems, leaves and roots like other vascular plants, but which reproduce via spores instead of seeds or flowers, such as bracken (*Pteridium esculentum*) and *Azolla pinnata*. Not all ferns have conventional fern fronds. Most ferns occur in freshwater wetlands, in inundated and dampland habitats. With approximately eighty species, WA is relatively poor in ferns. Two major groups are the highly endemic *Isoetes* species (Figure 14) which are submerged aquatics, and two species of floating aquatic fern, *Azolla* (Figure 15). *Azolla* looks like a fern frond floating on the water and may form a pink or green scum. It is reliant on nutrients in the water column and, to supplement its nutrition, *Azolla* supports a cyanobacterium called *Anabaena azollae* in the fronds of the plant. This bacterium is able to fix nitrogen from the atmosphere but, unlike other cyanobacteria, it is not toxic.

The closely related taxonomic group the fern allies is represented by *Marsilea* (Nardoo, Figure 16) and *Pilularia* (Figure 17). *Marsilea* grows in waterlogged and shallowly inundated habitats in a similar manner to water lilies and *Aponogeton*. The sporocarps (clusters of spores) of this plant are an Aboriginal food source.

Figure 14. *Isoetes drummondii*. Photo – B Keighery/OEPA.

Figure 15. *Azolla filiculoides.* (a) and (b) close up in red and green varieties; (c) at a Kemerton wetland. Photos – C Prideaux/DEC.

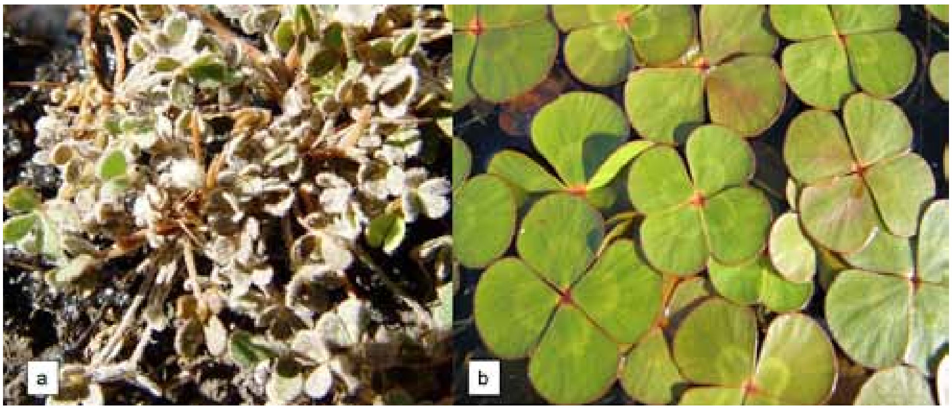


Figure 16. *Marsilea*. (a) plant. Photo – B Keighery/OEPA and (b) leaves. Photo – A Matheson/DEC.

Figure 17. *Pilularia novae-hollandiae*. Photo – B Keighery/OEPA.

Gymnosperms

These are plants with unprotected seeds, often in cones, and include the conifers and cycads. The conifers *Actinostrobus pyramidalis* (Figure 8c and Figure 166 in part 5) and *Callitris canescens* (Figure 95 in part 4) grow in wetlands. Cycads are not typically associated with wetlands. An example of a cycad is *Macrozamia riedlei* or zamia palm. There are relatively few wetland gymnosperms in WA.

Vascular plants with flowers (angiosperms)

Angiosperms are divided into two groups: monocotyledons and dicotyledons.

Monocotyledons (monocots)

These are flowering plants that typically have seedlings with one cotyledon (seed-leaf) and a fibrous root system. They do not form wood and have strappy leaves with parallel veins. These include some herbs and all grasses and sedges. All of these, except the palms, *Xanthorrhea* and *Kingia* species, are placed in the non-woody layers when describing vegetation (see below). As palms (Figure 18b) and *Xanthorrheas* (Figure 18f) have trunks they are grouped with trees or shrubs, depending upon their height.

Dicotyledons (dicots)

These flowering plants typically have seedlings with two cotyledons (seed leaves), a tap root system, and they can form wood and have network leaf venation. These include a range of herbs, shrubs and trees.

Vegetation: describing plant communities

Vegetation units (plant communities) are described according to three features of the plant community:

- plant growth form
- density of cover and height of the layers in each of these groups
- names of the species that dominate each layer.

Plant growth form

A set of terms are used to describe the plant growth forms. Firstly, plants are identified as either woody or non-woody plants. They are then divided into trees, mallees, shrubs, herbs, grasses and sedges as outlined below. The key in Appendix 2 describes these categories in further detail. The growth form of many wetland taxa of the Swan Coastal Plain is listed in Appendix 2 (in part 1).

Woody plants

Woody plants are plants with special thick-walled cells in their trunks and stems that form wood to support the plant. Most dicots are woody plants. A few monocots are considered trees and/or shrubs as outlined above. Plant growth forms of woody plants are trees, mallees and shrubs, outlined below.

- Trees: plants with a single trunk and a canopy. The canopy is less than or equal to two-thirds of the height of the trunk. No lignotuber is evident.
- Mallees: plants with many trunks (usually two to five) arising from a lignotuber. The canopy is usually well above the base of the plant. Most are from the genus *Eucalyptus*.
- Shrubs: plants with one or more woody stems and foliage all or part of the total height of the plant.

Non-woody plants

Non-woody plants are plants with no (or insufficient) special thick-walled support cells in their stems to form wood for support. These are sub-divided according to growth form, pollination method and plant family.

Non grass-like plants

These are generally not pollinated by wind. These can be monocots or dicots.

- Herbs: plants with non-woody stems that are not grasses or sedges. Generally under half a metre tall. Most monocots are herbs except for the larger ones which are classed as shrubs such as palms, grass trees (*Xanthorrhoea* and *Kingia* species) and cycads (*Zamia* species).

Grass-like plants

These plants are generally pollinated by wind and from the families Poaceae, Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae and Xyridaceae.

- Grass: tufted or spreading plant from the family Poaceae. The leaf sheath is always split, a ligule is present, the leaf is usually flat, a stem cross-section circular and all internodes evenly spaced. Some grasses are called reeds (the *Phragmites* and *Arundo* genera).
- Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath is generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some of the families in this group have widely used common names. For example, the Restionaceae are called rushes or jointed sedges; the Juncaceae are also called rushes and the Typhaceae are called bullrushes.

Vegetation layers

Vegetation is described as a set of layers with reference to the canopy cover (leaf area) and height of each layer. This topic uses a set of general terms to describe the various vegetation layers as descriptors of the general vegetation structure. For trees, reference is made to two cover classes: 'forest' has cover greater than or equal to 70 per cent, while 'woodland' has cover of 2–70 per cent.

For all other layers a single term is used:

- shrubland
- herbland
- grassland
- sedgeland.

Figure 18 shows examples of each vegetation layer. All of these layers may be present in a plant community. At times reference is made to the density of these layers using terms such as 'open' (plants not touching) and 'closed' (plants touching).

Within the literature reviewed for this topic, many different terms were used to describe the various layers. There were no consistently used terms, hence the use of the generalised terms described above. In a few instances the vegetation descriptions from a particular reference are directly quoted and specific terms are used for the vegetation units and their layers. In such examples the reference should be consulted to determine how these terms are applied. The Yalgorup wetlands example provided at the end of this topic (see 'Profile of a wetland complex: Yalgorup National Park wetlands' on page 179 in part 5) illustrates the use of a set of standard vegetation or plant community descriptions with a key (after Keighery[3]) showing how these are derived. When specific referenced terms are used for the vegetation layers, the name for a layer is capitalised, for example 'Forest' rather than 'forest'.

Figure 18. (below) Examples of the vegetation layers referred to in this topic. Photos – (a), (e), (h)–(n), (p), (r)–(v) B Keighery/OEPA; (b), (d), (f), (g), (o), (q) G Keighery/DEC; (c) M Lyons/DEC. Note: each of these photos is presented elsewhere in this topic, with full captions provided.

(a) forest

(b) forest

(c) woodland

(d) woodland (foreground), forest (background)

(e) shrubland

(f) shrubland

(g) shrubland

(h) shrubland

Figure 18. (continued)

(i) herblands (foreground)

(j) herbland

(k) herbland

(l) herbland

(m) grassland (foreground)

(n) grassland

(o) grassland

(p) sedgeland (foreground), grassland (mid-ground)

Figure 18. (continued)

(q) sedgeland

(r) woodland over sedgeland and grassland

(s) sedgeland, forest in background

(t) sedgeland (of annual species)

(u) sedgeland under forest

(v) sedgeland under shrubland

Bioregions

This topic refers to the regions of WA identified within the Interim Biogeographic Regionalisation for Australia[43] (IBRA). Australia has been grouped into eighty biogeographic regions (or bioregions) on the basis that the ecosystems within them have a high level of similarity. There are twenty-eight bioregions in WA (Figure 19). In this topic, each wetland described includes its bioregion in brackets after the wetland name.

The IBRA bioregions have been used to compare and group the listed nationally important wetlands[17] as well as in the consideration of the 'CAR' (comprehensive, adequate and representative) reserve system and ecosystem health in WA.[44]

FloraBase provides an informative visual guide to the main characteristics of each IBRA region. It is available at florabase.dec.wa.gov.au/help/ibra/. *FloraBase* refers to the distribution of species according to the bioregion codes in Figure 19.

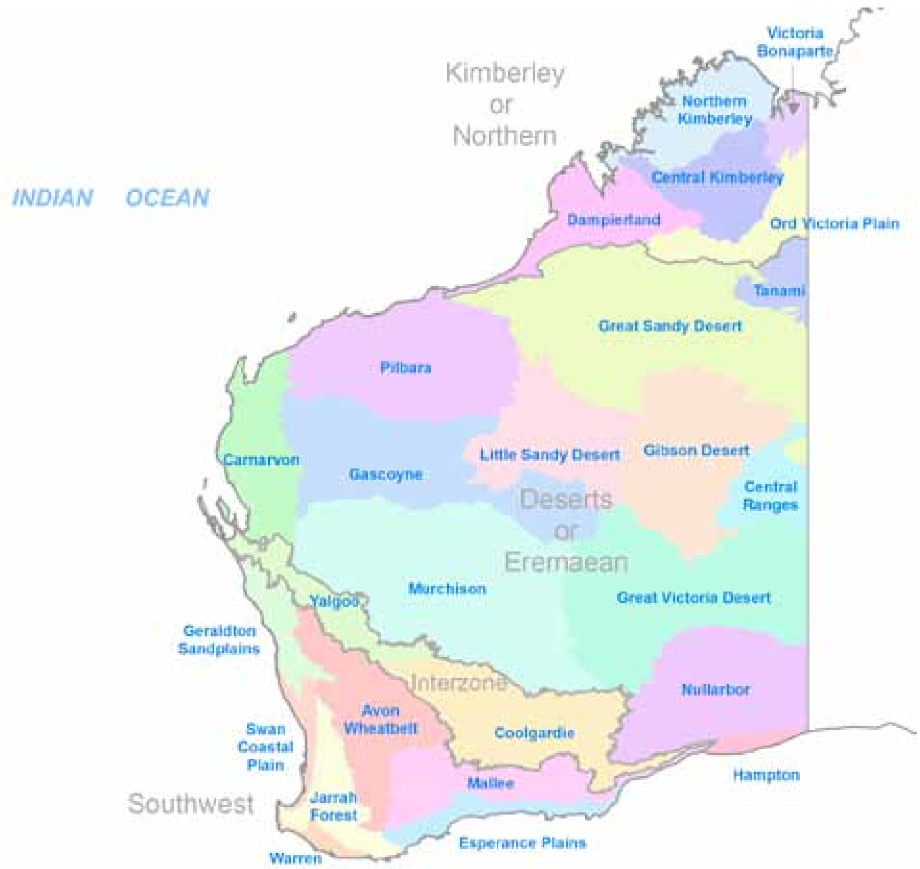


Figure 19. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

Nationally important wetlands (*)

Listed nationally important wetlands are marked with an asterisk (*) in this topic. To be accepted for listing as nationally important, a wetland needs to meet at least one of six criteria agreed to by the ANZECC Wetlands Network in 1994. Despite its size, only 120 of the 904 listed nationally important wetlands are from WA.[46] Of these, nineteen are from the Kimberley, forty-three from the Deserts (twenty from the Internally Drained and twenty-three from the Externally Drained) and fifty-eight from the Southwest. Since the original listings, further study has been undertaken to identify potential nationally important wetlands in under-represented bioregions.[47] Twelve of the sixty-four Australian wetland sites listed as internationally significant under the Ramsar Convention are from WA. It should be noted that a number of the nationally important sites and Ramsar sites contain multiple wetlands.

➤ For more information on nationally and internationally significant wetlands, see:

- DEC's wetlands webpage[15]
- the Australian Government's Department of Sustainability, Environment, Water, Population and Communities website[48]

Western Australia's wetland vegetation

Wetland vegetation in WA has some general characteristics:

- a generally lower species diversity compared to that of the surrounding dryland
- a small number of dominant species, sometimes with high foliar cover (Figure 20 and Figure 21)
- water-side vegetation occurs in a series of bands or zones related to degree of inundation and waterlogging (Figure 21a, Figure 22 and Figure 23)
- completely vegetated wetlands support a mosaic of vegetation units (Figure 24).

The dominant species then vary according to whether the water is saline or fresh. Saline and freshwater wetlands have distinctive floras as seen by comparing photos of saline and freshwater wetlands in this topic. However, in many wetlands and wetland complexes there may be freshwater patches within the predominantly saline area and vice versa.

Figure 20. Two forests and a woodland from a variety of wetlands across WA.
(a) *Melaleuca preissiana* forest (Swan Coastal Plain). Photo – B Keighery/OEPA.
(b) Palm (*Livistona alfredii*) forest (Pilbara). Photo – G Keighery/DEC.
(c) *Eucalyptus victrix* woodland over a herbland on a Desert claypan. Photo – W Thompson.

Figure 21. A variety of wetland plant communities from across WA with a few dominant species with high cover.

(a) *Melaleuca preissiana* forest (background) and *Baumea articulata* (Cyperaceae) sedgeland (Swan Coastal Plain). Photo – B Keighery/OEPA.

(b) *Sorghum plumosum* grassland after the wet (Pilbara). Photo – G Keighery/DEC.

(c) Samphire shrubland (Swan Coastal Plain). Photo – B Keighery/OEPA.

(d) *Stylidium longitubum* herbland (Swan Coastal Plain). Photo – B Keighery/OEPA.

Figure 22. Wetland plant community zonation at a saline lake, Rottnest (Swan Coastal Plain). Three zones are distinguished: the water fringing samphire shrubland (*Tecticornia indica* and *T. halocnemoides*), *Gahnia trifida* sedgeland and *Melaleuca lanceolata* forest. Photo – B Keighery/OEPA.

Figure 23. Wetland plant community zonation in the saline wetlands on the eastern shore of Lake Clifton in the Yalgorup wetlands (Swan Coastal Plain). Three zones are distinguished: the water-fringing *Juncus kraussii* subsp. *australiensis* sedgeland, *Melaleuca cuticularis* forest and tuart (*Eucalyptus gomphocephala*) forest. Photo – B Keighery/OEPA.

Figure 24. A mosaic of plant communities in the Brixton Street Wetlands (Swan Coastal Plain).

(a) A late spring view of the Brixton Street Wetlands including marri (*Corymbia calophylla*) woodland (background), *Viminaria juncea* shrublands, *Melaleuca lateritia* shrubland (circled), *Meeboldina cana* (Restionaceae) sedgelands (pink-brown) and *Amphibromus nervosus* grassland (pale green). Photo – G Keighery/DEC.

(b) *Melaleuca lateritia* shrubland in late spring/early summer. This community is the TEC 'Herb rich shrublands in clay pans'. Photo – B Keighery/OEPA.

Saline wetland vegetation

In this topic, the term 'saline wetland' is used to refer to wetlands that contain enough salt to significantly influence the vegetation composition. Strictly speaking, the term 'non-freshwater' is a more accurate description.

➤ For more information about wetland salinity, see the topic 'Conditions in wetland waters' in Chapter 2.

While the typical non-freshwater wetland is saline due to the presence of salt (mainly sodium chloride), two other chemicals are also naturally relatively common: gypsum (calcium sulphate) and lime (calcium carbonate). Wetlands with these chemicals present, either alone or in combination, support similar vegetation. The typical vegetation of these wetlands is **samphire** shrublands (Figure 21c and Figure 22). These have relatively low cover, being shrublands or open shrublands, and rarely closed shrublands (heaths). Woodlands dominated by species from three genera, sheoaks (*Casuarina*), paperbarks (*Melaleuca*) and eucalypts (*Eucalyptus*), are found on the outer areas of the wetlands and on low rises within the wetlands. **Perennial** sedges can form sedgelands on the margins of permanently inundated saline wetlands (Figure 23).

Generally, large areas of bare soil are associated with these wetlands (Figure 25b). However, when these wetlands are associated with soils with a significant clay component they typically support an annually renewed flora (renewed with wetting), forming areas of sedgeland and herbland (Figure 26). Such wetlands are typically perched and the growing period is extended by the time taken for the soils to dry.

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia*, *Halosarcia*, *Sarcocornia*, *Sclerostegia*, *Tegicornia* and *Pachycornia*, belonging to the family Chenopodiaceae

Perennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) in two or more growing seasons

Figure 25. Saline wetlands. Photos – B Keighery/OEPA.

(a) Rottnest Island salt lake with *Melaleuca lanceolata* and samphire shrublands (Swan Coastal Plain).

(b) Samphire shrublands in salt lake in Charles Darwin Reserve (Yalgoo).

Figure 26. Saline wetland on soils with a high clay fraction (clayflat) near Busselton (Swan Coastal Plain). Photos – B Keighery/OEPA.

(a) *Melaleuca cuticularis* woodland over annual herbland and sedgeland.

(b) *Centrolepis polygyna*, an annual sedge of saline wetlands.

(c) *Angianthus drummondii*, an annual daisy of saline wetlands.

An interesting feature of many of these saline wetlands is areas of seepage of freshwater from the groundwater, forming soaks or springs. These are significant features of these wetlands, providing a specialised habitat for flora and fauna. The soaks or springs, and the flora and fauna they support, are often destroyed either directly by their 'development' as watering points for human activities (livestock watering, agriculture, horticulture), by feral animals, or indirectly by overuse of groundwater.

Freshwater vegetation

Freshwater wetlands generally have a higher diversity of species than those of saline wetlands. All vegetation layers can be found in freshwater wetlands:

- forest and/or woodland, the common trees being eucalypts (*Eucalyptus*) and paperbarks (*Melaleuca*)
- shrubland from many families and genera, especially the Myrtaceae (including a large variety of melaleucas) (Figure 27)
- herbland from many families and genera, including families such as the Droseraceae (Figure 28) and Stylidiaceae (Figure 29)
- sedgeland, typically from the Cyperaceae (Figure 21a) and Restionaceae (Figure 24)
- grassland, the grasses (Poaceae) comprising a variety of genera (Figure 21b and Figure 24).

Some wetlands contain all of these layers, with different layers occurring in a variety of combinations forming a complex mosaic of plant communities within the one wetland (Figure 8b&c and Figure 24).

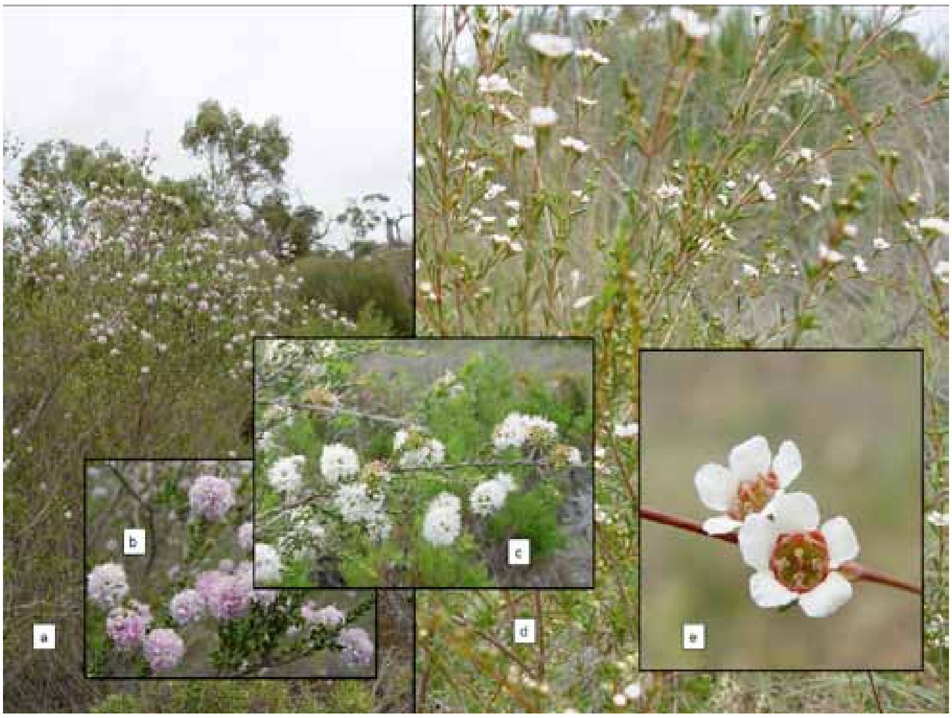


Figure 27. Members of the family Myrtaceae such as *Melaleuca* and many other genera are common in wetlands. Two examples of relatively widespread Southwest shrub taxa are illustrated here. Photos – B Keighery/OEPA.

(a) *Kunzea recurva* shrub, (b) pink-flowered *K. recurva*, and (c) white-flowered *K. recurva*, which has been called *K. limnicola*.

(d) *Astartea affinis* shrub and (e) detail flowers.

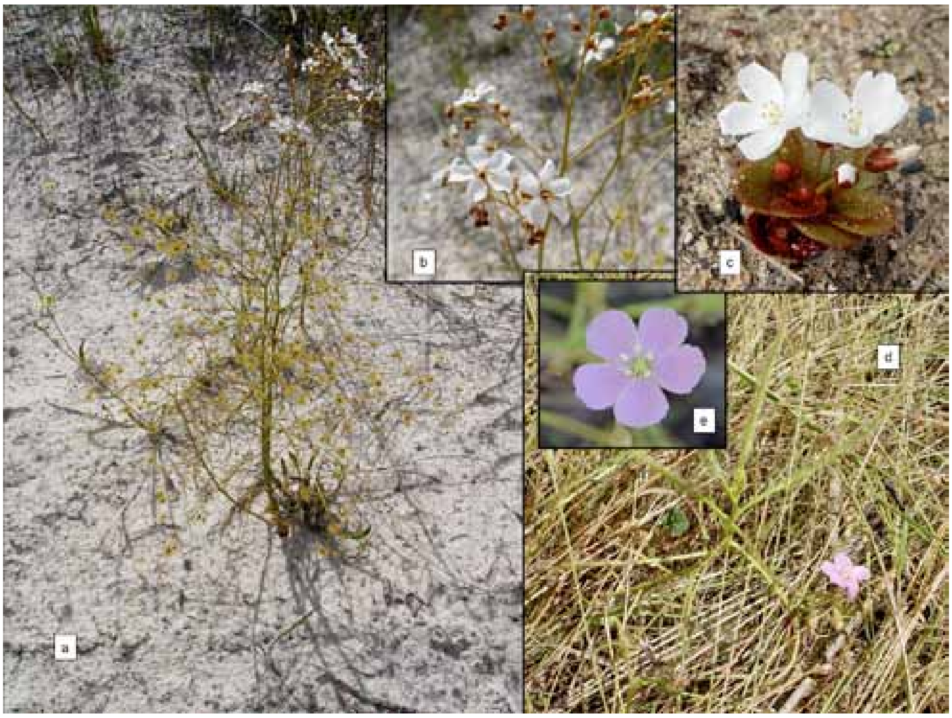


Figure 28. A selection of *Drosera* species found in wetland habitats. The genus *Drosera* is species diverse in the Kimberley and Southwest. Disjunct populations of some species are found in Desert wetlands. Photos – B Keighery/OEPA.

(a) and (b) *Drosera gigantea* from the Southwest.

(c) *D. tubaestylis* from the Southwest.

(d) and (e) *D. indica* from the Kimberley.

Figure 29. A selection of *Stylidium* species found in wetland habitats. The genus *Stylidium* is species diverse in the Kimberley (central and right boxes) and Southwest (two left boxes). Disjunct populations of some species are found in the Desert wetlands. Photos – B Keighery/OEPA.

Areas of bare soil are less common in freshwater wetlands than in saline wetlands but areas subject to long periods of inundation are typically bare on drying. However, as with saline wetlands, the freshwater wetlands that have soils with a significant clay component typically support patches of annual sedgelands and herblands, dominated by a diversity of annually renewed species (Figure 29 and Figure 30). Such wetlands are typically perched and the growing period is extended by the time taken for the pools, and then soils, to dry. The drying period may be extensive enough for a series of species to grow and flower, each of these species being dominant at different times of the wetting/drying cycle (Figure 30, Figure 31 and Figure 32). Wetlands that support a number of structural layers including combinations of woodland, shrubland, sedgeland, grassland and herbland are the most species diverse and have greater species diversity than some dryland communities.

Figure 30. A dense herbland patch is seen in this freshwater claypan in a late spring view of the Brixton Street Wetlands (Swan Coastal Plain). This community is the TEC 'Herb rich shrublands in clay pans'.

(a) *Melaleuca lateritia* shrubland (background) over annual herblands and sedgelands. Photo – B Keighery/OEPA.

(b) Two annual herbs *Stylidium longitubum* (pink) and *Hyalosperma cotula* (white). Photo – B Keighery/OEPA.

(c) Two annual sedges *Trithuria submersa* (left) and *Aphelia drummondii* (right). Photo – G Keighery/DEC.

Figure 31. Freshwater wetlands on soils with a high clay fraction (claypan) on the Ashburton River plains near Onslow (Gascoyne). Photos – B Keighery/OEPA.

(a) Claypan with annual herbland surrounded by red sand dunes.

(b) A variety of annual daisy species in the claypan.

(c) *Myriocephalus oldfieldii* ms, an annual daisy of claypans.

Figure 32. Barracca Nature Reserve (Swan Coastal Plain)

(a) A mosaic of plant communities with scattered *Eucalyptus wandoo* over *Melaleuca viminea* shrubland and herblands with *Brachycome pusilla* (white daisy), *Drosera menziesii* subsp. *menziesii* (pink) and *Utricularia multifida* (pink). These herbs are typical plants of the herblands of both claypans and granite rocks in the Southwest. Photos – B Keighery/OEPA.

(b) Close-up *Brachycome pusilla*.

(c) Close-up *Thelymitra antennifera*, a wetland orchid found in this herbland community.

(d) Close-up *Drosera menziesii* subsp. *menziesii*.

Rare plant communities

A number of wetland plant communities and mosaics of wetland plant communities are formally listed as threatened ecological communities (TECs) because they have been found to be vulnerable, endangered, critically endangered or presumed totally destroyed. At the time of publication, thirty-seven of WA's sixty-nine TECs are wetland communities, with thirty-three of these defined or reliant on vascular plant taxa; these thirty-three TECs are presented in Table 2. Note that Table 2 only includes TECs associated with wetland types covered in this guide. The wetlands in Figure 6a&c, Figure 24b and Figure 30 are TECs and other TECs are described and illustrated below.

➤ For more information, go to the threatened ecological communities webpage on DEC's website.[49] Further information regarding the Commonwealth process for listing TECs can be found on the Australian Government's Department for Sustainability, Environment, Water, Population and Communities website.[50]

Table 2: WA's wetland threatened ecological communities that are defined or reliant on vascular plant taxa

Source: DEC's Threatened Ecological Community Database endorsed by the Minister for the Environment (DEC, sourced August 2010)

Community identifier	Community name	General location (IBRA regions)	Category of threat and criteria met under WA criteria	Category under Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*
2. Toolibin	Perched wetlands of the Wheatbelt region with extensive stands of living swamp sheoak (*Casuarina obesa*) and paperbark (*Melaleuca strobophylla*) across the lake floor	Avon Wheatbelt	CR A) i); CR A) ii); CR C)	EN
3. SCP10b	Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)	Swan Coastal Plain	CR B) ii)	EN
4. SCP19	Sedgelands in Holocene dune swales of the southern Swan Coastal Plain	Swan Coastal Plain	CR B) ii)	EN
7. Mound Springs SCP	Communities of tumulus springs (organic mound springs, Swan Coastal Plain)	Swan Coastal Plain	CR A) i), CR A) ii), CR B) i), CR B) ii)	EN
10. Nthiron	Perth to Gingin ironstone association	Swan Coastal Plain	CR A) ii), CR B) ii), CR C)	EN
11. Muchea Limestone	Shrublands and woodlands on Muchea limestone	Swan Coastal Plain	EN B) ii)	EN
14. SCP18	Shrublands on calcareous silts of the Swan Coastal Plain	Swan Coastal Plain	VU B)	N/A
15. SCP02	Southern wet shrublands, Swan Coastal Plain	Swan Coastal Plain	EN B) ii)	N/A
17. SCP3c	*Eucalyptus calophylla – Xanthorrhoea preissii* woodlands and shrublands, Swan Coastal Plain	Swan Coastal Plain	CR B) ii)	EN
19. Scott Ironstone	Scott River Ironstone Association	Warren	EN B) i), EN B) ii)	N/A
21. SCP15	Forests and woodlands of deep seasonal wetlands of the Swan Coastal Plain	Swan Coastal Plain	VU C)	N/A
32. SCP07	Herb rich saline shrublands in clay pans	Swan Coastal Plain	VU B)	N/A
33. SCP08	Herb rich shrublands in clay pans	Swan Coastal Plain	VU B)	N/A
34. SCP09	Dense shrublands on clay flats	Swan Coastal Plain	VU B)	N/A
35. SCP10a	Shrublands on dry clay flats	Swan Coastal Plain	EN B) ii)	N/A
38. Morilla swamp	Perched fresh-water wetlands of the northern Wheatbelt dominated by extensive stands of living *Eucalyptus camaldulensis* (river red gum) across the lake floor	Avon Wheatbelt	PD B)	N/A
40. Bryde	Unwooded freshwater wetlands of the southern Wheatbelt of Western Australia, dominated by *Muehlenbeckia horrida* subsp. *abdita* and *Tecticornia verrucosa* across the lake floor	Avon Wheatbelt	CR B) i), CR B) ii)	N/A
42. Greenough River Flats	*Acacia rostellifera* low forest with scattered *Eucalyptus camaldulensis* on Greenough alluvial flats	Geraldton Sandplain	CR C)	N/A
46. Themeda Grasslands	Themeda grasslands on cracking clays (Hamersley Station, Pilbara). Grassland plains dominated by the perennial themeda (kangaroo grass) and many annual herbs and grasses	Pilbara	VU A)	N/A
49. Bentonite Lakes	Herbaceous plant assemblages on Bentonite Lakes	Avon Wheatbelt	EN B) iii)	N/A

Community identifier	Community name	General location (IBRA regions)	Category of threat and criteria met under WA criteria	Category under Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*
63. Irwin River Clay Flats	Clay flats assemblages of the Irwin River: Sedgelands and grasslands with patches of *Eucalyptus loxophleba* and scattered *E. camaldulensis* over *Acacia acuminata* and *A. rostellifera* shrubland on brown sand/loam over clay flats of the Irwin River	Avon Wheatbelt	PD A), PD B)	N/A
72. Ferricrete	Ferricrete floristic community (Rocky Springs type)	Geraldton Sandplain	VU B)	N/A
74. Herblands and Bunch Grasslands	Herblands and Bunch Grasslands on gypsum lunette dunes alongside saline playa lakes	Esperance Sandplain	VU B)	N/A
80. Theda Soak	Assemblages of Theda Soak rainforest swamp	North Kimberley	VU A), VU B)	N/A
81. Walcott Inlet	Assemblages of Walcott Inlet rainforest swamps	North Kimberley	VU B)	N/A
82. Roe River	Assemblages of Roe River rainforest swamp	North Kimberley	VU B)	N/A
84. Dragon Tree Soak	Assemblages of Dragon Tree Soak organic mound spring	Kimberley Region, Great Sandy Desert Bioregion	EN B) i)	N/A
85. Bunda Bunda	Assemblages of Bunda Bunda organic mound spring	West Kimberley, Dampierland Bioregion	VU A), VU B)	N/A
86. Big Springs	Assemblages of Big Springs organic mound springs	West Kimberley, Dampierland Bioregion	VU A), VU B)	N/A
89. North Kimberley mounds	Organic mound spring sedgeland community of the North Kimberley Bioregion	North Kimberley	VU A), VU B)	N/A
92. Black Spring	Black Spring organic mound spring community	North Kimberley	EN B) i), EN B) ii)	N/A
95. Mandora Mounds	Assemblages of the organic springs and mound springs of the Mandora Marsh area	West Kimberley, Dampierland and Greats Sandy Desert Bioregions	EN B) iii)	N/A
97. Mound Springs (Three Springs area)	Assemblages of the organic mound springs of the Three Springs area	Avon Wheatbelt	EN B) i), EN B) ii)	N/A

Western Australia's wetland flora

It is not possible currently to comprehensively document the wetland flora for the state, due to the incomplete knowledge of wetlands and their flora across the state as well as the biology and ecology of most species in WA. In some areas of the state, there are significant numbers of naturally uncommon species in wetlands, adding to the task of cataloguing the state's wetland flora. It is estimated that more than twenty per cent (3,000 taxa) of the currently known 12,500 flora for WA are wetland taxa (based on available data on regional and subregional floras). This compares with the 2,000 WA wetland taxa estimated in 2001.[9]

All taxa in some groups (families or genera) are found in wetlands but more commonly the occurrence in a wetland is taxon specific. Groups such as the grass genus *Amphibromus* and the family Aponogetonaceae are all wetland plants, while many members of the genus *Melaleuca* and the Orchidaceae are wetland species but many are not. For example, when 377 taxa in the Orchidaceae[51] are considered, 199 are dryland taxa, 105 are wetland taxa and seventy-three can occur in both habitats. As a general rule, orchid species in more arid areas, for example *Caladenia remota*, *C. incensa* and *C. cruscula*, are normally found in wetland habitats such as swamps or granite rock aprons. This is also true for other groups of Southwest Australian taxa at the inland margins of their ranges.[4]

Patterns of diversity of wetland vegetation and flora

Typically, Western Australian vegetation has high species diversity and a rapid turnover of different species from one plant community to another, even over very short distances. This is considered to be related to a series of factors including the ancient landscapes, soils, water availability and temperature/light. Overlaying this with wetland habitats is the wetting and drying climatic patterns and the sporadic nature of the distribution of many wetland plants. Many wetland plants rely on regimes of flooding to distribute the plants, so distribution is initially determined by a chance introduction through flooding then the possible loss of the plant after a drying period. For example, *Aponogeton hexatepalus* seeds germinate in the season they form and float to new locations when water is available. Within the one area this can result in the area sharing a group of taxa but having different taxa dominating in different wetlands, resulting in the typically disjunct distribution of a significant number of wetland taxa (see Figure 28 and Figure 29 for examples). Further adding to these disjunctions is the distribution of small-seeded taxa by wetland birds (such as with many sedge species including *Juncus kraussii* subsp. *australiensis*). The wetlands effectively form islands within the drier landscape and long distance dispersal accounts for such major disjunctions (Figure 33). At times some of these disjunct populations of native taxa are listed as weeds rather than native populations that have resulted from long distance dispersal.

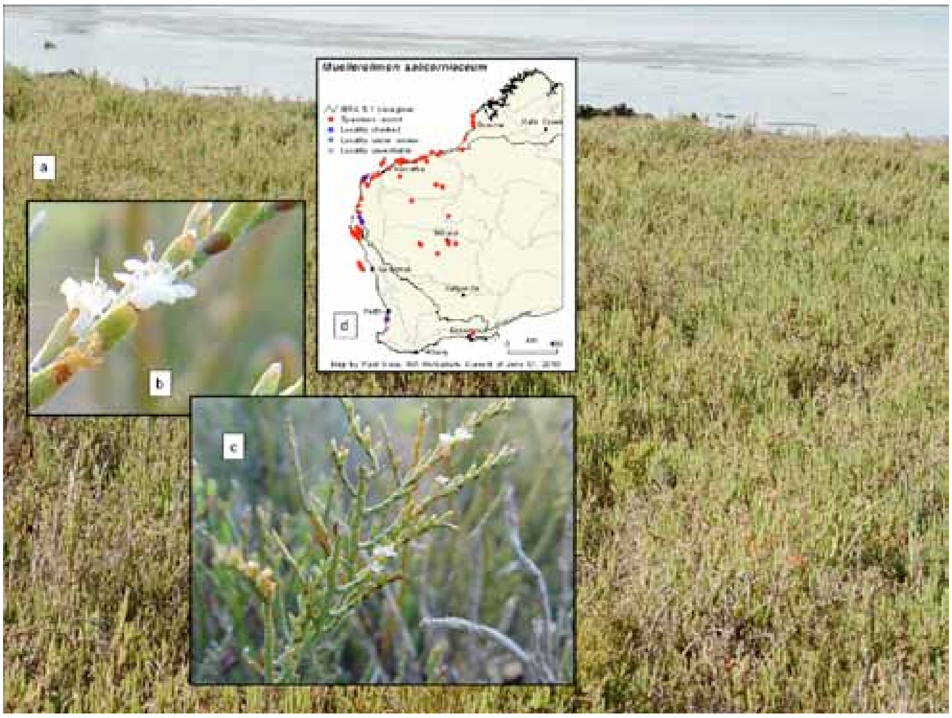


Figure 33. An example of a species, native status (*Muellerolimon salicorniaceum*), with a number of highly disjunct populations. Photos (a)–(c) – B Keighery/OEPA.

(a) *M. salicorniaceum* in the samphire shrublands of the Peel Harvey Estuary near Mandurah (Swan Coastal Plain).

(b) & (c) Detail of *M. salicorniaceum* branches and flowers.

(d) Recorded distribution, mostly Desert and Kimberley regions. Mapping – P Gioia. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

Rare wetland flora

As at 2010, WA has 402 taxa that are declared rare flora (DRF).[52] These taxa have been determined to be in danger of extinction, rare or otherwise in need of special protection and accordingly the Minister for Environment has declared them to be 'rare flora'. The forty-six taxa of DRF after Smith[13] that are found in wetlands are included in Appendix 1, together with the wetland zones they occur in. In addition to DRF, there are many species that are known from only a few collections, or a few sites, but which have not been adequately surveyed. Such flora may be rare or threatened, but cannot be considered for declaration as rare flora until such survey has been undertaken. These flora are included on a supplementary conservation list called the Priority Flora List. The Priority Flora List is dynamic – as new information comes to light the species' conservation status is reviewed and changes to the listing may result. Of the currently listed 2,704 priority taxa (M. Smith, pers. comm.) more than 270 are wetland plants and sixty-three of these are referred to in this topic, and listed in Appendix 1 (in part 1).

➤ For information on declared rare and priority flora, see the threatened flora webpage on DEC's website.[53]

Western Australia's wetland vegetation zones: the Kimberley, Deserts and Southwest

WA is a very large state and there is a great deal of variability in wetland vegetation and flora across it. To consider the wetland vegetation in more detail in this topic, the state is firstly divided into its three major climatic and biogeographical zones (Figure 34):

- Kimberley – tropical, warm to hot all year, summer rainfall and a dry winter
- Deserts – hot desert, infrequent erratic rainfall
- Southwest – Mediterranean, warm to hot dry summer, cool wet winter.

The differing climate of these three regions drives important variations in wetland vegetation.

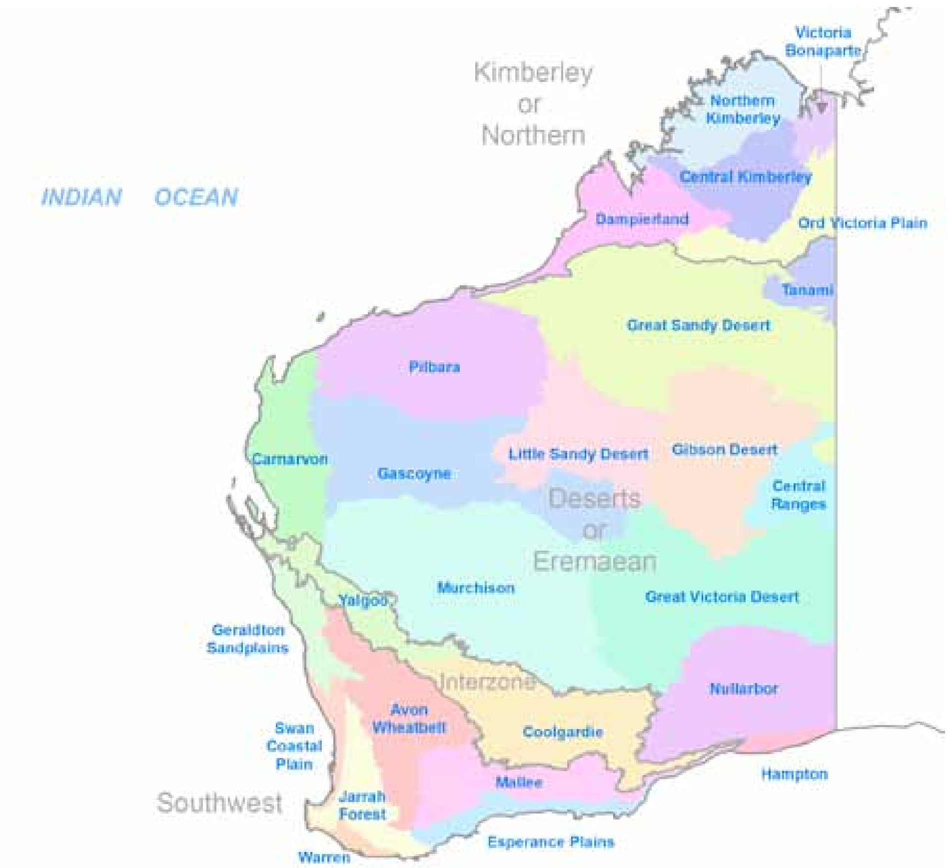


Figure 34. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

Within each of these zones is a second division of saline and freshwater wetlands. Wetland plant communities are distinctive of the zone and water chemistry, contributing both to the local and state identity and contributing greatly to the uniqueness of WA and Australia. Thirdly, in addition to zone and water chemistry divisions, this topic recognises various additional wetland groups that share similar vegetation characteristics. The following parts of this topic (parts 2 to 5) cover the wetland vegetation and flora of the Kimberley, Deserts and Southwest zones.

Glossary

Alluvial soil: soil deposited by flowing water on floodplains, in river beds, and in estuaries

Aquatic plant: a plant that grows for some period of time in inundated conditions and depends on inundation to grow and, where applicable, flower

Bentonite: a type of clay (aluminium phyllosilicate)

Birrida: a local Aboriginal name for a seasonally inundated gypsum saltpan wetland in sand dunes in the Shark Bay area. Some have a distinctive central raised platform and moat feature.

Community: a general term applied to any grouping of populations of different organisms found living together in a particular environment

Cosmopolitan: can be found almost anywhere in the world

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, forming fossil deposits

Dicotyledons (dicots): flowering plants that typically have seedlings with two cotyledons (seed leaves), a tap root system, and they can form wood and have network leaf venation. Dicots include a range of herbs, shrubs and trees.

Dongas: playas (intermittently inundated basins) in the Nullarbor, usually 2–3 metres deep and up to 800 metres in diameter, supporting trees. They hold water for a short time after rain due to their hard clay surface.

Ecotype: a genetically distinct geographic variety, population or race within a species which is adapted to specific environmental conditions. Typically ecotypes exhibit differences in morphology or physiology stemming from this adaptation, but are still capable of breeding with adjacent ecotypes without loss of fertility or vigour.

Endemic: naturally occurring only in a restricted geographic area

Ephemeral (plant): marked by short life cycles, usually a single season

Facultative plants: plants that can occur in both wetlands and dryland under natural conditions in a given setting

Ferns, fern allies: plants with stems, leaves and roots like other vascular plants, but which reproduce via spores instead of seeds or flowers

Flora: plant species, subspecies and varieties in a given area[1]

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyoongar origin.

Grass: tufted or spreading plant from the family Poaceae. The leaf sheath is always split, a ligule is present, the leaf is usually flat, a stem cross-section circular and all internodes evenly spaced. Some grasses are called reeds (the *Phragmites* and *Arundo* genera).

Gymnosperms: plants with unprotected seeds, often in cones, including the conifers and cycads

Herbs: plants with non-woody stems that are not grasses or sedges. Generally under half a metre tall. Most monocots are herbs.

Mallees: plants with many trunks (usually 2–5) arising from a lignotuber. The canopy is usually well above the base of the plant. In WA, most are from the genus *Eucalyptus*.

Mangrove: any of various tropical or semi-temperate trees or shrubs of the genera *Rhizophora*, *Bruguiera* and *Avicennia* growing in intertidal shore mud with many tangled roots above the ground

Mesa: an isolated flat-topped hill with steep sides

Monocotyledons (monocots): flowering plants that typically have seedlings with one cotyledon (seed-leaf) and a fibrous root system. They do not form wood and have strappy leaves with parallel veins. Some herbs and all grasses and sedges are monocots.

Monotypic: a genus with only one species

Obligate wetland plants: plants that are generally restricted to wetlands under natural conditions in a given setting

Pan-tropical: distributed throughout the tropical regions of the Earth

Perennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) in two or more growing seasons

Range ends: populations at the margins of the area to which a species is native

Rush: see 'sedge'

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia*, *Halosarcia*, *Sarcocornia*, *Sclerostegia*, *Tegicornia* and *Pachycornia*, belonging to the family Chenopodiaceae

Savanna: a grassy woodland; grassland with small or widely spaced trees so that the canopy is always open allowing a continuous layer of grasses underneath

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Shrubs: plants with one or more woody stems and foliage all or part of the total height of the plant

Taxa: a taxonomic group (the singular being taxon). Depending on the context, this may be a species or their subdivisions (subspecies, varieties etc), genus or higher group.[1]

Trees: plants with a single trunk and a canopy. The canopy is less than or equal to two-thirds of the height of the trunk. No lignotuber is evident.

Tufa: a porous rock composed of calcium carbonate and formed round mineral springs

Vascular plants: plants with defined tubular transport systems. Non-vascular plants include algae, liverworts and mosses.

Vegetation: combinations of plant species within a given area, and the nature and extent of each area[1]

Water regime: the pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, duration, frequency, extent and depth, and variability of water presence.

Wetland flora: wetland plant species, subspecies and varieties in a given area

Wetland plants: plants that inhabit wetlands

Wetland vegetation: combinations of wetland plants in a given area, and the nature and extent of each area

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Key to Appendix 1.

Native wetland vascular plant taxa of Western Australia referred to in this topic.

Column 1 **Scientific plant name**

Genus + species + infra species rank + infra species name + informal name. Some taxa yet to be formally described and named may have a reference collection number from the relevant collector. Names follow Western Australian Herbarium[81] except for those indicated as not having a current name (see column 4).

subsp.	Subspecies
var.	Variety
ms	A manuscript name yet to be published
PN	A phrase name for a taxon yet to be described and published.

Column 2 **Supra code**

Indicates broad supra-family classification.

Column 3 **Family name**

Column 4 **Current**

Scientific plant names are current (Western Australian Herbarium[81]) unless indicated with 'N'. In these cases, the authors prefer to use the names chosen.

Column 5 **Common names**

Sources for common names are the Western Australian Herbarium[81] and others as applied in references for this section.

Columns 6–8 **Listed conservation taxa**

Column 6 **Consv code = Western Australian-listed taxa**

Significant plant taxa (species, sub-species and varieties) listed under the *Wildlife Conservation Act 1950* (Government of Western Australia[52]) and by the Department of Environment and Conservation.[13] Priority taxa conservation code listings are current as at July 2010 (Western Australian Herbarium[81]). See Appendix 2 for further descriptions of the categories below.

R	Declared rare flora: extant taxa
X	Declared rare flora: presumed extinct taxa
1	Priority 1: poorly known taxa
2	Priority 2: poorly known taxa
3	Priority 3: poorly known taxa
4	Priority 4: rare taxa

Column 7 **WA IUCN rank = Internationally listed taxa**

Significant plant taxa (species, subspecies and varieties) listed from the IUCN Red List of Threatened Species according to Smith[13]

CR	Taxa that are critically endangered
E	Taxa that are endangered
V	Taxa that are vulnerable

Column 8	**EPBC rank = Commonwealth-listed taxa**	
	Significant plant taxa (species, subspecies and varieties) listed under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* according to Smith.[13] Taxa are listed by the Department of Sustainability, Environment, Water, Population and Communities[50]	
	E	Taxa that are endangered
	V	Taxa that are vulnerable
	In some instances, the codes for the Commonwealth and the internationally listed taxa differ; in these cases, the discrepancy is indicated by an asterisk.	
Column 9–11	**Wetland zone**	
	Zones listed are only those mentioned in the text or captions in this section.	
	K	Kimberley
	D	Deserts
	SW	Southwest
Column 12	**Figure no.**	
Column 13	**Name ID**	
	Positive name IDs are from the Western Australian Plant Census Database (Western Australian Herbarium[11, 81])	

Appendix 1. Native wetland vascular plant taxa of Western Australia referred to in this topic

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Acacia acuminata	DIC	Fabaceae		Jam						SW		3200
Acacia ampliceps	DIC	Fabaceae							D			3209
Acacia aneura	DIC	Fabaceae		Mulga					D			3217
Acacia blakelyi	DIC	Fabaceae								SW		3242
Acacia citrinoviridis	DIC	Fabaceae							D			3260
Acacia cyclops	DIC	Fabaceae		Coastal wattle, Red-eyed wattle						SW		3282
Acacia dictyophleba	DIC	Fabaceae		Sandhill wattle					D			3300
Acacia distans	DIC	Fabaceae		Black mulga					D			3305
Acacia eriopoda	DIC	Fabaceae		Broome pindan wattle					D			3326
Acacia flagelliformis	DIC	Fabaceae		Rush wattle	4					SW	149a, 149b	3339
Acacia holosericea	DIC	Fabaceae		Candelbra wattle					D			3372
Acacia maconochieana	DIC	Fabaceae							D			3433
Acacia monticola	DIC	Fabaceae		Gawar					D			3447
Acacia neurocarpa	DIC	Fabaceae						K	D		41	13401
Acacia rostellifera	DIC	Fabaceae		Summer-scented wattle						SW		3525
Acacia saligna	DIC	Fabaceae		Orange wattle, Coojong						SW		3527
Acacia spp.	DIC	Fabaceae							D			-20987
Acacia xiphophylla	DIC	Fabaceae		Snakewood					D			3606
Achyranthes aspera	DIC	Amaranthaceae		Chaff flower					D			2645
Acidonia microcarpa	DIC	Proteaceae		Acidonia						SW		10824
Acrostichum speciosum	FER	Pteridaceae		Mangrove fern					D			44
Actinostrobus acuminatus	GYM	Cupressaceae	N	Dwarf cypress, Creeping cypress						SW	166a, 166b, 166c	89
Actinostrobus pyramidalis	GYM	Cupressaceae	N	Swamp cypress						SW	8c, 106a, 110	91
Adenanthos meisneri	DIC	Proteaceae		Meisner's jugflower						SW		1790
Adiantum capillus-veneris	FER	Pteridaceae		Maidenhair	2			K	D			26
Aeschynomene indica	DIC	Fabaceae		Budda pea				K				3680
Agonis flexuosa var. flexuosa	DIC	Myrtaceae		Peppermint						SW		17202
Aldrovanda vesiculosa	DIC	Droseraceae			2					SW		11098

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Allocasuarina campestris	DIC	Casuarinaceae		Tamma						SW		1721
Alyogyne huegelii	DIC	Malvaceae		Lilac hibiscus						SW		4906
Amblysperma minor	DIC	Asteraceae	N	Swamp native gerbera						SW		25842
Amphibromus nervosus	MON	Poaceae		Swamp wallaby grass						SW	24a, 105a, 112	13380
Amphibromus vickeryae	MON	Poaceae		Swamp wallaby grass	1					SW		10758
Anarthria scabra	MON	Anarthriaceae		Anarthria						SW		1063
Andersonia ferricola	DIC	Ericaceae		Ironstone andersonia	1					SW		18102
Andersonia gracilis	DIC	Ericaceae		Slender andersonia	R	V	E*			SW		6309
Angianthus drummondii	DIC	Asteraceae		Star angianthus	3					SW	26c, 92c	7829
Angianthus preissianus	DIC	Asteraceae		Preiss's angianthus						SW		7833
Angianthus tomentosus	DIC	Asteraceae		Hairy angianthus, camel-grass						SW		7836
Anigozanthos bicolor subsp. minor	MON	Haemodoraceae			R	V	E*			SW		12102
Anigozanthos viridis subsp. terraspectans	MON	Haemodoraceae		Dwarf green kangaroo paw	R	V	V			SW		13891
Anthotium junciforme	DIC	Goodeniaceae		Anthotium	4					SW	148	12724
Aotus cordifolia	DIC	Fabaceae		Swamp aotus	3					SW		3686
Aphelia drummondii	MON	Centrolepidaceae		Drummond's aphelia						SW	30c	1118
Aphelia spp.	MON	Centrolepidaceae								SW		-21440
Aponogeton hexatepalus	MON	Aponogetonaceae		Stalked water ribbons	4					SW	5	141
Aponogeton spp.	MON	Aponogetonaceae						K				-21409
Argyroglottis turbinata	DIC	Asteraceae								SW	94b, 94c	7842
Aristida spp.	MON	Poaceae		Feathertop grass				K	D			-21362
Arthropodium sp.	MON	Asparagaceae								SW		-21388
Astartea affinis	DIC	Myrtaceae		Brixton astartea						SW	27d	20350
Asteridea athrixioides	DIC	Asteraceae		Bristle daisy						SW		7846
Astrebla elymoides	MON	Poaceae		Weeping mitchell grass					D			227
Astrebla pectinata	MON	Poaceae		Barley mitchell grass					D			229
Astrebla spp.	MON	Poaceae		Mitchell grass				K	D		81a, 82a	-21381
Astrebla squarrosa	MON	Poaceae		Bull mitchell grass					D			230
Atriplex amnicola	DIC	Chenopodiaceae		Swamp saltbush					D			2450

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Atriplex bunburyana	DIC	Chenopodiaceae		Silver saltbush					D		65a	2451
Atriplex paludosa	DIC	Chenopodiaceae		Marsh saltbush					D			2470
Atriplex semilunaris	DIC	Chenopodiaceae		Annual saltbush					D		76	2476
Atriplex spp.	DIC	Chenopodiaceae		Saltbush					D	SW		-21370
Atriplex vesicaria	DIC	Chenopodiaceae		Bladder saltbush					D			2481
Austrostipa juncifolia	MON	Poaceae								SW		17242
Austrostipa juncifolia subsp. Southern River (B.J. Keighery 2160) PN	MON	Poaceae			1					SW	127a, 127b	20733
Austrostipa sp. Harvey (B.J. Keighery GWAL/1) PN	MON	Poaceae								SW		34356
Avicennia marina	DIC	Acanthaceae		White mangrove					D	SW		6828
Azolla filiculoides	FER	Salviniaceae		Pacific azolla						SW	15	80
Azolla pinnata	FER	Salviniaceae		Azolla						SW		17737
Banksia dentata	DIC	Proteaceae		Tropical banksia				K			52	1813
Banksia littoralis	DIC	Proteaceae		Swamp banksia						SW	99, 125a	1830
Banksia nivea subsp. uliginosa	DIC	Proteaceae			R	E	E			SW	123e	32204
Banksia squarrosa subsp. argillacea	DIC	Proteaceae			R	V	V			SW	122a, 122b	32046
Banksia strictifolia	DIC	Proteaceae								SW		32042
Barringtonia acutangula	DIC	Lecythidaceae		Freshwater mangrove				K			39	5289
Baumea articulata	MON	Cyperaceae		Jointed rush					D	SW	21a, 97	741
Baumea juncea	MON	Cyperaceae		Bare twigrush						SW		743
Baumea preissii	MON	Cyperaceae		Preiss's baumea						SW		745
Baumea riparia	MON	Cyperaceae		River baumea						SW		746
Baumea rubiginosa	MON	Cyperaceae		Baumea					D	SW		747
Baumea vaginalis	MON	Cyperaceae		Sheath twigrush						SW		748
Beaufortia sparsa	DIC	Myrtaceae		Swamp bottlebrush, swamp beaufortia						SW		5392
Blennospora doliiformis	DIC	Asteraceae		Golden blennospora	3					SW	92b	20026
Blyxa sp.	MON	Hydrocharitaceae						K			47	-21430
Boronia capitata subsp. gracilis	DIC	Rutaceae		Slender boronia	2					SW		11612
Boronia exilis	DIC	Rutaceae			R	E	E*			SW		16318

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Boronia juncea subsp. juncea	DIC	Rutaceae			1					SW	102	16633
Boronia megastigma	DIC	Rutaceae		Scented boronia, brown boronia						SW		4428
Borya constricta	MON	Boryaceae		Palm pincushions						SW	128b	1267
Borya sp.	MON	Boryaceae								SW	108	-21159
Bossiaea cucullata	DIC	Fabaceae								SW	95c	18427
Brachyscias verecundus	DIC	Apiaceae		Brachyscias	R	CR	CR			SW		18492
Brachyscome bellidioides	DIC	Asteraceae		Brachyscome						SW		7867
Brachyscome pusilla	DIC	Asteraceae		Brachyscome						SW	32a, 32b	7883
Burchardia bairdiae	MON	Colchicaceae		Baird’s kara						SW	137a, 137b	1383
Burchardia multiflora	MON	Colchicaceae		Dwarf burchardia, kara						SW	137c	1385
Byblis filifolia	DIC	Byblidaceae							D			18073
Byblis guehoi	DIC	Byblidaceae						K			54	33487
Caladenia cruscula	MON	Orchidaceae								SW		15342
Caladenia incensa	MON	Orchidaceae							D	SW		15356
Caladenia paludosa	MON	Orchidaceae		Swamp spider orchid						SW		15503
Caladenia remota	MON	Orchidaceae							D	SW		18028
Calandrinia granulifera	DIC	Portulacaceae		Pygmy purslane						SW	118a	2854
Calandrinia sp. Kemerton (B.J. Keighery s.n.) PN	DIC	Portulacaceae		Tiny clay calandrinia						SW	118a, 118b	-21246
Callistachys lanceolata	DIC	Fabaceae		Wonnich, native willow						SW		10861
Callistemon phoeniceus	DIC	Myrtaceae		Lesser bottlebrush					D	SW		5395
Callitris canescens	GYM	Cupressaceae								SW	95b	92
Callitris verrucosa	GYM	Cupressaceae								SW		8637
Calocephalus sp.	DIC	Asteraceae							D			-21421
Calothamnus hirsutus	DIC	Myrtaceae		Hairy calothamnus						SW	108	5411
Calothamnus lateralis	DIC	Myrtaceae		Swamp calothamnus						SW		5415
Calothamnus lateralis var. crassus ms	DIC	Myrtaceae			3					SW		35799
Calothamnus quadrifidus subsp. teretifolius ms	DIC	Myrtaceae			4					SW	12	35796
Calytrix breviseta subsp. breviseta	DIC	Myrtaceae		Rare starflower	R	CR	E*			SW		13653

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Calytrix sp. Tutunup (G.J. Keighery & N. Gibson 2953) PN	DIC	Myrtaceae		Ironstone starflower	2					SW	124e, 124f	19974
Canarium australianum	DIC	Burseraceae		Jalkay				K				4512
Carallia brachiata	DIC	Rhizophoraceae						K				5293
Cartonema spicatum	MON	Commelinaceae						K			50b	1163
Casuarina obesa	DIC	Casuarinaceae		Swamp sheoak					D	SW	2, 104, 119	1742
Casuarina pauper	DIC	Casuarinaceae		Black oak					D		60a	12658
Caustis dioica	MON	Cyperaceae		Caustis						SW		760
Celtis philippensis	DIC	Cannabaceae						K				1744
Centella asiatica	DIC	Apiaceae		Centella						SW		6214
Centrolepis polygyna	MON	Centrolepidaceae		Wiry centrolepis						SW	26b, 92a	1134
Cephalotus follicularis	DIC	Cephalotaceae		Albany pitcher plant						SW		3148
Chaetanthus aristatus	MON	Restionaceae		Chaetanthus						SW	106a	17685
Chamaescilla gibsonii	MON	Asparagaceae		Blue squill	3					SW	114c, 114d	19338
Chamelaucium sp. C Coastal Plain (R.D. Royce 4872) PN (Chamelaucium roycei ms)	DIC	Myrtaceae	N	Royce's wax	R	V	V			SW	124c, 124d	13627
Chenopodium auricomum	DIC	Chenopodiaceae		Swamp bluebush, Queensland bluebush					D			2485
Chordifex isomorphus	MON	Restionaceae		Chordifex	4					SW		17828
Chorizandra enodis	MON	Cyperaceae		Black bristlerush						SW		763
Chrysocephalum sp. Pilbara (H. Demarz 2852) PN	DIC	Asteraceae							D		82a, 82b	35017
Chrysopogon fallax	MON	Poaceae		Ribbon grass, golden beard grass				K	D			273
Cladium procerum	MON	Cyperaceae			2				D			766
Corybas sp.	MON	Orchidaceae								SW		-20761
Corymbia calophylla	DIC	Myrtaceae		Marri						SW	24a	17104
Corymbia confertiflora	DIC	Myrtaceae						K				17080
Corymbia greeniana	DIC	Myrtaceae						K				17089
Cosmelia rubra	DIC	Ericaceae		Spindle heath						SW		6352
Craspedia argillicola ms	DIC	Asteraceae		Swamp bachelor's buttons	2					SW	141	19858

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Cratystylis spp.	DIC	Asteraceae							D			-21372
Cyathochaeta teretifolia	MON	Cyperaceae		Terete leaved swamp cyathochaeta	3					SW	103a, 103b, 103c	16245
Cyclosorus interruptus	FER	Thelypteridaceae		Cyclosorus						SW		54
Cyperus aquatilis	MON	Cyperaceae						K			56a, 56b	773
Cyperus laevigatus	MON	Cyperaceae								SW	88b, 88c	-21433
Cyperus vaginatus	MON	Cyperaceae		Stiffleaf sedge					D		68a, 68b	818
Cyrtostylis sp.	MON	Orchidaceae								SW		-20616
Darwinia ferricola	DIC	Myrtaceae			R	E	E			SW	124a	34774
Darwinia foetida	DIC	Myrtaceae			R	E	CR*			SW		34773
Darwinia whicherensis	DIC	Myrtaceae			R	CR	E*			SW	124b	34765
Dichanthium sericeum	MON	Poaceae		Queensland blue grass				K	D		48	304
Dillwynia dillwynioides	DIC	Fabaceae		Swamp dillwynia	3					SW	101a, 101b	3863
Disphyma crassifolium subsp. clavellatum	DIC	Aizoaceae								SW	91b	11681
Diuris drummondii	MON	Orchidaceae		Tall donkey orchid	R	V	V			SW		10796
Diuris micrantha	MON	Orchidaceae		Dwarf bee orchid	R	V	V			SW		12938
Drosera burmanni	DIC	Droseraceae		Tropical sundew					D			3093
Drosera derbyensis	DIC	Droseraceae							D			17215
Drosera gigantea	DIC	Droseraceae		Giant sundew						SW	28a, 28b, 100a	3097
Drosera glanduligera	DIC	Droseraceae		Pimpernel sundew						SW		3098
Drosera hartmeyerorum	DIC	Droseraceae							D			19964
Drosera indica	DIC	Droseraceae		Indian sundew				K			28d, 28e	3103
Drosera menziesii	DIC	Droseraceae		Pink rainbow						SW		3109
Drosera menziesii subsp. menziesii	DIC	Droseraceae		Menzies' rainbow						SW	32a, 32d	11853
Drosera occidentalis	DIC	Droseraceae		Western sundew						SW		3115
Drosera spp.	DIC	Droseraceae								SW		-21406
Drosera tubaestylis	DIC	Droseraceae		Sundew						SW	28c	13205
Elatine spp.	DIC	Elatinaceae							D			-21415
Eleocharis acuta	MON	Cyperaceae		Common spikerush						SW		822

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Eleocharis brassii	MON	Cyperaceae						K				824
Eleocharis dulcis	MON	Cyperaceae		Spike rush, chinese water chestnut				K			53	826
Eleocharis geniculata	MON	Cyperaceae							D			827
Eleocharis keigheryi	MON	Cyperaceae		Keighery's spikerush	R	V	V			SW	104	17605
Eleocharis sphacelata	MON	Cyperaceae		Tall spikerush					D			831
Eleocharis spiralis	MON	Cyperaceae						K			51	832
Enneapogon purpurascens	MON	Poaceae		Purple nineawn				K				12749
Epiblema grandiflorum	MON	Orchidaceae		Babe-in-a-cradle						SW		1645
Epiblema grandiflorum var. cyaneum ms (this taxon is no longer recognised by the WA Herbarium)	MON	Orchidaceae		Blue babe-in-a-cradle	R	CR	E*			SW		17347
Eragrostis australasica	MON	Poaceae		Canegrass					D	SW		369
Eragrostis desertorum	MON	Poaceae		Desert lovegrass					D			377
Eragrostis dielsii	MON	Poaceae		Mallee lovegrass					D			378
Eragrostis falcata	MON	Poaceae		Sickle lovegrass					D		74c	381
Eragrostis setifolia	MON	Poaceae		Neverfail grass					D			393
Eragrostis speciosa	MON	Poaceae		Handsome lovegrass					D			395
Eragrostis xerophila	MON	Poaceae		Knotty-butt neverfail					D			399
Eremophila glabra subsp. chlorella	DIC	Scrophulariaceae			R	CR	*			SW	146a	17150
Eremophila lactea	DIC	Scrophulariaceae			R	CR	E*			SW		7229
Eremophila spongiocarpa	DIC	Scrophulariaceae			1				D		7bc	17363
Eremophila youngii subsp. lepidota	DIC	Scrophulariaceae			4				D		75a	16040
Eriachne benthamii	MON	Poaceae		Swamp wanderrie grass, swamp grass, swamp wanderrie					D		73b, 77, 78	403
Eriachne festucacea	MON	Poaceae		Wanderrie grass, plains wandarrie grass				K				407
Eriachne flaccida	MON	Poaceae		Claypan grass					D			408
Eriachne obtusa	MON	Poaceae		Northern wandarrie grass					D			414
Eriocaulon setaceum	MON	Eriocaulaceae		Water pincushions				K	D		46a	1160
Eryngium ferox ms	DIC	Apiaceae		Spiky devil	3					SW	116c	19602

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Eryngium pinnatifidum subsp. palustre ms	DIC	Apiaceae		Swamp devil	3					SW	116a, 116b	14553
Eryngium subdecumbens ms	DIC	Apiaceae		Prickly swamp devil	3					SW		14720
Erythrina vespertilio	DIC	Fabaceae		Yulbah					D			3871
Erythrophleum chlorostachys	DIC	Fabaceae		Ironwood				K				3662
Eucalyptus camaldulensis	DIC	Myrtaceae		River gum				K	D	SW	38a, 38b, 60c, 68a	5580
Eucalyptus clelandii	DIC	Myrtaceae		Cleland's blackbutt					D			5592
Eucalyptus coolabah	DIC	Myrtaceae		Coolibah					D			5603
Eucalyptus decipiens	DIC	Myrtaceae								SW	125a	5615
Eucalyptus dolorosa	DIC	Myrtaceae			R	CR	E*			SW		13546
Eucalyptus foecunda	DIC	Myrtaceae		Fremantle mallee, narrow-leaved red mallee						SW		5649
Eucalyptus gomphocephala	DIC	Myrtaceae		Tuart						SW	6a, 11, 23, 98, 154a, 159a	5659
Eucalyptus kondininensis	DIC	Myrtaceae		Kondinin blackbutt						SW		5686
Eucalyptus lesouefii	DIC	Myrtaceae		Goldfields blackbutt					D			5697
Eucalyptus loxophleba	DIC	Myrtaceae		York gum						SW		5702
Eucalyptus microtheca	DIC	Myrtaceae		Coolibah				K	D			5714
Eucalyptus occidentalis	DIC	Myrtaceae		Yate, flat-topped yate						SW		5723
Eucalyptus orthostemon	DIC	Myrtaceae								SW		20047
Eucalyptus rudis	DIC	Myrtaceae		Flooded gum						SW		5763
Eucalyptus rudis subsp. cratyantha	DIC	Myrtaceae		Swamp flooded gum	4					SW		13512
Eucalyptus salicola	DIC	Myrtaceae		Salt gum						SW		12693
Eucalyptus sargentii	DIC	Myrtaceae		Salt river gum						SW		5768
Eucalyptus striaticalyx	DIC	Myrtaceae		Cue york gum					D		60b	5779
Eucalyptus tectifica	DIC	Myrtaceae		Darwin box				K				5785
Eucalyptus victrix	DIC	Myrtaceae		Coolibah					D		20c, 67a, 78	14548
Eucalyptus wandoo	DIC	Myrtaceae		Wandoo						SW	32a	5797
Euchilopsis linearis	DIC	Fabaceae		Swamp pea						SW	101c	3872
Eulalia aurea	MON	Poaceae		Silky browntop					D			11011

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Evandra aristata	MON	Cyperaceae		Graceful evandra						SW		834
Ficinia nodosa	MON	Cyperaceae		Knotted club rush						SW		20216
Ficus brachypoda	DIC	Moraceae							D			19648
Ficus racemosa	DIC	Moraceae		Stem-fruit fig				K				1755
Ficus virens	DIC	Moraceae		Albayi				K				1759
Fimbristylis caespitosa	MON	Cyperaceae						K			56c, 56d	841
Fimbristylis ferruginea	MON	Cyperaceae							D			855
Fimbristylis velata	MON	Cyperaceae		Fimbristylis						SW		894
Flaveria australasica subsp. gilgai	DIC	Asteraceae	N						D		81b	33621
Frankenia cinerea	DIC	Frankeniaceae							D		61a	5191
Frankenia parvula	DIC	Frankeniaceae		Short-leaved frankenia	R	E	E			SW		5208
Frankenia pauciflora	DIC	Frankeniaceae		Seaheath						SW		5209
Fuirena ciliaris	MON	Cyperaceae						K				896
Gahnia trifida	MON	Cyperaceae		Coast saw-sedge						SW	22, 88a, 136a, 136b, 155b, 161b	907
Gardenia megasperma	DIC	Rubiaceae		Wild gardenia				K				7327
Gastrolobium ebracteolatum	DIC	Fabaceae		River gastrolobium						SW	150a, 150b	20473
Gastrolobium papilio	DIC	Fabaceae		Butterfly gastrolobium	R	CR	E*			SW		20509
Gastrolobium sp. Harvey (G.J. Keighery 16821) PN	DIC	Fabaceae			2					SW	150c, 150d	30295
Glossostigma diandrum	DIC	Phrymaceae		Mudmat						SW	117b	7060
Glossostigma drummondii	DIC	Phrymaceae		Mudmat						SW		7061
Glossostigma spp.	DIC	Phrymaceae							D	SW		-21404
Glyceria drummondii	MON	Poaceae		Nangetty grass	R	E	E			SW		436
Glycyrrhiza acanthocarpa	DIC	Fabaceae		Native liquorice						SW		3943
Goodenia viscida	DIC	Goodeniaceae		Viscid goodenia						SW		7562
Grevillea curviloba	DIC	Proteaceae								SW		1984
Grevillea curviloba subsp. curviloba	DIC	Proteaceae		Freeway grevillea	R	CR	E*			SW		14408
Grevillea curviloba subsp. incurva	DIC	Proteaceae		Freeway grevillea	R	E	E			SW		14409

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Grevillea elongata	DIC	Proteaceae		White ironstone grevillea	R	E	V*			SW		14526
Grevillea maccutcheonii	DIC	Proteaceae		Maccutcheon's grevillea	R	CR	E*			SW		17112
Grevillea obtusifolia	DIC	Proteaceae		Obtuse leaved grevillea, blunt-leaved grevillea						SW	151a	8836
Grevillea sp. Gillingarra (R.J. Cranfield 4087) PN	DIC	Proteaceae								SW	151c	31354
Grevillea thelemanniana subsp. Coojarloo (B.J. Keighery 28 B) PN	DIC	Proteaceae			1					SW	151b	31353
Haemodorum simplex	MON	Haemodoraceae		Haemodorum						SW	109a	1472
Hakea ceratophylla	DIC	Proteaceae		Horned leaf hakea						SW		2137
Hakea lasiocarpha	DIC	Proteaceae			3					SW		12229
Hakea oldfieldii	DIC	Proteaceae		Oldfield's hakea	3					SW	122c, 122d	2190
Hakea tuberculata	DIC	Proteaceae			3					SW		16640
Hakea varia	DIC	Proteaceae		Variable-leaved hakea						SW	165a, 165b	2216
Haloragis platycarpa	DIC	Haloragaceae			R	CR	CR			SW		6177
Heliotropium sp.	DIC	Boraginaceae							D			-20828
Hemiandra sp. Ironstone (B.J. Keighery & N. Gibson 614) PN	DIC	Lamiaceae		Ironstone snakebush						SW		-21245
Hemichroa diandra	DIC	Amaranthaceae		Hemichroa						SW	157c, 157d	2688
Heteropogon contortus	MON	Poaceae		Spear grass, bunch speargrass				K				443
Hibbertia perfoliata	DIC	Dilleniaceae								SW		5154
Hibbertia stellaris	DIC	Dilleniaceae		Orange stars, swamp hibbertia						SW	152	5172
Homalospermum firmum	DIC	Myrtaceae								SW		5816
Hopkinsia anoectocolea	MON	Anarthriaceae			3					SW		17742
Hyalosperma cotula	DIC	Asteraceae		Hyalosperma						SW	30b, 109	12741
Hydrocotyle lemnoides	DIC	Araliaceae		Aquatic pennywort	4					SW	5c	6233
Hydrocotyle tetragonocarpa	DIC	Araliaceae		Pennywort						SW	156c	6241
Hypocalymma angustifolium	DIC	Myrtaceae		White myrtle						SW	9	5817
Hypolaena exsulca	MON	Restionaceae		Common hypolaena						SW		1070
Hypoxis occidentalis	MON	Hypoxidaceae		Yellow star						SW	114b	1503
Ischaemum albovillosum	MON	Poaceae		Tableland white grass					D			12663

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Isoetes drummondii	FER	Isoetaceae		Quillwort, isoetes						SW	14, 130b	11
Isolepis cernua	MON	Cyperaceae		Nodding club-rush						SW	113b	910
Isolepis cernua var. cernua	MON	Cyperaceae								SW	157b	20199
Isopogon formosus subsp. dasylepis	DIC	Proteaceae		Rose coneflower	3					SW	123d	16522
Isotoma pusilla	DIC	Campanulaceae		Small isotome						SW	117d	7398
Isotoma scapigera	DIC	Campanulaceae		Long-scaped isotome						SW	118a	7399
Isotropis cuneifolia subsp. glabra	DIC	Fabaceae		Swamp granny's bonnets	2					SW		16317
Jacksonia gracillima	DIC	Fabaceae		Swamp jacksonia	3					SW	147d, 147e	20462
Juncus kraussii subsp. australiensis	MON	Juncaceae		Salt rush						SW	23, 90, 159a	11922
Juncus pallidus	MON	Juncaceae		Giant rush, pale rush						SW	97	1188
Kennedia coccinea	DIC	Fabaceae		Coral vine, coral kennedia						SW	161c	4037
Kippistia suaedifolia	DIC	Asteraceae							D	SW	93b	8094
Kunzea aff. micrantha	DIC	Myrtaceae								SW		-21275
Kunzea limnicola	DIC	Myrtaceae	N							SW	27a	-20122
Kunzea micrantha	DIC	Myrtaceae		Clay kunzea						SW		5835
Kunzea recurva	DIC	Myrtaceae		Purple swamp kunzea						SW	27a, 121	5841
Labichea lanceolata	DIC	Fabaceae		Tall labichea						SW		3667
Lambertia echinata subsp. occidentalis	DIC	Proteaceae		Ironstone lambertia	R	CR	E*			SW	123c	17734
Lambertia orbifolia subsp. Scott River Plains (L.W. Sage 684) PN	DIC	Proteaceae			R	E	E			SW		19186
Lawrencia glomerata	DIC	Malvaceae								SW		4955
Lawrencia squamata	DIC	Malvaceae		Lawrencia					D	SW	93c, 93d	4959
Lepidosperma gladiatum	MON	Cyperaceae		Coast sword-sedge						SW	90, 161a	933
Lepidosperma longitudinale	MON	Cyperaceae		Pithy sword-sedge, swamp swordsedge						SW		937
Lepidosperma rostratum	MON	Cyperaceae			R	E	E			SW		942
Lepilaena bilocularis	MON	Potamogetonaceae		Water mat					D			119
Leptochloa fusca	MON	Poaceae		Brown beetle grass				K	D			19061
Leptomeria ellytes	DIC	Santalaceae		Currant bush						SW	167b, 167c	17703
Lepyrodia monoica	MON	Restionaceae		Lepyrodia						SW		1089
Lindernia sp.	DIC	Linderniaceae						K			50d	-21422

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					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Livistona alfredii	MON	Arecaceae		Millstream palm, millstream fan-palm	4				D		20b, 79	1039
Livistonia sp.	MON	Arecaceae							D			-20833
Lobelia quadrangularis	DIC	Campanulaceae							D			7404
Lophostemon grandiflorus	DIC	Myrtaceae						K				5859
Loxocarya magna	MON	Restionaceae		Tall ironstone loxocarya	3					SW		13779
Loxocarya striata subsp. implexa	MON	Restionaceae		Tangled ironstone loxocarya						SW		-21148
Lycopodiella serpentina	FER	Lycopodiaceae		Clubmoss						SW		12783
Maireana aphylla	DIC	Chenopodiaceae		Spiny bluebush, cotton bush					D			2534
Maireana platycarpa	DIC	Chenopodiaceae		Shy bluebush					D			2557
Maireana polypterygia	DIC	Chenopodiaceae		Gascoyne bluebush					D			2558
Maireana pyramidata	DIC	Chenopodiaceae		Sago bush					D			2560
Marsilea drummondii	FER	Marsileaceae		Common nardoo, nardoo						SW	16	74
Marsilea sp.	FER	Marsileaceae						K	D	SW	77	-20834
Meeboldina cana	MON	Restionaceae		Meeboldina						SW	24a, 105a, 112	17683
Meeboldina coangustata	MON	Restionaceae		Meeboldina						SW		17679
Meeboldina scariosa	MON	Restionaceae		Meeboldina						SW		17694
Melaleuca acuminata	DIC	Myrtaceae								SW		5869
Melaleuca alsophila	DIC	Myrtaceae						K	D			9178
Melaleuca argentea	DIC	Myrtaceae		Cadjeput, silver cadjeput				K	D		37	5875
Melaleuca atroviridis	DIC	Myrtaceae								SW	120a	20284
Melaleuca bracteata	DIC	Myrtaceae		River teatree					D			5879
Melaleuca brevifolia	DIC	Myrtaceae		Swamp melaleuca						SW		5881
Melaleuca brophyi	DIC	Myrtaceae								SW		18527
Melaleuca cajuputi	DIC	Myrtaceae						K	D			5883
Melaleuca croxfordiae	DIC	Myrtaceae								SW		18184
Melaleuca cuticularis	DIC	Myrtaceae		Saltwater paperbark						SW	2, 3, 23, 26a, 154a, 159a, 160	5900
Melaleuca densa	DIC	Myrtaceae								SW		5902
Melaleuca glomerata	DIC	Myrtaceae							D			5915

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Melaleuca halmaturorum	DIC	Myrtaceae								SW		5916
Melaleuca hamata	DIC	Myrtaceae								SW		19486
Melaleuca huegelii	DIC	Myrtaceae		Chenille honeymyrtle						SW		5920
Melaleuca incana	DIC	Myrtaceae		Grey honeymyrtle						SW	164a, 164b, 167a	5921
Melaleuca incana subsp. incana	DIC	Myrtaceae		Grey honeymyrtle						SW		13273
Melaleuca interioris	DIC	Myrtaceae							D			20288
Melaleuca lanceolata	DIC	Myrtaceae		Rottnest teatree						SW	22, 25a, 87, 162a, 162b	5922
Melaleuca lasiandra	DIC	Myrtaceae						K	D		68b	5923
Melaleuca lateriflora	DIC	Myrtaceae		Gorada						SW		5925
Melaleuca lateritia	DIC	Myrtaceae		Robin redbreast bush						SW	24, 30a, 107a	5926
Melaleuca leucadendra	DIC	Myrtaceae						K	D			5932
Melaleuca linophylla	DIC	Myrtaceae							D			5933
Melaleuca nervosa	DIC	Myrtaceae		Fibrebark				K	D			5942
Melaleuca osullivanii	DIC	Myrtaceae		O'sullivan's melaleuca						SW		20297
Melaleuca preissiana	DIC	Myrtaceae		Moonah, preiss's paperbark						SW	1b, 8a, 20a, 21a, 97, 100a	5952
Melaleuca rhaphiophylla	DIC	Myrtaceae		Swamp paperbark, freshwater paperbark						SW	1a, 4, 5a, 11a, 98, 161a	5959
Melaleuca scabra	DIC	Myrtaceae		Rough honeymyrtle						SW	8c, 110	5961
Melaleuca scalena	DIC	Myrtaceae								SW		20290
Melaleuca sp. Kemerton (B.J. Keighery 2907) PN	DIC	Myrtaceae								SW	125a, 125b	-21264
Melaleuca spp.	DIC	Myrtaceae						K	D	SW		-20996
Melaleuca strobophylla	DIC	Myrtaceae								SW		5972
Melaleuca systena (unnamed variant)	DIC	Myrtaceae								SW		-21418
Melaleuca teretifolia	DIC	Myrtaceae		Banbar, swamp honeymyrtle						SW		5978
Melaleuca thyoides	DIC	Myrtaceae		Scale-leaved honeymyrtle						SW		5981

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Melaleuca viminea	DIC	Myrtaceae		Mohan						SW	32a, 105a, 120a, 121, 126, 127a, 163a, 163b, 164a, 167a	5987
Melaleuca viridiflora	DIC	Myrtaceae		Broadleaf paperbark				K			53	5989
Melaleuca xerophila	DIC	Myrtaceae							D	SW		5991
Melicope elleryana	DIC	Rutaceae						K				12361
Mesomelaena tetragona	MON	Cyperaceae		Large semaphore sedge, semaphore sedge						SW		957
Meziella trifida	DIC	Haloragaceae			R	V	V			SW		6184
Mimulus gracilis	DIC	Phrymaceae							D		66a	7082
Mimulus uvedaliae	DIC	Phrymaceae							D			13721
Montia australasica	DIC	Portulacaceae		Montia	2					SW		2874
Muehlenbeckia adpressa	DIC	Polygonaceae		Climbing lignum, muehlenbeckia						SW	98	2412
Muehlenbeckia florulenta	DIC	Polygonaceae		Lignum					D	SW	61c	16982
Muehlenbeckia horrida subsp. abdita	DIC	Polygonaceae		Lignum	R	E	CR*			SW		17050
Muellerolimon salicorniaceum	DIC	Plumbaginaceae		Mueller's native statice					D	SW	33, 72, 73a	6490
Myoporum turbinatum	DIC	Scrophulariaceae		Salt myoporum	R	CR	E*			SW		7296
Myriocephalus helichrysoides	DIC	Asteraceae		Woolly-heads						SW		8117
Myriocephalus oldfieldii	DIC	Asteraceae							D		31	17925
Myriocephalus rudallii	DIC	Asteraceae							D		67b, 83c	8121
Myriocephalus sp.	DIC	Asteraceae							D			-21290
Myriophyllum balladoniense	DIC	Haloragaceae			4					SW		6186
Myriophyllum crispatum	DIC	Haloragaceae		Myriophyllum						SW	145a, 145b	6189
Myriophyllum lapidicola	DIC	Haloragaceae			R	V	E*			SW		13082
Myriophyllum petraeum	DIC	Haloragaceae		Granite myriophyllum	4					SW		6197
Myriophyllum verrucosum	DIC	Haloragaceae		Red water milfoil					D			6201
Najas marina	MON	Hydrocharitaceae		Prickly water nymph					D			138
Nauclea orientalis	DIC	Rubiaceae		Leichardt pine				K				7337
Nesaea muelleri	DIC	Lythraceae							D			12369

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Nicotiana heterantha	DIC	Solanaceae			1				D			14817
Nymphaea hastifolia	DIC	Nymphaeaceae						K			44a, 44b	13915
Nymphaea ondinea subsp. ondinea	DIC	Nymphaeaceae						K				36377
Nymphaea ondinea subsp. petaloidea	DIC	Nymphaeaceae			1			K				36378
Nymphaea violacea	DIC	Nymphaeaceae						K			44c	13916
Nymphoides aurantiaca	DIC	Menyanthaceae		Marshwort				K			45a, 45b	6545
Nymphoides beaglensis	DIC	Menyanthaceae			2			K				6546
Nymphoides crenata	DIC	Menyanthaceae		Wavy marshwort				K	D		46c	6547
Nymphoides indica	DIC	Menyanthaceae		Marshwort				K	D		46b	6549
Oldenlandia sp. nov.	DIC	Rubiaceae							D			-21385
Opercularia vaginata	DIC	Rubiaceae		Dog weed, opercularia						SW		18255
Ornduffia spp.	DIC	Menyanthaceae						K		SW		-21432
Ornduffia submersa	DIC	Menyanthaceae			4					SW	115	36200
Oryza spp.	MON	Poaceae		Native rice				K				-21360
Ottelia ovalifolia	MON	Hydrocharitaceae		Swamp lily						SW	143	168
Oxalis sp. Greenough (G.J. Keighery & B.J. Keighery 1566) PN	DIC	Oxalidaceae								SW		-21401
Pandanus aquaticus	MON	Pandanaceae						K			40	100
Pandanus spiralis	MON	Pandanaceae		Screwpine				K			55a	104
Pandanus spiralis var. flammeus	MON	Pandanaceae		Edgar range pandanus	R	E	E	K				11511
Patersonia occidentalis var. angustifolia	MON	Iridaceae		Swamp flag						SW	13c, 13d	30471
Peplidium sp. fortescue marsh (S. van Leeuwen 4865) PN	DIC	Phrymaceae			1				D			20810
Pericalymma ellipticum	DIC	Myrtaceae		Swamp teatree						SW	100a	6006
Petrophile latericola	DIC	Proteaceae		Ironstone petrophile	R	CR	E*			SW	123a, 123b	14085
Phragmites karka	MON	Poaceae		Tropical reed	3			K	D			556
Pilularia novae-hollandiae	FER	Marsileaceae		Austral pillwort						SW	17, 130a	78
Pimelea imbricata var. major	DIC	Thymelaeaceae		Swamp banjine						SW	109a	11404
Podolepis capillaris	DIC	Asteraceae		Wiry podolepis						SW		8173

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Pogonolepis stricta	DIC	Asteraceae		Pogonolepis						SW	92b	8188
Potamogeton crispus	MON	Potamogetonaceae		Curly pondweed					D			109
Potamogeton tricarinatus	MON	Potamogetonaceae		Floating pondweed					D			113
Pteridium esculentum	FER	Dennstaedtiaceae		Bracken						SW		57
Pteris vittata	FER	Pteridaceae		Chinese brake				K	D			45
Pterostylis sp. Northampton (S.D. Hopper 3349) PN	MON	Orchidaceae			R	CR	E*			SW		13868
Ptilotus polakii	DIC	Amaranthaceae							D			2750
Puccinellia stricta	MON	Poaceae		Marsh grass						SW		592
Reedia spathacea	MON	Cyperaceae			R	E	CR*			SW		958
Regelia ciliata	DIC	Myrtaceae		Mouse plant						SW		6012
Regelia inops	DIC	Myrtaceae		Mouse plant						SW		6014
Rhagodia eremaea	DIC	Chenopodiaceae		Tall saltbush, thorny saltbush					D			2582
Rhodanthe manglesii	DIC	Asteraceae		Mangles's rhodanthe						SW	121	13234
Rhodanthe pyrethrum	DIC	Asteraceae		Claypan rhodanthe	3					SW	117c	13312
Ricinocarpos trichophorus	DIC	Euphorbiaceae			R	V	E*			SW		4702
Roycea pycnophylloides	DIC	Chenopodiaceae		Saltmat	R	V	E*			SW		2588
Ruppia polycarpa	MON	Ruppiaceae		Ruppia					D			116
Ruppia tuberosa	MON	Ruppiaceae		Ruppia					D	SW		117
Salsola australis	DIC	Chenopodiaceae							D		76, 85	30434
Samolus junceus	DIC	Primulaceae		Reed samolus					D			6483
Samolus repens var. paucifolius	DIC	Primulaceae								SW	89b, 158	14107
Samolus sp. Clay Flats (G.J. & B.J. Keighery 718) PN	DIC	Primulaceae		Clay samolus						SW		29911
Sarcocornia quinqueflora	DIC	Chenopodiaceae		Beaded samphire						SW	154a	2593
Scaevola collaris	DIC	Goodeniaceae							D		65c	7604
Scaevola spinescens	DIC	Goodeniaceae		Currant bush					D			7644
Schoenolaena sp.	DIC	Apiaceae								SW		-21420
Schoenoplectus litoralis	MON	Cyperaceae							D			965
Schoenoplectus subulatus	MON	Cyperaceae							D			16257

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Schoenoplectus validus	MON	Cyperaceae		Lake club-rush						SW		969
Schoenus falcatus	MON	Cyperaceae						K			55a, 55b	989
Schoenus natans	MON	Cyperaceae		Floating schoenus, floating bog-rush	4					SW	115	1003
Schoenus plumosus	MON	Cyperaceae		Schoenus						SW		17614
Schoenus tenellus	MON	Cyperaceae		Schoenus						SW	113b	1023
Sclerolaena bicornis	DIC	Chenopodiaceae		Goathead burr					D		76	2597
Sesbania cannabina	DIC	Fabaceae		Sesbania pea				K	D			4196
Sesbania erubescens	DIC	Fabaceae						K			51	4197
Sesbania formosa	DIC	Fabaceae		White dragon tree				K	D		38c, 38d	4198
Sida trichopoda	DIC	Malvaceae							D			16923
Sonchus hydrophilus	DIC	Asteraceae		Native sowthistle					D	SW	159b	9367
Sorghum plumosum	MON	Poaceae		Sorghum, plume canegrass					D		21b, 80	619
Spermacoce sp.	DIC	Rubiaceae						K			50e	-21435
Sphagnum novozelandicum	MOS	Sphagnaceae			2					SW		30807
Sporobolus mitchellii	MON	Poaceae		Ratstail couch					D			633
Sporobolus virginicus	MON	Poaceae		Native couch, marine couch, salt couch				K	D	SW	42	635
Spyridium globulosum	DIC	Rhamnaceae		Basket bush						SW		4828
Stemodia florulenta	DIC	Plantaginaceae								SW		12487
Stylidium adenophorum	DIC	Stylidiaceae							D			17445
Stylidium brunonianum	DIC	Stylidiaceae		Pink fountain triggerplant						SW	100a, 100b	7693
Stylidium ceratophorum	DIC	Stylidiaceae						K			50c	7700
Stylidium divaricatum	DIC	Stylidiaceae		Daddy-long-legs						SW	108	7717
Stylidium ferricola	DIC	Stylidiaceae			1					SW		31872
Stylidium fissilobum	DIC	Stylidiaceae							D			7726
Stylidium fluminense	DIC	Stylidiaceae						K	D			7729
Stylidium inaequipetalum	DIC	Stylidiaceae							D		66c	7739
Stylidium leptorrhizum	DIC	Stylidiaceae							D			7750
Stylidium longitubum	DIC	Stylidiaceae		Jumping jacks	3					SW	21d, 30b, 107a	7756
Stylidium schizanthum	DIC	Stylidiaceae							D			7797
Stylidium spp.	DIC	Stylidiaceae							D	SW		-20795

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Stylidium weeliwolli	DIC	Stylidiaceae			2				D			18123
Syzygium angophoroides	DIC	Myrtaceae						K				6042
Taxandria juniperina	DIC	Myrtaceae		River peppermint						SW		20115
Taxandria linearifolia	DIC	Myrtaceae		Creek peppermint						SW		20135
Tecticornia arborea	DIC	Chenopodiaceae		Bulli bulli					D			2641
Tecticornia auriculata	DIC	Chenopodiaceae							D		72, 74a	31616
Tecticornia bibenda	DIC	Chenopodiaceae			3				D			31677
Tecticornia bulbosa	DIC	Chenopodiaceae		Large-articled samphire	R	V	V			SW		31617
Tecticornia calyptrata	DIC	Chenopodiaceae							D		70a	31917
Tecticornia chartacea	DIC	Chenopodiaceae							D		70c	31719
Tecticornia doleiformis	DIC	Chenopodiaceae		Samphire					D			31918
Tecticornia flabelliformis	DIC	Chenopodiaceae			1				D			31834
Tecticornia halocnemoides	DIC	Chenopodiaceae		Shrubby samphire					D	SW	22	33236
Tecticornia indica	DIC	Chenopodiaceae							D	SW	22	33317
Tecticornia indica subsp. bidens	DIC	Chenopodiaceae		Samphire					D			33319
Tecticornia indica subsp. leiostachya	DIC	Chenopodiaceae		Samphire					D			33318
Tecticornia pergranulata	DIC	Chenopodiaceae								SW	72	33296
Tecticornia pergranulata subsp. pergranulata	DIC	Chenopodiaceae		Blackseed samphire					D			33297
Tecticornia sp. Christmas Creek (K.A. Shepherd & T. Colmer et al. KS 1063) PN	DIC	Chenopodiaceae			1				D			34177
Tecticornia sp. Fortescue Marsh (K.A. Shepherd et al. KS 1055) PN	DIC	Chenopodiaceae			1				D			31842
Tecticornia sp. Roy Hill (H. Pringle 62) PN	DIC	Chenopodiaceae			3				D			31843
Tecticornia spp.	DIC	Chenopodiaceae						K	D			-21369
Tecticornia syncarpa	DIC	Chenopodiaceae		Samphire						SW		31716
Tecticornia triandra	DIC	Chenopodiaceae		Desert glasswort					D			31494
Tecticornia undulata	DIC	Chenopodiaceae							D	SW	72	31717
Tecticornia uniflora	DIC	Chenopodiaceae		Mat samphire	4					SW		31493

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Tecticornia verrucosa	DIC	Chenopodiaceae							D	SW		2642
Templetonia retusa	DIC	Fabaceae		Cockies tongues						SW		4256
Terminalia canescens	DIC	Combretaceae		Joolal				K				5300
Thelymitra antennifera	MON	Orchidaceae		Vanilla orchid, lemon-scented sun orchid						SW	32c	1701
Themeda triandra	MON	Poaceae		Kangaroo grass					D			673
Thomasia triphylla	DIC	Malvaceae		Thomasia						SW		5105
Thysanotus chinensis	MON	Asparagaceae							D			1326
Timonius timon	DIC	Rubiaceae						K				7364
Trachymene pilosa	DIC	Araliaceae		Small laceflower, native parsnip						SW		6280
Trianthema oxycalyptra	DIC	Aizoaceae		Star pigweed					D			2827
Trianthema triquetra	DIC	Aizoaceae		Red spinach					D			2832
Tribonanthes aff. longipetala	MON	Haemodoraceae								SW	131	-21431
Tribonanthes purpurea	MON	Haemodoraceae		Granite pink	R	V	V			SW		1484
Tribonanthes uniflora	MON	Haemodoraceae	N	Tribonanthes						SW	114	8798
Trichanthodium exile	DIC	Asteraceae								SW		12650
Triglochin mucronata	MON	Juncaginaceae		Triglochin						SW	157b	147
Triglochin muelleri	MON	Juncaginaceae		Mueller's triglochin						SW		148
Triglochin striata	MON	Juncaginaceae		Triglochin						SW		151
Triodia pungens	MON	Poaceae		Soft spinifex					D			696
Triraphis mollis	MON	Poaceae		Needle grass				K				706
Trithuria occidentalis	MON	Hydatellaceae		Swan hydatella	R	CR	E*			SW		32658
Trithuria submersa	MON	Hydatellaceae		Trithuria						SW	30c	1141
Typha domingensis	MON	Typhaceae		Bulrush, native bulrush					D	SW		98
Typha sp.	MON	Typhaceae						K				-21357
Utricularia chrysantha	DIC	Lentibulariaceae		Sun bladderwort				K			50g	7130
Utricularia fulva	DIC	Lentibulariaceae						K			50f	-21424
Utricularia gibba	DIC	Lentibulariaceae		Yellowcoats					D			12493
Utricularia menziesii	DIC	Lentibulariaceae		Redcoats						SW	129a, 129b	7145
Utricularia multifida	DIC	Lentibulariaceae		Pink petticoats						SW	32a, 120a, 126	7148

Scientific plant name	Supra code	Family name	Current	Common names	Listed conservation taxa			Wetland zone			Figure no.	Name ID
					Consv code	WA IUCN rank	EPBC rank	K	D	SW		
Utricularia volubilis	DIC	Lentibulariaceae		Twining bladderwort						SW		7158
Utricularia westonii	DIC	Lentibulariaceae								SW		7159
Verticordia chrysantha	DIC	Myrtaceae		Yellow featherflower						SW	8b, 108	6073
Verticordia huegelii	DIC	Myrtaceae		Variegated featherflower						SW	8b, 108	6088
Verticordia plumosa var. pleiobotrya	DIC	Myrtaceae		Mundijong featherflower	R	V	E			SW	8b, 106a, 106b, 108	12452
Verticordia spp.	DIC	Myrtaceae								SW		-21439
Viminaria juncea	DIC	Fabaceae		Swishbush						SW	24a, 109a, 111a, 111b, 125	4325
Wahlenbergia queenslandica	DIC	Campanulaceae							D			7390
Whiteochloa cymbiformis	MON	Poaceae							D			728
Wilsonia backhousei	DIC	Convolvulaceae		Narrow-leaf wilsonia						SW	154a, 156b	6658
Wilsonia humilis	DIC	Convolvulaceae		Silky wilsonia						SW	89a	6659
Wurmbea dioica subsp. alba	MON	Colchicaceae		Early nancy						SW		12072
Wurmbea dioica subsp. Brixton (G.J. Keighery 12803) PN	MON	Colchicaceae	N	Swamp wurmbea						SW	120a, 120b	-20194
Wurmbea monantha	MON	Colchicaceae		Wurmbea						SW		1398
Wurmbea saccata	MON	Colchicaceae			3				D			16813
Wurmbea tubulosa	MON	Colchicaceae		Long-flowered nancy	R	V	E*			SW		1404
Xanthorrhoea brunonis	MON	Xanthorrhoeaceae		Squat balga						SW	100a	1251
Xanthorrhoea preissii	MON	Xanthorrhoeaceae		Balga, grass tree						SW	6, 10	1256
Xerochloa barbata	MON	Poaceae		Rice grass				K				729
Xerochloa laniflora	MON	Poaceae		Rice grass				K				731
Xyris complanata	MON	Xyridaceae						K			57	1142
Xyris exilis	MON	Xyridaceae			R	E	V*			SW		17482
Xyris lanata	MON	Xyridaceae								SW	135a, 135b	1150
Xyris maxima	MON	Xyridaceae			2					SW		17481
Zygophyllum simile	DIC	Zygophyllaceae		Little twinleaf					D			12359

Key to Appendix 2.

Native wetland vascular plant taxa of the Southern Swan Coastal Plain (Moore River–Dunsborough) referred to in this topic, or otherwise common to the region.

Column 1	**Scientific plant name**	
	Genus + species + infra species rank + infra species name + informal name. Some taxa yet to be formally described and named may have a reference collection number from the relevant collector. Taxa (genera, species, subspecies and varieties) are listed alphabetically within families. Names follow Western Australian Herbarium[81] except for those indicated as not having a current name (see column 4)	
	subsp.	Subspecies
	var.	Variety
	ms	A manuscript name yet to be published
	PN	A phrase name for a taxon yet to be described and published.

Column 2	**Supra code**	
	Indicates broad supra-family classification.	
	FER	Ferns
	GYM	Gymnosperms
	MON	Monocotyledons
	DIC	Dicotyledons

Column 3	**Family name**

Column 4	**Current**
	Scientific plant names are current (Western Australian Herbarium[81]) unless indicated with 'N'. In these cases, the authors prefer to use the names chosen.

Column 5	**Endemic (state)**
	Sources for common names are the Western Australian Herbarium[81] and others as applied in references for this section.

Column 6	**Growth form 1** (See key to growth forms at the end of this key for definitions)	
	Woody plants	
	T	Tree
	M	Mallee
	SH/T	Shrub/tree
	SH	Shrub
	SH-H	Shrub which is often called a herb
	Non-woody plants: non-grass-like	
	H	Herb
	H-SH	Herb which is often called a shrub
	Non-woody plants: grass-like	
	G	Grass
	S-C	Sedge – Cyperaceae and others
	S-R	Sedge – Restionaceae
	S-J	Sedge – Juncaceae and others

Column 7	**Growth form 2** (See key to growth forms at the end of this key for definitions)	
	CL	Climber
	PR	Prostrate

Column 8	**Life form**	
	A	Annual
	A2	Biennial
	P	Perennial
	PAA	Perennial annually renewed from above ground part
	PAB	Perennial annually renewed from below ground part
	A-PAR	Annual – parasite or semi-parasite
	P-PAR	Perennial – parasite or semi-parasite

Column 9	**Life form aquatic**	
	AQD	Aquatic – damp flowering. Grows in water, flowers in damp mud
	AQE	Aquatic – emergent. Grows and flowers in water with some parts emergent above water (e.g. leaves, flowers)
	AQF	Aquatic – floating. Whole plant floats on water
	AQS	Aquatic – supported. Grows and flowers in water with most parts supported by water (e.g. leaves); flowers may be emergent above water

Column 10	**Common SSWA wetland species**
	From an analysis of more than 1,000 plots on the southern Swan Coastal Plain, there were 166 most commonly encountered wetland species (150 native species). Commonly encountered species were determined to be those that occurred in ten or more plots of wetland floristic community types 75 per cent or more of the time.

Column 11	**Name ID**
	Positive name IDs are from the Census of Western Australian Plants (Western Australian Herbarium[11, 81])

Key to growth form defintions

Definitions adapted from BJ Keighery[3], McDonald et al.[110] and Executive Steering Committee for Australian Vegetation Information[111]

Growth form 1

Woody plants

Plants with special thick-walled cells in their trunks and stems that form wood to support the plant. Trees are able to build up layer upon layer of this woody support tissue to form trunks and branches. All woody plants are perennial.

Tree	Plants with a single trunk and a canopy. The canopy is less than or equal to two-thirds of the height of the trunk. No lignotuber is evident.
Shrub/tree	Shrub or tree
Mallee	Plants with many trunks (usually 2–5) arising from a lignotuber. The canopy is usually well above the base of the plant. Most are from the genus *Eucalyptus*.
Shrub-herb	Shrub that appears herb-like. Plants with a woody stem/s that is lax enough to give the shrub a non-woody herb-like appearance, often called sub-shrubs.

Non-woody plants

Plants with no (or insufficient) special thick-walled support cells in their stems to form wood for support. May be either annuals or perennials. Sub-divided according to growth form, pollination method and plant family.

Non-woody plants – non grass-like

Generally not pollinated by wind; monocots and dicots

Herb	Plants with non-woody stems that are not grasses or sedges. Generally under half a metre tall. Most monocots are herbs except for the larger ones which are classed as shrubs such as palms, grass trees (*Xanthorrhoea* and *Kingia* species) and cycads (*Zamia* species).
Herb-shrub	Herb that appears shrub-like. Plants with non-woody stems that are stiff enough to give the herb a woody shrub-like appearance, often called sub-shrubs.

Non-woody plants – grass-like

Generally pollinated by wind; from the families Poaceae, Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae or Xyridaceae

Grasses	Leaf sheath always split, ligule present, leaf usually flat, stem cross-section circular, evenly spaced internodes.
Grass	Tufted or spreading plants from the family Poaceae. Some species form hummocks but none of these occur in south-west WA.
Sedges	Leaf sheath never split (except in some Restionaceae), usually no ligule, leaf not always flat, extended internode below inflorescence.
Sedge – Cyperaceae and others	Tufted or spreading plants from the families Cyperaceae, Centrolepidaceae, Hydatellaceae or Juncaginaceae.
Sedge – Restionaceae	Tufted or spreading plants from the family Restionaceae. Commonly called rushes.
Sedge – Juncaceae and others	Tufted or spreading plants from the families Juncaceae, Typhaceae or Xyridaceae. Some of these are also called rushes.

Growth form 2

Climber	Plants in need of other plants or objects for support.
Prostrate	Spreading plants, often supported by the ground.

Appendix 2. Native wetland vascular plant taxa of the southern Swan Coastal Plain (Moore River–Dunsborough) referred to in this topic, or otherwise common to the region

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Acacia acuminata	DIC	Fabaceae	Y	WA	SH/T		P			3200
Acacia cyclops	DIC	Fabaceae	Y	AUST	SH		P			3282
Acacia flagelliformis	DIC	Fabaceae	Y	WA	SH		P			3339
Acacia rostellifera	DIC	Fabaceae	Y	WA	SH/T		P			3525
Acacia saligna	DIC	Fabaceae	Y	WA	SH		P			3527
Acidonia microcarpa	DIC	Proteaceae	Y	WA	SH		P			10824
Actinostrobus acuminatus	GYM	Cupressaceae	N	WA	SH	PR	P			89
Actinostrobus pyramidalis	GYM	Cupressaceae	N	WA	T		P		y	91
Adenanthos meisneri	DIC	Proteaceae	Y	WA	SH	PR	P			1790
Allocasuarina campestris	DIC	Casuarinaceae	Y	WA	SH		P			1721
Amblysperma minor	DIC	Asteraceae	N	WA	H		PAB	AQD		25842
Amphibromus nervosus	MON	Poaceae	Y	WA	G		P	AQD	y	13380
Amphibromus vickeryae	MON	Poaceae	Y	WA	G		P			10758
Anarthria scabra	MON	Anarthriaceae	Y	WA	S-R		P			1063
Andersonia ferricola	DIC	Ericaceae	Y	WA	SH		P	AQD		18102
Andersonia gracilis	DIC	Ericaceae	Y	WA	SH		P	AQD		6309
Angianthus drummondii	DIC	Asteraceae	Y	WA	H		A	AQD		7829
Angianthus preissianus	DIC	Asteraceae	Y	AUST	H		A	AQD	y	7833
Angianthus tomentosus	DIC	Asteraceae	Y	WA	H		A			7836
Anthotium junciforme	DIC	Goodeniaceae	Y	WA	H		A/P			12724
Aotus cordifolia	DIC	Fabaceae	Y	WA	SH		P			3686
Aphelia drummondii	MON	Centrolepidaceae	Y	WA	S-C		A	AQD		1118
Aponogeton hexatepalus	MON	Aponogetonaceae	Y	WA	H		PAB	AQF	y	141
Astartea affinis	DIC	Myrtaceae	Y	WA	SH		P	AQD	y	20350
Asteridea athrixioides	DIC	Asteraceae	Y	WA	H		A			7846
Avicennia marina	DIC	Acanthaceae	Y	>AUST	T		P	AQE		6828
Azolla filiculoides	FER	Salviniaceae	Y	AUST	H		P	AQF		80
Azolla pinnata	FER	Salviniaceae	Y	AUST	H		P	AQF		17737
Banksia littoralis	DIC	Proteaceae	Y	WA	T		P		y	1830

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Baumea articulata	MON	Cyperaceae	Y	>AUST	S-C		P	AQE	y	741
Baumea juncea	MON	Cyperaceae	Y	>AUST	S-C		P		y	743
Baumea riparia	MON	Cyperaceae	Y	WA	S-C		P	AQE		746
Baumea rubiginosa	MON	Cyperaceae	Y	WA	S-C		P	AQE		747
Baumea vaginalis	MON	Cyperaceae	Y	WA	S-C		P	AQE	y	748
Beaufortia sparsa	DIC	Myrtaceae	Y	WA	SH		P			5392
Blennospora doliiformis	DIC	Asteraceae	Y	WA	H		A	AQD	y	20026
Borya constricta	MON	Boryaceae	Y	WA	H		P			1267
Brachyscome bellidioides	DIC	Asteraceae	Y	WA	H		A		y	7867
Brachyscome pusilla	DIC	Asteraceae	Y	WA	H		A			7883
Burchardia bairdiae	MON	Colchicaceae	Y	WA	H		PAB		y	1383
Burchardia multiflora	MON	Colchicaceae	Y	WA	H		PAB		y	1385
Caladenia paludosa	MON	Orchidaceae	Y	WA	H		PAB	AQD		15503
Calandrinia granulifera	DIC	Portulacaceae	Y	AUST	H		A			2854
Callistachys lanceolata	DIC	Fabaceae	Y	WA	SH/T		P			10861
Calothamnus hirsutus	DIC	Myrtaceae	Y	WA	SH		P		y	5411
Calothamnus lateralis	DIC	Myrtaceae	Y	WA	SH		P		y	5415
Casuarina obesa	DIC	Casuarinaceae	Y	WA	T		P	AQE	y	1742
Caustis dioica	MON	Cyperaceae	Y	WA	S-C		P			760
Centella asiatica	DIC	Apiaceae	Y	>AUST	H	PR	P			6214
Centrolepis polygyna	MON	Centrolepidaceae	Y	AUST	S-C		A			1134
Chaetanthus aristatus	MON	Restionaceae	Y	WA	S-R		P	AQD/AQE	y	17685
Chamaescilla gibsonii	MON	Asparagaceae	Y	WA	H		PAB	AQD		19338
Chamelaucium sp. C Coastal Plain (Chamelaucium roycei ms)	DIC	Myrtaceae	N	WA	SH		P			13627
Chordifex isomorphus	MON	Restionaceae	Y	WA	S-R		P	AQD		17828
Chorizandra enodis	MON	Cyperaceae	Y	AUST	S-C		P	AQD	y	763
Cyathochaeta teretifolia	MON	Cyperaceae	Y	WA	S-C		P	AQD/AQE		16245
Cyclosorus interruptus	FER	Thelypteridaceae	Y	AUST	H	PR	P	AQD/AQE		54
Darwinia foetida	DIC	Myrtaceae	Y	WA	SH		P			34773
Darwinia whicherensis	DIC	Myrtaceae	Y	WA	SH		P	AQD		34765

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Dillwynia dillwynioides	DIC	Fabaceae	Y	WA	SH		P	AQD		3863
Diuris micrantha	MON	Orchidaceae	Y	WA	H		PAB			12938
Drosera gigantea subsp. gigantea	DIC	Droseraceae	Y	WA	H		PAB	AQD	y	15453
Drosera glanduligera	DIC	Droseraceae	Y	AUST	H		A		y	3098
Drosera menziesii subsp. menziesii	DIC	Droseraceae	Y	WA	H		PAB	AQD		11853
Drosera tubaestylis	DIC	Droseraceae	Y	WA	H		PAB	AQD		13205
Eleocharis acuta	MON	Cyperaceae	Y	AUST	S-C		PAB	AQE		822
Eleocharis keigheryi	MON	Cyperaceae	Y	WA	S-C		PAB	AQE		17605
Eleocharis sphacelata	MON	Cyperaceae	Y	>AUST	S-C		P	AQE		831
Eremophila glabra subsp. chlorella	DIC	Scrophulariaceae	Y	WA	SH		P	AQD		17150
Eryngium ferox ms	DIC	Apiaceae	Y	WA	H		PAB			19602
Eryngium pinnatifidum subsp. palustre ms	DIC	Apiaceae	Y	WA	H		PAB	AQE	y	14553
Eryngium subdecumbens ms	DIC	Apiaceae	Y	WA	H		PAB	AQD		14720
Eucalyptus foecunda	DIC	Myrtaceae	Y	WA	M		P			5649
Eucalyptus rudis subsp. cratyantha	DIC	Myrtaceae	Y	WA	T/M		P	AQD		13512
Eucalyptus rudis subsp. rudis	DIC	Myrtaceae	Y	WA	T		P	AQD	y	13511
Euchilopsis linearis	DIC	Fabaceae	Y	WA	SH		P			3872
Evandra aristata	MON	Cyperaceae	Y	WA	S-C		P			834
Ficinia nodosa	MON	Cyperaceae	Y	>AUST	S-C		P			20216
Fimbristylis velata	MON	Cyperaceae	Y	>AUST	S-C		P			894
Frankenia pauciflora	DIC	Frankeniaceae	Y	AUST	SH		P			5209
Gahnia trifida	MON	Cyperaceae	Y	AUST	S-C		P		y	907
Gastrolobium ebracteolatum	DIC	Fabaceae	Y	WA	SH/T		P			20473
Gastrolobium papilio	DIC	Fabaceae	Y	WA	SH		P	AQE		20509
Glossostigma diandrum	DIC	Phrymaceae	Y	AUST	H		A	AQD		7060
Glossostigma drummondii	DIC	Phrymaceae	Y	AUST	H		A	AQD		7061
Grevillea curviloba subsp. curviloba	DIC	Proteaceae	Y	WA	SH	PR	P			14408
Grevillea curviloba subsp. incurva	DIC	Proteaceae	Y	WA	SH	PR	P			14409
Grevillea elongata	DIC	Proteaceae	Y	WA	SH		P			14526
Grevillea maccutcheonii	DIC	Proteaceae	Y	WA	SH		P			17112
Grevillea obtusifolia	DIC	Proteaceae	Y	WA	SH	PR	P			8836

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Haemodorum simplex	MON	Haemodoraceae	Y	WA	H		PAB		y	1472
Hakea ceratophylla	DIC	Proteaceae	Y	WA	SH		P		y	2137
Hakea oldfieldii	DIC	Proteaceae	Y	WA	SH		P			2190
Hakea varia	DIC	Proteaceae	Y	WA	SH		P		y	2216
Hemichroa diandra	DIC	Amaranthaceae	Y	AUST	H	PR	P			2688
Hibbertia perfoliata	DIC	Dilleniaceae	Y	WA	SH	CL	P			5154
Hibbertia stellaris	DIC	Dilleniaceae	Y	WA	SH		P	AQD	y	5172
Homalospermum firmum	DIC	Myrtaceae	Y	WA	SH		P			5816
Hyalosperma cotula	DIC	Asteraceae	Y	WA	H		A			12741
Hydrocotyle lemnoides	DIC	Araliaceae	Y	WA	H		A	AQF		6233
Hydrocotyle tetragonocarpa	DIC	Araliaceae	Y	WA	H		A			6241
Hypocalymma angustifolium	DIC	Myrtaceae	Y	WA	SH		P			5817
Hypolaena exsulca	MON	Restionaceae	Y	WA	S-R		P			1070
Hypoxis occidentalis var. occidentalis	MON	Hypoxidaceae	Y	WA	H		PAB		y	11736
Isoetes drummondii	FER	Isoetaceae	Y	AUST	H		PAB	AQD		11
Isolepis cernua	MON	Cyperaceae	Y	>AUST	S-C		A		y	910
Isopogon formosus subsp. dasylepis	DIC	Proteaceae	Y	WA	SH		P		y	16522
Isotoma pusilla	DIC	Campanulaceae	Y	WA	H		A			7398
Isotoma scapigera	DIC	Campanulaceae	Y	WA	H		A			7399
Isotropis cuneifolia subsp. glabra	DIC	Fabaceae	Y	WA	H-SH		P	AQD		16317
Jacksonia gracillima	DIC	Fabaceae	Y	WA	SH/T		P			20462
Juncus kraussii subsp. australiensis	MON	Juncaceae	Y	>AUST	S-J		P	AQD/AQE	y	11922
Juncus pallidus	MON	Juncaceae	Y	>AUST	S-J		P		y	1188
Kennedia coccinea	DIC	Fabaceae	Y	WA	H	PR	P			4037
Kunzea recurva	DIC	Myrtaceae	Y	WA	SH		P		y	5841
Lambertia echinata subsp. occidentalis	DIC	Proteaceae	Y	WA	SH		P			17734
Lawrencia squamata	DIC	Malvaceae	Y	AUST	SH		P			4959
Lepidosperma gladiatum	MON	Cyperaceae	Y	AUST	S-C		P			933
Lepidosperma longitudinale	MON	Cyperaceae	Y	AUST	S-C		P		y	937
Leptomeria ellytes	DIC	Santalaceae	Y	WA	SH		P-PAR			17703
Loxocarya magna	MON	Restionaceae	Y	WA	S-R		P	AQD/AQE		13779

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Lycopodiella serpentina	FER	Lycopodiaceae	Y	>AUST	H		P	AQD		12783
Marsilea drummondii	FER	Marsileaceae	Y	AUST	H		PAB	AQF		74
Meeboldina cana	MON	Restionaceae	Y	WA	S-R		P	AQD/AQE	y	17683
Meeboldina coangustata	MON	Restionaceae	Y	WA	S-R		P	AQD/AQE	y	17679
Meeboldina scariosa	MON	Restionaceae	Y	WA	S-R		P	AQD/AQE	y	17694
Melaleuca brevifolia	DIC	Myrtaceae	Y	WA	SH		P			5881
Melaleuca cuticularis	DIC	Myrtaceae	Y	WA	T		P	AQD	y	5900
Melaleuca incana subsp. incana	DIC	Myrtaceae	Y	WA	SH		P	AQD	y	13273
Melaleuca lanceolata	DIC	Myrtaceae	Y	AUST	SH/T		P			5922
Melaleuca lateritia	DIC	Myrtaceae	Y	WA	SH		P	AQD	y	5926
Melaleuca osullivanii	DIC	Myrtaceae	Y	WA	SH		P		y	20297
Melaleuca preissiana	DIC	Myrtaceae	Y	WA	T		P		y	5952
Melaleuca rhaphiophylla	DIC	Myrtaceae	Y	WA	SH		P	AQD	y	5959
Melaleuca scabra	DIC	Myrtaceae	Y	WA	SH		P			5961
Melaleuca teretifolia	DIC	Myrtaceae	Y	WA	SH		P		y	5978
Melaleuca thyoides	DIC	Myrtaceae	Y	WA	SH		P			5981
Melaleuca viminea subsp. viminea	DIC	Myrtaceae	Y	WA	SH		P	AQD	y	13280
Mesomelaena tetragona	MON	Cyperaceae	Y	WA	S-C		P			957
Montia australasica	DIC	Portulacaceae	Y	>AUST	H		PAB	AQE		2874
Muehlenbeckia adpressa	DIC	Polygonaceae	Y	AUST	SH	CL	P			2412
Muellerolimon salicorniaceum	DIC	Plumbaginaceae	Y	AUST	H-SH		P			6490
Myriocephalus helichrysoides	DIC	Asteraceae	Y	WA	H		A	AQD	y	8117
Myriophyllum crispatum	DIC	Haloragaceae	Y	AUST	H		A	AQE		6189
Myriophyllum verrucosum	DIC	Haloragaceae	Y	AUST	H		P	AQE		6201
Najas marina	MON	Hydrocharitaceae	Y	>AUST	H		P	AQS		138
Opercularia vaginata	DIC	Rubiaceae	Y	WA	SH-H		P			18255
Ornduffia submersa	DIC	Menyanthaceae	Y	WA	H		PAB	AQS		36200
Ottelia ovalifolia subsp. ovalifolia	MON	Hydrocharitaceae	Y	>AUST	H		PAB	AQS		14531
Patersonia occidentalis var. angustifolia	MON	Iridaceae	Y	WA	H		P		y	30471
Pericalymma ellipticum	DIC	Myrtaceae	Y	WA	SH		P		y	6006
Petrophile latericola	DIC	Proteaceae	Y	WA	SH		P	AQD		14085

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Pilularia novae-hollandiae	FER	Marsileaceae	Y	AUST	H		PAB	AQD		78
Pimelea imbricata var. major	DIC	Thymelaeaceae	Y	WA	SH		P	AQD	y	11404
Podolepis capillaris	DIC	Asteraceae	Y	AUST	H		P			8173
Pogonolepis stricta	DIC	Asteraceae	Y	AUST	H		A		y	8188
Pteridium esculentum	FER	Dennstaedtiaceae	Y	AUST	H		P			57
Pteris vittata	FER	Pteridaceae	Y	AUST	H	PR	P	AQD/AQE		45
Regelia ciliata	DIC	Myrtaceae	Y	WA	SH		P		y	6012
Regelia inops	DIC	Myrtaceae	Y	WA	SH		P			6014
Rhodanthe manglesii	DIC	Asteraceae	Y	WA	H		A			13234
Rhodanthe pyrethrum	DIC	Asteraceae	Y	WA	H		A	AQD		13312
Ruppia polycarpa	MON	Ruppiaceae	Y	>AUST	H		A/P	AQS		116
Ruppia tuberosa	MON	Ruppiaceae	Y	AUST	H		PAB	AQS		117
Samolus junceus	DIC	Primulaceae	Y	WA	H		P	AQD/AQE	y	6483
Sarcocornia quinqueflora	DIC	Chenopodiaceae	Y	>AUST	SH		P	AQD	y	2593
Schoenoplectus validus	MON	Cyperaceae	Y	>AUST	S-C		P	AQE		969
Schoenus natans	MON	Cyperaceae	Y	WA	S-C		A	AQS		1003
Schoenus plumosus	MON	Cyperaceae	Y	WA	S-C		A		y	17614
Schoenus tenellus	MON	Cyperaceae	Y	WA	S-C		A	AQE	y	1023
Sonchus hydrophilus	DIC	Asteraceae	Y	AUST	H		A/P	AQD/AQE		9367
Sporobolus virginicus	MON	Poaceae	Y	>AUST	G		P	AQD	y	635
Spyridium globulosum	DIC	Rhamnaceae	Y	AUST	SH		P			4828
Stylidium divaricatum	DIC	Stylidiaceae	Y	WA	H		P		y	7717
Stylidium longitubum	DIC	Stylidiaceae	Y	WA	H		A	AQD	y	7756
Taxandria juniperina	DIC	Myrtaceae	Y	WA	SH		P			20115
Taxandria linearifolia	DIC	Myrtaceae	Y	WA	SH		P		y	20135
Tecticornia indica subsp. bidens	DIC	Chenopodiaceae	Y	>AUST	SH		P	AQD		33319
Tecticornia pergranulata subsp. pergranulata	DIC	Chenopodiaceae	Y	AUST	SH		P	AQD		33297
Tecticornia syncarpa	DIC	Chenopodiaceae	Y	WA	SH		P			31716
Templetonia retusa	DIC	Fabaceae	Y	AUST	SH		P			4256
Thelymitra antennifera	MON	Orchidaceae	Y	WA	H		PAB		y	1701
Themeda triandra	MON	Poaceae	Y	>AUST	G		P			673

Scientific plant name	Supra code	Family name	Current	Endemic	Growth form 1	Growth form 2	Life form	Life form aquatic	Common SSWA wetland species	Name ID
Thomasia triphylla	DIC	Malvaceae	Y	WA	SH		P			5105
Trachymene pilosa	DIC	Araliaceae	Y	AUST	H		A			6280
Tribonanthes uniflora	MON	Haemodoraceae	N	WA	H		PAB	AQD		8798
Triglochin mucronata	MON	Juncaginaceae	Y	AUST	S-C		A		y	147
Triglochin striata	MON	Juncaginaceae	Y	>AUST	S-C		P			151
Trithuria occidentalis	MON	Hydatellaceae	Y	WA	S-C		A	AQE		32658
Trithuria submersa	MON	Hydatellaceae	Y	WA	S-C		A	AQD/AQE		1141
Typha domingensis	MON	Typhaceae	Y	>AUST	S-J		PAB	AQE		98
Utricularia gibba	DIC	Lentibulariaceae	Y	>AUST	H		P	AQS		12493
Utricularia menziesii	DIC	Lentibulariaceae	Y	WA	H		PAB	AQD		7145
Utricularia multifida	DIC	Lentibulariaceae	Y	WA	H		A	AQD	y	7148
Utricularia volubilis	DIC	Lentibulariaceae	Y	WA	H	CL	PAB	AQE		7158
Verticordia chrysantha	DIC	Myrtaceae	Y	WA	SH		P			6073
Verticordia plumosa var. pleiobotrya	DIC	Myrtaceae	Y	WA	SH		P			12452
Viminaria juncea	DIC	Fabaceae	Y	AUST	SH/T		P		y	4325
Wilsonia backhousei	DIC	Convolvulaceae	Y	AUST	H	PR	P	AQD		6658
Wurmbea dioica subsp. alba	MON	Colchicaceae	Y	AUST	H		PAB		y	12072
Wurmbea dioica subsp. Brixton (G.J. Keighery 12803) PN	MON	Colchicaceae	N	WA	H		PAB	AQD		-20194
Wurmbea monantha	MON	Colchicaceae	Y	WA	H		PAB			1398
Xanthorrhoea brunonis	MON	Xanthorrhoeaceae	Y	WA	SH		P			1251
Xanthorrhoea preissii	MON	Xanthorrhoeaceae	Y	WA	SH		P			1256
Xyris lanata	MON	Xyridaceae	Y	WA	S-J		P	AQE		1150

Appendix 3. Data used in graphs and charts in this topic

Table 1. Data used for Figure 69: Internally Drained Desert wetland and dryland vascular plant taxa found in various plant groups (after Jessop[27])

Group	Wetland	Dryland
Ferns	12	6
Gymnosperms	0	3
Monocotyledons	30	133
Dicotyledons	114	1,245
Total (% total flora)	**156 (10.1%)**	**1,387 (89.9%)**

Table 2. Data used for Figure 84: Pilbara wetland and dryland vascular plant taxa found in various plant groups (after Western Australian Herbarium[75])

Group	Wetland (% wetland flora)	Dryland
Mangroves (saline)	8 (2%)	
Saline	31 (8%)	
Freshwater	103 (26.5%)	
Seasonally waterlogged freshwater	246 (63.4%)	
Total (% total flora)	**388 (25.7%)**	**1,121 (74.3%)**

Table 3. Data used for Figure 133: Endemism of wetland and dryland vascular plant taxa of the southern Swan Coastal Plain

Group	Wetland	Dryland	Total
>Australia	49 (11.1%)	30 (2.1%)	79
Australian Endemic	67 (15.1%)	179 (12.6%)	256
WA Endemic	327 (73.8%)	1,224 (85.4%)	1,551
Total	**443**	**1,434**	**1,877**

Table 4. Data used for Figure 134: Plant groups of the wetland and dryland vascular plant taxa of the southern Swan Coastal Plain

Group	Wetland	Dryland	Total
Ferns	15 (3.4%)	5 (0.3%)	20
Gymnosperms	1 (0.2%)	6 (0.4%)	7
Monocotyledons	207 (46.7%)	337 (26.3%)	544
Dicotyledons	220 (49.7%)	1,046 (72.9%)	1,266
Total	**443 (24%)**	**1,434 (76%)**	**1,877**

Table 5. Data used for Figure 138: Growth forms groups of wetland and dryland vascular plants of the southern Swan Coastal Plain

Group	Wetland	Dryland	Total
Trees	9 (2%)	26 (1.8%)	35
Mallees	0 (0%)	5 (0.3%)	5
Shrubs	85 (19.2%)	727 (50.7%)	812
Grasses	14 (3.2%)	35 (2.4%)	49
Sedges	123 (27.8%)	105 (7.3%)	228
Herbs	212 (47.9%)	536 (37.4%)	748

Table 6. Data used for Figure 139: Life forms of wetland and dryland vascular plants of the southern Swan Coastal Plain

Group	Wetland	Dryland	Total
Annual	95 (21.4%)	131 (9.1%)	226
Annual or Perennial	8 (1.8%)	8 (0.6%)	16
Perennial	340 (76.7%)	1,295 (90.3%)	1,635
Total	**443**	**1,434**	**1,877**

Table 7. Data used for Figure 140: Life form groups of wetland and dryland vascular plants of the southern Swan Coastal Plain

Habitat	Annual (A)	Annual or Perennial (A/P)	Perennial (P)	Perennial annually renewed, above ground part (PAA)	Perennial annually renewed from storage organ (PAB)	Perennial Parasite (P-PAR)
Wetland	95 (21.4%)	8 (1.8%)	237 (53.5%)	4 (0.9%)	98 (22.1%)	1 (0.2%)
Dryland	131 (9.1%)	8 (0.6%)	1,095 (76.4%)	11 (0.8%)	162 (11.3%)	27 (1.9%)

Table 8. Data used for Figure 142: Life form of annually renewed groups of wetland and dryland plants of the southern Swan Coastal Plain

Habitat	Annually renewed (A, PAA, PAB)	Perennial annually renewed, above ground part (PAA)	Perennial annually renewed from storage organ (PAB)	Total (% total wetland or dryland plants)
Wetland	95 (48.2%)	4 (2%)	98 (49.8%)	197 (44.5%)
Dryland	131 (43.1%)	11 (3.7%)	162 (53.3%)	304 (21.2%)

Table 9. Data used for Figure 144: Life forms of aquatic vascular plants of the southern Swan Coastal Plain (443 total)

Post inundation (AQD)	Dampland/emergent (AQD/AQE)	Emergent (AQE)	Floating (AQF)	Submerged (AQS)	Total aquatic taxa (% total wetland plants)
163 (60.2%)	35 (12.9%)	51 (18.8%)	9 (3.3%)	13 (4.8%)	271 (61%)

A guide to managing and restoring wetlands in Western Australia

Wetland vegetation and flora, part 2: Kimberley

In Chapter 2: **Understanding wetlands**

Australian Government

Department of Environment and Conservation

Our environment, our future

Contents

Wetland profiles

Introduction

Western Australia is a very large state and there is a great deal of variability in wetland vegetation and flora across it. The Kimberley is one of three major climatic and biogeographical zones (Figure 35):

- Kimberley – tropical, warm to hot all year, summer rainfall and a dry winter
- Deserts – hot desert, infrequent erratic rainfall
- Southwest – Mediterranean, warm to hot dry summer, cool wet winter.

The differing climate of these three regions drives important variations in wetland vegetation.

The next major driver of Kimberley wetland vegetation and flora characteristics is whether they inhabit freshwater or saline wetlands. Wetland plant communities are distinctive of the zone and water chemistry, contributing both to the local and state identity and contributing greatly to the uniqueness of WA and Australia.

Thirdly, in addition to zone and freshwater/saline divisions, the Kimberley wetlands can be grouped according to the similarity of their vegetation characteristics. In the Kimberley zone, these groups are:

- coastal and estuarine saline wetlands
- alluvial flats
- dune swamps of truncated drainage lines
- springs
- perched wetlands.

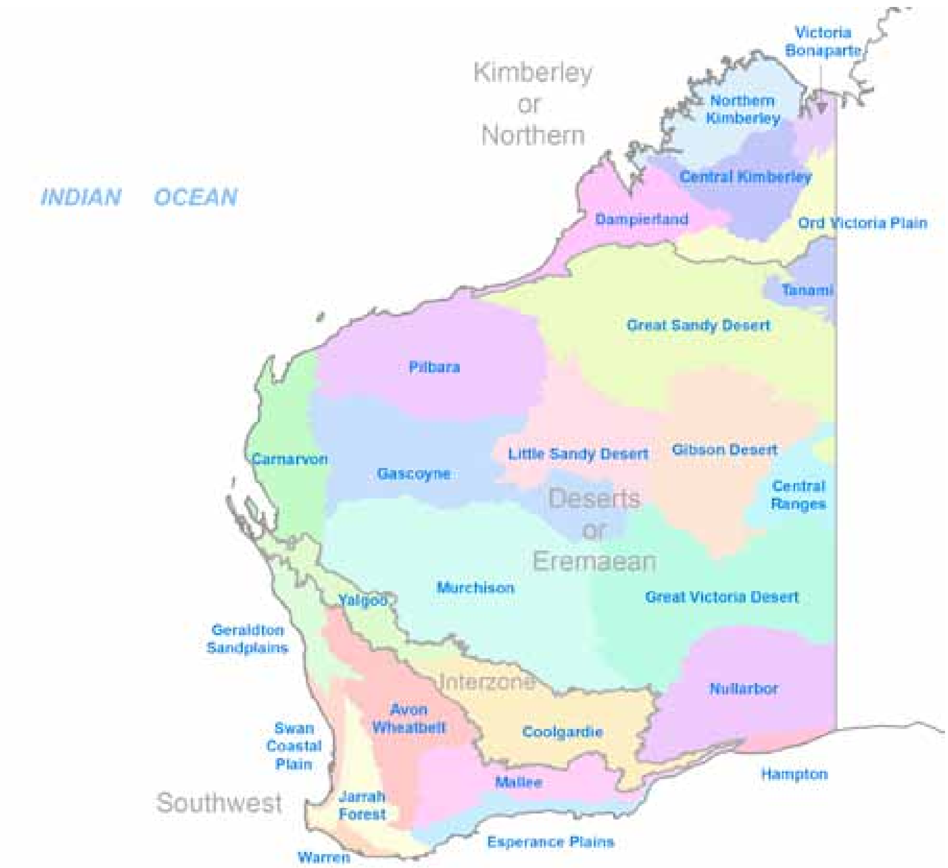

Figure 35. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

Kimberley

The summer rainfall Kimberley (or Northern Province) of WA comprises five natural regions: the Central Kimberley, Dampierland, Northern Kimberley, Ord-Victoria Plains and part of the Victoria-Bonaparte (the remainder is in the Northern Territory).

Kimberley wetlands are largely fresh and generally associated with the large river systems (Figure 36). These wetlands have a large number of species only evident during the wet season, being annually renewed from seed or underground storage organs. These annually renewed species contribute greatly to the species richness of the communities. These wetlands are largely intact.

Figure 36. Kimberley landscape-scale nationally significant wetlands of the Ord River in the North Kimberley. Photos – G Keighery/DEC.
(a), (b) and (d) Ord Estuary; (c) Parry Lagoons.

Wetland vegetation of the Kimberley

More than one hundred Kimberley wetland plant communities have been described in literature. Except for a set of perched wetlands, most of the Kimberley wetlands are associated with rivers and/or the coast; however, these wetlands can be so extensive they should be described as wetlands in this treatment. Coastal and river fringing vegetation is not covered here.

Savanna: a grassy woodland; grassland with small or widely spaced trees so that the canopy is always open allowing a continuous layer of grasses underneath

Most of the Kimberley is dryland covered in tropical **savanna** grasslands with an overstorey of trees and/or shrubs with variable cover. The principal dominant genera are *Eucalyptus* or *Acacia*. Besides this, the Kimberley is vegetated with forests, woodlands, samphire shrublands, shrublands, bunch grasslands (dominated by perennial grasses, other than spinifex), tropical savanna grasslands (dominated by a complex of species including spinifex), sedgelands and herblands. The samphire shrublands are confined to wetlands, and the forests, sedgelands and herblands are rare outside of wetlands. Common dominant plants of the wetlands include the trees *Melaleuca argentea* (Figure 37), *M. cajuputi*, *M. leucadendra*, *M. viridiflora*, *Eucalyptus camaldulensis* and *Sesbania formosa* (Figure 38), *Barringtonia acutangula* (Figure 39) and the shrub *Pandanus aquaticus* (Figure 40). While not dominant, *Acacia neurocarpa* (Figure 41) is notable as it is virtually confined to the Kimberley, with only a few occurrences in the Internally Drained Deserts.

There are nineteen listed nationally significant wetlands in the Kimberley.[54] However, as with the other zones, the Kimberley supports significant wetlands that have not yet been considered for listing as nationally significant.

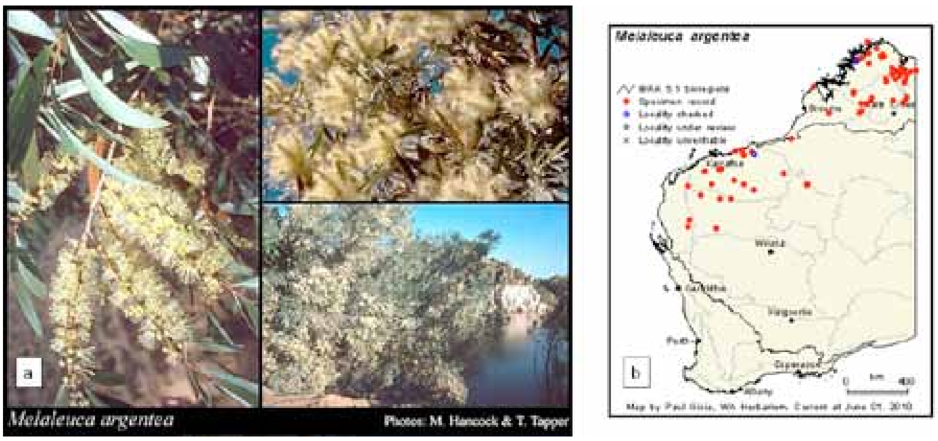

Figure 37. (a) and (b) *Melaleuca argentea* is a widespread wetland species in the Kimberley and Externally Drained Deserts. Photos – M Hancock and T Tapper. Mapping – P Gioia.

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Figure 38 (below). Two widespread wetland trees found in wetlands in the Kimberley.

(a) and (b) *Eucalyptus camaldulensis* is a widespread wetland species in the Kimberley, Deserts and northern Southwest (changes over to *E. rudis* south of Geraldton; the original Perth area population was introduced (planted) and many weed populations now exist in Perth). Photos – M Hancock and SD Hopper. Mapping – P Gioia.

(c) and (d) *Sesbania formosa* is widespread in the Kimberley and Externally Drained Deserts with outliers in the Internally Drained Deserts. Photos – G Byrne. Mapping – P Gioia.

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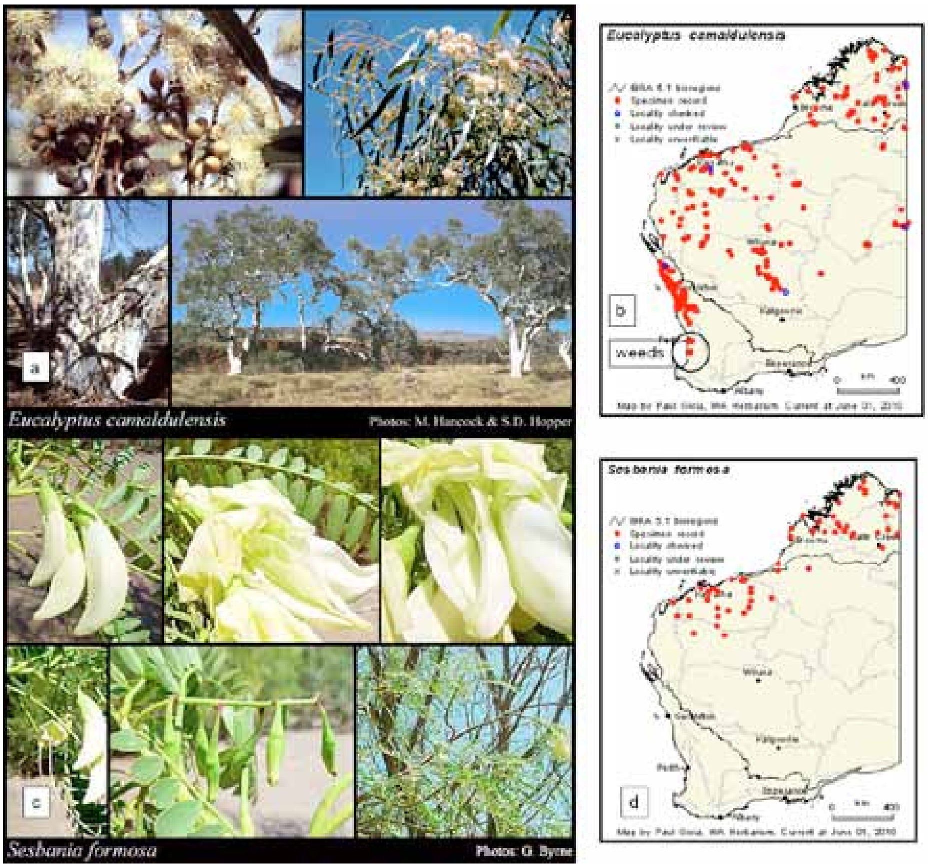

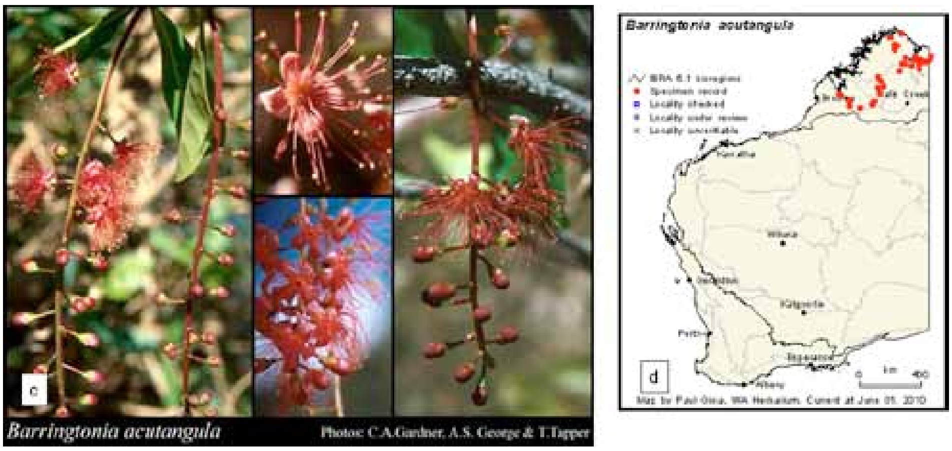

Figure 39. *Barringtonia acutangula* is a common dominant wetland tree that is virtually confined to the Kimberley. Photos – CA Gardner, AS George and T Tapper. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

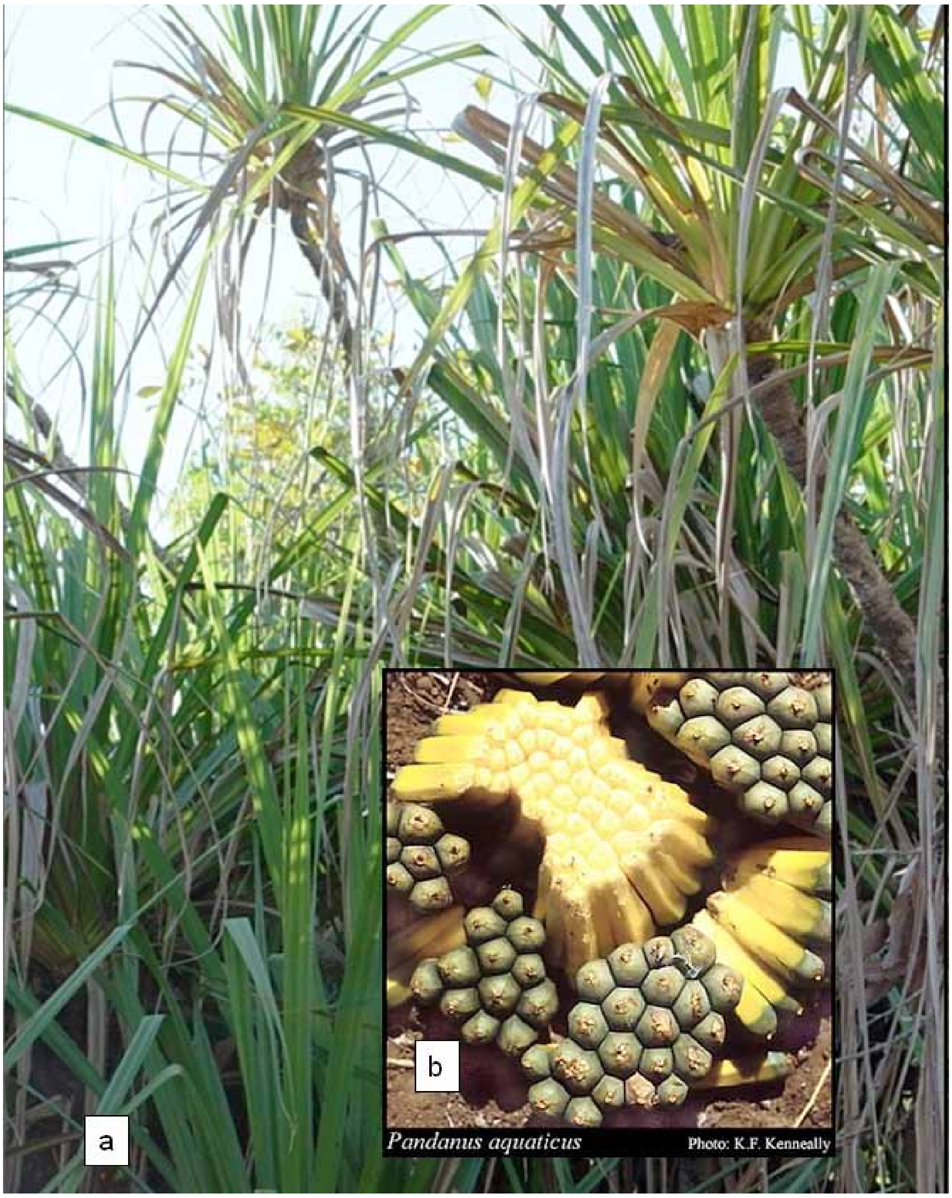

Figure 40. *Pandanus aquaticus* is a widespread tropical wetland shrub (a) with conspicuous fruit (b). Photo (a) taken in the Northern Territory. Photos – (a) B Keighery/OEPA (b) KF Kenneally. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

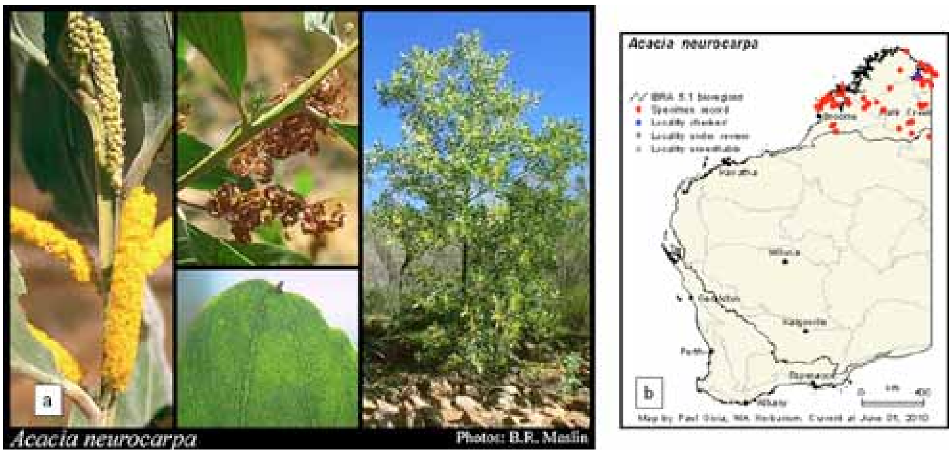

Figure 41. *Acacia neurocarpa* (a) is virtually confined to the Kimberley (b). Photo – BR Maslin. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

Saline wetlands of the Kimberley

The Kimberley contains only coastal and estuarine saline wetlands; there are no known saline lakes. These saline wetlands are dominated by **mangrove** forests and woodlands, which form rich and diverse habitats and are described in Semeniuk et al.[55]

Mangrove: any of various tropical or semi-temperate trees or shrubs of the genera *Rhizophora*, *Bruguiera* and *Avicennia* growing in intertidal shore mud with many tangled roots above the ground

The largest areas of saline wetlands are found along the edges of Roebuck Bay (south-east of Broome, Dampierland) and extend along Eighty Mile Beach to the De Grey River. The typical pattern is a sequence of communities from sea to dry land with, from the sea, mangrove forests and woodlands, samphire shrublands and then grasslands typically dominated by *Sporobolus virginicus* (Figure 42).

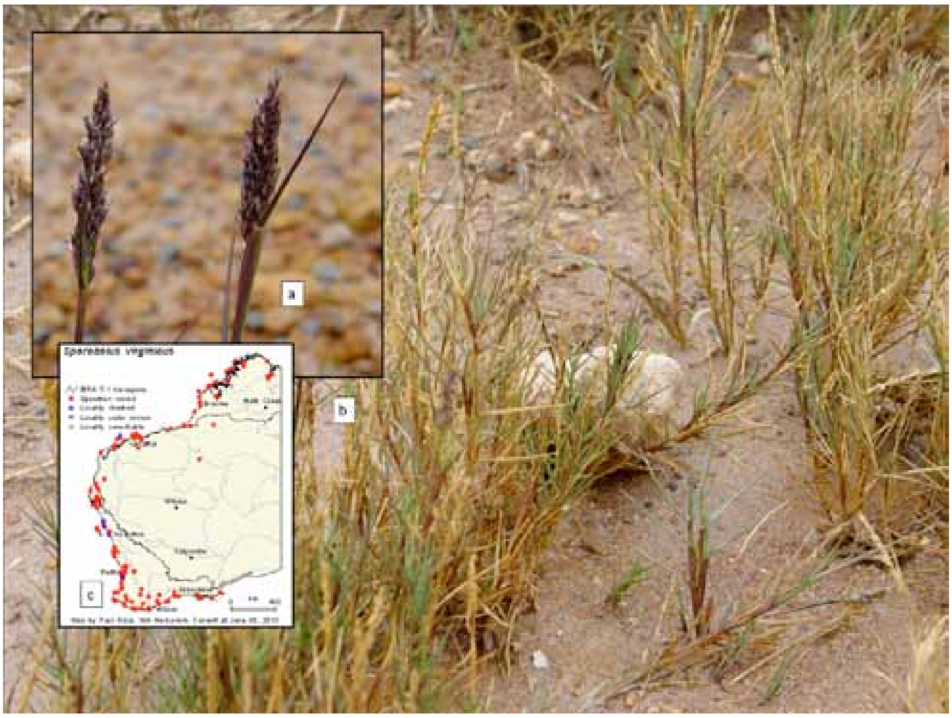

Figure 42. *Sporobolus virginicus* flowers (a) and habit (b), a widespread, virtually cosmopolitan, generally coastal species of saline wetlands (c) in WA. Photos – B Keighery/OEPA. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

The saline wetlands of the Roebuck Plains along Eighty Mile Beach are very complex wetlands with the more inland freshwater areas merging with the adjacent tidally inundated coastal saline wetlands. This vast wetland system covers 48,000 hectares, an area almost as large as the adjacent mudflats. The plains flood every 5–10 years and were formerly dominated by perennial grasslands composed mainly of *Sporobolus virginicus*, *Xerochloa barbata*, *Enneapogon purpurascens* and *Triraphis mollis* and combinations of these species. However, the weed buffel grass (*Cenchrus ciliaris*) has invaded these wetlands and now forms the dominant cover. Buffel grass (Figure 43) was introduced as livestock forage. It is shade and fire tolerant, and adapted to frequent defoliation. It reproduces by seed and short rhizome and is dispersed primarily by wind and water, also mammals (on skin and fur), birds and vehicles. It has developed resistance to some post-emergent herbicides.[11] In the wet season a rich and diverse suite of annual herbs are associated with the grasslands, especially when they flood.

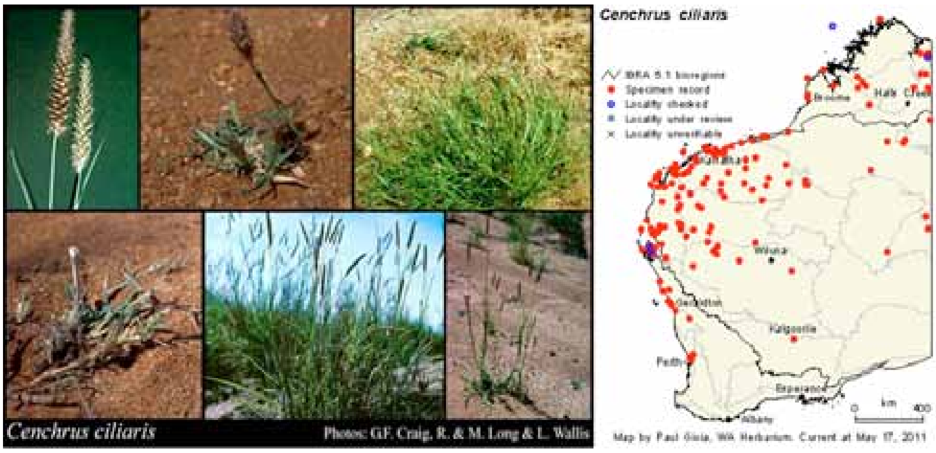

Figure 43. Buffel grass (*Cenchrus ciliaris*) (a) is a widespread weed (b) which has replaced a suite of perennial grasses in the saline wetlands of the Roebuck Plains. Photos – GF Craig, R & M Long and L Wallis. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

Alluvial soil: soil deposited by flowing water on floodplains, in river beds, and in estuaries

Other areas of saline, brackish and freshwater wetlands are the poorly documented coastal grasslands and wetlands found on the eastern side of the false mouths of the Ord River, and, further east, those on the Chenier Beach ridges and flats (north of Kununurra). These back and adjoin the Ord River Floodplain*, a saline estuarine wetland of tidal flats and mangrove swamps.

Freshwater wetlands of the Kimberley

The vegetation of the freshwater Kimberley wetlands is described under a set of principal wetland groups: alluvial flats, dune swamps of truncated drainage lines, springs and perched wetlands.

Permanently and seasonally inundated basin wetlands (that is, lakes and sumplands) are rare in the Kimberley. The largest permanently inundated freshwater wetlands in the Kimberley, Lake Argyle* and Lake Kununurra* (100,000–200,000 hectares) (Victoria Bonaparte), are human made. These support fringing vegetation and aquatics identical to that of the permanent river pools. Lake Kununurra is eutrophic and also supports a series of weeds such as *Leucaena leucocephala* in the forest vegetation fringing the water.

Alluvial flats

The Kimberley's high rainfall supports a set of very significant large river systems being the Drysdale*, Fitzroy, Lennard, Mitchell*, Ord* (Figure 36) and Prince Regent rivers. These rivers and their associated wetlands constitute the majority of the listed nationally important wetlands in the region.[9] There is no discrete boundary between the 'river' vegetation and the vegetation of these wetlands. The largest and most complex freshwater wetlands have developed on the **alluvial soils** deposited by these rivers, either along their course or at their mouths. These wetlands include the Parry Floodplain* (c. 9,000 hectares) of the Ord River and the Camballin Floodplain* (Le Lievre Swamp System, c. 30,000 hectares) on the Fitzroy. The different river systems support a diverse suite of plant communities, some of which are described below.

Other freshwater wetlands are creeks with their fringing vegetation and the riverine/creek pools that often remain during the dry. A variety of trees fringe and/or cover the pools including *Melaleuca argentea*, *M. cajuputi*, *M. leucadendra*, *Eucalyptus camaldulensis*, *Barringtonia acutangula*, *Sesbania formosa* and *Pandanus aquaticus*. Numerous floating aquatics grow in the pools, especially the genera *Nymphaea* (Figure 44), *Aponogeton*, *Nymphoides* (Figure 45 and Figure 46), *Ornduffia* (previously *Villarsia*), and *Eriocaulon* (Figure 46).

Figure 44. Aquatic waterlilies. *Nymphaea hastifolia* (a and b) and *N. violacea* (c). These photos were taken in the Northern Territory. Photos – B Keighery/OEPA.

Figure 45. A tropical wetland with *Melaleuca* forest over an aquatic herbland dominated by *Nymphoides aurantiaca* (a), with detail of the *Nymphoides* flower (b). This photo was taken in the Northern Territory. Photos – B Keighery/OEPA.

Figure 46. Three tropical aquatic species: *Eriocaulon setaceum* (a), *Nymphoides indica* (b), and *N. crenata* (c). The aquatic *Nymphoides* and *Eriocaulon* genera are almost confined to the Kimberley in WA but have outliers in the Deserts. *Nymphoides* has nine species in WA and Eriocaulon eighteen.[11] These photos were taken in the Northern Territory. Photos – B Keighery/ OEPA.

The Parry Floodplain* (Victoria Bonaparte) supports a complex mosaic of floodplain, billabongs, seasonal marshes and wooded swamps and is the largest of the few substantial tropical floodplains in WA. As well as being listed as a nationally important wetland, Parry Floodplain is listed jointly with the Ord Estuary System as a Wetland of International Importance under the Ramsar Convention. Rarely recorded communities such as native rice (*Oryza* species) and brown beetle grass (*Leptochloa fusca*) grasslands, budda pea (*Aeschynomene indica*) herblands and sedgelands dominated by *Eleocharis brassii*, and the reed *Phragmites karka* occur here. The rare *Pandanus spiralis* closed forest community is associated with the Parry Floodplain's Palm Spring. Numerous aquatics are found in the inundated areas (Figure 44 to Figure 48).

Figure 47. *Blyxa* sp., a common submerged aquatic from the Kimberley. Photo – B Keighery/ OEPA.

Two principal wetland types, basins and flats, are found in the Camballin Wetlands (Dampierland). The basins are covered with forests of *Eucalyptus* and *Melaleuca* and fresh water mangroves (*Barringtonia acutangula*), *Typha* sedgelands and herblands of *Sesbania cannabina*. The flats are grasslands dominated by mitchell grass (*Astrebla* species), *Chrysopogon fallax* and *Dichanthium* species (Figure 48). In the wet season these flats support a rich annual flora in both the periods of inundation and drying (Figure 44 to Figure 46, Figure 49 and Figure 50).

Figure 48. A tropical wetland grassland dominated by *Dichanthium sericeum* (a), and detail of the *Dichanthium inflorescence* (b). This photo was taken in the Northern Territory. Photos – B Keighery/OEPA.

Figure 49. A tropical wetland annual sedgeland and herbland in soils with a clay fraction. This photo was taken in the Northern Territory. Photo – B Keighery/OEPA.

Figure 50. (a) A tropical wetland annually renewed sedgeland and herbland in soils with a clay fraction, with inserts of species from these communities: (b) *Cartonema spicatum*, (c) *Stylidium ceratophorum*, (d) a *Lindernia* species, (e) a *Spermacoce* species, (f) *Utricularia fulva*, and (g) *U. chrysantha* detail. These photos were taken in the Northern Territory. Photos – B Keighery/ OEPA.

Another alluvial flat wetland group is the elongate estuarine wetlands complex associated with drowned river valleys. The best examples of this group are in Walcott Inlet (North Kimberley) at the mouths of the Isdell, Calder and Charnley rivers. The wetlands include areas of estuary, river, riverine floodplain and scarp-foot seepage rainforests. Part of this complex is the Munja Lagoon, a freshwater swamp which supports a diverse aquatic flora including waterlilies (*Nymphaea violacea*, Figure 44) and dense fringing beds of the sedge *Eleocharis dulcis* (the largest known stands in the Kimberley). Another interesting community occurs in the small areas of Seepage Swamp Rainforest dominated by *Melaleuca*, *Ficus* species, *Nauclea orientalis* and *Celtis philippensis*. This community is floristically unique and is listed as the TEC 'Assemblages of Walcott Inlet rainforest swamps'. Another TEC of a similar type is the 'Assemblages of Roe River rainforest swamp' (North Kimberley).

Alluvial flats subject to seasonal flooding are found throughout the Kimberley. These are associated with all soil/rock types and support a diverse range of grasses and herbs. Examples include the grasslands dominated by mitchell (*Astrebla* species) or feathertop (*Aristida* species) grasses on black cracking clay soils in Bungle Bungles[56] (north-east of Halls Creek, Ord Victoria Plains) and those dominated by *Leptochloa fusca* and *Xerochloa laniflora* on claypans with cracking clays in the Edgar Ranges (south-east of Broome, Dampierland). These alluvial soil communities are more diverse in the wetter north, central and east Kimberley but they are poorly documented. An example from the north, on the Walcott Inlet, is the extensive grasslands dominated by spear grass (*Heteropogon contortus*) and wanderrie grass (*Eriachne festucacea*) with scattered trees of *Eucalyptus tectifica*, *Corymbia greeniana*, *C. confertiflora*, *Terminalia canescens*, *Gardenia megasperma* and *Erythrophleum chlorostachys*.

As noted previously, the coastal section of the Roebuck Plains* (Dampierland) is saline influenced; the plains themselves are an extensive floodplain that, interestingly, now lacks any major riverine input. These plains contain many types of freshwater wetlands, including seasonally flooded grassland, permanently inundated freshwater lakes, seasonally inundated freshwater lakes and marshes. The permanently inundated[57] Lake Eda supports emergent *Sesbania erubescens* shrubs and a sedgeland dominated by *Eleocharis spiralis* (Figure 51) over the herb *Phyla nodiflora* and the grass *Cynodon dactylon*. It is yet to be determined if *Phyla nodiflora* and *Cynodon dactylon* are native or weed taxa in this wetland.

Figure 51. *Sesbania erubescens* (foreground) and a sedgeland dominated by *Eleocharis spiralis* at Lake Eda. Photo – Wetlands Section/DEC.

Dune swamps of truncated drainage lines

In sandy areas such as the Dampier Peninsula (Dampierland), coastal dunes truncate (that is, cut off/terminate) drainage lines to form freshwater swamps.[58] These typically support low woodlands of *Lophostemon grandiflorus*, *Melaleuca alsophila* and *M. viridiflora*. As these swamps dry a rich annual herb/grassland develops. Rarely, these result in permanently inundated wetlands, such as at Beagle Bay (Dampierland) where the lakes have a range of unusual aquatics including *Nymphaea violacea* and *Nymphoides indica*, at their southern limits, and the endemic *Nymphoides beaglensis*.

Springs

Freshwater seepages forming springs are found throughout the region and are typically associated with drainage lines or impeded groundwater flow. Many of these support rainforest communities, being woodlands or forests not dominated by the *Eucalyptus* or *Acacia* genera.[59] These communities are fire sensitive and are now restricted to relatively fire-protected sites, including wetlands.

An example is the unique Willie Creek Wetlands* found north of Broome on the tidally inundated mudflats (Dampierland). Here are two spring-fed wetlands, Nimalaica Swamp and an unnamed lake. These are vegetated with spike rush (*Eleocharis dulcis*) sedgelands, *Melaleuca cajuputi*, *Timonius timon* and *Pandanus spiralis* forest. Many of the species found here are at their southern range limits or are disjunct populations.

Another type of spring is found in the east Kimberley. An example of this type is Point Springs (north-east of Kununurra, Victoria Bonaparte) which supports a closed canopy rainforest dominated by *Canarium australianum*, *Carallia brachiata*, *Melicope elleryana*, *Ficus racemosa* and *F. virens* and combinations of these. Rainforest patches are rare in the lowland east Kimberley, this area normally being dominated by open savanna woodlands.

Similar rainforest communities are associated with the cliff-foot springs in the Devonian limestone ranges (Oscar and Napier ranges of the Central Kimberley and Nimbing Ranges of the Victoria Bonaparte). It is reported that many of these are drying through dewatering of the karst system, by bores for livestock water and irrigation. One rainforest community is listed as the TEC 'Assemblages of Theda Soak rainforest swamp' (Northern Kimberley).

In places the seepages form organic mound springs. Each mound spring appears to support a unique community, with a forest of *Melaleuca cajuputi* and/or *Timonius timon*, and spike rush (*Eleocharis dulcis*) sedgelands being key elements. Black Springs (North Kimberley), Big Springs* (Dampierland), Lolly Well (Dampierland) and Bunda Bunda Springs* (Dampierland) support such communities. Of these three are listed as TECs: 'Black Spring organic mound spring community', 'Assemblages of Big Springs organic mound springs' and 'Assemblages of Bunda Bunda organic mound spring'. Another five mound springs are associated with the Drysdale River (North Kimberley) and have been listed as the TEC 'Organic mound spring communities of the North Kimberley Bioregion'. These are generally covered in sedgeland with a sparse overstorey of *Melaleuca nervosa*, *Pandanus spiralis* and *Banksia dentata* (Figure 52), or in the case of the Black Spring, a forest of *Melaleuca viridiflora*, *Ficus* species, *Timonius timon* and *Pandanus spiralis* with fringing *Phragmites karka* grassland.

Figure 52. *Banksia dentata* is a widespread tropical wetland tree. This photo was taken in the Northern Territory. Photo – B Keighery/OEPA.

In a deeply incised gully in the Edgar Ranges (south-west of Broome, Dampierland) a series of pools fed by the permanent Logues Spring are vegetated with a woodland of *Eucalyptus microtheca* and an endemic variety of pandanus, *Pandanus spiralis* var. *flammeus*.[60] Gorges in the Bungle Bungles (Ord Victoria Plains) contain permanent pools with rare aquatics and lined by relict disjunct rainforest of *Melaleuca leucadendra*, *Melicope elleryana* and *Syzygium angophoroides*.

Perched wetlands

Perched wetlands are relatively uncommon in the region but they are typically quite similar to the wetlands of the alluvial flats. Seasonally inundated freshwater basins and swamps include Airfield Swamp[61] on the Mitchell Plateau (North Kimberley) with forests of *Melaleuca* species (Figure 53) over a diverse annually renewed aquatic flora (Figure 44) and herblands as the wetlands dry (Figure 49 and Figure 50). Lake Gladstone* (Central Kimberley) is covered with a sedgeland of *Eleocharis dulcis* and fringed by woodlands of *Barringtonia acutangula* and *Eucalyptus camaldulensis*.[62] Rarely, some are even found on offshore islands; for example on the Sir Graham Moore Islands (North Kimberley) there is a large swamp with woodlands of *Melaleuca viridiflora* and sedgelands of *Fuirena ciliaris*. Herblands on basalt were recorded on Wargul Island (North Kimberley, Figure 54), and these are also common on the adjacent mainland. A dampland (seasonally waterlogged basin) on Mary Island (North Kimberley) also appears to be perched and has scattered *Pandanus spiralis* over *Schoenus falcatus* sedgeland (Figure 55).

Figure 53. *Melaleuca viridiflora* forest over *Eleocharis dulcis* sedgeland at Airfield Swamp. Photo – Wetlands Section/DEC.

Figure 54. A perched wetland on basalt on Wargul Island (North Kimberley) with a herbland of *Byblis guehoi* (a). *Byblis guehoi* (b) is one of six *Byblis* species currently known from wetlands in WA.[11] Photo – G Keighery/DEC.

Figure 55. A dampland on Mary Island (North Kimberley) of scattered *Pandanus spiralis* over *Schoenus falcatus* sedgeland (a) and a *Schoenus falcatus* plant (b). Annual sedges and herbs are found in the bare patches in the wet season. Photo – G Keighery/DEC.

Wetland flora of the Kimberley

Pan-tropical: distributed throughout the tropical regions of the Earth

The systematic allocation to wetland or dryland habitats of all taxa listed in the *Flora of the Kimberley*[24] results in a list of 1,977 native vascular plant taxa for the Kimberley, of which approximately 535 (27 per cent) are considered to be wetland obligates, that is, restricted to wetlands (Table 3).

Table 3. Kimberley vascular plant taxa found in various plant groups (after Wheeler et al.[24])

Group	Wetland obligate taxa					Wetland facultative & dryland
	Saline	Freshwater submerged or floating aquatic	Freshwater emergent aquatic	Freshwater seasonally waterlogged wetlands	Obligate wetlands, total	Wetland facultative & dryland
Ferns	2	1	7	22	32	15
Gymnosperms	0	0	0	0	0	5
Monocotyledons	0	24	9	190	223	281
Dicotyledons	30	30	14	206	280	1,141
Total	**32**	**55**	**30**	**418**	**535**	**1,442**

Of particular note is that thirty-two of fifty-seven ferns are confined to, or reliant on, wetlands. The composition of this wetland flora is markedly different to the dryland flora and the presence of wetland habitats contributes greatly to the richness and diversity of the flora of the Kimberley. For example, the families Aponogetonaceae, Alismataceae, Lentibulariaceae and Menyanthaceae are entirely aquatic. In addition, all of the following are wetland plants in the Kimberley: all of the Centrolepidaceae and all members of the genera *Nymphoides* (seven species, Figure 45 and Figure 46), *Utricularia* (twenty-seven species, Figure 50f&g), *Eleocharis* (thirteen species), *Cyperus* (fifty species, Figure 56a&b), *Fimbristylis* (most of the c. 60 species, Figure 56c&d) and *Xyris* (Figure 57). Interestingly, a number of genera are species diverse in wetlands in both the Kimberley and the Southwest, including the genera *Drosera* (Figure 28), *Stylidium* (Figure 29) and *Xyris* (Figure 57).

Most of the Kimberley saline and floodplain wetland taxa are either **pan-tropical** or widespread across northern Australia, as is also the case with the Northern Territory wetland flora.[25] However, in WA there is a significant endemic element, especially in those wetlands of the North Kimberley that are inundated only after unpredictable rain. Of particular note is the endemic waterlily genus *Ondinea* (sometimes placed in the genus *Nymphaea*) that occurs on the high rainfall sandstone areas of the north-western Kimberley. Two subspecies are currently recognised; both are endemic and one (*Ondinea purpurea* subsp. *petaloidea*) is highly restricted. This endemic element is also found in the dryland flora.

Figure 56 (below). Two tropical wetland sedges: *Cyperus aquatilis* (a and b) which is confined to the Kimberley and *Fimbristylis caespitosa* (c and d) which is virtually confined to the Kimberley. Photos – (a) C Budgen, D Clarke and T Whiteway; and (b) CP Campbell. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC.
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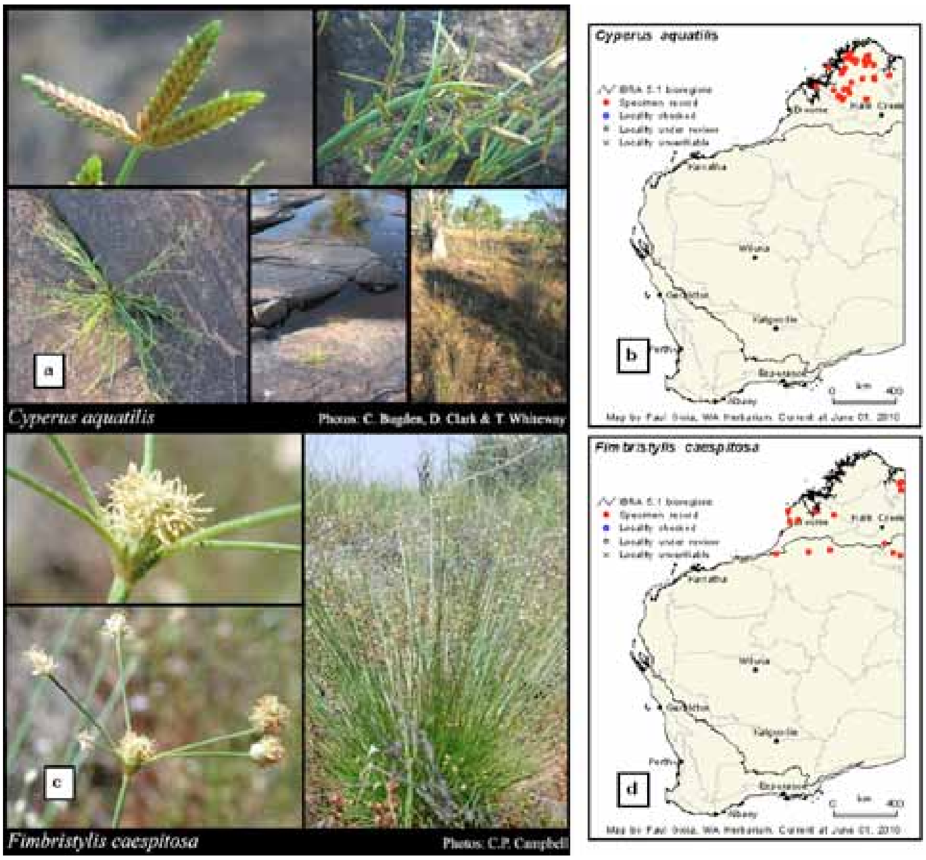

Figure 57. A tropical wetland with *Eucalyptus* forest over a sedgeland dominated by *Xyris complanata* (a), with detail of the *Xyris* flowers (b). This photo was taken in the Northern Territory. Members of the *Xyris* genus are found in Kimberley and Southwest wetlands; they all have yellow flowers. Photos – B Keighery/OEPA.

A guide to managing and restoring wetlands in Western Australia

Wetland vegetation and flora, part 3: Desert

In Chapter 2: **Understanding wetlands**

Australian Government

Department of Environment and Conservation

Our environment, our future

Contents

Wetland profiles

Introduction

Western Australia is a very large state and there is a great deal of variability in wetland vegetation and flora across it. The Deserts are one of three major climatic and biogeographical zones (Figure 58):

- Kimberley – tropical, warm to hot all year, summer rainfall and a dry winter
- Deserts – hot desert, infrequent erratic rainfall
- Southwest – Mediterranean, warm to hot dry summer, cool wet winter.

The differing climate of these three regions drives important variations in wetland vegetation.

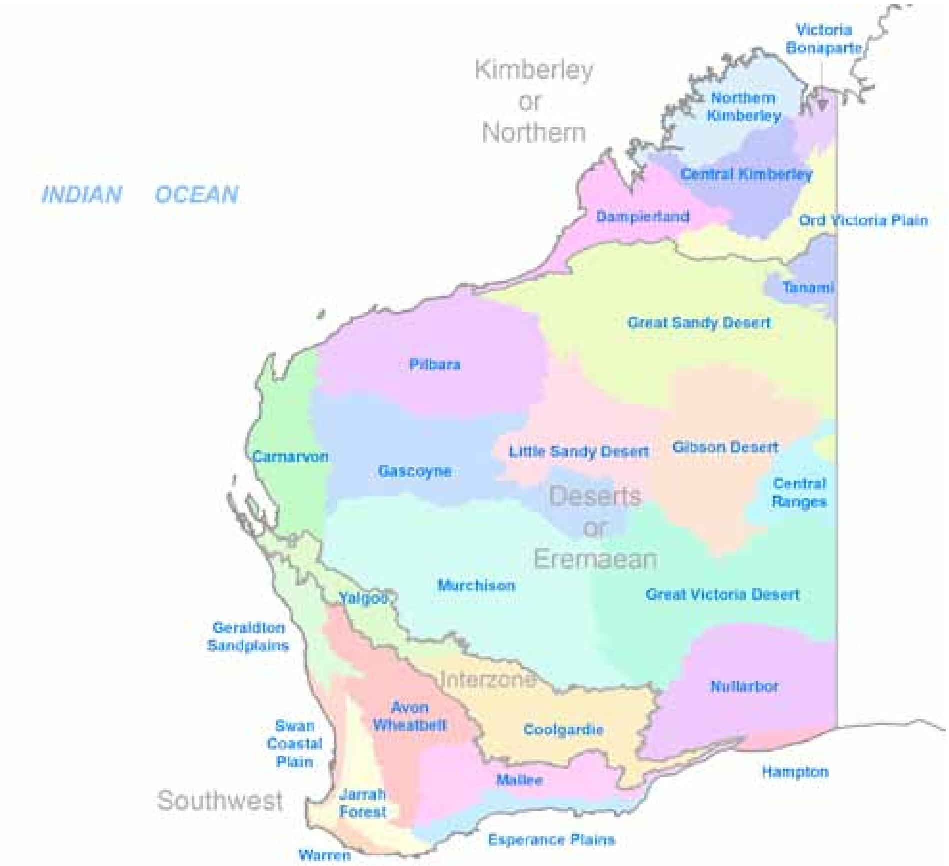

Figure 58. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

The next major driver of the wetland vegetation and flora characteristics of the Deserts is whether they inhabit freshwater or saline wetlands. Wetland plant communities are distinctive of the zone and water chemistry, contributing both to the local and state identity and contributing greatly to the uniqueness of WA and Australia.

Thirdly, in addition to zone and freshwater/saline divisions, the Desert wetlands can be grouped according to the similarity of their vegetation characteristics. In the Desert zone, these groups are:

- Internally Drained Deserts
    - extensive saline wetland chains
    - playas and barlkarras
    - springs
    - claypans
    - riverine

- Externally Drained Deserts
    - saline riverine
    - saline lakes
    - alluvial flats
    - springs
    - seasonally waterlogged wetlands
    - claypans.

Deserts

The arid zone of WA encompasses most of the land area of the state. Over this huge area the erratic rainfall patterns can be tropical (summer), bixeric (erratic non-seasonal rain) or winter rainfall, and combinations of these. Generally, the majority of the Desert wetlands are saline and species poor (Figure 59). The uncommon freshwater wetlands are major refugia for plants and animals[63] at a national scale with many species showing great range disjunctions.

Figure 59. The dry salt encrusted bed of Lake Disappointment (Tanami) with a band of samphire shrubland and surrounding low dunes. Photo – W Thompson.

Two distinct forms of drainage are present in the Desert, and these influence wetland types. Accordingly, the Desert vegetation and flora is split into two key subzones:

- Internally Drained Deserts: central deserts with internal or uncoordinated drainage (occluded tertiary palaeo-drainage systems)
- Externally Drained Deserts: western externally drained deserts which extend to the coast.

The western Externally Drained Deserts are more diverse in all wetland types and contain rare endemics and communities. In both subzones the vegetation of the catchment and wetlands are largely intact. However, there are still many threatening processes affecting wetlands including water extraction, grazing and trampling by domestic and feral animals, mining activities and fire.

Internally Drained Deserts

The biogeographic regions of the Internally Drained Deserts are the Little Sandy Desert, Gibson Desert, Murchison; and parts of the Tanami, Central Ranges, Great Sandy Desert, and Great Victoria Desert. Only the Carnegie Salient part of the Gascoyne (the eastern part of the Gascoyne) is included in the Internally Drained Deserts as the western portion of the Gascoyne drains to the coast. These arid regions are typified by sandy soils with scattered rocky ranges and internal uncoordinated drainage, there being no obvious exterior drainage. Unlike the tropics and the temperate regions of WA, there are few wetlands that consistently hold water year-round in this region.

There are twenty listed nationally important wetlands in the Internally Drained Deserts[54] and May and McKenzie[44] propose that twenty-three wetlands are of state significance.

Wetland vegetation of the Internally Drained Deserts

The Internally Drained Deserts vegetation is dominated by hummock grasslands (grasslands dominated by spinifex), tussock grasslands (grasslands dominated by perennial grasses other than spinifex), *Acacia* shrublands, chenopod and samphire succulent shrublands and *Eucalyptus* dominated woodlands and mallee shrublands. In the wetlands the common vegetation is forests, sedgelands, herblands and chenopod and samphire succulent shrublands, which are normally rare elsewhere. Common wetland species include the trees *Eucalyptus camaldulensis* (Figure 60c), *E. victrix* and *E. microtheca*; the shrubs *Muehlenbeckia florulenta* (Figure 61c&d), *Frankenia* species (Figure 61a&b), samphires (*Tecticornia halocnemoides*, *T. undulata*, *T. indica*, *T. doleiformis*) and a variety of *Melaleuca* and *Acacia* species; and the freshwater grass *Eragrostis australasica*.

Figure 60 (below). Three trees from the Internally Drained Deserts.
(a) *Casuarina pauper*. Photo – R Davis.
(b) *Eucalyptus striaticalyx*. Photo – A Doley and M French.
(c) *Eucalyptus camaldulensis*. Photo – W Thompson.
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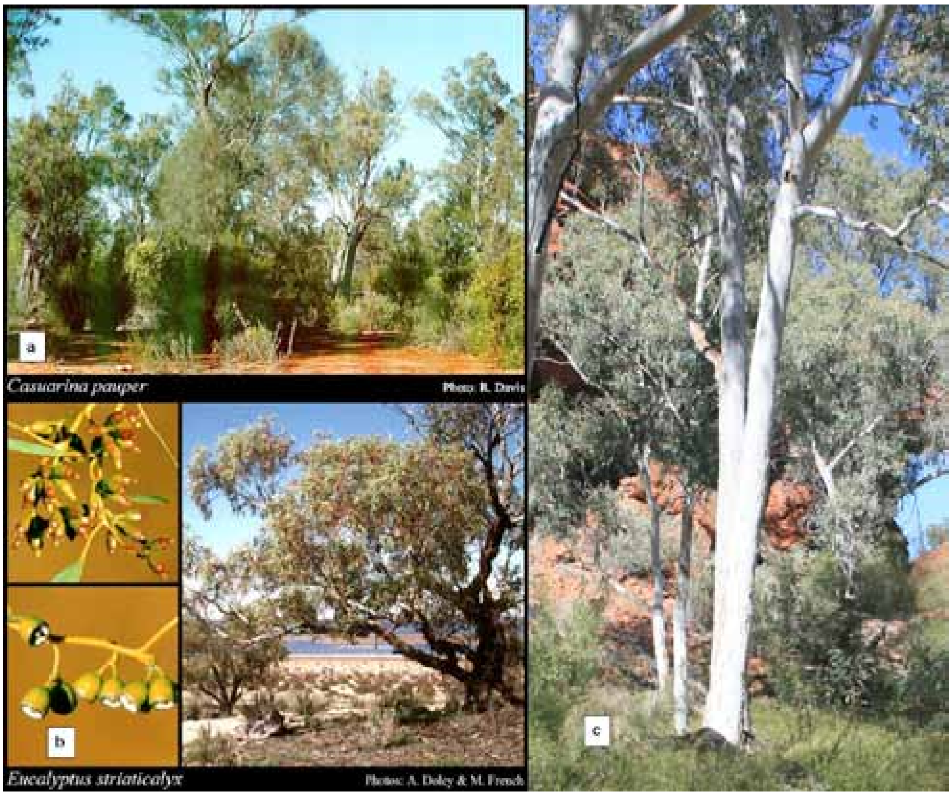

Figure 61 (below). Two shrubs of Desert wetlands.
(a) *Frankenia cinerea*. Photo – R Davis and (b) Distribution in WA. Mapping – P Gioia.
(c) *Muehlenbeckia florulenta*. Photo – SJ Patrick and (d) Distribution in WA. Mapping – P Gioia.
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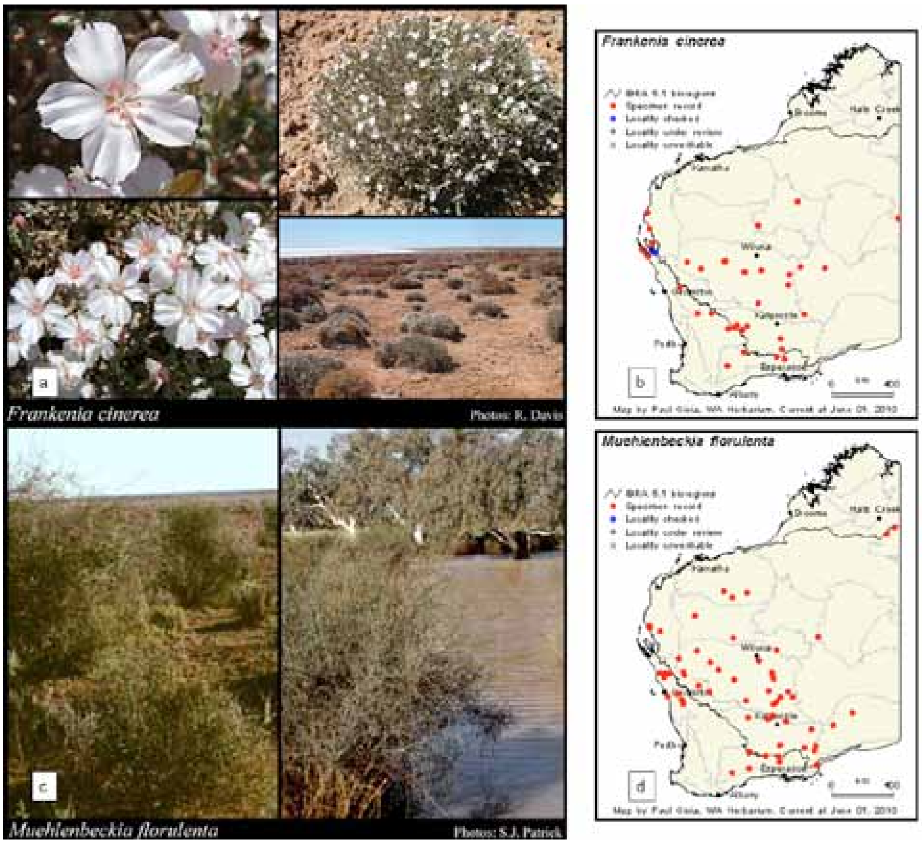

The wetland vegetation of the Internally Drained Desert is generally very poorly documented and around eighty vegetation units are described in the available publications and reports. This is obviously an underestimate as the detailed studies of Lake Way (near Wiluna, Murchison) by Blackwell and Trudgen[64] demonstrate. Here they described twenty-eight plant communities:

- twenty-two Lacustrine and Allied Halophytic Associations – eleven Chenopod Steppe Associations, mainly *Tecticornia* species Low Samphire Shrub associations; and eleven Halophytic Shrublands (dominated by *Atriplex*, *Tecticornia*, *Frankenia*, *Cratystylis* and *Samolus junceus*)
- six Strand Vegetation Types – *Muellerolimon salicorniaceum* and *Melaleuca interioris* shrubland, four mulga (*Acacia aneura*) dominated and a *Melaleuca xerophila* Low Closed Forest.

Saline wetlands of the Internally Drained Deserts

Extensive saline wetland chains are the major wetland type of the inland deserts. There are more than one hundred such wetlands (Figure 62 to Figure 64) of which the largest are listed below in the bioregions in which they are located:

- Central Ranges – Lake Christopher
- Great Sandy Desert – Lakes MacDonald, Auld, Dora*, Tobin, Mackay, Wills, Percival and Wakarlcarly
- Gibson Desert – Lakes Blair, Cohen and Hancock, and the Breaden System are considered wetlands of regional significance.[44] Other large lakes are Gillen and Newell. Figure 67 illustrates a Gibson Desert claypan
- Little Sandy Desert – Lakes Disappointment* (150,000 hectares; Figure 59, Figure 62 and Figure 63), Keene, Terminal, Sunshine, Yanneri and Wilderness
- Tanami – Lake Hopkins
- Gascoyne – these are mainly in the Carnegie Salient, being Lakes Burns, Carnegie* (153,000 hectares) and Nabberu
- Great Victoria Desert – Lakes Minigwal* (Figure 64), Throssell*, Raeside, Rason, Wells and Yeo*
- Murchison – Lakes Annean* (120,000 hectares), Austin, Ballard* (60,000 hectares), Barlee* (194,000 hectares), Carey, Cowan, Darlot, Lefroy, Marmion*, Moore (extends across several bioregions) and Rebecca. These are generally smaller than the more inland desert wetlands, although they are much better documented.

These wetlands rarely fill and are often bare or covered in a variety of samphire shrublands dominated by *Tecticornia* species (*T. halocnemoides*, *T. undulata*. *T. indica* and *T. doleiformis*) and other shrubs such as *Atriplex* species (Figure 65a) (especially Bladder Saltbush, *A. vesicaria*), *Maireana* species and/or *Frankenia* species. Despite their importance and size, remarkably few (noted by an asterisk *) are listed as nationally important wetlands and most of these are from the southern areas.

Figure 62. An area of Lake Disappointment (Tanami) with a band of samphire shrubland and surrounding low dunes. Photo – W Thompson.

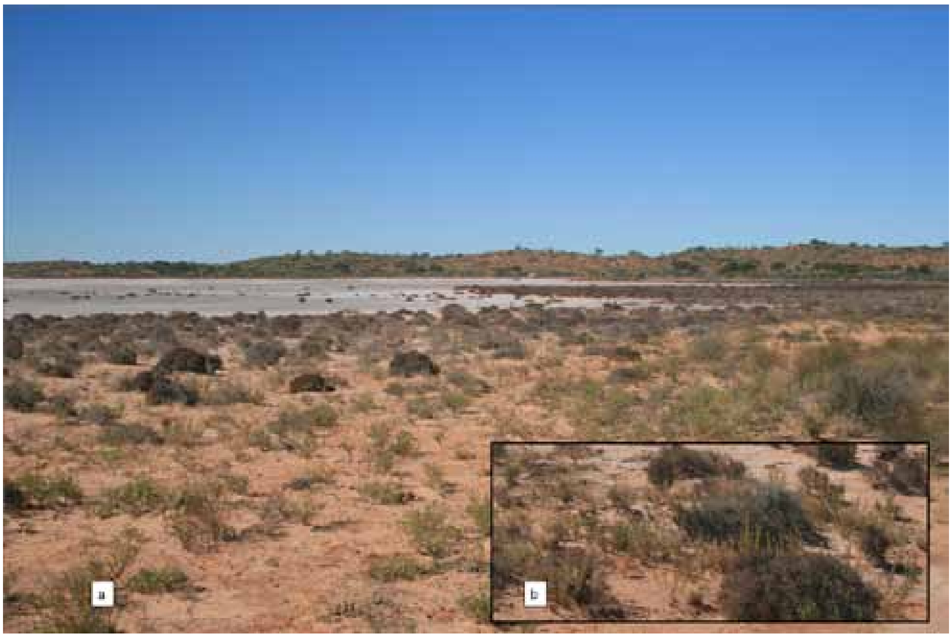

Figure 63. An area of Lake Disappointment (Tanami) showing a broader band of samphire shrubland and other salt tolerant shrubs (detail in b) and surrounding low dunes. Photo – W Thompson.

Figure 64. Lake Minigwal (Great Victoria Desert) with a dry salt encrusted lake bed, a samphire shrubland band and eucalypts on the surrounding dryland dunes. Photo - W Thompson.

Figure 65 (below). Two shrubs of Desert wetlands.

(a) *Atriplex bunburyana*. Photo – J English and (b) Distribution in WA. Mapping – P Gioia.

(c) *Scaevola collaris*. Photo – R Davis and AS George and (d) Distribution in WA. Mapping – P Gioia.

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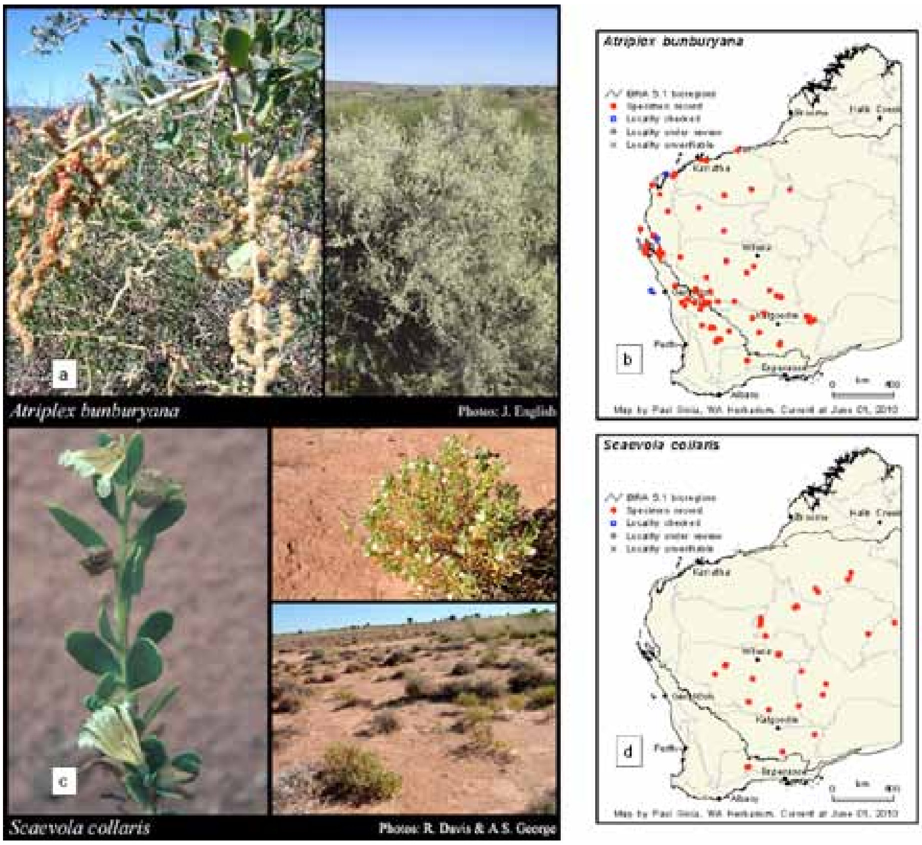

Associated with the salt lakes are two groups of flat wetlands subject to waterlogging.[65] The first of these are on the calcrete surfaces (hardened calcium carbonate deposits). Drainage in these areas is via sheet flow and open flow lines into the salt lakes. These are covered in 'calcrete woodlands' dominated by *Casuarina pauper* (Figure 60a) or *Eucalyptus clelandii*, usually over chenopod shrublands. The second group are the Kopi (gypsum) dunes that often fringe the desert salt lakes, and in Lake Rebecca they cover much of the lake bed. These dunes typically have *Eucalyptus striaticalyx* (Figure 60b), *E. lesouefii* or *Casuarina pauper* woodlands.

Higher on the alluvial plains are incised (that is, relatively steeply eroded) drainage lines carrying flows to the salt lakes. These apparently less saline sites support silver saltbush (*Atriplex bunburyana*, Figure 65a&b) shrublands or, rarely, *Eucalyptus camaldulensis* woodlands.

In a few instances there are salt marshes close to the coast, such as the Mandora Saltmarsh (part of the Mandora Palaeo-river, Great Sandy Desert). This wetland complex extends over 95 kilometres and covers an area of more than 200,000 hectares. This vast area supports a complex and diverse set of wetlands and plant communities including lakes that are largely bare of vegetation or have low open shrublands of samphires, grasslands and fringing alluvial flats with shrublands of *Acacia ampliceps* and *Melaleuca alsophila*. Of particular interest is Salt Creek, a permanently inundated wetland lined by white mangrove (*Avicennia marina*) and samphire shrublands. These populations of white mangroves are the second largest inland occurrence of mangroves in WA (the largest being at Lake McLeod in the externally drained deserts). Within the salt marsh are also a series of freshwater wetlands: swamps with open forests of *Melaleuca argentea*; and a variety of mound springs such as Eil Eil Springs that supports a tall *Melaleuca leucadendra* closed forest and Saunders Springs (a sub-saline mound spring) with *Sesbania formosa* forest over mangrove fern (*Acrostichum speciosum*) on the top of the mound and *Typha domingensis* and *Fimbristylis ferruginea* sedgeland on the slopes. The springs are listed as the TEC 'Assemblages of the organic springs and mound springs of the Mandora Marsh area'.

Freshwater wetlands of the Internally Drained Deserts

Four groups of wetlands are distinguished here: playas and barlkarras, springs, claypans and riverine.

Playas and barlkarras

Rare freshwater playas and barlkarras (intermittently inundated basins and flats respectively; see Table 1 for more information) fill after rainfall events; some examples of these, from various bioregions, are listed below.

- Gibson Desert – Lake Gruszka* (up to 2,000 hectares) covered by coolibah (*E. victrix*) woodland over cane grass (*Eragrostis australasica*) grassland. A similar wetland, Boyd Lagoon, is listed as a wetland of regional significance.[44]
- Tanami Desert – Lake Gregory*, known as Paruku by the Tjurabalan traditional owners (38,700 hectares) which is filled by Sturt Creek and holds surface water for extended periods. The waterline is fringed by *Eucalyptus victrix* and *E. microtheca* (both called coolibah) woodlands, *Melaleuca* shrublands and samphire shrublands. The creeks and the outer areas of the wetland support an *Acacia maconochieana* shrubland with scattered emergent *E. camaldulensis*, *E. victrix* and *E. microtheca* woodland over *Acacia holosericea* and *A. maconochieana* shrubland. There are two additional zones: shrublands dominated by *M. glomerata* over grassland of *Eulalia aurea* and the weed buffel grass (*Cenchrus ciliaris*); and a samphire shrubland dominated by *Tecticornia indica* and *T. halocnemoides* with herbs and grasses. Aquatics include *Myriophyllum verrucosa*, *Najas marina* and *Ruppia* species. Lake Wilson (10,000 hectares when full to 200 hectares in drought) is fringed by *Melaleuca glomerata* woodland and grassland of *Eragrostis desertum*.
- Murchison – Lakes Breberle and Wooleen covered by *Eucalyptus camaldulensis* woodlands and lignum (*Muehlenbeckia florulenta*) shrublands. Lake Boonderoo* fills with freshwater when the palaeo-drainage line, Ponton Creek, flows. This large wetland at the end of the drainage line initially contains freshwater and becomes more saline as it dries. Samphire shrublands fringe the bed.

Springs

Many of the freshwater wetlands rely on seepages (natural springs); some examples of these, from various bioregions, are listed below.

- Great Sandy Desert – Dragon Tree Soak*, also called the Munro Springs, in the McLarty Hills, is a permanently inundated wetland which contains a central sedgeland of *Baumea articulata* fringed by woodlands to forests of *Sesbania formosa* over *Typha domingensis*. This spring has formed an organic peat mound and is a rare example of a true mound spring in the Western Australian deserts. Small claypan areas are also associated with this wetland; these have a cover of grasslands dominated by *Sporobolus virginicus* or samphire shrubland of *Tecticornia indica*. The entire complex is listed as the TEC 'Assemblages of Dragon Tree Soak organic mound spring'. Freshwater springs within the saline Mandora Saltmash, such as Eil Eil Springs, are discussed in the previous section on saline wetlands.
- Gascoyne (Carnegie salient portion) – Windich Springs*, a permanently inundated channel lined by *Eucalyptus camaldulensis* forest over sedgeland with aquatics such as *Lepilaena bilocularis* and *Potamogeton crispus*. *Casuarina obesa* and *Schoenoplectus subulatus* are also found in these springs.

- Tanami (Gardner and Dennison Ranges, Coates et al.[66] and Kenneally and Edinger[67]) – Mt Brophy Springs is fringed by *Eucalyptus camaldulensis* and *Acacia neurocarpa* and *Melaleuca nervosa* shrubland. A *Livistona* sp. forest has been recorded at Talbot, Palm (Tanami) and Maurice springs. These springs support a suite of typical Kimberley wetland species including *Byblis filifolia*, *Drosera derbyensis*, *D. hartmeyerorum*, *Stylidium fissilobium*, *S. leptorhizum*, *S. schizanthum*, *Thysanotus chinensis*, *Nesaea muelleri*, *Nymphoides indica* and *Utricularia gibba*. These are the most southern and disjunct populations of these plants and the only Desert populations. Other highly disjunct populations present are *Drosera burmanni*, *Mimulus uvedaliae*, *Stylidium adenophora*, *S. inaequipetalum* (Figure 66) and *Wahlenbergia queenslandica*, but these have also been recorded in wetlands in the Central Ranges.

Figure 66 (below). Two herbs of Internally Drained Desert wetlands.
(a) *Mimulus gracilis*. Photo – CP Campbell and (b) Distribution in WA. Mapping – P Gioia.
(c) *Stylidium inaequipetalum*. Photo – KF Kenneally and (d) Distribution in WA. Mapping – P Gioia.
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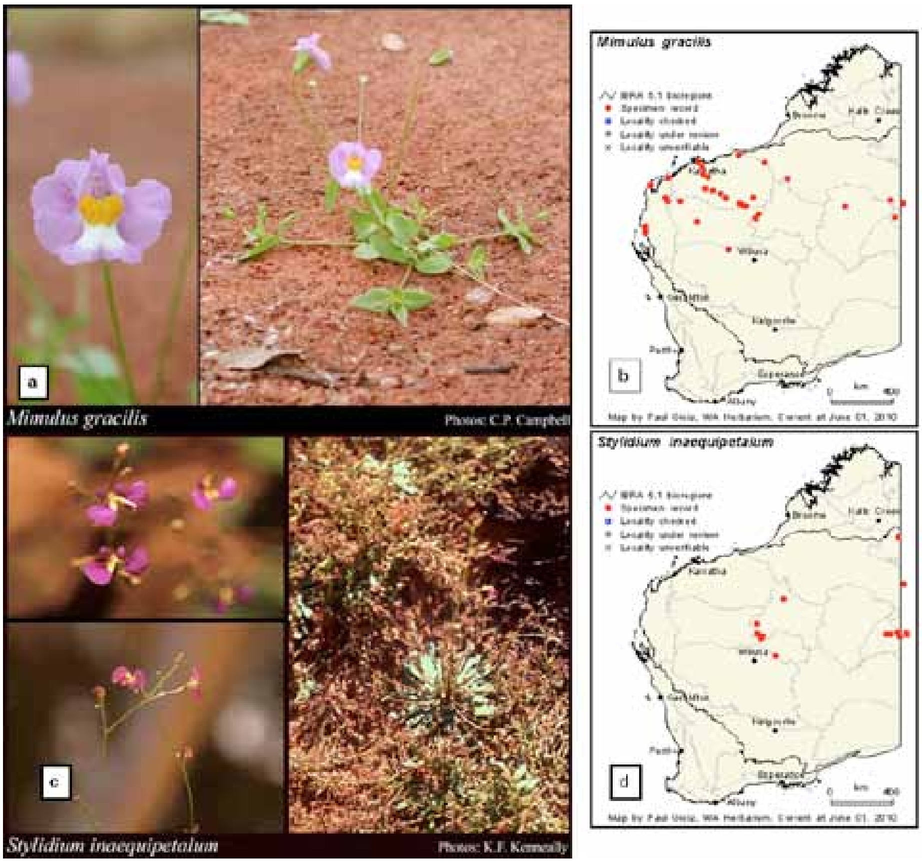

Claypans

Scattered through these Deserts are many poorly documented perched claypans (Figure 67). Pringle et al.[68] record mulga shrublands with claypan grass understoreys (*Eriachne flaccida*, *Eragrostis setifolia*). Other claypans have *Tecticornia arborea* (a freshwater samphire) herblands, *Callistemon phoeniceus* shrublands, *Melaleuca interioris* shrublands, lignum (*Muehlenbeckia florulenta*) shrublands and cane grass (*Eragrostis australasica*) grasslands.

The largest are Mungilli Claypan* (Gibson Desert, also called Mangkili Claypans), fringed by *Eucalyptus victrix* woodland and covered with *Eragrostis australasica* grassland over herbs; and Mungawolagudgi Claypan (Gascoyne) with scattered *Eucalyptus victrix* and *Melaleuca interioris* shrublands. Such large claypans are uncommon; in general the claypans are small and undocumented unless associated with other features such as Dragon Tree Soak (see above under 'Springs').

Figure 67. Mina Mina soak (Gibson Desert), a Desert claypan.
(a) *Eucalyptus victrix* woodland over *Myriocephalus* herbland.
(b) *Myriocephalus rudallii* flowers.
Photos – W Thompson.

Riverine

Most of the Desert ranges contain short freshwater creek lines and pools fringed by *Eucalyptus camaldulensis* over sedges (Figure 68). A variety of different wetlands may be associated with these watercourses, including the following:

- **Gnamma** holes (for example, Gibson Desert gnamma holes*) on granitic and sandstone surfaces, generally supporting little vascular flora but supporting aquatic algae and **diatom** assemblages.
- Larger pools and springs typically having a fringing margin of seasonally waterlogged wetland that supports ferns and herbs and *Eucalyptus camaldulensis* woodlands on the outflow creeks. These are found in the West Clutterbuck Hills in the Gibson Desert; Breaden* and Southesk Tablelands, around Lake Percival in the Great Sandy Desert; Calvert, Durba (Durba and Biella springs, Figure 68) and Carnarvon Hills

Gnamma: a hole (commonly in granite) that collects rainwater, forming a wetland. This word is of Nyoongar origin.

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, forming fossil deposits

(Virgin, Muirs, Yamad, Kadyara, Miringka and Wandan pools) in the Little Sandy Desert; Erong Springs in the Gascoyne (Carnegie Salient), Queen Victoria Springs in the Great Victoria Desert, Walter James Range*, Rawlinson Range and the Rebecca and Giles creek systems in the Central Ranges. Sedgelands of *Cyperus vaginatus* (Figure 68b) are a rare feature of these pools and springs, mainly where water is permanent.

Two unique channel wetlands are found in the Great Sandy Desert: the Rudall River System* (more than 300 kilometres long) and Savory Creek (more than 280 kilometres long). These are the only examples of arid zone rivers with wetlands that are almost always permanently inundated along their courses. The Rudall River flows from drylands across the desert to empty into Lake Dora, while Savory Creek empties into Lake Disappointment about 160 kilometres north of Lake Dora. The Rudall River is lined by *Eucalyptus camaldulensis* and *E. microtheca* woodlands, over a *Erythrina vespertilio* woodland, over mixed *Acacia ampliceps*, *A. dictyophleba*, *A. holosericea* and *A. eriopoda* shrublands, over grasslands dominated by *Whiteochloa cymbiformis*, *Leptochloa fusca* and *Eragrostis speciosa*. Patches of paperbark (*Melaleuca cajuputi*) woodlands are uncommon. Alluvial flats support grasslands of *Eriachne obtusa* with scattered shrubs of *Melaleuca lasiandra* and *Acacia monticola*. Closer to Lake Dora the river becomes more saline and claypans dominated by succulent shrublands occur, with *Tecticornia calyptrata*, *Trianthema oxycalyptra*, *Salsola australis* and *Frankenia* species. Savory Creek flows around every 3–4 years and is fresh in its upper reaches and supports similar vegetation to the Rudall River but with some semi-permanent pools. As it becomes more saline it forms wide braided channels, minor salt lakes, claypans and a permanently inundated saline swamp, all dominated by succulent shrublands.

Figure 68. Durba Springs (Little Sandy Desert) supports:
(a) *Eucalyptus camaldulensis* forest and fringing *Cyperus vaginatus* sedgeland
(b) *Melaleuca lasiandra* shrubland and *Cyperus vaginatus* sedgeland.
Photos – W Thompson.

Wetland flora of the Internally Drained Deserts

On the basis of the critical review of taxa allocated to wetland and dryland habitats in the *Flora of Central Australia*[27], the wetland flora of the Internally Drained Deserts comprises only about 10 per cent of the total Internally Drained Deserts flora (Figure 69). This reflects the paucity of wetlands in the area and, possibly, the limited number of detailed studies of the flora of these wetlands.

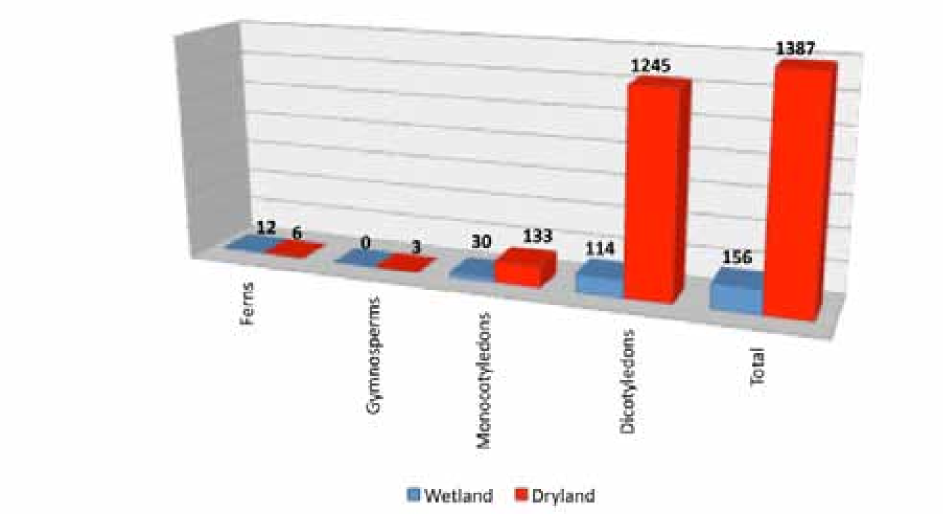

Figure 69. Internally Drained Desert wetland and dryland vascular plant taxa found in various plant groups (after Jessop[27]).

Few endemic wetland species are known from the Internally Drained Deserts and most of these are saline wetland species such as *Tecticornia* species including: *T. calyptrata* (Figure 70a&b), *T. chartacea* (Figure 70c&d), *T. flabelliformis*, *T. triandra* and the recently described *T. bibenda*. The *Livistona* species from the Talbot, Palm and Maurice springs in Tanami has never been fully documented and may be an undescribed endemic species.

Figure 70 (below). Two samphire shrubs of Internally Drained Desert wetlands.
(a) *Tecticornia calyptrata*. Photo – KA Shepherd and (b) Distribution in WA. Mapping – P Gioia.
(c) *Tecticornia chartacea*. Photo – KA Shepherd and (b) Distribution in WA. Mapping – P Gioia.
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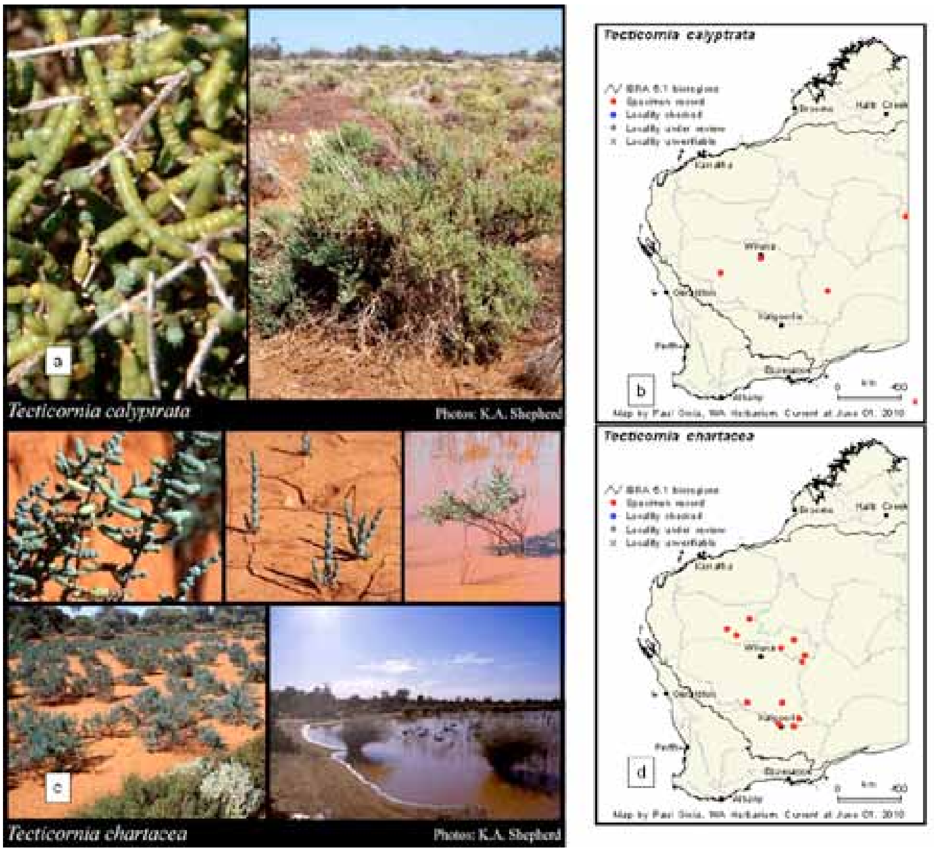

Typically all Desert freshwater wetlands support fringing species with a few claypan taxa from genera such as *Peplidium*, *Glossostigma* and *Elatine*. Aquatic species are also uncommon, being confined to permanently inundated sites to those inundated on a semi-permanent basis, and include *Myriophyllum verrucosum*, *Potamogeton crispus* and *Lepilaena bilocularis*.

A number of highly disjunct wetland plants are known from several permanently inundated springs:

- *Baumea articulata* and *Sesbania formosa* from Dragon Tree Soak, disjunct from the Pilbara
- a set of Kimberley species in the Talbot, Palm and Maurice springs – *Byblis filifolia*, *Drosera derbyensis*, *D. hartmeyerorum*, *Stylidium fissilobium*, *S. leptorhizum*, *S. schizanthum*, *Thysanotus chinensis*, *Nesaea muelleri*, *Nymphoides indica* and *Utricularia gibba*
- the widespread tropical and arid species *Drosera burmanni*, *Mimulus uvedaliae*, *Stylidium adenophorum*, *S. inaequipetalum* and *Wahlenbergia queenslandica*, from the Talbot, Palm and Maurice springs and wetlands in the Central Ranges.

Externally Drained Deserts

These deserts of the Pilbara, Carnarvon and western portion of the Gascoyne bioregions differ from the deserts covered above in having large rivers that flow to the sea. The main rivers of the regions are:

- Pilbara – De Grey, Fortescue and Lyons Rivers
- Gascoyne (western part) – Ashburton and upper Gascoyne Rivers (western part)
- Carnarvon – Lyndon, Gascoyne and Wooramel Rivers.

These deserts have summer rain in the north grading to winter in the south. In general, the Externally Drained Deserts have fewer salt lakes and more freshwater wetlands (especially the seasonally waterlogged wetlands of the extensive alluvial plains) than are found in the Internally Drained Deserts.

The southern-most deserts, the Nullarbor and Hampton, are included here but are highly unusual in being almost devoid of wetland flora. This is a unique feature of these bioregions. Drainage is to the sea but through underground 'rivers'. The only wetlands are small surface expressions such as rockholes (Figure 71), beach seeps and ephemeral dongas.[47] **Dongas** are found in the limestone surface of the Nullarbor. They are basin landforms usually 2–3 metres deep and up to 800 metres in diameter, containing trees. They hold water for a short time after rain due to their hard clay surface. Tree cover helps to reduce evaporation.[69,70]

There are twenty-three listed nationally important wetlands in these Deserts.[54]

Figure 71. Limestone rockhole wetlands on the Nullarbor. Photos – G Keighery/DEC.

(a) DEC staff inspecting the wetlands.

(b) Algal Community in the Cologna Rockhole, one of a series of rockhole wetlands collectively known as the Hampton Scarp Rockholes.[47]

Wetland vegetation of the Externally Drained Deserts

The vegetation of the Externally Drained Deserts is dominated by hummock grasslands, *Acacia* woodlands, forest and shrublands, tussock grasslands, chenopod and samphire succulent shrublands, heath, mangroves, *Eucalyptus* woodlands and mallee shrublands. The common vegetation units of the wetlands are mangrove forest, forests, sedgelands, herblands, chenopod and samphire succulent shrublands. All of these are normally rare, or not listed, for drylands.

More than one hundred Externally Drained Desert wetland plant communities are described in the literature. Unlike the Internally Drained Deserts, these Deserts have been the subject of both recent pastoral reports and regional biological surveys. These surveys have listed the vegetation units and described the floristics of the Carnarvon, Pilbara and Gascoyne.

➤ For more information refer to the biological surveys webpage on DEC's website.[71]

Saline wetlands of the Externally Drained Deserts

The Externally Drained Deserts have fewer saline wetlands; however, there are two very large and distinctive saline wetlands—Fortescue Marshes and Lake MacLeod—in the area, as well as a variety of smaller saline wetlands. These wetlands are described below in two groups: riverine and lakes.

Riverine

The Fortescue Marshes (Pilbara) lie in the mid-reaches of the Fortescue River and cover a vast floodplain of more than 100,000 hectares (Figure 72 and Figure 73). This huge seasonally inundated area supports a complex mosaic of plant communities.[72] The vegetation can broadly be described according to the mid- and down-slopes of the marsh. On the mid-slopes, scattered *Melaleuca lasiandra*, *M. glomerata* and *Acacia ampliceps* trees occur over *Sporobolus virginicus* and *S. mitchellii* grasslands. The scattered common shrubs are the lignums, *Muellerolimon salicorniaceum* and *Muehlenbeckia florulenta*, and less common are some unusual *Tecticornia* species. Down-slope are samphire shrublands (Figure 72) with a variety of *Tecticornia* species including *T. auriculata* (Figure 74a&b), *T. pergranulata* subsp. *pergranulata*, *T. indica* subsp. *bidens* and subsp. *leiostachya*, *T. halocnemoides* and *T. undulata*, as well as the rare priority listed *T.* sp. Christmas Creek, *T.* sp. Fortescue Marsh and *T.* sp. Roy Hill. Within the samphire shrublands are areas of grasslands dominated by *Eragrostis* (Figure 74c&d) and *Eriachne* (Figure 73b) species. The endemic shrub *Eremophila spongiocarpa* and the rare *Eremophila youngii* subsp. *lepidota* (Figure 75c&d) are also found. Patches of herbs are found in this vegetation including *Sida trichopoda* and *Zygophyllum simile* and the rare *Nicotiana heterantha* and *Peplidium* sp. fortescue marsh.

Freshwater seepages/springs and inflows are also associated with these marshes. Freshwater down-slope communities include woodlands dominated by *Eucalyptus victrix* and shrublands dominated by a variety of taxa including *Acacia xiphophylla*, *Melaleuca glomerata* and *M. bracteata*. Weeli-Wolli Spring flows into the marsh. This spring is fringed with forests and woodlands that support unique understorey assemblages of sedges and herbs, including the restricted *Stylidium weeliwolli*.

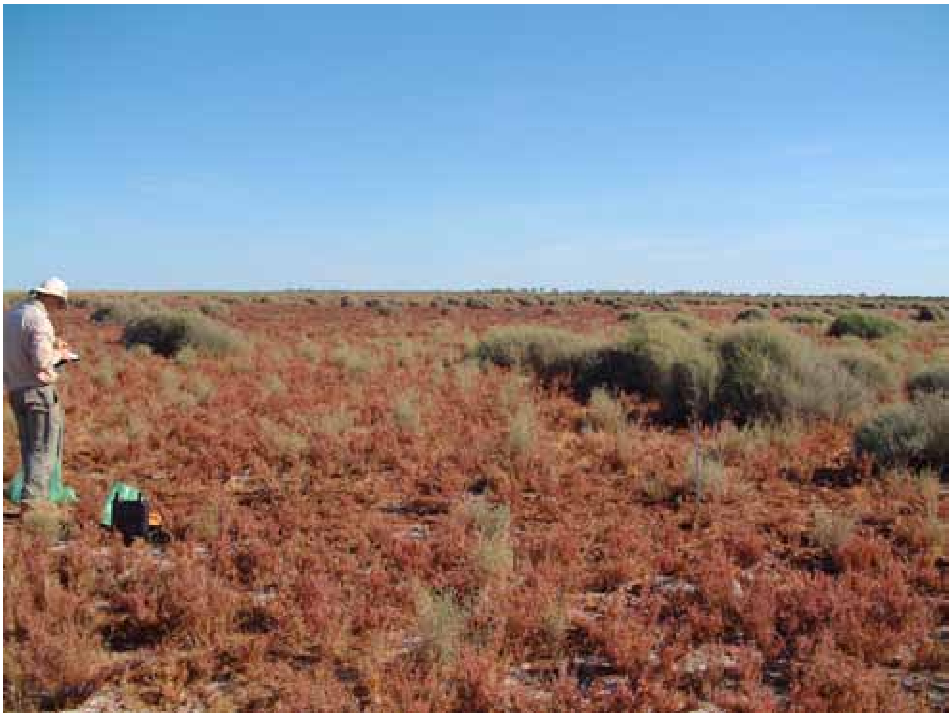

Figure 72. Samphire shrubland with *Tecticornia pergranulata*, *T. auriculata* and *T. undulata* on the outer edge of Fortescue Marsh (Pilbara), with scattered *Muellerolimon salicorniaceum*. Photo – M Lyons/DEC.

Figure 73. Fortescue Marsh (Pilbara).

(a) Fortescue Marsh edge after a major fill event. *Muellerolimon salicorniaceum* shrubland over aquatics including *Lepilaena* and *Chara* (Pilbara). Photo – M Lyons/DEC.

(b) *Eriachne benthamii* in a claypan at Fortescue Marsh (Pilbara). Photo – G Keighery/DEC.

Figure 74 (below). Two plants of the Desert wetlands.

(a) *Tecticornia auriculata*, a samphire shrub mostly found in the Externally Drained Desert. Photo – GF Craig and KA Shepherd and (b) Distribution in WA. Mapping – P Gioia.

(c) *Eragrostis falcata*, a widespread wetland grass commonly found in Desert wetlands. Photo – GF Craig and (d) Distribution in WA. Mapping – P Gioia.

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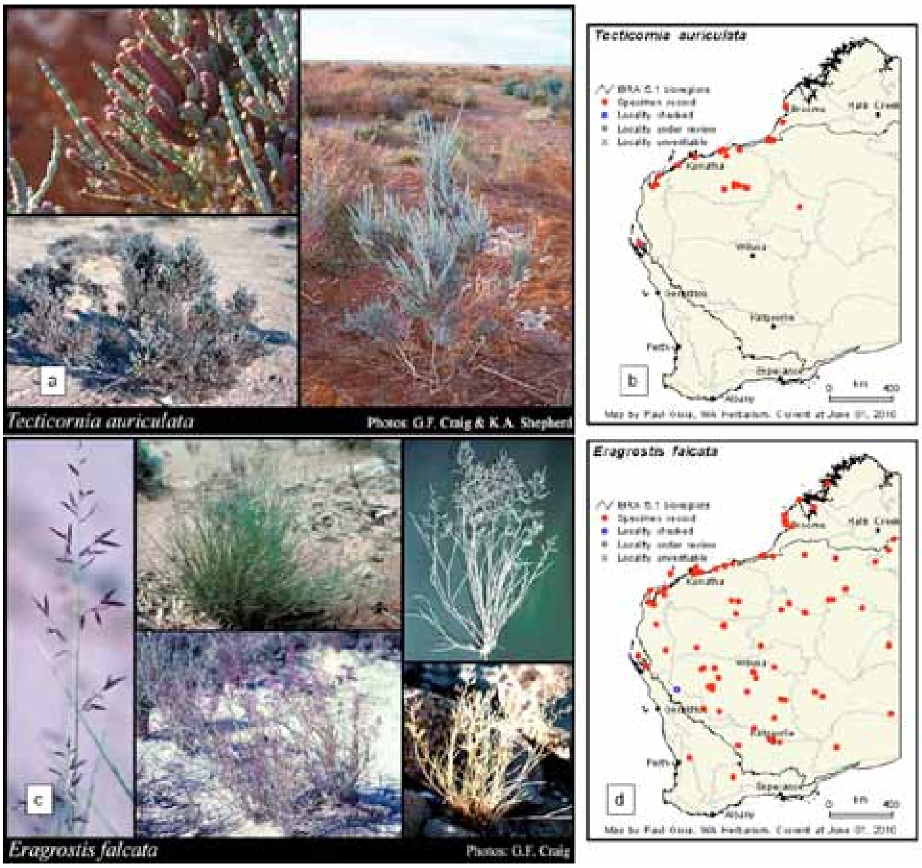

Figure 75 (below). Two restricted shrubs of the Desert wetlands.

(a) *Eremophila youngii* subsp. *lepidota* found in the Externally Drained Desert. Photo – B Buirchell and MJ Start (b) Distribution in WA. Mapping – P Gioia.

(c) *Eremophila spongiocarpa* confined to the Fortescue Saltmarsh in the Externally Drained Desert. Photo – A Mitchell and SJ Patrick (d) Distribution in WA. Mapping – P Gioia.

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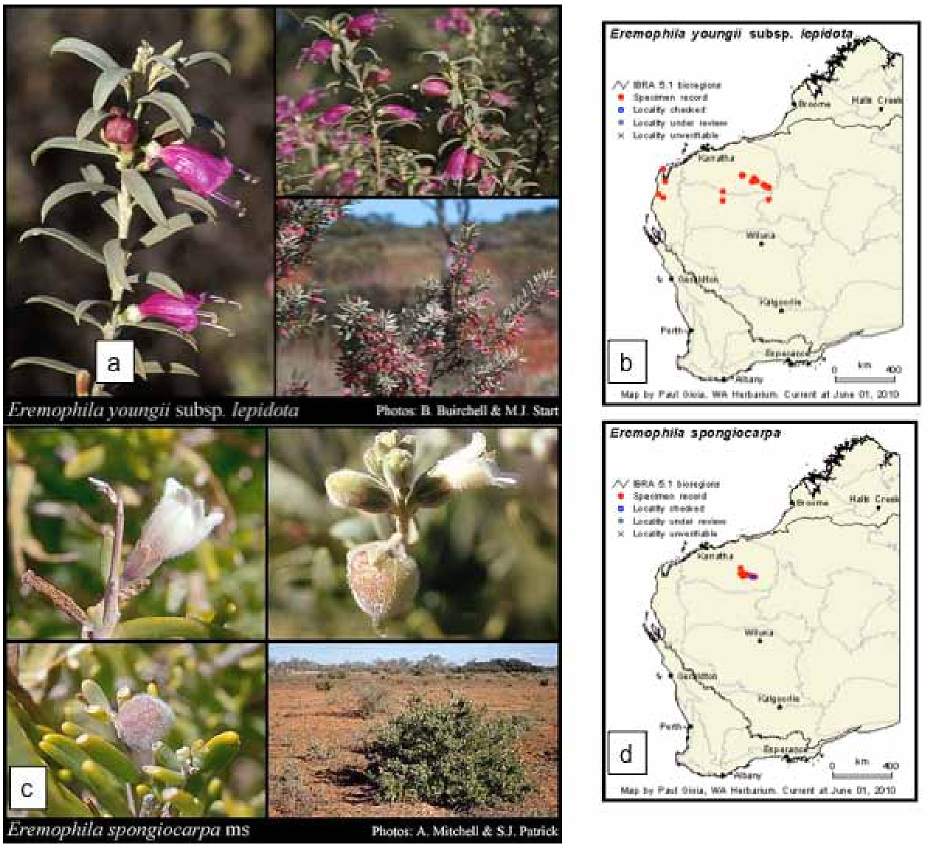


Birrida: a local Aboriginal name for a seasonally inundated, hypersaline, gypsum saltpan wetland in sand dunes in the Shark Bay area. Some have a distinctive central raised platform and moat feature.

Lakes

Lake MacLeod* (Carnarvon) is an extensive saline wetland system (150,000 hectares) associated with a permanently inundated salt lake (6,000 hectares) located north of Carnarvon. The permanently inundated lake is fringed by the largest inland occurrence of mangroves (*Avicennia marina*) known in WA. A complex of seasonally waterlogged wetland communities are found on the adjacent flats.

In the Shark Bay area (Carnarvon) there are a series of hypersaline **birridas**. These support the aquatic *Ruppia tuberosa* and are covered with samphire shrublands.

Freshwater wetlands of the Externally Drained Deserts

There is a vast variety of freshwater wetlands in these Deserts. These are described below in four groups: alluvial flats, springs, seasonally waterlogged wetlands and claypans.

Alluvial flats

Not surprisingly, alluvial flats that are subject to regular to occasional inundation are only well developed in the Externally Drained Deserts where they contribute greatly to the variety of wetlands, species richness and endemism. The Western Australian Department of Agriculture have described these areas in reports on the Pilbara, Ashburton River Catchment, Carnarvon Basin and Murchison River Catchment.[73,74,75,76] The vegetation of some of these alluvial plains is outlined below by bioregion:

- Gascoyne (western portion) – Along the Ashburton River the alluvial flats are described by Payne et al.[74] as supporting 'Bluebush Pasture Lands' which are a complex of shrubland communities dominated and/or typified by: gascoyne bluebush (*Maireana polypterygia*), sago bush (*M. pyramidata*), spiny bluebush (*M. aphylla*), tall saltbush (*Rhagodia eremaea*) and swamp bluebush (*Chenopodium auricoma*).
- Murchison – Along the Murchison River, Curry et al.[73] describe two major vegetation types: 'Non Calcareous Shrubby Grasslands' being woodlands and tall shrublands of black mulga (*Acacia distans*), *A. aneura* and *Eucalyptus coolabah* over grasslands dominated by *Eriachne benthamii* and *Eriachne flaccida*; and 'Alluvial tussock Grasslands' being grasslands dominated by *Eragrostis setifolia*, *Eriachne flaccida*, *Sporobolus virginicus* and *Eragrostis dielsii* with scattered trees and shrubs.
- Carnarvon – Similarly in the Carnarvon Basin, Payne et al.[75] describe alluvial areas along the Lyndon, Minilya, Gascoyne and Wooramel rivers as a series of complex 'pasture types' grouped after surfaces on which they occur. These are summarised below.
  - Saline loams, clays and duplex soils (Figure 76)
    - 'Bluebush' with three presentations: 'Gascoyne Bluebush community' of *Mariana polypterygia* and *M. platycarpa* shrublands; 'Gascoyne Mulla Mulla community' of *Ptilotus polakii*, *Mariana polypterygia* and *M. platycarpa* shrublands (each of these are often with occasional tall shrubs of *Acacia* species and low shrubs of *Atriplex vesicaria* and *A. bunburyana*); and 'Spiny Bluebush community' with shrublands dominated by *Maireana aphylla* with *Rhagodia eremaea*, *Atriplex bunburyana* and *Muehlenbeckia florulenta*.
    - 'Sago Bush' (*Maireana pyramidata*) community, being shrublands dominated by currant bush (*Scaevola spinescens*) and mixed shrubs. This is apparently a marginal seasonally waterlogged wetland community.
  - 'Saltbush' with four presentations being shrublands dominated by silver saltbush (*Atriplex bunburyana*), bladder saltbush (*A. vesicaria*), swamp or river saltbush (*A. amnicola*) and marsh saltbush (*A. paludosa*).
  - Alluvial loams and clays
    - 'Acacia Creek-line' being Acacia aneura and A. citrinoviridis woodlands.
    - 'Tussock Grass' being a suite of open tussock grasslands to open grassy woodlands with four forms: the 'Roebourne Plains grass community' of grasslands dominated by a variety of mitchell grasses (Astrebla squarrosa, A. elymoides, A. pectinata) and Eragrostis setifolia and three grasslands dominated by ribbon grass (Chrysopogon fallax), swamp wanderrie grass (Eriachne benthamii) or rats tail grass (Sporobolus mitchellii). The last three are considered highly local and restricted in distribution, and the mitchell grass grasslands near the Minilya River is a range end of this mainly tropical grass community.

- Pilbara – In the Pilbara, Van Vreeswyk et al.[76] list an extensive series of river floodplains as 'Alluvial Plain Tussock Grasslands' (Figure 77 and Figure 78). These grasslands occupy more than 7.5 per cent of the Pilbara (an area of more than 19,000,000 hectares), hence they cover more than 1,000,000 hectares! These wetlands are typically associated with duplex or cracking clay soils and are segregated into eleven types (Van Vreeswyk et al.76, pages 155–173). The divisions are based on the dominant grasses, including mitchell grasses (*Astrebla* sp.), ribbon grass (*Chrysopogon fallax*), neverfail grass (*Eragrostis setifolia*), swamp grass (*Eriachne benthamii*), silky browntop (*Eulalia aurea*), kangaroo grass (*Themeda triandra*), buffel grass or mixed grasses. Mixed communities include the Roebourne Plains type dominated by mitchell grasses and *Eragrostis xerophila* or rarely by *Sorghum plumosum*; plain mosaic grassland (mixture of previous species and *Triodia pungens*); stony alluvial plain snakewood grassy shrubland (*Acacia xiphophylla* shrubland over *Eragrostis xerophila* and/or *Astrebla pectinata* and *Eriachne benthamii* grassland). A form of the kangaroo grass type is listed as the TEC 'Themeda grasslands on cracking clays (Hamersley Station, Pilbara)'. Grassland plains also have a rich flora of annual herbs and grasses.

Figure 76. Saline wetland chenopod (*Sclerolaena bicornis*, *Atriplex semilunaris* and *Salsola australis*) herbland and grassland on the Roebourne Common (Pilbara). Photo – G Keighery/DEC.

Figure 77. Turbid pools in a crabhole clay flat (Pilbara). The holes filled after a summer thunderstorm. The flat is covered with *Eriachne benthamii* grassland. A *Fimbristylis* is visible in the foreground and the floating leaves of *Marsilea* sp. are visible in the pool. Photo – M Lyons/DEC.

Figure 78. Large claypan with *Eucalyptus victrix* woodland over *Eriachne benthamii* grassland (Pilbara). Photo – M Lyons/DEC.

Springs

Most of the springs are associated with riverine channels. The best known of these spring-fed wetlands are those in the Karijini gorges and the Millstream Wetlands from the Pilbara; these are described below.

- Karijini gorges (Pilbara) – A series of spring fed pools are found along the Karijini gorges. These pools are fringed with river gum (*Eucalyptus camaldulensis*), *Melaleuca leucadendra* and *Sesbania formosa*; shrublands dominated by *M. linophylla* and *M. bracteata*; sedgelands dominated by *Cladium procerum*, *Schoenoplectus subulatus* and *S. littoralis*; and *Phragmites karka* grasslands. These permanently inundated, cool (shaded) habitats support disjunct populations of plants more typically located in the Kimberley and Southwest. These include:
  - ferns *Adiantum capillus-veneris* (**cosmopolitan**) and *Pteris vittata* (Kimberley)
  - aquatics such as *Schoenoplectus littoralis* (Kimberley)
  - species of seasonally waterlogged wetlands such as *Sonchus hydrophilus* (Southwest) and *Stylidium fluminense* (Kimberley).
- Millstream Wetlands (Pilbara) – This extensive set of permanently spring-fed wetlands on the Fortescue River contain pools, streams, swamps and marshes. The principal communities are: forests to woodlands dominated by silver cadjeput (*Melaleuca argentea*), river gum (*Eucalyptus camaldulensis*) and Millstream palm (*Livistona alfredii*, Figure 79); all sometimes over grasslands dominated by *Phragmites karka* and sedgelands dominated by *Cyperus vaginatus*, *Schoenoplectus subulatus*, *Typha domingensis* and *Fimbristylis ferruginea*. Submerged aquatic species of the pools include *Eleocharis geniculata*, *Potamogeton tricarinatus*, *Najas marina* and *Ruppia polycarpa*. Along the feeding creeks *Eucalyptus victrix* and *Acacia ampliceps* fringe the wetlands. A further area of Millstream Palm forest is found in Palm Spring on Duck Creek (a tributary of the Fortescue).

Cosmopolitan: an organism that is widespread in its distribution

Figure 79. Millstream Palm (*Livistona alfredii*) forest in the Hamersley Range along a tributary of the Fortescue River (Pilbara). Photo – G Keighery/DEC.

Other less well-known spring wetlands include Mibbley, Yinnietharra and Ewrong springs on the Lyons River (Pilbara); Cattle and Edithana springs along the Gascoyne River (Ashburton); seepages along the Chichester Range in the Mount Montague area (Pilbara), dominated by *Heliotropium* and cane grass[77]; and the permanently spring-fed streams and pools of the Barlee Range Gorges (Gascoyne). The springs of the Barlee Range Gorges support the endemic *Wurmbea saccata* which is also found at Minnie Spring on the Henry River, Irragully Spring and in granite rock pools and margins of the Ashburton. The communities in which it grows are dominated by the trees *Eucalyptus victrix*, *E. camaldulensis* and *Ficus brachypoda* and/or *Melaleuca* shrublands.

A spring of particular interest is a calcareous mound spring noted at Mount Salt (Pilbara).[78] This apparently unique community is reported to be dry at the time of publication, due to lowering of the watertable by a mesquite (*Prosopis species*) invasion.

A series of specialised wetland habitats are also associated with Yardie Creek in the Cape Range (Carnarvon). Yardie Creek, with its creek system, deep gorge and permanently inundated wetlands, provides refugia for wetland and dryland species at the extremities of their ranges[79]; these include *Livistona alfredii*, *Achyranthes aspera* and *Typha domingensis*.

Seasonally waterlogged wetlands

This wetland group is also found within the alluvial flats group which has been described above. However, away from the watercourses in the Pilbara in the Chichester and Mungarroona ranges are the 'Upland Plain Tussock Grasslands' (Figure 80, Figure 81 and Figure 82). These are likely to be unique to this bioregion. These plant communities are associated with basalt soils and are typically dominated by grasses from the genera *Astrebla* (Figure 81 and Figure 82), *Aristida*, *Chrysopogon*, *Eragrostis* and *Sorghum* (Figure 80) or tableland white grass (*Ischaemum albovillosum*). These seasonally waterlogged wetlands contain a series of local endemic herbs including *Flaveria australasica* subsp. *gilgai* (Figure 81b), *Chrysocephalum* sp. Pilbara (Figure 82b), and a yet to be named *Oldenlandia* species and the tableland white grass.

Figure 80. *Sorghum* grassland on Hamersley Plateau (Pilbara). Photo – G Keighery/DEC.

Figure 81. A rocky clayflat wetland covered with Mitchell Grass grassland (including *Astrebla* species) and a mixed herbland in the Hamersley Range (Pilbara). Photos – B Keighery/OEPA.

(a) Wetland on flat between bands of rocky hills.

(b) *Flaveria australasica* subsp. *gilgai*.

Figure 82. A rocky clayflat wetland covered with mitchell grass grassland (including *Astrebla* species) and a mixed herbland in the Hamersley Range (Pilbara). Photos – B Keighery/OEPA.

(a) Wetland on flat between bands of rocky hills with *Chrysocephalum* sp. Pilbara (yellow).

(b) *Chrysocephalum* sp. Pilbara flower heads.

Claypans

Scattered through the Externally Drained Deserts are a variety of perched claypans (Figure 83). Some specific examples of these are given below.

- McNeill Claypan (Carnarvon) – this large 2,500-hectare claypan is situated in the alluvial deposits of the Gascoyne River floodplain south-east of Carnarvon and is covered by a shrubland of lignum (*Muehlenbeckia florulenta*), herblands dominated by the semi-woody annual *Sesbania cannabina*, and sedgelands and grasslands. This is the largest known claypan in WA.
- Peedamulla Swamp (Pilbara) – this 500-hectare claypan is located on the Cane River and is dominated by *Eucalyptus victrix* woodland over a sedgeland of *Cyperus* species.
- Newman (south Pilbara) – Desmond et al.[80] record a claypan dominated by the aquatic perennial marshwort (*Nymphoides indica*) (a major disjunction from the Kimberley) 70 kilometres south of Newman.
- Yadjiyugga (Ashburton River Catchment section of Gascoyne) – this claypan supports *Eucalyptus victrix* woodlands, *Tecticornia verrucosa* shrubland and *Eriachne benthamii* grasslands.

Figure 83. Claypan on the alluvial flats of the Ashburton River near Onslow (Gascoyne). Photos – B Keighery/OEPA.

(a) Claypan surrounded by sand dunes.

(b) Annual *Asteraceae* species.

(c) Plant and flowers of *Myriocephalus rudallii*.

Wetland flora of the Externally Drained Deserts

Range ends: populations at the margins of the area to which a species is native

There is no comprehensive data for the Externally Drained Deserts. However, the Pilbara and the Carnarvon Basin have recent biological surveys available to assess the diversity and contribution of wetlands to the flora of the Externally Drained Deserts.

The Pilbara, with a recorded flora of 1,509 species[81], contains a significant wetland component of 388 species, which comprises 25.7 per cent of the flora (Figure 84). Although this includes eight species of mangrove along the coast and another thirty-one species of the saline marshes, most Pilbara wetland plants are from freshwater sites, with 246 occurring in damplands (seasonally waterlogged basin wetlands) and 103 being aquatics.

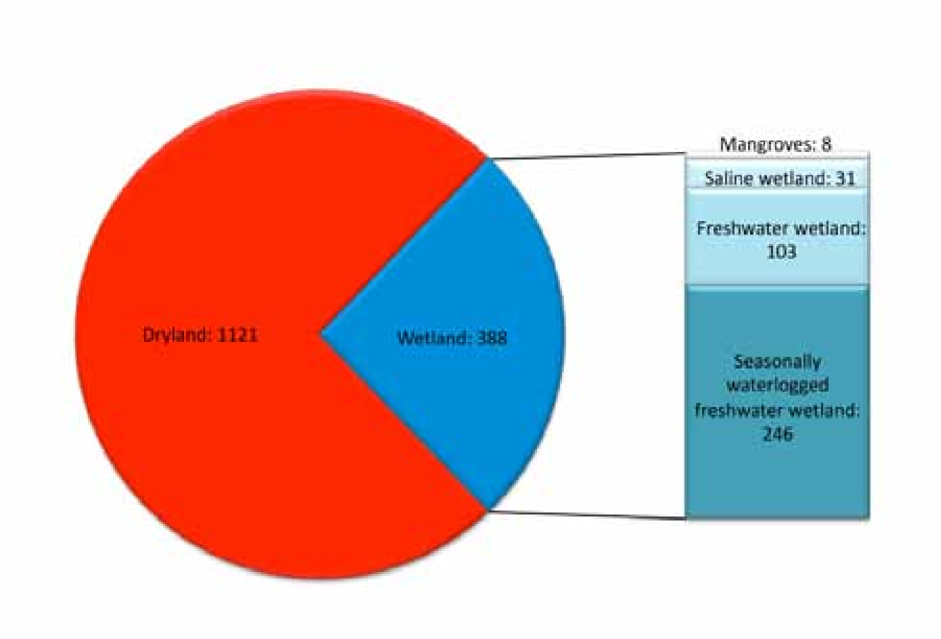


Figure 84. Pilbara wetland and dryland vascular plant taxa found in various plant groups (after Western Australian Herbarium[81]).

As with the Internally Drained Desert, there are many **range ends** and disjunct populations, including: *Adiantum capillus-veneris*, *Pteris vittata*, *Lobelia quadrangularis*, *Cladium procerum*, *Baumea rubiginosa*, *Sonchus hydrophilus* and *Eleocharis sphacelata*. Most of these species are found in the deep gorges of the Hamersley Range. All fourteen ferns and fern allies are wetland plants.

A number of local endemics are found in the seasonally inundated Fortescue Marshes and on claypans and cracking clays (see above, Figure 74a&b and Figure 75).

Gibson et al.[82] in a regional study of the wetlands of the Carnarvon Basin recorded a total of 258 species from fifty-eight wetlands; again constituting about a quarter of the total flora recorded. There were few endemics recorded, most species being widespread arid species. However, thirty-four taxa were temperate wetland taxa at their northern range ends and eighteen were tropical wetland taxa at their southern range ends. The floristics of these wetlands confirmed the major saline and freshwater divisions described above, as well as demonstrating the same trends noted in the Southwest, that is that there are significant numbers of naturally uncommon species in wetlands. The study by Gibson et al.[82] found that 25 per cent of species were recorded at only one study site and 46–55 per cent of records were recorded once (singletons). This uncommon component adds significantly to the biodiversity, but is not predictable. As a consequence, the use of this information in ranking the conservation status of wetlands is difficult as each wetland has significant differences for a few taxa. Unlike with the Internally Drained Deserts, wetlands contribute significantly to the diversity and apparently the endemism of the flora of the Externally Drained Deserts. The endemism of the wetlands remains to be comprehensively documented (see Figure 85, for example).

Figure 85. Wetland shrubs all from the *Salsola australis* complex. Photos – B Keighery/OEPA.

A guide to managing and restoring wetlands in Western Australia

Wetland vegetation and flora, part 4: Southwest

In Chapter 2: **Understanding wetlands**

Australian Government

Department of Environment and Conservation

Our environment, our future

Contents

Wetland profiles

Introduction

Western Australia is a very large state and there is a great deal of variability in wetland vegetation and flora across it. The Southwest is one of three major climatic and biogeographical zones (Figure 86):

- Kimberley – tropical, warm to hot all year, summer rainfall and a dry winter
- Deserts – hot desert, infrequent erratic rainfall
- Southwest – Mediterranean, warm to hot dry summer, cool wet winter.

The differing climate of these three regions drives important variations in wetland vegetation.

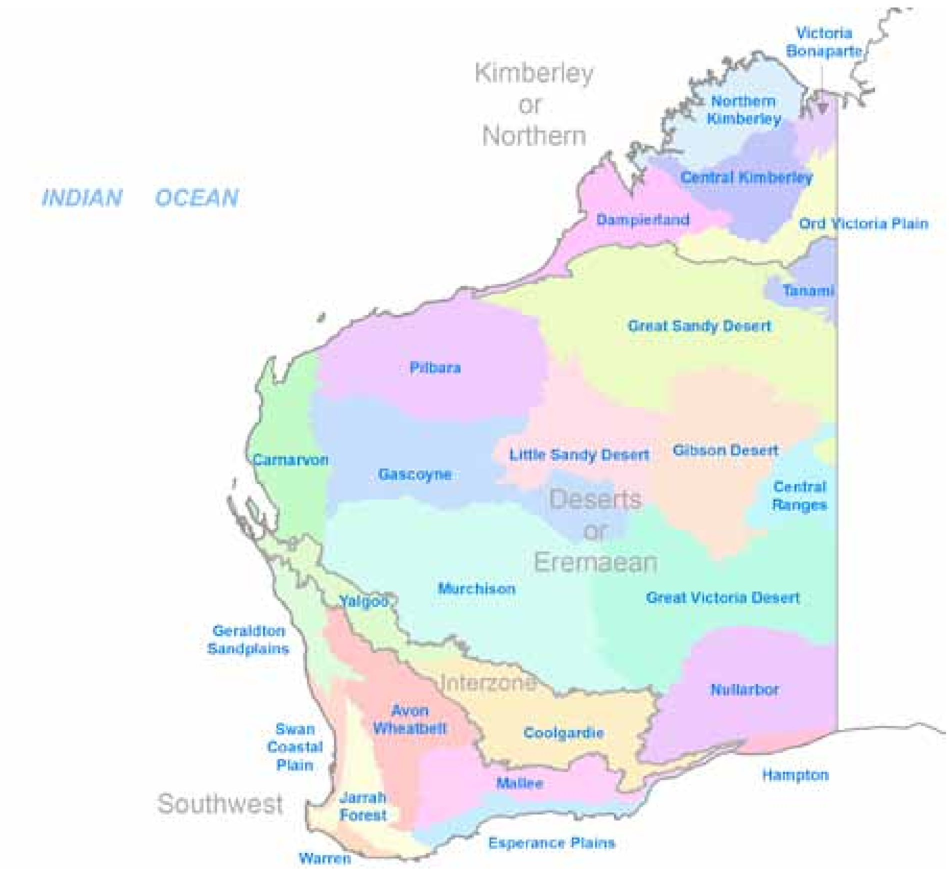


Figure 86. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

The next major driver of the wetland vegetation and flora characteristics of the Southwest is whether they inhabit freshwater or saline wetlands. Wetland plant communities are distinctive of the zone and water chemistry, contributing both to the local and state identity and contributing greatly to the uniqueness of WA and Australia.

Thirdly, in addition to zone and freshwater/saline divisions, the Southwest wetlands can be grouped according to the similarity of their vegetation characteristics. In the Southwest zone, these groups are:

- saline lagoons
- saline basin wetlands
- saline riverine
- groundwater fed
- perched wetlands.

Southwest

The Southwest is world renowned for its plant diversity and large number of endemic plant species and communities. This diversity, combined with it being the wettest area of the state, has resulted in an immense variety of wetlands. Also, being in the most populous area of the state, these wetlands have suffered the greatest impacts from clearing, agriculture and urban uses, leading to loss, fragmentation and degradation.

The Southwest wetlands are the best known and most studied in WA. A substantive number of reports deal with a variety of plant-related wetland topics including: descriptions of individual wetlands, groups of wetlands and regional groups, wetland mapping; regional floristic data; and wetland management (related to various aspects such as regions, reserves, rare species and communities). However, there are no true regional overviews, databases or bibliographies on the Southwest's wetland plants.

For the purposes of this topic, the Southwest incorporates nine bioregions: Yalgoo, Geraldton Sandplains, Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest, Warren, Esperance Plains, Mallee and Coolgardie. The Yalgoo and Coolgardie are generally considered to form an inter-zone between the Desert and the Southwest but, for wetland vegetation and flora, are more closely related to that of the dry Southwest. While the nine bioregions share some wetland characteristics, the overall variety of wetland vegetation and flora is great.

There are fifty-eight listed nationally important wetlands in the Southwest, the most for any of the three wetland zones.

Wetland vegetation of the Southwest

Broadly, the vegetation of the Southwest consists of *Eucalyptus*-dominated tall forest and woodlands, *Melaleuca*-dominated forest and woodlands; *Acacia* woodlands, shrublands and heath, *Casuarina* and *Banksia* low woodland; mallee woodlands and shrublands, chenopod and samphire succulent shrublands and heath. As with the Kimberley and Deserts, many of these vegetation types are present in wetlands but chenopod and samphire succulent shrublands are confined to wetlands; further, some vegetation types that are common in wetlands are rare at the broader level, including sedgelands and herblands. There are so many wetland species in the Southwest that the most common taxa cannot be listed here.

From the literature reviewed during the development of this topic, in excess of several thousand different plant communities are potentially associated with the Southwest's wetlands, depending on the scale and detail of mapping. The wetland vegetation is grouped below after a series of key features of the wetland habitats.

Many wetlands combine freshwater and saline wetland features in wetland complexes. Two examples are provided at the end of this topic: the Yalgorup National Park wetlands and Brixton Street wetlands complexes.

Saline wetlands of the Southwest

Saline wetlands are found in both coastal and inland locations throughout the region and are described below in four principal groups: lagoons, saline basin wetlands, riverine (including rejuvenated drainage and palaeo-drainage channels) and springs. The four principal groups are subdivided further.

A feature of many of these saline wetlands is freshwater areas fed by seepages/springs of fresh groundwater. These are described in this section on saline wetlands as they are a significant component of these wetlands and are becoming increasingly rare as groundwater levels generally decline in the Southwest. Most seepage areas associated with salt lakes are of freshwater, forming unique communities and providing a water supply for fauna.

Marl: fine-grained calcareous material (usually from dead charophyte algae that are able to biogenically precipitate calcium carbonate)

Lagoons

These saline wetlands are closely allied to the estuarine and marine fringing wetlands but have recently (in geological timeframes) been isolated from the estuary or ocean. A few retain seasonal linkages to the estuary or ocean and the boundaries with the saline estuarine areas are poorly defined. Brearley[83] describes the estuarine systems. A number of wetland types are distinguished in this group and a series of examples from across the bioregions are used to illustrate the vegetation of each type.

Island saline wetlands

Only three of these are known and they are all included below.

- Abrolhos Islands (Geraldton Sandplains) – These lagoons are fringed by white mangroves (*Avicennia marina*) and remain connected to the surrounding ocean.
- Rottnest Island* (Swan Coastal Plain) (Figure 87) – Located on Perth's doorstep these are the best documented and well known of the lagoon wetlands. The island's lakes are a unique wetland complex of eighteen salt lakes, sumplands and damplands, covering more than 180 hectares. Seven are permanently inundated (lakes). The three deepest lakes, Government House, Herschell and Serpentine lakes, are unique in Australia[9] having cool, low-salinity water overlying warmer higher saline water (meromictic). In these wetlands low shrublands of *Tecticornia indica*, *T. halocnemoides* and *Sarcocornia quinqueflora* with *Gahnia trifida* typically fringe the water. Patches of *Melaleuca lanceolata* occur on the slight rises over the shrubs and sedges. The aquatic *Ruppia tuberosa* found in these lakes is one of only two occurrences outside Shark Bay. Cropped grasslands dominated by native couch (*Sporobolus virginicus*) grow at the freshwater seepages found dotted around some of these lakes. These communities are maintained by quokka grazing and are true marsupial lawns. Interestingly, this complex contained some freshwater wetlands, rainfall being perched on a **marl** layer. Unfortunately, these wetlands were mined for their marl, for use in road works. Attempts are currently being made to reform these wetlands.
- Recherche Archipelago Islands (Esperance Plains) – Middle Island in the Recherche Archipelago contains Lake Hillier, a saline lake usually coloured pink with the alga *Duniellia salina*. The vegetation of the lagoon is similar to that of the Esperance Coastal Lakes (see below).

Figure 87. Rottnest Island salt lake with fringing *Melaleuca lanceolata* forest and samphire shrublands. Photo – B Keighery/OEPA.

West coast lagoonal lakes

- Hutt Lagoon* (Geraldton Sandplains) – Hutt Lagoon (Figure 88 and Figure 89) is a brackish to saline wetland covering around 3,000 hectares, and fed by rain, surface inflows and groundwater seepage. The wetland contains a complex series of fresh to saline wetlands, with more than twenty distinct wetland plant communities.[84] Low rises in the wetland are covered with *Casuarina* obesa low woodlands over *Gahnia trifida*; the flats with low succulent shrublands of *Tecticornia* species (*T. indica*, *T. undulata*, *T. syncarpa* and *T. halocnemoides*); and the lower wetter areas with *Sarcocornia* species over *Triglochin striata* and *Wilsonia humilis*. Freshwater seepages occur on the eastern side of these wetlands and support sedgelands of *Juncus kraussii* subsp. *australiensis* and *Baumea articulata*.
- Leeman Lagoons (Geraldton Sandplains) – Around Leeman there are a series of permanently and seasonally inundated saline and gypsum wetlands with low rises covered by *Casuarina obesa* woodlands over *Gahnia trifida* sedgelands[85] (Figure 2). Freshwater seeps are located on the eastern side; one of these, Etha Springs, is dominated by *Juncus kraussii* subsp. *australiensis*, *Cyperus laevigatu*s and *Typha domingensis* sedgelands. Further examples of similar types of wetland are found at Coolimba (Geraldton Sandplains).
- Lake Thetis* (near Cervantes, Swan Coastal Plain) – Water in this lake is saline to hypersaline, with only the aquatic *Ruppia tuberosa* on the lake bed. Edges have succulent shrublands of *Sarcocornia quinqueflora*, *Tecticornia halocnemoides* or sedgelands of *Gahnia trifida* and *Baumea juncea*, all over herbs. The stromatolite community of Lake Thetis is a TEC.
- Lakes Walyungup and Cooloongup (Swan Coastal Plain) – Like most lakes in the Southwest, these periodically dry out and have also been called White Lakes in reference to the dazzling white salt beds exposed on drying (Figure 90). Low woodlands of *Melaleuca cuticularis* over sedgelands dominated by *Gahnia trifida* and/or *Juncus kraussii* subsp. *australiensis* and samphire shrublands are associated with these wetlands. Freshwater seepage areas on the margins of both lakes are associated with low or tall forests dominated by *Melaleuca rhaphiophylla* and/or tuart

(*Eucalyptus gomphocephala*) over sedgelands dominated by *Lepidosperma gladiatum*, *Gahnia trifida* and *Baumea juncea*. Some of these wetland communities are the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain' (Figure 11).

- Yalgorup Lakes* (Swan Coastal Plain) – The waters of these lakes are seasonally hyposaline (winter) or permanently hypersaline (for more information on the Yalgorup Lakes complex, see 'Profile of a wetland complex: Yalgorup National Park wetlands', located near the end of this topic).

Figure 88. A view of the Hutt Lagoons (Geraldton Sandplains). Photos – B Keighery/OEPA.
(a) Eastern margin dominated by *Gahnia trifida* sedgelands.
(b) and (c) Habit and flowers of the native *Cyperus laevigatus*, a cosmopolitan sedge of the areas with fresher water.

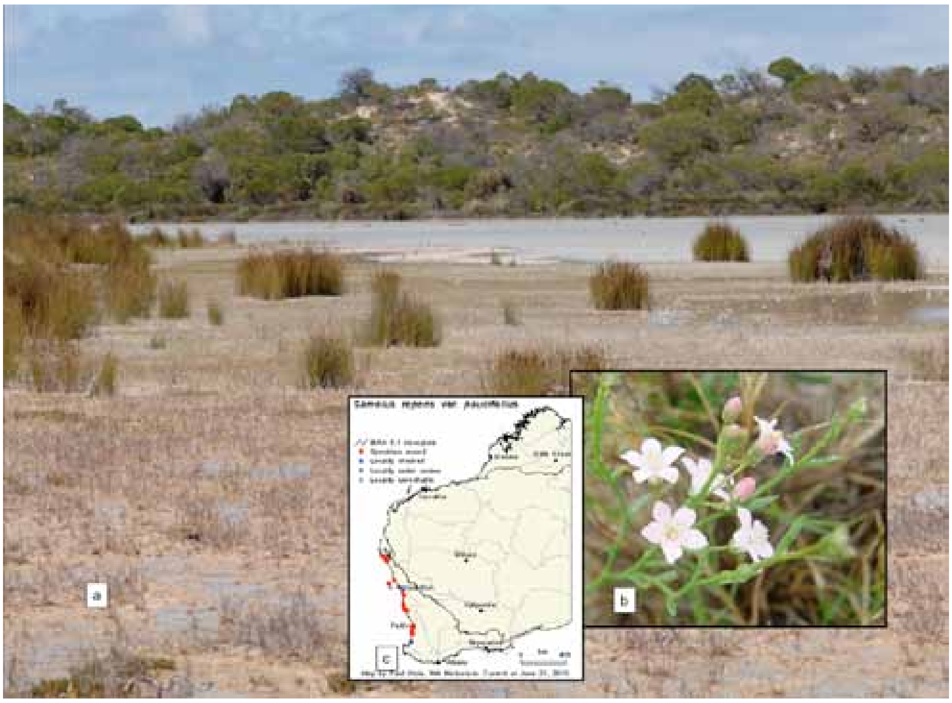


Figure 89. Another view of the Hutt Lagoons (Geraldton Sandplains). Photos – B Keighery/OEPA.

(a) Looking west towards the coastal holocene dunes across a saline flat with patches of *Juncus kraussii* subsp. *australiensis* sedgeland and *Wilsonia humilis* herbland.

(b) Flowers of *Samolus repens* var. *paucifolius*, a plant scattered through these communities.

(c) This is a plant of the coastal saline wetlands between Shark Bay and the Yalgorup Wetlands. Mapping – P Gioia. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

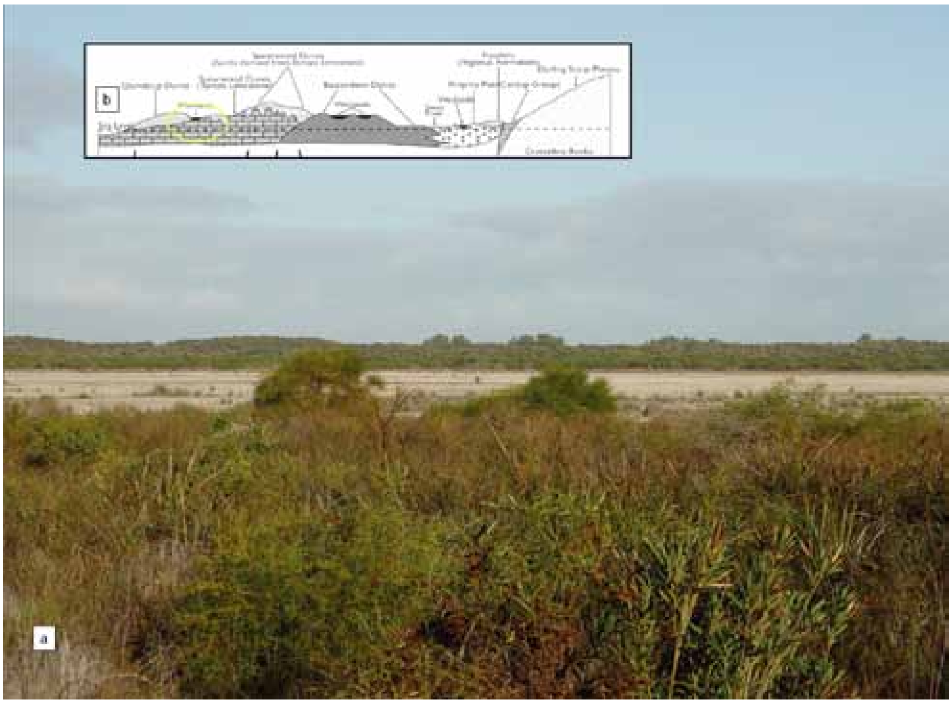


Figure 90. Lake Walyungup, a salt lake near Rockingham (Swan Coastal Plain).

(a) The salt encrusted dry lakebed is surrounded by bands of *Juncus kraussii* subsp. *australiensis* sedgelands and samphire shrublands. Wetlands with fresher water around the outside margins are dominated by *Lepidosperma gladiatum*. *Acacia* shrublands are found on the dry rises. Photo – B Keighery/OEPA.

(b) Lake Walyungup lies to the west of a band of Quindalup Dunes, with Spearwood Dunes to the east (transect diagram reproduced and adapted from Department of Minerals and Energy[86] with permission).

South Coast lagoonal

Culham Inlet Lagoons* (Esperance Sandplains) – These wetlands are estuarine areas where the sand bar is rarely breached; they are, therefore, no longer truly estuarine and are fed by naturally saline rivers. For example, Culham Inlet, fed by the Phillips and Steere rivers, had not breached to the sea for at least 150 years before recent clearing for agriculture in the catchment. Similar systems include the Fitzgerald and Dempster inlets. These have the same vegetation as the Esperance Coastal Lakes.

Saline basin wetlands

Southern basin wetlands

These extend from near Frankland and Albany to east of Esperance (Figure 91). An example is Kwornicup Lake (Jarrah Forest), with a mosaic of vegetation units including: a *Wilsonia backhousei* herbland (on the lake bed); *Tecticornia syncarpa* and *Sarcocornia quinqueflora* (samphires) shrubland; shrublands dominated by *Melaleuca thyoides*, *M. acuminata*, *M. viminea* and *M. halmaturorum*; and woodlands of *Casuarina obesa* and/or *Eucalyptus rudis*. To the east, north of the Stirling Ranges, is the Balicup System (1,400 hectares) containing Camel, Balicup, Jebarjup and Swan lakes (Esperance Sandplains). The Balicup System is typical of naturally saline lakes around the range.[87] Although the lake beds are largely bare, the margins are covered in zones of low samphire shrubland, *Austrostipa juncifolia* grassland and *Melaleuca cuticularis* woodland. Several very unusual species are found in the samphire shrublands, including *Tecticornia uniflora*. A further example of this type is the Jerdacuttup Lakes (east of Hopetoun, Esperance Sandplains) with *Tecticornia indica* samphire shrubland and a *Melaleuca cuticularis* forest to woodland.

Figure 91. Salt lake in Truslove Nature Reserve (Esperance Sandplain). Photos – B Keighery/OEPA.

(a) *Melaleuca* shrubland on the low gypsum dunes and succulent shrubland adjacent to the bare drying lake bed.

(b) Samphire shrubs and the prostrate succulent *Disphyma crassifolium* subsp. *clavellatum*.

Esperance coastal lakes (Esperance Sandplains)

This complex includes the Lake Gore System*, Lake Warden System*, Mortijinup Lake System* and Pink Lake*. All are fringed by *Melaleuca cuticularis* woodlands often over a sedgeland dominated by *Juncus kraussii* subsp. *australiensis*, *Gahnia trifida*, *Baumea juncea* and/or *Ficinia nodosa*. Areas of samphire shrublands are also found in the system.

Swan Coastal Plain lakes/sumplands/damplands

Where groundwater is naturally saline, as in the northern Perth Basin, the lakes are saline. An example is Lake Eganu (north of Moora) which is bare in the middle then edged with zoned vegetation from *Tecticornia pergranulata* samphire shrubland to *Casuarina obesa* and *Melaleuca cuticularis* woodland. Lake Guraga (south-west of Cataby) has bands of vegetation relating to inundation and salinity.[88] The lake is bare in the centre, then fringed with a low *Wilsonia backhousei*, *Tecticornia pergranulata* and *Lawrencia glomerata* shrubland, a *Tecticornia indica* and *T. pergranulata* samphire shrubland with herbs and grasses and finally a fringing shrubland of *Melaleuca viminea*. Patches of saline wetland are found within a number of predominantly freshwater wetlands. When these saline wetlands are on clays they support a suite of annual herbs and sedges (Figure 92). These same herbs and sedges are also found in some of the saline wetlands.

Figure 92. Some annual species renewed from seed found in the herblands of saline clayflats. Photos – B Keighery/OEPA.

(a) The sedge *Centrolepis polygyna*.

(b) Two daisies, the newly described *Blennospora doliiformis* (left) and *Pogonolepis stricta*.

(c) *Angianthus drummondii*, one of the wetland species recently separated from the species complex.

Riverine

Rejuvenated drainage

Much of southern WA is composed of a low relief lateritised plateau with active drainage. In the higher rainfall areas (including the Jarrah Forest and Avon Wheatbelt) the rejuvenated drainage lines still connect to the sea and flow most years. Further inland, as rainfall decreases, flows decline and occur only in wet periods, forming braided saline drainage systems. Extensive braided drainage systems are found on all of the major rivers. These often have high vegetation and flora values, especially those of the Mortlock River and the Yenyening System on the Avon River (Avon Wheatbelt). Work on mapping the vegetation of the Yenyening System[36] has distinguished twenty-two vegetation units, ten of these being wetland units. The saline wetland units occur in a mosaic and include: saline wetlands with three types of samphire shrublands, *Casuarina obesa* forest over *Juncus kraussii* subsp. *australiensis* sedgeland, *Hopkinsia anaectocolea* sedgeland, herblands, *Eucalyptus sargentii* woodland over chenopod shrubland, *Eucalyptus orthostemon* mallee, *Melaleuca atroviridis* shrubland and shrublands dominated by mixes of *Melaleuca hamata*, *M. brophyi*, *M. halmaturorum* and *M. lateriflora*. Scattered through the area are perched, mostly freshwater, wetlands that support *Callistemon phoeniceus* and *Melaleuca thyoides* shrubland and *M. brevifolia* shrubland over *Baumea riparia* and *Juncus kraussii* subsp. *australiensis* sedgelands. Eight species of uncommon flora (priority flora) are located in the wetlands, including the only known populations of a new *Arthropodium* species. All of the braided systems are threatened by hydrological changes.

Palaeo-river systems

Inland from the rejuvenated drainage area in the Avon Wheatbelt, Mallee, Coolgardie and Yalgoo, there is no connected drainage. In these areas, salt lake chains occur (Figure 93, Figure 94 and Figure 95). They are remnants of ancient drainage systems (palaeo-drainage lines) and only function as connected systems in very wet years. These include Lake Goorly, Lake Deborah, Lake Moore, Lake Dumbleyung*, Johnston Lakes, Lake King (Figure 95), Mollerin Lakes and Cowcowing Lakes. Normally the lakes are bare of vegetation then have zones of vegetation from the water body outwards being: samphire shrublands, saltbush (*Atriplex* species) shrublands, *Melaleuca* shrublands and mallee shrublands to woodlands over saltbush shrublands. Rises are covered by samphire shrublands or saltbush shrublands, and rarely *Eucalyptus kondininensis* and *E. salicola* woodlands and *Callitris verrucosa* over samphire shrubland.

Fringing many of these inland lakes are areas of gypsum wetland flats and associated dunes, which contain many unusual to rare species. For example Lake Tay (Mallee) has *Anigozanthos bicolor* subsp. *minor, Eremophila lactea*, *Ricinocarpus trichophorus* and *Myoporum turbinatum*. There are eighty species endemic to the Southwest confined to gypsum rich soils. Gypsum dunes and flats are found in the Lake Grace* system (Mallee), Chinnocup System (Mallee), Kondinin Salt Marsh (Avon Wheatbelt), Kent Road braided saline drainage lines (Mallee), Lake King (Mallee, Figure 95) and in the Buntine-Marchagee area (Avon Wheatbelt).

Figure 93. Samphire shrubland on a lake bed in Charles Darwin Reserve (Yalgoo). Similar wetlands are also located in the adjacent Murchison. Photos – B Keighery/OEPA.

(a) Wetland between sand dunes.

(b) *Kippistia suaedifolia* in samphires.

(c) and (d) *Lawrencia squamata* bush and flowers.

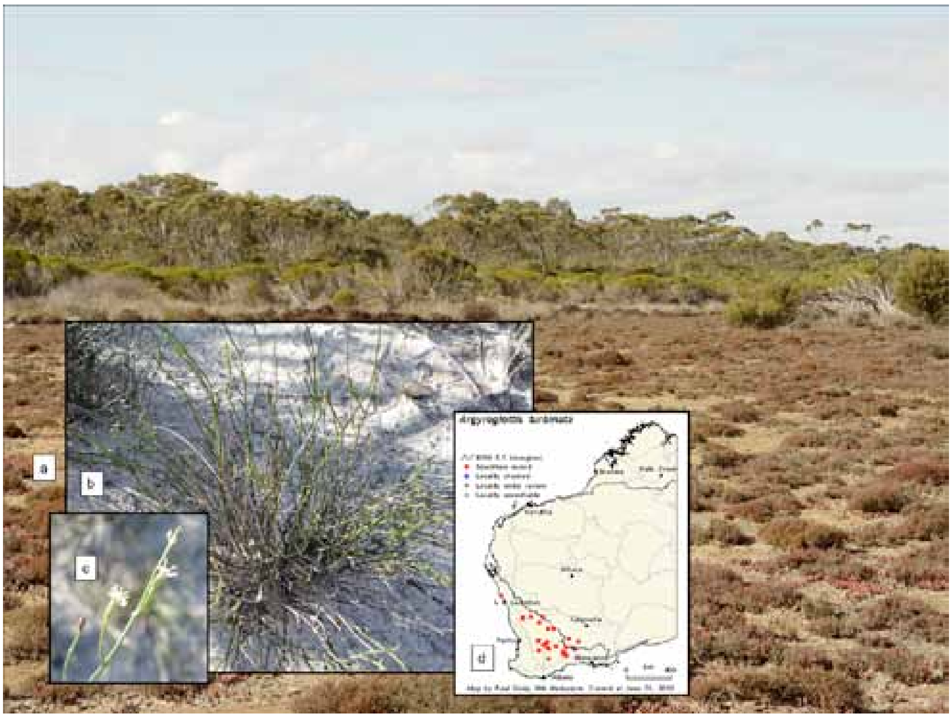


Figure 94. A saline wetland in Truslove Nature Reserve (Esperance Sandplain). Photos – B Keighery/OEPA.

(a) Saline wet flat between dunes, covered with a samphire shrubland.

(b) and (c) A wetland daisy *Argyroglottis turbinata*.

(d) In Truslove Nature Reserve this species is at the eastern end of its range. Mapping – P Gioia. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

Figure 95. A gypsum dune alongside Lake King (Mallee). Photos – B Keighery/OEPA.
(a) The flat lake bed between gypsum dunes with a shrubland of samphires and other shrubs.
(b) A gnarled native conifer, *Callitris canescens*.
(c) A flower of the pea *Bossiaea cucullata*, which grows on the gypsum dune (green bush central foreground).

Springs

A unique saline system is Arinya Springs near Dowerin (Avon Wheatbelt), first described by John Septimus Roe in the nineteenth century. This is a natural permanent saline seep covered with succulent shrubland of *Sarcocornia quinqueflora*, *Tecticornia halocnemoides* and *Wilsonia backhousei* with scattered sedges of *Juncus kraussii* subsp. *australiensis* and shrubs of *Frankenia pauciflora* on quaking deep organic soils.

Freshwater wetlands of the Southwest

Freshwater wetlands are found in both coastal and inland locations throughout the zone. They are separated into two main groups based on the principal source of water: groundwater or rainfall held by an impeding layer (perched wetlands). Of course, most wetland systems contain wetlands from both groups and some individual wetlands are fed by water from both sources.

Groundwater fed

This wetland group is further divided into inundated basin wetlands, seasonally waterlogged wetlands and springs where water is actively discharged. Again, many wetlands have water from both sources.

Inundated basin wetlands

The vegetation of inundated basin wetlands is very much related to the period of inundation. Groundwater changes are leading to widespread drying of these wetlands. With changing hydrological conditions many lakes and sumplands are developing characteristics of seasonally waterlogged wetlands, and at times the opposite changes prevail.

Lakes and sumplands

The Southwest contains numerous permanently inundated basins (lakes) and seasonally inundated basins (sumplands) (Figure 96, Figure 97 and Figure 98). As outlined previously these are shallow by world standards, usually being less than 3 metres deep. Changes in land use throughout the Southwest have influenced the seasonality and the salinity of many water bodies.

Figure 96. Lake Mount Brown (Spearwood Dunes, Swan Coastal Plain), a brackish sumpland with fresh inflows. Zones of sedgelands and *Melaleuca* forest can be seen on far shore. Photo – K Clarke/Western Australian Local Government Association.

Figure 97. Shirley Balla Lake (Bassendean Dunes, Swan Coastal Plain), a sumpland with sedgeland dominated by *Juncus pallidus* and *Baumea articulata* then a band of *Melaleuca preissiana* forest. Photo – G Keighery/DEC.

Figure 98. Minninup Swamp (Quindalup/Spearwood Dune interface, Swan Coastal Plain) south of Bunbury, a freshwater wetland supporting a mosaic of communities including Tuart (*Eucalyptus gomphocephala*) forest (background), *Melaleuca rhaphiophylla* forest (mid-ground) and sedgeland. *Muehlenbeckia adpressa* (broad leaf) can be seen in among the sedges (foreground). The TEC 'Sedgelands in Holocene dune swales of the southern Swan Coastal Plain' is found in parts of this wetland. Freshwater wetlands in the Quindalup/ Spearwood Dune interface are uncommon. Photo – B Keighery/OEPA.

Most freshwater wetlands of the heavily cleared agricultural areas (principally the Avon Wheatbelt) have become secondarily salinised and have lost most of their original vegetation. The original vegetation may be replaced by samphire shrublands and/ or completely lost in the permanently inundated areas. These changes are particularly evident at Lakes Dumbleyung*, Taarblin and Wannamal*. Lake Toolibin* (297 hectares) is one of the last remaining wooded freshwater wetlands of the Avon Wheatbelt. This group of wetlands was usually covered by *Casuarina obesa* woodlands over *Melaleuca strobophylla*. The Lake Toolibin example of this community, together with another occurrence at Dowerin (13 hectares), are listed as the TEC 'Perched wetlands of the Wheatbelt region with extensive stands of living Swamp Sheoak (*Casuarina obesa*) and Paperbark (*Melaleuca strobophylla*) across the lake floor'. The catchment of Lake Toolibin is a natural diversity recovery catchment.

➤ For information on natural diversity recovery catchments, see the DEC website.[89]

➤ For more information on secondary salinisation and its management, see the topic 'Secondary salinity' in Chapter 3.

Outside these heavily cleared areas a large number of lakes and sumplands remain. These typically have a central water body fringed by zoned wetland vegetation. A series of these wetlands is described below, grouped according to development of organic layers as this drives the type of vegetation associated with the wetland.

Poorly developed organic layers

Some key groups are described below to illustrate the variation in the group.

- Yate (*Eucalyptus occidentalis*) Swamps
  These extend from east of Esperance, north to Kojonup and west to the Tone River (Esperance Sandplains, Avon Wheatbelt and Jarrah Forest), and can be segregated into six types.[90] Some examples from the Esperance Sandplains are Yellilup Yate

Swamp*, Bremer Bay and Pabellup Swamp, Fitzgerald River National Park, which have Yate woodland over *Melaleuca cuticularis* and *M. rhaphiophylla* woodlands. Other types have *Baumea* sedgelands, shrublands dominated by combinations of *Melaleuca strobophylla*, *M. lateritia* and *M. atroviridis*.

- Lake Bryde and East Lake Bryde* (Mallee)
  These seasonally inundated wetlands are completely vegetated. The wetland bed is covered with shrublands dominated by lignum (*Muehlenbeckia horrida* subsp. *abdita*) and/or *Tecticornia verrucosa*, surrounded by *Eucalyptus occidentalis* woodland over *Melaleuca* species shrublands. These are the only wetlands dominated by shrubs in the mallee part of the agricultural zone. Interestingly, *Muehlenbeckia horrida* subsp. *abdita* is declared rare flora (DRF) and its community is the TEC 'Unwooded freshwater wetlands of the southern Wheatbelt of WA, dominated by *Muehlenbeckia horrida* subsp. *abdita* and *Tecticornia verrucosa* across the lake floor'. The entire system is a natural diversity recovery catchment.
- Lake Cronin* (Mallee)
  This sumpland supports the largest and best examples of a *Melaleuca*-dominated wetland in the eastern Wheatbelt.[8] The sumpland is fringed by shrublands and woodlands of *Melaleuca strobophylla*, *M. cuticularis*, and *M. atroviridis* over lignum (*Muehlenbeckia florulenta*). When flooded, the sumpland supports mixtures of the grass *Amphibromus vickeryae*, the sedge *Eleocharis acuta* and the herb *Stemodia florulenta*. As the sumpland dries, a herbland dominated by *Goodenia viscida* and *Glycyrrhiza acanthocarpa* develops.
- Lake Logue* (fresh) and Lake Indoon* (brackish) (Geraldton Sandplains)
  These are most similar to the coastal saline lakes of Coolimba-Jurien Bay. The Lake Logue bed has areas of cane grass (*Eragrostis australasica)*, *Casuarina obesa* woodland and fringing *Eucalyptus rudis* or *Melaleuca rhaphiophylla* woodlands. Lake Indoon is similar but the bed is bare.
- Rowles Lagoon System* (Coolgardie)
  This system north-west of Kalgoorlie includes Rowles Lagoon[91] (150 hectares), Clear Lake and Brown Lagoon (20 hectares each), Carnage and Muddy lakes (100 hectares each) and many smaller lakes and lagoons, including Canegrass Lagoon. This freshwater complex, with both seasonally inundated and near-permanently inundated wetlands, can cover more than 200 hectares when flooded. The lake beds have lignum (*Muehlenbeckia florulenta*) shrubland or cane grass (*Eragrostis australasica*) grasslands, with a fringe of *Melaleuca xerophila* shrubland.

Well developed organic layers ('peat lakes')

The peat of these wetlands is typically formed from sedges, principally *Baumea articulata* (Figure 97). There are no true sphagnum swamps in WA though sphagnum (formed from the moss *Sphagnum novozelandicum*) is present in the Warren.[92] Many of the lakes around the Perth area (Swan Coastal Plain) are of this type including Benger Swamp*, Herdsman Lake* and Lake Joondalup*. Some examples from across the Southwest are described below.

- Byenup Lagoon System* (5,000 hectares) and Lake Muir* (4,600 hectares) (Jarrah Forest)
  The vegetation of these systems has been mapped[34] and thirty structural vegetation units have been distinguished. Both freshwater and saline wetlands are found in the system. The freshwater plant communities include: *Eucalyptus rudis* woodland, forest or woodland dominated by *Melaleuca preissiana* and *Banksia littoralis* (Figure 99) or *M. preissiana* and *E. rudis* or *Melaleuca rhaphiophylla*; shrublands dominated by *Pericalymma ellipticum* and/or *Taxandria* species; and sedgelands dominated by *Baumea articulata*, *B. vaginalis* and/or *Lepidosperma longitudinale*. Within these freshwater areas are clayflats with shrublands dominated by *Melaleuca lateritia* or *M. viminea* and *M. densa* and *Meeboldina* species sedgeland. The partly saline areas in

Lake Muir have: *Melaleuca cuticularis* woodland; shrublands dominated by a variety of shrubs including *Kunzea* and *Melaleuca* species; samphire shrublands; and *Gahnia trifida* sedgeland. The sedgelands in these wetlands are often dominated by trees and shrubs. Within these saline communities *Taxandria juniperina* and *Callistachys lanceolata* woodland is found in freshwater inflow areas.

Figure 99. *Banksia littoralis*, a Southwest wetland tree. Forest and woodlands dominated by this tree are becoming rare as wetlands dry, are infested with *Phytophthora* and are more frequently burnt. Photos – B Keighery/OEPA.

(a) Tree.

(b) Flowers.

- South Coast coastal plain wetlands (including Mount Soho Swamps, Maringup Lakes System, Owingup Swamp System, Doggerup Creek System in the Warren)
  This suite of wetlands supports a similar set of vegetation units: mosaics of sedgeland dominated by combinations of *Baumea articulata*, *B. preissii* and sixteen species of *Chaetanthus* and *Meeboldina*. The margins of the sedgelands have *Taxandria juniperina* forest or shrublands dominated by *Homalospermum firmum* and/or *Beaufortia sparsa*. The nearby Gingilup-Jasper wetland system is similar to the Doggerup system, and includes Lake Jasper. At 10 metres, Lake Jasper is considerably deeper than most wetlands in the Southwest. The vegetation and flora of these wetlands have been well documented.[93]
- South Coast freshwater wetlands
  There are a large number of these wetlands in the areas between Albany and the Esperance area and then north to the Stirling Ranges. Some typical examples are Moates Lagoon* and Shark Lake. Moates Lagoon (Jarrah Forest) has a series of zones: sedgelands of *Baumea articulata* and *Baumea juncea*, followed by sedgelands dominated by *Meeboldina coangustata*, *M. scariosa*, *Anarthria scabra* and *Evandra aristata*, and lastly *Taxandria juniperina* woodlands. East of Esperance, Shark Lake (Esperance Sandplains) has a central *Baumea articulata* sedgeland and sedgeland of *Ficinia nodosa* and *Juncus* species over *Centella asiatica* herbland. A distinctive set of similar wetlands are the Cape le Grand Swamps. These are deep almost permanently inundated freshwater wetlands, also covered with *Baumea articulata* sedgelands, but

supporting several rare aquatic taxa, *Utricularia westonii* and *Aldrovanda vesiculosa*. Many wetland species in the Cape le Grand swamps (Esperance Sandplains) are at their eastern range limits.

- Swan Coastal Plain lakes and sumplands
  There are a series of freshwater lakes and sumplands developed on the Swan Coastal Plain in the Bassendean and Spearwood dunes (Figure 96, Figure 97 and Figure 98) and their interfaces south from Cervantes, including Chandala Swamp*, Loch McNess*, Joondalup Lake*, Herdsman Lake*, Booragoon Lake*, Forrestdale Lake*, Spectacles Swamp*, Thompsons Lake*, Lake McLarty* and Benger Swamp*. These wetlands have been the subjects of numerous comprehensive studies. They were/are covered by *Baumea articulata* sedgeland (now often replaced by *Typha orientalis*), and fringed by woodlands of *Melaleuca rhaphiophylla* and shrublands of *Melaleuca teretifolia*, *M. viminea* and *Astartea* species. Others have *Eucalyptus rudis* and *Banksia littoralis* woodlands, and *Melaleuca preissiana* woodlands over *Pericalymma ellipticum* heath. With declining rainfall and increasing water extraction many of these wetlands, which are surface expressions of the groundwater, are becoming disconnected from the groundwater system (with some now fed by surface water via drains). This change in water regime in many wetlands is leading to a loss of the native annual species such as *Fimbristylis velata*, and replacement by weedy perennial grasses and garden escapes.
- Holocene dune wetlands: Becher Point Wetlands* and Lake Richmond
  These are the freshwater part of the Becher wetland suite on the Rockingham Beach Ridge Plain. These wetlands consist of more than 250 lakes, sumplands and damplands (130 hectares), many of which have well-developed organic layers. These wetlands support *Xanthorrhoea preissii* and *Acacia saligna* shrublands, *Muehlenbeckia adpressa* shrublands and *Baumea juncea* and *Ficinia nodosa* sedgelands. These wetlands are the state listed TEC 'Sedgelands in Holocene dune swales of the southern Swan Coastal Plain'. Similar Holocene swale communities occur at Alkimos, Jurien Bay and Bunbury. Lake Richmond also supports this TEC, with dense sedgeland dominated by *Baumea juncea* and *Ficinia nodosa*. It is the deepest wetland in the Southwest, reported to reach up to 14.4 metres. Prior to the 1960s it was saline but has become fresh following urban development of the surrounds.

Seasonally waterlogged wetlands of basins and flats (damplands and palusplains)

Seasonally waterlogged wetlands are grouped because they support similar units of vegetation. These palusplains and damplands were typically naturally extensive, but due to development many are now remnant portions, such as Hay Park palusplain (Figure 100). Similarly, there has been extensive clearing of seasonally waterlogged areas associated with lakes and sumplands, the wetland vegetation associated with these lakes and sumplands being confined to the fringe of inundated areas. As in all other areas of WA these wetlands, together with those described below under 'Claypans and clayflats' in the 'Perched wetlands', have the greatest diversity of vegetation units and often flora. Again, declining rainfall and groundwater tables are leading to widespread drying of these wetlands. With changing hydrological conditions many seasonally waterlogged wetlands are developing characteristics of the adjacent drylands.

Seasonally waterlogged wetlands typically support a mosaic of vegetation units especially woodlands, shrublands, sedgelands, herblands and rarely grasslands. Woodlands are dominated by *Eucalyptus rudis* and *Melaleuca* species including *M. preissiana* and *M. croxfordiae* and shrublands dominated by a very diverse suite of species such as *Calothamnus lateralis*, *Hakea ceratophylla*, *Melaleuca teretifolia*, *M. viminea*, *M. scabra*, *Astartea* species, *Pericalymma ellipticum*, *Euchilopsis linearis* (Figure 101c), *Regelia ciliata*, *R. inops*, *Kunzea* species, *Adenanthos meisneri* and *Hypocalymma angustifolium*. Within these shrublands there are is often a sedge layer which includes *Hypolaena* *exsulca*, *Mesomelaena tetragona*, *Lepidosperma longitudinale*, *Anarthria scabra* and *Lepyrodia* species. Herbs are generally scattered rather than forming a layer and include *Drosera* species, for example *D. occidentalis* and *D. gigantea*, *Burchardia multiflora* and *Asteraceae* species such as *Hyalospermum cotula*. Uncommon species such as *Dillwynia dillywynioides* (Figure 101a&b), *Boronia juncea* subsp. *juncea* (Figure 102) and *Boronia capitata* subsp. *gracilis* are associated with these wetlands. *Boronia megastigma* is a species of these habitats.

Figure 100. A seasonally waterlogged flat (palusplain), Hay Park in Bunbury (Swan Coastal Plain). Photos – B Keighery/OEPA.

(a) Scattered *Melaleuca preissiana* over shrublands dominated by *Xanthorrhoea brunonis* and *Pericalymma ellipticum*, and herblands dominated by *Stylidium brunonianum* and *Drosera gigantea*.

(b) *Stylidium brunonianum* flowers.

Figure 101. Members of the family Fabaceae are found in wetlands, and many of these are uncommon. Photos – B Keighery/OEPA.

(a) and (b) The uncommon shrub *Dillwynia dillywynioides*.

(c) Flowers of *Euchilopsis linearis*, a monotypic wetland genus (i.e. a genus with only one species).

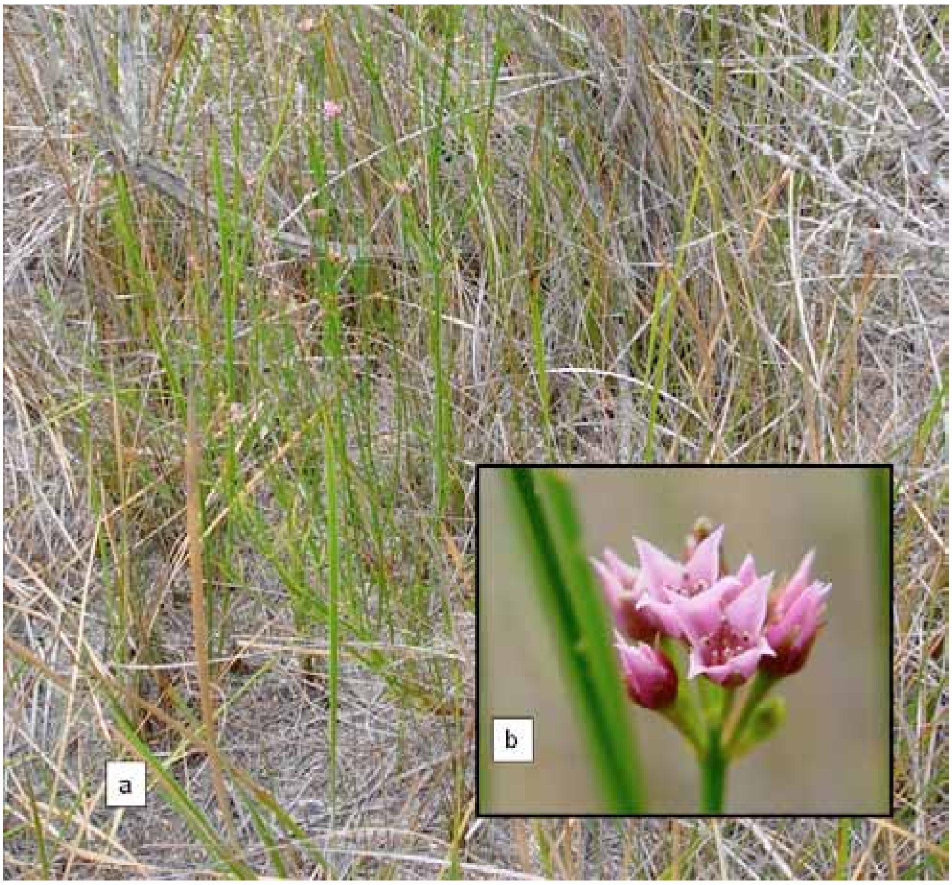


Figure 102. *Boronia juncea* subsp. *juncea*, an uncommon wetland shrub confined to the wetlands in the Kemerton area on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) The *Juncus*-like plant is not very conspicuous when surrounded by sedges.

(b) Flowers.

Springs

There are a variety of wetlands fed by permanent seepages of fresh groundwater. These are often found within other wetland systems and are associated with such species as *Cyathochaeta teretifolia* and *Gastrolobium ebracteolatum* on the Swan Coastal Plain. A few distinctive wetlands of this type are listed below.

- Cape Leeuwin System* (Warren) – This is a permanently inundated coastal wetland, fed by springs covered by sedgelands of *Baumea articulata*, *Baumea juncea* and/or *Schoenoplectus validus* and patches of sedgelands dominated by the weed *Typha orientalis* or *Lepidosperma gladiatum*. In coastal locations, seepage of calcium-rich water from these wetlands over granites forms **tufa** formations that support unique microbial communities.
- Blackwood River seeps* (Warren) – Water from the deep Yarragadee groundwater aquifer surfaces along the Blackwood River and supports distinctive wetland communities. An example is Spearwood Swamps, a permanently inundated wetland with a shrubland dominated by *Homalospermum firmum* and *Taxandria linearifolia* over a *Baumea rubiginosa* and *B. articulata* sedgeland. Within the sedgeland are the rare *Xyris maxima* and *Reedia spathacea*.
- Seeps from **mesas** in the Northampton region (Geraldton Sandplains) – These are poorly documented but have a rich **ephemeral** flora and support many species at the end of their range. The rare endemic *Pterostylis* sp. Northampton is associated with these wetlands.

A particular type of spring, a **mound spring**, is associated with the development of a substantial mound of organic matter at the outlet of the water. These are all rare and three examples are given below.

- Mound springs of the Three Springs area (Geraldton Sandplains) – These are associated with the Dandaragan Scarp, west of Three Springs. At least twenty-four have been historically recorded but now only seventeen remain. These are typified by *Melaleuca preissiana*, *Eucalyptus rudis*, *E. dolorosa* and *E. camaldulensis* woodlands over *Baumea vaginalis* sedgeland. This community is the TEC 'Assemblages of the organic mound springs of the Three Springs area'.
- High altitude peat swamps of the eastern Stirling Range (Esperance Sandplains) – These have a *Homalospermum firmum* shrubland over sedgeland and support a series of endemic species, including the rare *Xyris exilis*.
- Swan Coastal Plain mound springs – These are found between Bayswater and Muchea but the Bayswater occurrence is cleared. Extant (still existing) examples support forest to woodland dominated by combinations of *Melaleuca preissiana*, *M. rhaphiophylla*, *Banksia littoralis* and *Eucalyptus rudis*, with *Taxandria linearifolia* shrubland, *Cyathochaeta teretifolia* sedgeland (Figure 103) and fernlands of *Pteridium esculentum* and/or *Cyclosorus interruptus*. These continuously wet sites contain many species outside their normal ranges, including *Hibbertia perfoliata*, *Lycopodiella serpentina* and *Utricularia volubilis*. These communities all belong to the TEC 'Communities of Tumulus Springs (Organic Mound Springs, Swan Coastal Plain)'.

Tufa: a porous rock composed of calcium carbonate and formed around mineral springs

Mesa: an isolated flat-topped hill with steep sides

Ephemeral (plant): marked by short life cycles, usually a single season

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Figure 103. The plants that define wetland sedgelands come from a variety of families including the *Cyperaceae*. An example is the perennial sedge *Cyathochaeta teretifolia*, a very large sedge (sometimes up to 2 metres tall) of freshwater seepages, especially mound springs. Photos – B Keighery/OEPA.

(a) *C. teretifolia* sedgeland under Melaleuca forest at Piney Lakes (Swan Coastal Plain).

(b) Flowers.

(c) Seeds. The seeds of the genus *Cyathochaeta* distinguish the various species.

Perched wetlands

These wetlands support the greatest diversity of vegetation and flora found in wetlands in the Southwest. This is associated with the variety of habitats formed in response to:

- the base impeding layer which can be clay or rock (ironstone, calcrete or granite and combinations of these)
- the pattern of sequential inundation and drying
- the variety of soils laid at various depths over the water impeding layer.

As a consequence, what may appear to be a very hostile environment in summer supports a rich diversity of habitats in winter and spring. These summer hard surfaces are often damaged by vehicles accessing them when the surface is dry but the underlying soils are wet. Wheel ruts in these wetlands can persist for decades.

These wetlands typically support diverse shrublands and annually renewed sedgelands and herblands. Many of the taxa in these communities are uncommon and many have only recently been recognised.

Examples of these wetlands are described below according the principal impeding layer type, i.e. clay or rock (then ironstone, calcrete or granite). However, it should be noted that all or several impeding layer types may be present in a wetland system.

Claypans or clayflats

A series of examples are listed below. These are best known from the Swan Coastal Plain but occur in many of the bioregions.[94]

- Claypans or vernal pools of the Pinjarra Plain (Swan Coastal Plain, Figure 104 to Figure 111) – These wetlands support many different wetlands and wetland plant communities.[37,95] A number of these communities are TECs: 'Herb rich saline shrublands in clay pans', 'Herb rich shrublands in clay pans', 'Dense shrublands on clay flats' and 'Shrublands on dry clay flats', as well as supporting many uncommon plant taxa. These plant communities include: forests to woodlands dominated by *Casuarina obesa* (Figure 104); woodlands dominated by Wandoo (*Eucalyptus wandoo*) and Marri (*Corymbia calophylla*); and most commonly shrublands dominated by *Melaleuca* species (including *M. osullivanii*, *M. viminea* and *M. lateritia* (Figure 107), *Viminaria juncea* (Figure 109 and Figure 111), *Astartea affinis* and *Hypocalymma angustifolium*, and combinations of these. Associated with all of these are perennial sedgelands dominated by *Meeboldina* species (including *M. cana*, (Figure 112) and *M. coangustata*), *Chorizandra enodis* and *Chaetanthus aristatus*. The deepest of the wetlands (claypans) are typically dominated by *Melaleuca lateritia* shrubland and support annually renewed grasslands, herblands and sedgelands at different times of winter and spring. For example, annual sedgelands dominated by *Centrolepis*, *Trithuria*, *Schoenus* (Figure 113) and *Aphelia* species occur in spring with the drying mud, as do herblands dominated by *Tribonanthes* (Figure 114a), *Stylidium* and *Asteraceae* species. Earlier, when the claypan is flooded, aquatic species such as *Aponogeton hexatepalus*, *Ornduffia* (previously *Villarsia*) *submersa* (Figure 115) and *Triglochin* and other *Ornduffia* species form herblands. *Amphibromus nervosus* grassland is present in early summer (Figure 105). Many taxa are confined to claypans and clayflats in the Southwest, and some of these are confined to the Swan Coastal Plain (SWA). Examples of these taxa are: *Marsilea drummondii*, *Chamaescilla gibsonii* (Figure 114c&d, endemic SWA), *Aponogeton hexatepalus*, *Eleocharis keigheryi* (DRF, Figure 104), *Schoenus natans* (Figure 115), *Triglochin muelleri* (endemic SWA), *Amphibromus nervosus* (Figure 105), *Eryngium ferox* ms (Figure 116c), *E. pinnatifidum* subsp. *palustre* (Figure 116a&b), *E. subdecumbens*, *Amblysperma minor*, *Aphelia drummondii*, *Myriocephalus helichrysoides*, *Isotoma pusilla* (Figure 117d), *Calandrinia* sp. Kemerton (Figure 118, endemic SWA), *Montia australasica*, *Samolus* sp. Clay Flats (endemic SWA), *Rhodanthe pyrethrum* (Figure

117a&c), *Pimelea imbricata* var. *major*, *Glossostigma diandrum* (Figure 117b) and *Stylidium longitubum* (Figure 107). Of particular interest in this group is the diversity of *Eryngium* taxa (Figure 116). Interestingly *Eryngium* has also speciated (i.e. new species have evolved) in the vernal pools of California.[96] A well-known example of this group of wetlands is the Brixton Street Wetlands*. The flora of these wetlands has been documented in a variety of reports, the most recent being Keighery and Keighery.[97] A few similar claypans are also found in the Jarrah Forest, for example in Drummond Nature Reserve north of Toodyay, which is a natural diversity recovery catchment.

➤ For more information on the Brixton Street Wetlands* complex, see 'Brixton Street Wetlands' profile at the end of this topic.

➤ For information on natural diversity recovery catchments, see the DEC website.[89]

Figure 104. A Pinjarra Plain (Swan Coastal Plain) claypan in late winter. Photos – G Keighery/ DEC.

(a) *Casuarina obesa* forest over a sedgeland and grassland. This community is a TEC.

(b) *Eleocharis keigheryi*, a rare sedge that inhabits claypans. Nineteen species of *Eleocharis* occur across WA; all are aquatic plants.

Figure 105. Bandicoot Creek Bushland (Swan Coastal Plain).

(a) Clayflats and claypans on the Pinjarra Plain with *Melaleuca viminea* shrublands (mid-ground and shrub in foreground), *Meeboldina cana* sedgeland (brown) and *Amphibromus nervosus* grassland. Photo – B Keighery/OEPA.

(b) Transect of the Swan Coastal Plain showing location of wetland (reproduced and adapted from Department of Minerals and Energy[86] with permission).

Figure 106. A view of the seasonally inundated flats in Bullsbrook Nature Reserve (Swan Coastal Plain). Photos – B Keighery/OEPA.

(a) *Actinostrobus pyramidalis* shrubland (background) and a sedgeland dominated by *Chaetanthus aristatus* with scattered *Verticordia plumosa* subsp. *pleiobotrya*.

(b) Flowers of *Verticordia plumosa* subsp. *pleiobotrya*, a rare wetland shrub.

Figure 107. A plant community of the seasonally inundated claypans in the Brixton Street Wetlands (Swan Coastal Plain) in late spring/early summer. Photo – B Keighery/OEPA.

(a) *Melaleuca lateritia* shrubland and *Stylidium longitubum* herbland.

(b) A transect of the seasonally inundated clayflat (illustration by M Pieroni, from Keighery et al.[98]) and seasonally inundated claypan in the Brixton Street Wetlands showing the location of this community.

Figure 108. A clayflat shrubland dominated by *Calothamnus hirsutus* (green bush), *Verticordia* species (yellow *V. chrysantha*, pink *V. plumosa* subsp. *pleiobotrya* and red/cream *V. huegelii*) and herbland with *Stylidium divaricatum* (cream) and *Borya* (gold). Photo – G Keighery/DEC.

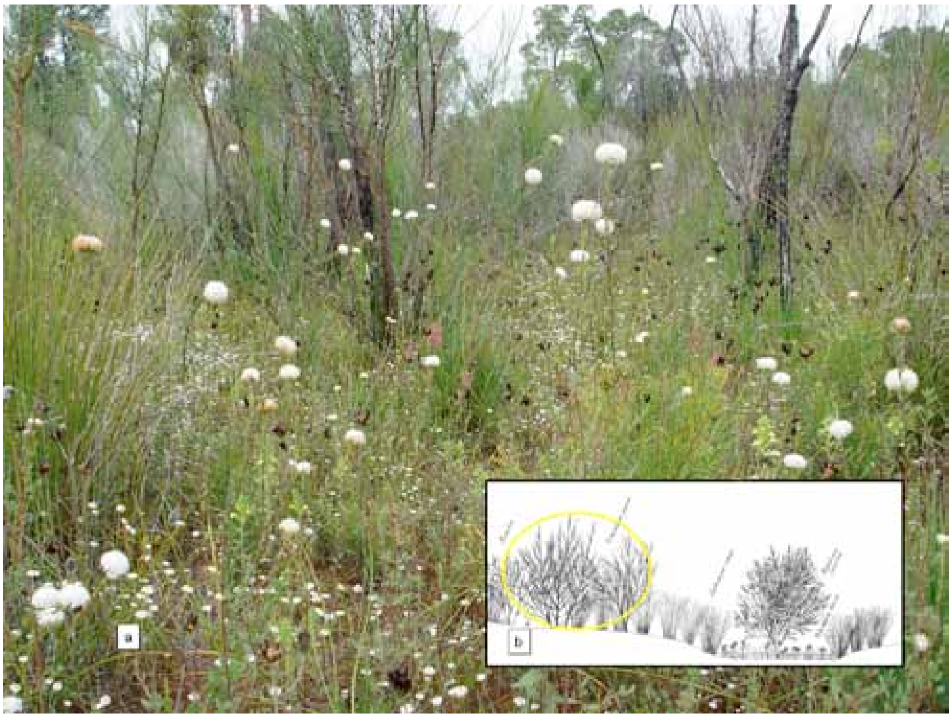


Figure 109. A plant community of the seasonally inundated clayflats in the Brixton Street Wetlands (Swan Coastal Plain) in spring.

(a) Within the *Viminaria juncea* shrubland, *Pimelea imbricata* subsp. *major* (tall white), *Haemodorum simplex* (black) and *Hyalospermum cotula* (small white) are flowering. The yellow flowered plants are *Parentucellia viscosa* which is a weed. Photo – B Keighery/OEPA.

(b) A transect (illustration by M Pieroni, from Keighery et al.[98]) of the seasonally inundated clayflat and seasonally inundated claypan in the Brixton Street Wetlands showing the location of this community.

Figure 110. A view of the seasonally waterlogged flats in Bullsbrook Nature Reserve (Swan Coastal Plain) with *Actinostrobus pyramidalis* and *Melaleuca scabra* dominated shrublands. Photo – B Keighery/OEPA.

Figure 111. *Viminaria juncea* is a widespread wetland species and represents another monotypic genus (i.e. a genus with only one species). *Viminaria* has air breathing roots (pneumatophores) for living in water.[99,100] Photos – B Keighery/OEPA.

(a) *Viminaria juncea* shrubland in the Brixton Street Wetlands.

(b) Flowers.

Figure 112. The plants that define wetland sedgelands come from a variety of families including the Restionaceae. An example is the perennial sedge *Meeboldina cana* (foreground) in Bandicoot Creek Bushland (Swan Coastal Plain). *M. cana* has male (brown plant to right) and female (two gray-white plants to left) plants, as do most Restionaceae. The bright green grass in the mid-ground is *Amphibromus nervosus*. Photo – B Keighery/OEPA.

Figure 113. Some sedgelands are formed by annual species. Photos – B Keighery/OEPA.

(a) An annual aquatic sedgeland in a claypan on the Swan Coastal Plain.

(b) *Schoenus tenellus* and (c) *Isolepis cernua* flower as the claypan water levels fall.

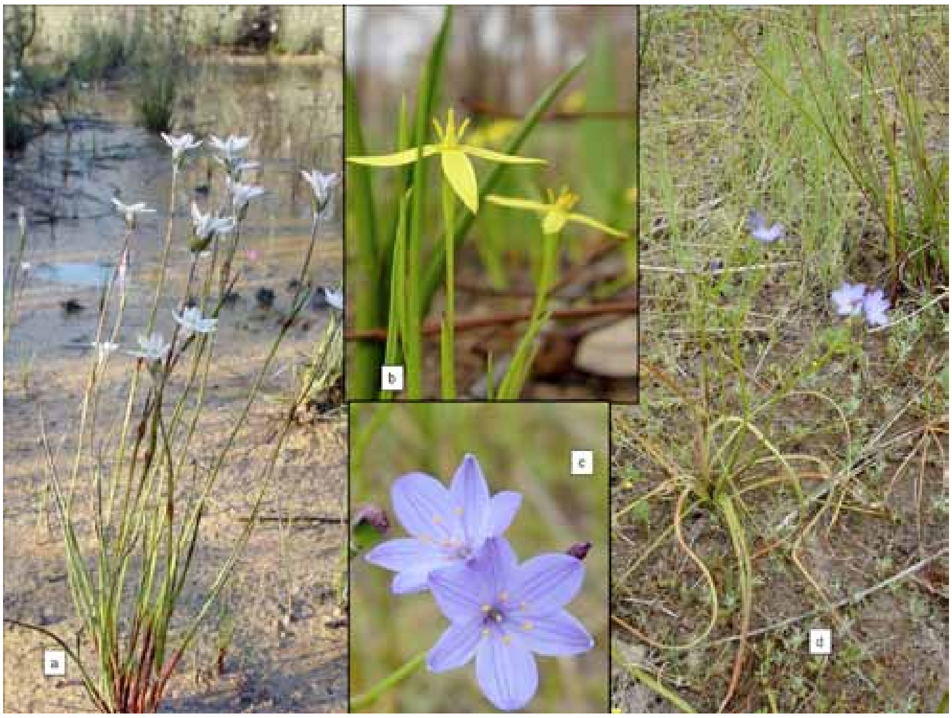


Figure 114. Three plants which, following inundation, are annually renewed from bulbs, corms, rhizomes or tubers, from wetlands on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) *Tribonanthes uniflora* (bulbs)

(b) *Hypoxis occidentalis* (corm)

(c) *Chamaescilla gibsonii* flowers and (d) plant (tubers).

Figure 115. Some aquatic plants from a claypan in Bandicoot Creek Bushland (Swan Coastal Plain). The floating oval leaves are *Ornduffia* (previously *Villarsia*) *submersa* and the submerged brown aquatic plant is *Schoenus natans*. Photo – G Keighery/DEC.

Figure 116. Two uncommon *Eryngium* plants from wetlands on the Swan Coastal Plain annually renewed from a tuber. The *Eryngium* is species diverse in wetlands of the Swan Coastal Plain and a series of species are yet to be described. Photos – B Keighery/OEPA.

(a) and (b) *Eryngium pinnatifidum* subsp. *palustre* ms plant (a) and flowers (b).

(c) *Eryngium ferox* ms

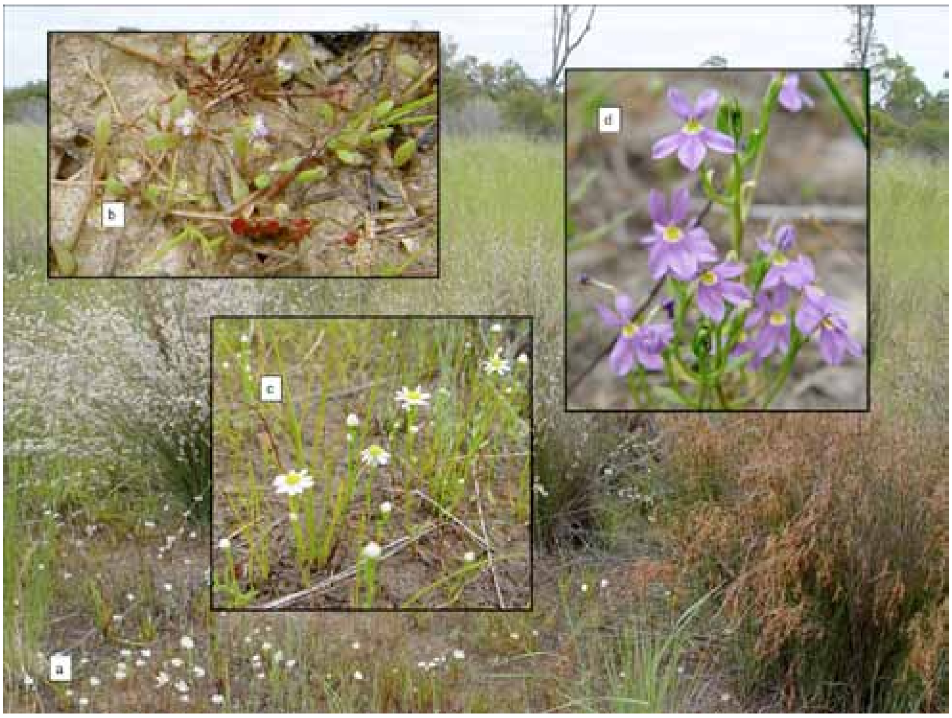


Figure 117. A large variety of annual herbs flower in the drying soils of clayflats and claypans. These are all renewed from seed. Photos – B Keighery/OEPA.

(a) Clayflats in Bandicoot Creek Bushland (Swan Coastal Plain).

(b) *Glossostigma diandrum*.

(c) *Rhodanthe pyrethrum* (and white flowers in (a)).

(d) *Isotoma pusilla*.

Figure 118. A mixture of annuals in Kemerton Nature Reserve seasonally inundated wet flats. Photos – B Keighery/OEPA.

(a) *Calandrinia* sp. Kemerton (red), *Calandrinia granulifera* (green) and *Isotoma scapigera* (single blue flower top left).

(b) *Calandrinia* sp. Kemerton.

Bentonite: a type of clay (aluminium phyllosilicate)

- Geraldton area river flats (Geraldton Sandplains) – These communities are associated with the rivers of the Geraldton area such as the Greenough, Irwin and Chapman rivers. The centres of the claypans are normally bare with a fringe of *Eucalyptus camaldulensis*, but sometimes lignum (*Muehlenbeckia florulenta*) and/or cane grass (*Eragrostis australasica*) is present. *Melaleuca strobophylla* or *Casuarina obesa* woodland may be found throughout the wetlands. These wetlands were common, especially on the Greenough Flats and the lower reaches of the Irwin River, but are now largely destroyed.[101] The remaining areas are the major habitat of *Wurmbea tubulosa* and *Oxalis* sp. Greenough and they form part of the TEC 'Clay flats assemblages of the Irwin River: Sedgelands and grasslands with patches of *Eucalyptus loxophleba* and scattered *E. camaldulensis* over *Acacia acuminata* and *A. rostellifera* shrubland on brown sand/loam over clay flats of the Irwin River' (extending into the Avon Wheatbelt). Claypans are found elsewhere in the Geraldton Sandplains and these are typically fringed by *E. camaldulensis*. All remaining claypans are threatened by hydrological change.
- **Bentonite** wetlands of the Watheroo Marchagee area (Geraldton Sandplains) – These thirty intermittently inundated claypans fill by rain and water is perched upon the bentonite clay, also known as 'saponite'. When drying, these bentonite wetlands are covered by herblands dominated by combinations of *Triglochin mucronata*, *Asteridea athrixioides*, *Trichanthodium exile*, *Puccinellia stricta*, *Podolepis capillaries*, *Angianthus tomentosa* and *Pogonolepis stricta*.[35] They are listed as the TEC 'Herbaceous plant assemblages on Bentonite Lakes'.
- Avon Wheatbelt claypans – A variety of significant claypans are scattered in the Avon Wheatbelt. These are generally fringed by York Gum (*Eucalyptus loxophleba*) woodlands over *Gahnia trifida* sedgelands. An extensive area of clay-based wetlands is associated with the flats of the Beaufort River (Figure 119 and Figure 120). These support a mosaic of wetland communities including *Casuarina obesa* woodlands, mallee woodlands, shrublands dominated by *Melaleuca atroviridis*, *M. scalena* and *M. viminea*, perennial sedgelands and diverse annually renewed sedgelands and herblands. This community shares many taxa with the Swan Coastal Plain group, including *Wurmbea dioica* subsp. Brixton (Figure 120b). These communities are under considerable threat by hydrological change, including rising saline groundwater.

Figure 119. A view of the clayflat and claypan communities at Beaufort River Flats (Avon Wheatbelt) during winter when claypans are filled with water. *Casuarina obesa* woodland over *Melaleuca* species shrublands fringe the claypan. Photo – B Keighery/OEPA.

Figure 120. Clayflat and claypan communities at Beaufort River Flats (Avon Wheatbelt). Photos – B Keighery/OEPA.

(a) Shrublands dominated by *Melaleuca atroviridis* and *M. viminea* over herblands (background) and *Meeboldina* sedgeland and herblands (foreground), with the herbs *Utricularia multifida* (pink) and *Wurmbea dioica* subsp. Brixton (white).

(b) *Wurmbea dioica* subsp. Brixton growing in the inundated phase of the wetland. This plant is most likely a new species of *Wurmbea* that renews itself from a bulb each spring. This aquatic also grows in the Brixton Street Wetlands.

Rockpans

The impeding layer of rockpans can be ironstone, calcrete or granite. The first two are sometimes found together and typically are overlaid by varying depths of loams and/or clays.

Ironstone (also called ferricrete or bog iron ore)

These perched wetlands are usually seasonally inundated and dry in summer, and normally have soils that are shallow red-brown sandy clays over ironstone. The ironstone soil type has formed due to the precipitation of iron from the groundwater, mainly in the zone of water table fluctuation. Scattered occurrences from Eneabba to the Porongurups are known to support distinctive plant communities. The plant communities are similar to those formed on the claypans and clayflats, and show the same sequence of flowering, diversity of communities and diversity of flora. However, dense shrublands tend to be the dominant community, and open patches dominated by sedgelands and herblands are generally only widespread in these communities after fire. As outlined below, a series of taxa are only found in these communities and a number of the larger occurrences are described below. The first four are listed TECs. While these surfaces are naturally rare, clearing means they are even rarer now. For example, the Scott River Ironstones originally covered 1,780 hectares and now are reduced to just 325 hectares and the Busselton Ironstones originally covered 1,100 hectares and now are under 100 hectares, mostly in small fragments.

- Rocky Springs, south east of Eneabba (Geraldton Sandplain) – These are typified by an *Acacia blakelyi*, *Allocasuarina campestris*, *Banksia* (previously *Dryandra*) *stricta* and *Labichea lanceolata* shrubland and are the TEC 'Ferricrete floristic community (Rocky Springs type)'.

- Gingin (Swan Coastal Plain) – These are typified by *Melaleuca viminea* and *Kunzea limnicola* shrublands over *Rhodanthe manglesii* herbland (Figure 121). The Declared Rare Flora (DRF) taxon *Grevillea curviloba* subsp. *incurva* and the Priority Flora species *Isotropis cuneifolia* subsp. *glabra* are associated with these habitats. These are the TEC 'Perth to Gingin Ironstone Association'.

Figure 121. The TEC 'Perth to Gingin Ironstone Association' in Timaru Nature Reserve with *Melaleuca viminea* and *Kunzea recurva* (white flowers) shrubland over *Rhodanthe manglesii* herbland. *Rhodanthe manglesii* is also associated with wetlands on granite rocks. Photo – G Keighery/DEC.

- Busselton Southern Ironstone Association (Swan Coastal Plain) – Again, a shrubland (Figure 122a&c and Figure 123e) typifies these wetlands[102,103] and is the most species-rich of the ironstone shrublands, being dominated by *Kunzea* aff. *micrantha*, *Banksia* (previously *Dryandra*) *squarrosa* subsp. *argillacea* (Figure 122a&b, DRF, endemic SWA), *Hakea oldfieldii* (Figure 122c&d), *Pericalymma ellipticum* and *Viminaria juncea*. At times *Eucalyptus rudis* subsp. *cratyantha* is scattered through the community. These communities also contain patches or layers of perennial sedgelands dominated by *Caustis dioica*, *Chordifex isomorphus*, *Lepyrodia monoica*, *Loxocarya magna* and/or *L. striata* subsp. *implexa*; annual sedgelands; and annually renewed herblands which include *Tribonanthes*, *Asteraceae* and *Apiaceae* species, *Utricularia* species (*U. menziesii*, *U. multifida*, *U. volubilis*) and *Stylidium* species. After fire the rare *Brachyscias verecundus* (DRF, endemic SWA) and *Stylidium ferricola* (endemic SWA) are common. This community supports more than fifteen endemic species, of which eleven are DRF, including: *Darwinia whicherensis* (Figure 124b, endemic SWA), *Andersonia ferricola*, *Hemiandra* sp. Ironstone, *Calothamnus lateralis* var. *crassus*, *Calothamnus quadrifidus* subsp. *teretifolius*, *Calytrix* sp. Tutunup (Figure 124e&f, endemic SWA), *Banksia* (previously *Dryandra*) *nivea* subsp. *uliginosa* (Figure 123e, endemic SWA), *Grevillea elongata*, *Grevillea maccutcheonii* (endemic SWA), *Lambertia echinata* subsp. *occidentalis* (Figure 123c, endemic SWA), *Petrophile latericola* (Figure 123a&b, endemic SWA), *Opercularia vaginata* (Ironstone form) and *Gastrolobium papilio* (endemic SWA). *Isopogon formosus* subsp. *dasylepis* (Figure 123d) and *Chamelaucium* sp. C Coastal Plain (Figure 124c&d, endemic SWA) are also found in these communities. This community is the TEC 'Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)'.

Figure 122. The TEC 'Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)' or Busselton Ironstones contain many restricted and rare plants. Photos – B Keighery/OEPA.

(a) Busselton Ironstone community with emergent *Banksia squarrosa* subsp. *argillacea*.

(b) *Banksia squarrosa* subsp. *argillacea* flowers.

(c) Busselton Ironstone community with emergent *Hakea oldfieldii*.

(d) *Hakea oldfieldii* flowering branchlet.

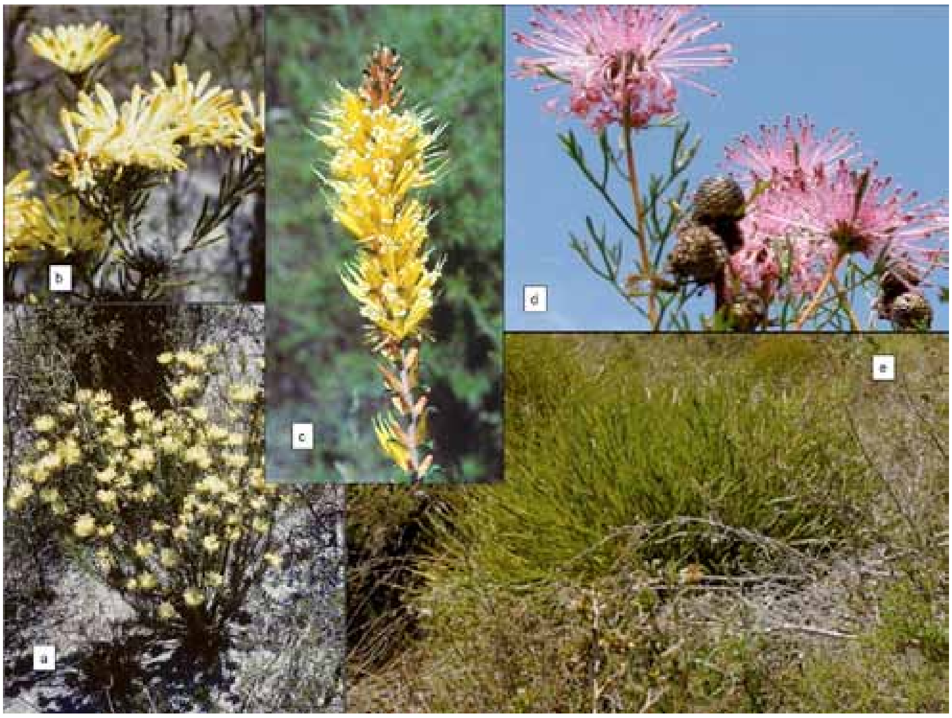


Figure 123. The TEC 'Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)' or Busselton Ironstones contain many restricted and rare plants, including a number from the Proteaceae family.

(a) and (b) *Petrophile latericola* plant (a) and flowers (b). Photos – G Keighery/DEC.

(c) *Lambertia echinata* subsp. *occidentalis* flowers. Photo – G Keighery/DEC.

(d) *Isopogon formosus* subsp. *dasylepis*. Photo – B Keighery/OEPA.

(e) *Banksia nivea* subsp. *uliginosa* plant. Photo – B Keighery/OEPA.

Figure 124. The TEC 'Scott River Ironstone Association' and the Busselton Ironstones contain many restricted and rare plants, including a number from the Myrtaceae family.

(a) *Darwinia ferricola* from the Scott River Ironstones. Photo – G Keighery/DEC.

(b) Busselton Ironstone *Darwinia whicherensis*. Photo – B Keighery/OEPA.

(c) and (d) Busselton Ironstone *Chamelaucium* sp. C Coastal Plain. Photos – B Keighery/OEPA.

(e) and (f) Busselton Ironstone *Calytrix* sp. Tutunup. Photos – B Keighery/OEPA.

- Scott River Ironstone Heaths (Warren) – These shrublands are dominated by *Hakea tuberculata*, *Kunzea micrantha*, *Melaleuca incana* and/or *Melaleuca preissiana* over sedgelands typically dominated by *Loxocarya magna*. This community supports six endemics and most of these are DRF including *Boronia exilis* and *Darwinia ferricola* (Figure 124a). This community is the TEC 'Scott River Ironstone Association'.
- North Porongurup Ironstone Shrubland (Jarrah Forest) – These shrublands are dominated by *Kunzea recurva*, *Hakea tuberculata* and *H. lasiocarpha*.

Calcrete

Calcrete generally refers to a cemented accumulation of carbonate minerals, such as limestone. A series of calcrete surfaces are associated with wetlands in the Southwest; these are often associated with saline wetlands. Examples are found in the Yalgorup Lakes complex (see 'Profile of a wetland complex: Yalgorup National Park wetlands' at the end of this topic for more information) and Muchea Limestones of the Swan Coastal Plain.[104] The Muchea Limestones are formed from the deposition of calcium carbonate rich water associated with springs on the eastern Swan Coastal Plain. Ironstone on the eastern Swan Coastal Plain is formed in a similar fashion from iron rich spring water.

The TEC 'Shrublands and Woodlands of the Muchea Limestones' is a variable set of communities formed on a few isolated naturally vegetated occurrences of Muchea Limestones from near Gingin to Kemerton north of Bunbury (Figure 125 and Figure 126). These support a mosaic of plant communities. On the flats where clay overlays or is mixed with the limestone, communities are similar to those of claypans and clayflats (including *Casuarina obesa* woodlands). On the rises with outcropping limestone, mallee forests and/or woodlands dominated by *Eucalyptus decipiens* and/or *E. foecunda* occur. All of the occurrences have significant differences related to the presence of a series of disjunct flora, some of which are normally associated with coastal limestones. For example, *Melaleuca huegelii* (a coastal limestone species) and *Grevillea curviloba* are only found in the occurrences north of Perth, *Alyogyne huegelii* is scattered throughout the occurrences, and *Eucalyptus decipiens* is found in most occurrences. A number of new taxa are being found to be associated with these communities including an unnamed variant of *Melaleuca systena* associated with the Kemerton occurrence (Figure 125), a new *Austrostipa* species associated with the Perth occurrence and another new *Austrostipa* species confined to the Kemerton occurrence. The first of the new *Austrostipa* species is also found in another calcareous community in Bunbury (Figure 127).

Figure 125. Tall shrubs and trees in part of the TEC 'Shrublands and woodlands on Muchea Limestone' in Kemerton Nature Reserve. Photos – B Keighery/OEPA.

(a) *Eucalyptus decipiens*, *Viminaria juncea*, *Melaleuca* sp. Kemerton and *Banksia littoralis* dominate the community.

(b) Flowers of *Melaleuca* sp. Kemerton.

Figure 126. A view of some of the plant communities of the TEC 'Shrublands and woodlands on Muchea Limestone': *Melaleuca viminea* shrubland and *Utricularia multifida* (pink) herbland and sedgeland. Photo – B Keighery/OEPA.

Figure 127. Claypan in Hay Park in Bunbury (Swan Coastal Plain). Photos – B Keighery.

(a) *Melaleuca viminea* shrublands and *Austrostipa juncifolia* subsp. Southern River grassland in the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain'.

(b) Flowers of *A. juncifolia* subsp. Southern River. This newly recognised species is related to *A. juncifolia* found in saline wetlands well to the south and east of this location. Another newly recognised species, *A.* sp. Harvey is found nearby in another TEC 'Shrublands and woodlands on Muchea Limestone' (see Figure 125).

Granite

Granite outcrops support a variety of wetlands and wetland plant communities (Figure 128 and Figure 129) which have similar characteristics to those of claypans and clayflats, sharing many species (for example *Utricularia menziesii*, Figure 129a&b). The ephemeral pools (gnamma holes, Figure 129c&d) are usually small and contain a suite of aquatics including species from the following genera: *Isoetes* (six out of eight species present in the Southwest are endemic, Figure 130b), *Glossostigma* and *Myriophyllum* (several endemic, including *M. balladoniensis*, *M. petraeum* and *M. lapidicola*[105]). A number of other granite rock wetland species are endemic (Figure 131) and some are yet to be described. The edges of the rocks and the moss pillow seepage communities on the rocks support a wide variety of annual and annually renewed herbs including members of the genera *Drosera*, *Hydrocotyle*, *Stylidium*, *Utricularia* and *Wurmbea*, members of which are also typical of the claypans and clayflats. Granite rocks have a rich flora of more than 2,000 species, many endemic to WA, but most moss pillow species are found in other intermittently inundated wetlands (Figure 129c&d). These wetlands are described in numerous publications (for example Royal Society of WA[106], Jones et al.[107]) and are not further detailed here. One, Yorkrakine Rock, supports a listed nationally significant wetland.

Figure 128. Granite rocks in Charles Darwin Reserve (Yalgoo) support a variety of wetland herbland communities. The herblands on granite rocks share many species with claypan and clayflat wetlands (see Figure 32b,c&d and Figure 117b&d). Photos – B Keighery/OEPA.

(a) Pockets of soil collect in depressions.

(b) *Borya constricta* herbland. *Borya* species are shared with claypan and clayflat wetlands.

Figure 129. Two wetland habitats restricted to granite rocks are moss pillows and rock pools.

(a) and (b) *Utricularia menziesii* growing in a moss pillow. This species also grows in clayflat and claypan communities. Photos – B Keighery/OEPA.

(c) Rock pool.

(d) Rock pools support a variety of algae and when they contain soil support herblands very similar to those on claypans. These communities both support the ferns *Pilularia novae-hollandiae* and *Isoetes drummondii*.

Figure 130. Rock pools and claypans support similar herblands. The aquatic ferns *Pilularia novae-hollandiae* (a) and *Isoetes drummondii* (b) are found in both types of communities. Photos – B Keighery/OEPA.

Figure 131. Some plants are restricted to wetlands on granite rocks. For example, on Petrudor Rocks (Yalgoo) is a population of *Tribonanthes* aff. *longipetala*. Photo – B Keighery/OEPA.

Wetland flora of the Southwest

Monotypic (genus): a genus with only one species

Despite having a Mediterranean climate with prolonged summer dry periods, the diversity of the wetland flora of the Southwest reflects the listing of the area as a world biodiversity hot spot for flowering plants. The Southwest is the world centre of diversity for a range of wetland-centred groups including the families Droseraceae, Restionaceae, Juncaginaceae, Centrolepidaceae[108] and Hydatellaceae and the samphire genus *Tecticornia*. There are a range of endemic wetland genera including *Reedia* (Cyperaceae), *Cephalotus* (Cephalotaceae), *Tribonanthes* (Haemodoraceae), *Epiblema* (Orchidaceae), *Schoenolaena* (Apiaceae), *Cosmelia* (Epacridaceae), *Euchilopsis* (Fabaceae), *Acidonia* (Proteaceae), *Homalospermum*, *Pericalymma* and *Taxandria* (Myrtaceae). The majority of rare wetland species of WA, ranging from **monotypic** genera such as *Reedia spathacea* to orchids, such as *Epiblema grandiflorum*, are found in the Southwest, as are the majority of wetland TECs.

With this background it is surprising that it has been often reported that Australian freshwater wetlands display remarkably low levels of endemism, with many genera and some species being almost cosmopolitan (for example, Commonwealth of Australia[109]). Apart perhaps for the flora of the larger lakes and freshwater swamps, this statement is incorrect for southern WA. As can be seen in the preceding information, high levels of local and regional endemism is found in nearly all perched wetlands in the Southwest, regardless of substrate (granite, clay, ironstone).

To better consider endemism and diversity in the Southwest wetlands, a detailed analysis of the wetland flora of the Southern Swan Coastal Plain (Moore River to Dunsborough) has been undertaken. This is presented in part 5: Southern Swan Coastal Plain.

A guide to managing and restoring wetlands in Western Australia

Wetland vegetation and flora, part 5: Southern Swan Coastal Plain

In Chapter 2: **Understanding wetlands**

Australian Government

Department of Environment and Conservation

Our environment, our future

Contents

Wetland profiles

Introduction

This section provides a more in-depth analysis of the characteristics of the wetland vegetation and flora of the Swan Coastal Plain bioregion (Figure 132), which is part of the Southwest climatic and biogeographical zone, described in Part 4 of this topic.

Figure 132. The Swan Coastal Plain bioregion and surrounding bioregions. Image – C. Auricht, Auricht Projects.

Features of the southern Swan Coastal Plain wetland flora

To better consider endemism and diversity in the Southwest wetlands, a detailed analysis of the wetland flora of the southern Swan Coastal Plain (Moore River to Dunsborough) has been undertaken. This region has been subject to an intensive quadrat and specific area-based floristic survey over many years. This analysis is based on 1,150 quadrats, flora lists of seventy-eight reserves and bushland areas, flora revisions, flora treatments, *FloraBase* and *Australia's Virtual Herbarium*. Taxa were allocated to drylands and wetlands, as well as being placed in a series of other categories including life form and growth form (see Appendix 2 in part 1). In total 1,877 native plant taxa were recorded.

This information highlighted some interesting features of the Swan Coastal Plain's wetland flora, summarised below. Information regarding Swan Coastal Plain wetland taxa is provided in Appendix 2, while the data used to compile the below charts is provided in Appendix 3 (in part 1).

Very high rate of endemism

The percentage of wetland species endemic to WA is very high at 74 per cent, as compared to 85 per cent for dryland taxa (Figure 133). These figures refute the notion that our wetland species are not also highly endemic (at least for vascular plants). While not determined at this stage, it is expected that around 3 per cent of the Swan Coastal Plain flora will be locally endemic to wetlands on the plain (for example *Banksia squarrosa* subsp. *argillacea* (Figure 122a&b), *Darwinia whicherensis* (Figure 124b), *Calothamnus quadrifidus* subsp. *teretifolius*, *Calytrix* sp. Tutunup (Figure 124e&f), *Banksia nivea* subsp. *uliginosa* (Figure 123e), *Lambertia echinata* subsp. *occidentalis* (Figure 123c) and *Petrophile latericola* (Figure 123a&b)).

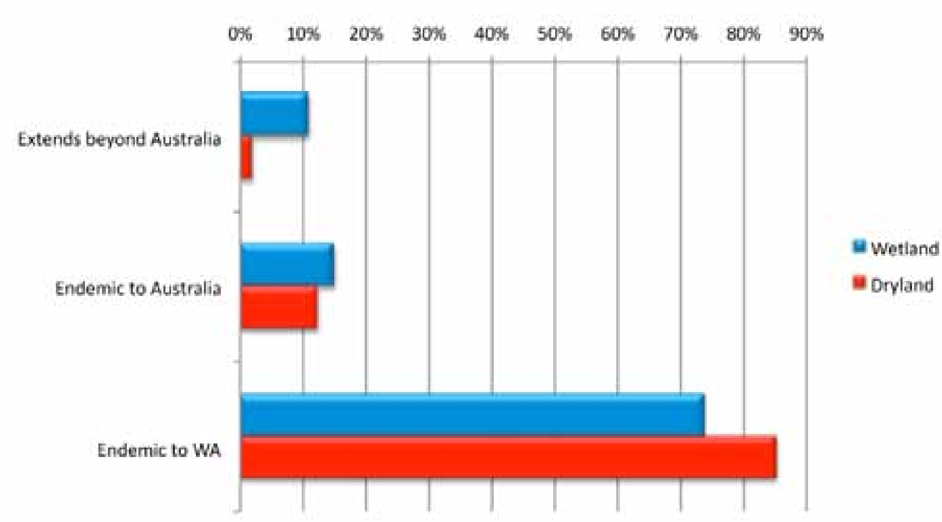


Figure 133. Endemism of wetland and dryland vascular plant taxa of the southern Swan Coastal Plain

The percentage of taxa that occur outside Australia (Figure 133) is higher for wetland species (11 per cent) than for dryland species (2 per cent). Taxa with Australia-wide distributions comprise similar percentages for both habitat types (15 per cent for wetland species and 13 per cent for dryland species).

Monocotyledons are more prevalent

Plant taxa are more likely to be monocotyledons in wetlands than dryland (Figure 135, Figure 136 and Figure 137) with 46 per cent in wetlands as compared with 26 per cent for drylands (Figure 134). This is probably a reflection of the successful life and growth forms of wetland plants. The dominance of monocotyledons is reflected in the higher percentages of sedges, grasses and herbs (Figure 138).

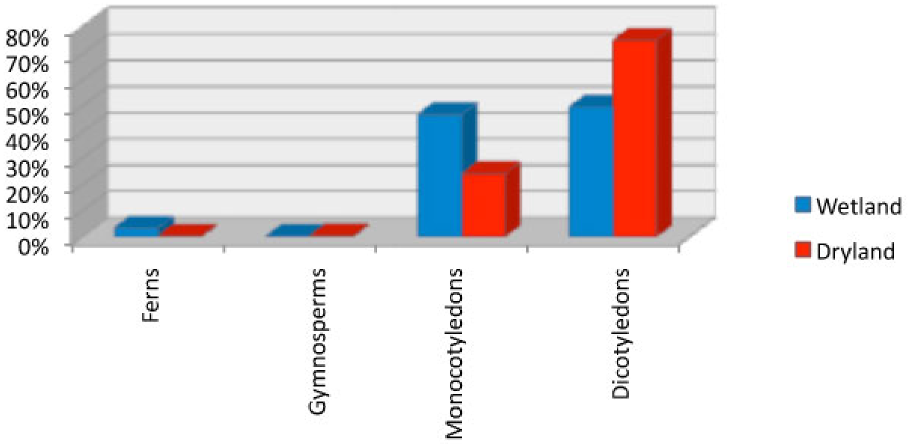


Figure 134. Plant groups of the wetland and dryland vascular plant taxa of the southern Swan Coastal Plain.

Figure 135. The plants that define sedgelands come from a variety of families including the Xyridaceae. Figure 57 shows a *Xyris* from the Kimberley; this very similar looking *Xyris lanata* is from the Southwest. Photos – B Keighery/OEPA.

(a) A seasonally inundated wetland dominated with *X. lanata* sedgeland under a *Melaleuca* shrubland.

(b) *X. lanata* flowers.

Figure 136. The plants that define sedgelands come from a variety of families including the Cyperaceae. An example is the perennial sedge *Gahnia trifida*, a large domed, widespread sedge of saline, calcareous and brackish wetlands. Photos – (a) B Keighery/OEPA (b) J Lawn/DEC.

Figure 137. About 46 per cent of the wetland flora of the Swan Coastal Plain are annually renewed, including *Burchardia bairdiae* (a and b) and *B. multiflora* (c) which are both renewed from tubers. Photos – B Keighery/OEPA.

Shrub-rich relative to international wetlands but not shrub-rich compared to local dryland

Swan Coastal Plain wetlands are not shrub-rich with 19 per cent, as compared to drylands, where 51 per cent of the flora are shrubs (Figure 138). However, they are shrub-rich when compared with wetlands in other countries.

Herbs and sedges predominate

Herbs and sedges are the most common plant group in wetlands (48 and 29 per cent respectively) while shrubs and herbs are the most common in drylands (51 and 37 per cent respectively) (Figure 138). Examples are shown in Figure 135–137 and Figure 141.

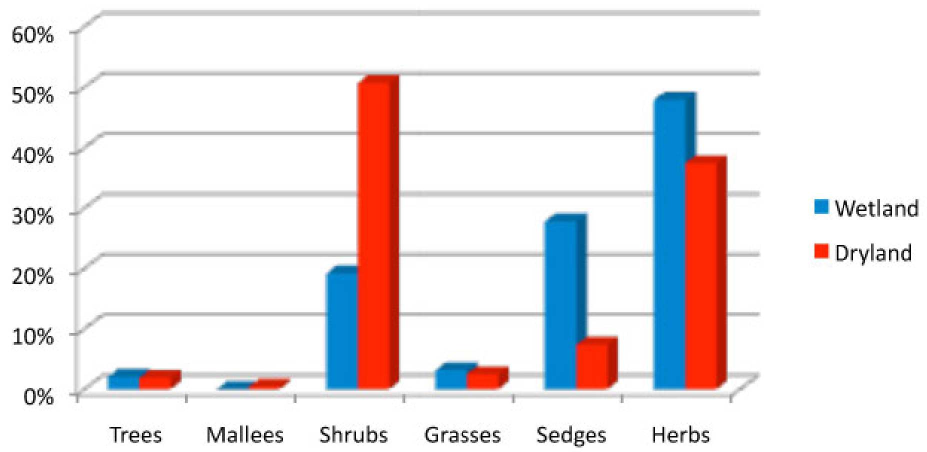


Figure 138. Growth forms groups of wetland and dryland vascular plants of the southern Swan Coastal Plain.

Underground storage organs are much more prevalent

Wetland species have a large percentage (22 per cent) renewed from underground storage organs compared with those in drylands (11 per cent) (Figure 139 and Figure 140). Examples are shown in Figure 137, Figure 141 and Figure 143.

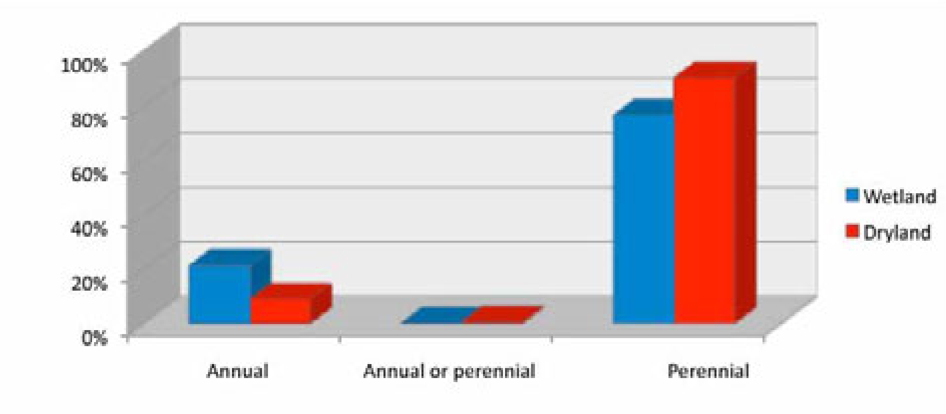


Figure 139. Life forms of wetland and dryland vascular plants of the southern Swan Coastal Plain.

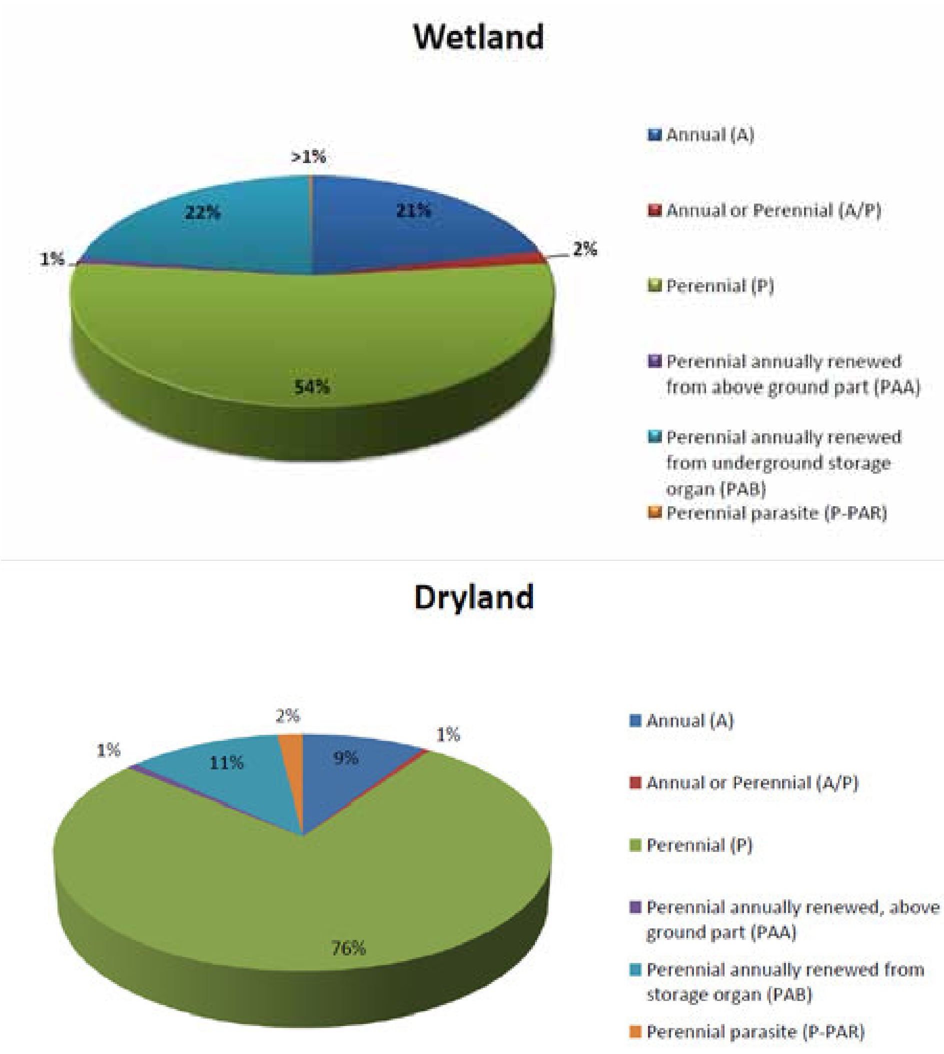


Figure 140. Life form groups of wetland and dryland vascular plants of the southern Swan Coastal Plain.

Figure 141. A newly recognised Swan Coastal Plain claypan endemic, *Craspedia argillicola* ms from Meelon Nature Reserve. Plants (a) and basal rosette (b) are annually renewed from tubers when the claypans fill with water and flower (c) as the claypan dries. Photos – B Keighery/OEPA.

Annually renewed plants are much more prevalent

Wetland species have a large percentage (45 per cent) that are annually renewed (seed, underground and above ground storage organs) compared with those in drylands (21 per cent) (Figure 142).

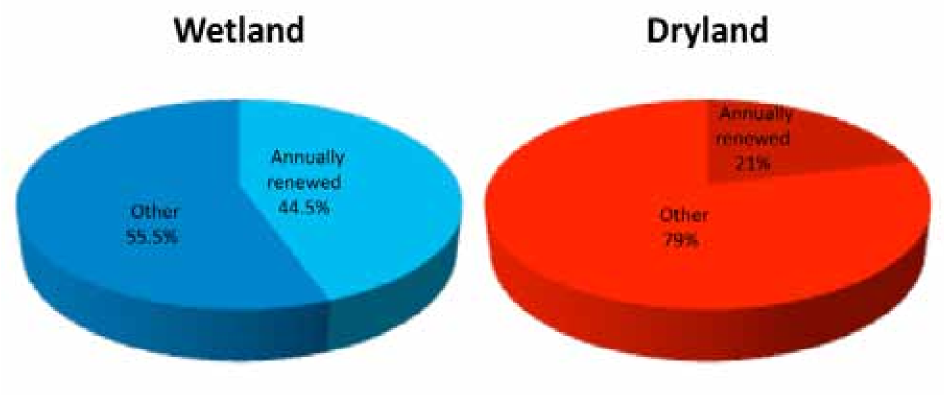


Figure 142. Life form of annually renewed groups of wetland and dryland plants of the southern Swan Coastal Plain.

Aquatics: a unique group

A unique group of wetland taxa are the aquatics (Figure 143). Aquatics taxa (as defined in the southern Swan Coastal Plain study) comprise 61 per cent (271 taxa) of the wetland flora. The majority of these, 163 taxa, or 60 per cent, grow in water and flower when the sites dry (the 'post inundation' category in Figure 144). Those plants that require inundated conditions to both grow and flower form 27 per cent (73 taxa) of the wetland flora (comprising 'emergent', 'floating' and 'submerged' categories in Figure 144; see the key in Appendix 2 in part 1 for more information on these categories). These are the flora that are generally listed as aquatic taxa in the literature. The remaining 13 per cent (35 taxa) could not be allocated to either of these groups.

Figure 143. Claypans on the Pinjarra Plain (Swan Coastal Plain) persist in the paddocks. As they are too wet for winter grazing, some native species persist in the pasture. This claypan south of Pinjarra contains the aquatic *Ottelia ovalifolia*. Other paddock claypans in the same area support populations of the bright green grass *Amphibromus nervosus*. Photo – B Keighery/ OEPA.

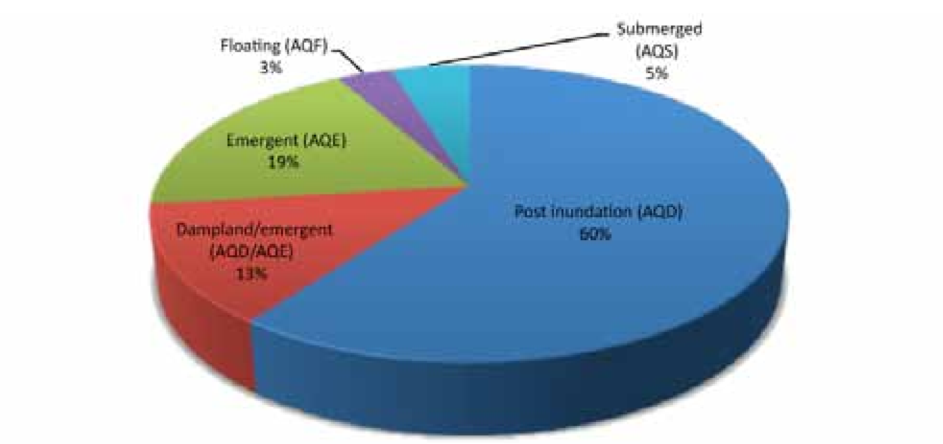


Figure 144. Life forms of aquatic vascular plants of the southern Swan Coastal Plain.

Figure 145. A lake in Harvey Flats Nature Reserve (Swan Coastal Plain) supports a population of *Myriophyllum crispatum*. The plants flower on branches above the water (b). Photos – B Keighery/OEPA.

Conclusion

These data show that wetlands contribute greatly to the richness and diversity of the unique Swan Coastal Plain and Southwest flora. Features of this rich flora (illustrated from the Swan Coastal Plain flora) include:

- wetland taxa with closely related dryland relatives (Figure 146 and Figure 147)
- taxa endemic to wetlands of the Plain (Figure 146a and Figure 147d&e)
- rare wetland taxa (Figure 146a, Figure 147d&e, Figure 148 and Figure 149)
- newly recognised taxa that are yet to be described (Figure 150c&d and Figure 151)
- different wetland forms that may prove to be separate taxa (Figure 152).

Figure 146. Many wetland plants have closely related species in the drylands. Two subspecies of *Eremophila glabra* illustrate this relationship. Photos – B Keighery/OEPA.

(a) The wetland *Eremophila glabra* subsp. *chlorella* is confined to a few wetlands on the Swan Coastal Plain and is very rare.

(b) *E. glabra* subsp. *albicans* is a common dryland plant found in near coastal dune communities.

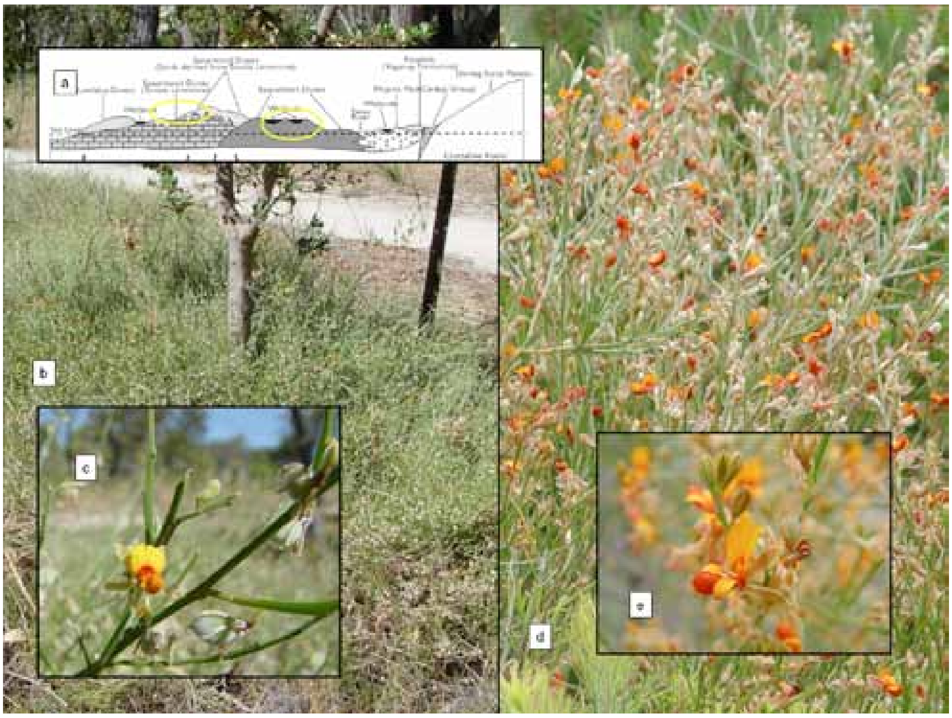


Figure 147. Many wetland plants have closely related species in the drylands. Two Swan Coastal Plain endemic *Jacksonia* species illustrate this relationship. Photos – B Keighery/OEPA.

(a) Transect (reproduced and adapted from Department of Minerals and Energy[86] with permission) of the Swan Coastal Plain showing locations of habitats of each species.

(b) and (c) The dryland Spearwood Dune *Jacksonia sericea*.

(d) and (e) The wetland Bassendean Dune *J. gracillima*.

Figure 148. *Anthotium junciforme* is a rare (Priority 4) Swan Coastal Plain species. Like many wetland plants, it persists into the dry season and is highly visible when it flowers in the dried soils in early summer, but is inconspicuous when it stops growing. Photos – B Keighery/OEPA.

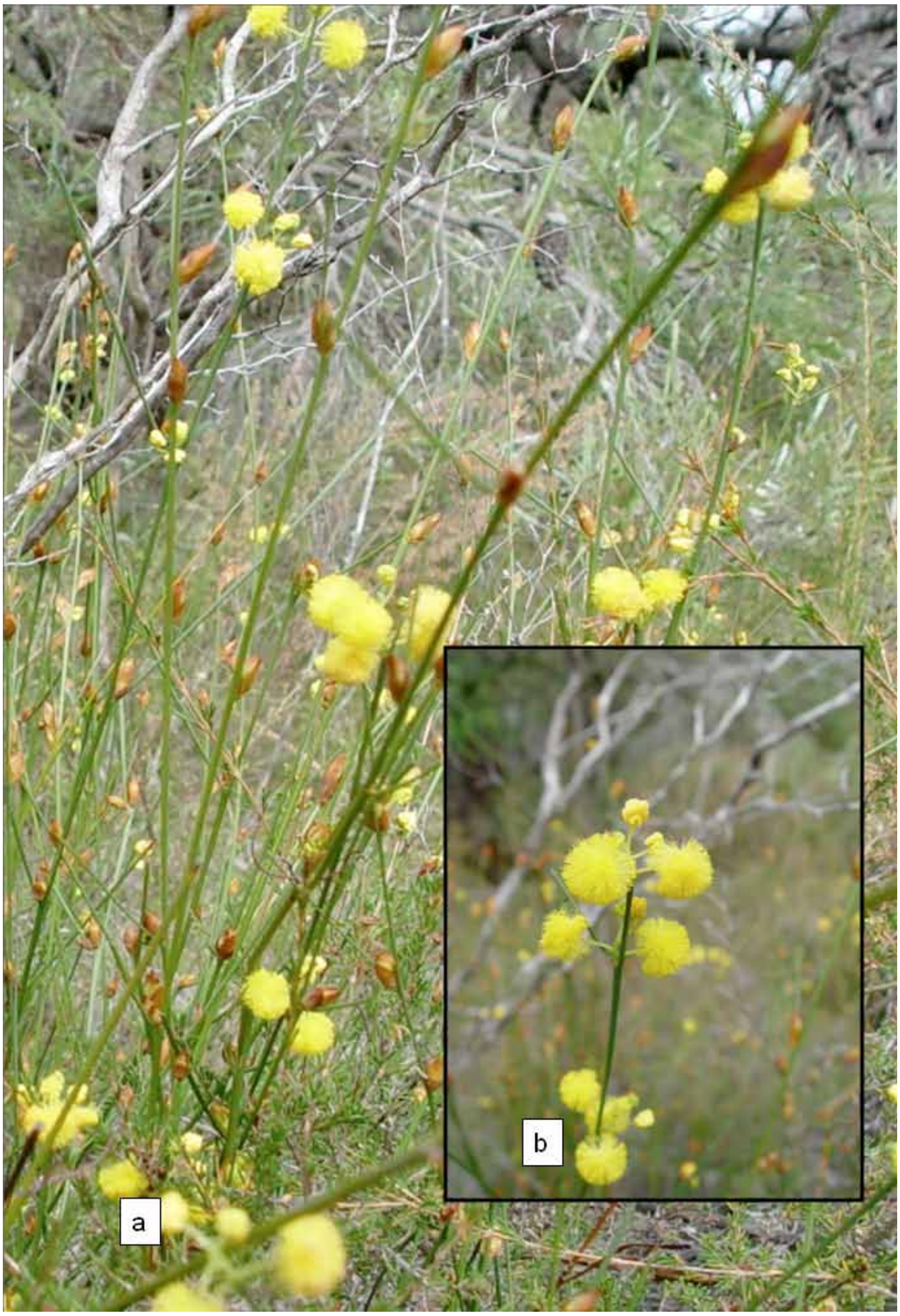


Figure 149. *Acacia flagelliformis*, an uncommon wetland shrub confined to the wetlands in the Bunbury/Busselton area principally on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) Plant.

(b) Flowers.

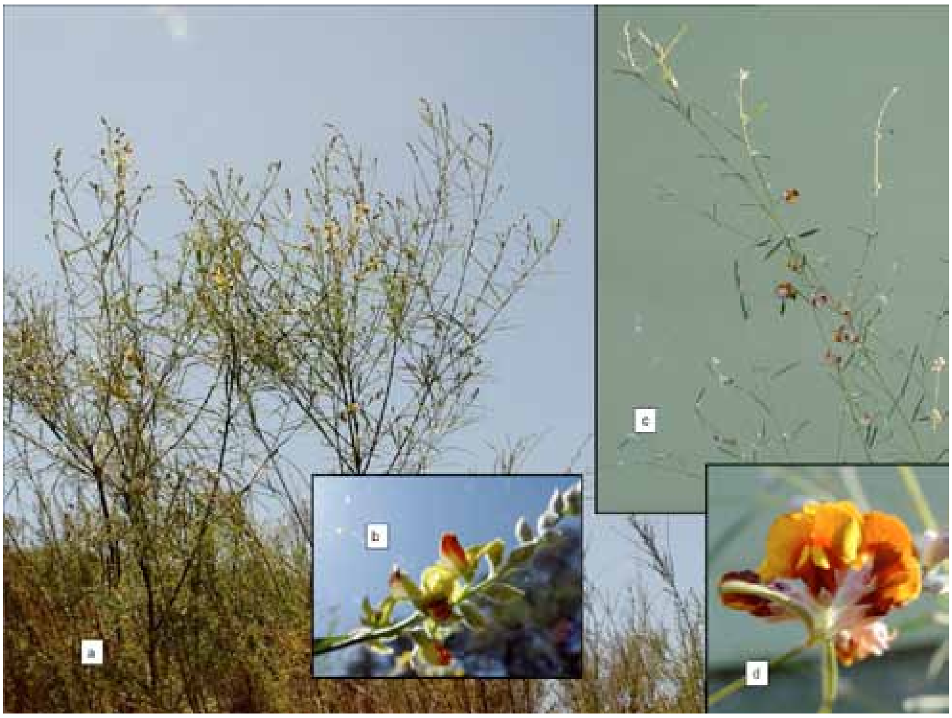


Figure 150. Members of the family Fabaceae are found in wetlands. Many of these are uncommon or rare. Photos – B Keighery/OEPA.

(a) and (b) The widespread *Gastrolobium ebracteolatum* favours freshwater seepage areas in wetlands.

(c) and (d) Another new taxon from wetland habitats near the Harvey River on the Swan Coastal Plain, *Gastrolobium* sp. Harvey.

Figure 151. Members of the family Proteaceae are found in wetlands. Three wetland shrubs of the genus *Grevillea* are illustrated here, all confined to the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) The prostrate form of *Grevillea obtusifolia* in Bullsbrook Nature Reserve.

(b) and (c) Two newly recognised grevilleas, *G. thelemanniana* subsp. Cooljarloo (b) and *Grevillea* sp. Gillingarra (c).

Figure 152. *Hibbertia stellaris*, a shrub of seasonally waterlogged wetlands in the Southwest, has two colour forms: the more restricted yellow form (a), and the bright orange form (b). Both forms are found on the Swan Coastal Plain. Photos – B Keighery.

wetland profile

Profile of a wetland complex: Yalgorup National Park wetlands

The Yalgorup National Park wetlands (Swan Coastal Plain) lie within the interface of the Quindalup and Spearwood dunes and within the Spearwood Dunes (Figure 153 and Figure 154). The wetland plant communities of Yalgorup National Park are many and varied, combining aspects of the saline and freshwater wetlands. The diversity of wetlands and associated wetland communities is related to the degree of inundation/waterlogging and the salinity of the water. Most of the wetlands in the national park are permanently inundated (that is, they are lakes). Communities beside the lakes are saline communities being heavily influenced by the saline waters of the lake. However, with increasing distance from the lakes, the saline influence decreases and freshwater seepages alongside the lakes support communities dominated by mostly freshwater species. This wetland vegetation is described below under saline and freshwater wetlands. All lake communities are annotated to indicate their position relative to the inundated area of the lake. Lake Community 1 is closest to the water and Lake Community 3 is the community adjacent to the drylands. A variety of freshwater wetland communities are also found in the park. Boundaries between these communities are gradational and, at times, the lakeside communities are a combination of all units described.

Figure 153. Yalgorup National Park and surrounding bushland, looking south-west with Lake Clifton in the foreground. Photo – G Whisson/DEC.

wetland profile

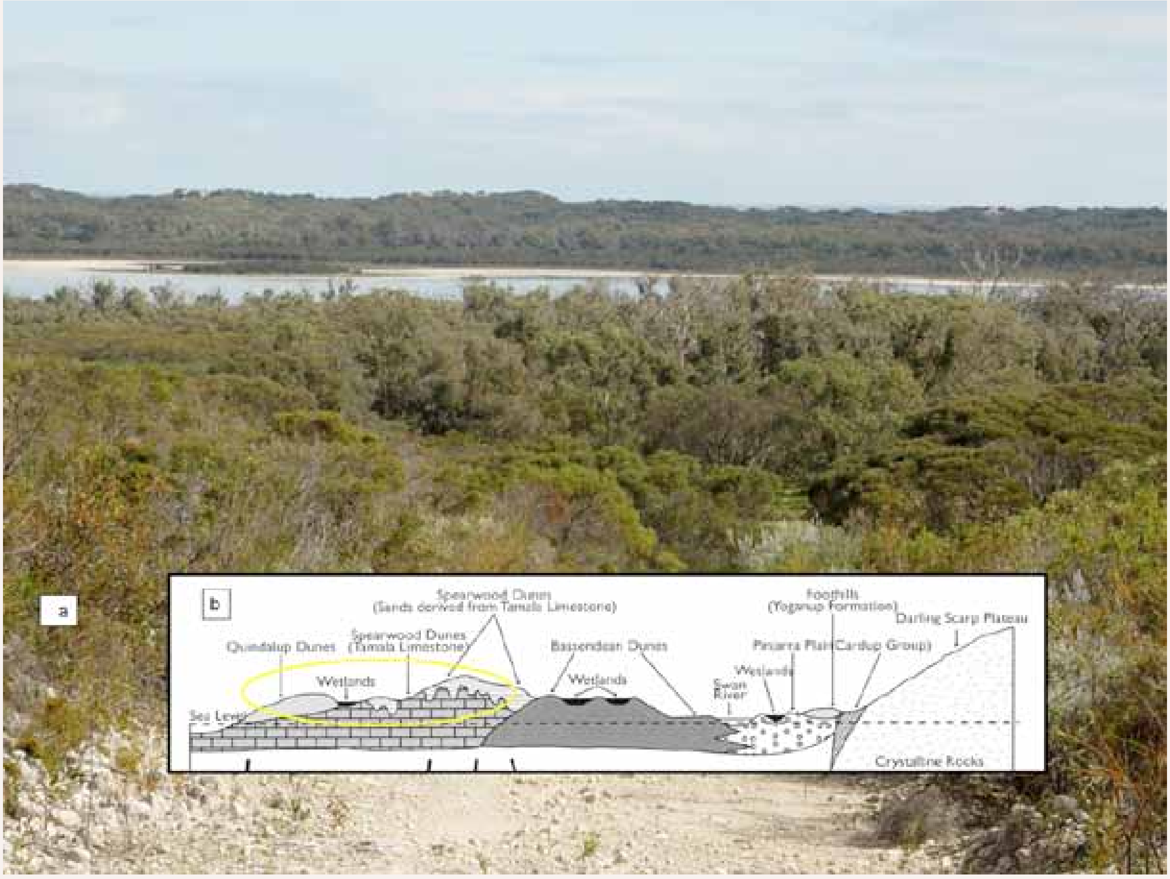


Figure 154. Quindalup and Spearwood dunes in Yalgorup National Park.

(a) Plant communities of the Quindalup and Spearwood dunes in Yalgorup National Park looking west across Lake Preston. Heaths can be seen on the Quindalup Dunes (far west) and Tamala limestone ridge of the Spearwood Dunes, with tuart (*Eucalyptus gomphocephala*) woodland on the gentler slopes of Lake Preston. On the margins of Lake Preston there is a set of zoned wetland communities from *E. gomphocephala* Woodland on the upper margin, through to *Melaleuca cuticularis* Closed Low Forest and lastly *Sarcocornia quinqueflora* and *Wilsonia backhousei* Open Low Heath on the water's margin. Photo – B Keighery/OEPA.

(b) Transect of the Swan Coastal Plain showing the location of the Quindalup and Spearwood dunes (reproduced and adapted with permission from Department of Minerals and Energy[86]).

Each of the major wetland communities are listed below, together with a standard description (after Keighery[3]; see part 1 pages 19 to 23, key to Appendix 1 and Table 4) derived from information collected from 10 by 10-metre quadrats located in each community. As discussed previously (part 1, page 20) the many sources for this topic did not use a consistent terminology to describe the vegetation layers. This profile has been included to both illustrate the complexity of plant communities in a wetland system and to illustrate the use of a set of standard vegetation or plant community descriptions with a key (after Keighery[3] and Table 4) showing how these are derived. When specific referenced terms are used for the vegetation layers the name for a layer is capitalised, for example Forest rather than forest.

wetland profile

Table 4: Vegetation structure classification system (based on Keighery[3]). Each row indicates a different vegetation layer.

Growth form/height class	Canopy cover			
	100–70%	70–30%	30–10%	10–2%
Trees over 30m	Closed Tall Forest **CTF**	Open Tall Forest **OTF**	Tall Woodland **TW**	Open Tall Woodland **OTW**
Trees 10–30m	Closed Forest **CF**	Open Forest **OF**	Woodland **W**	Open Woodland **OW**
Trees under 10m	Closed Low Forest **CLF**	Open Low Forest **OLF**	Low Woodland **LW**	Open Low Woodland **OLW**
Mallee over 8m (Tree mallee)	Closed Tree Mallee **CTM**	Tree Mallee **TM**	Open Tree Mallee **OTM**	Very Open Tree Mallee **VOTM**
Mallee under 8m (Shrub mallee)	Closed Shrub Mallee **CSM**	Shrub Mallee **SM**	Open Shrub Mallee **OSM**	Very Open Shrub Mallee **VOSM**
Shrubs over 2m	Closed Scrub **CSC**	Open Scrub **OSC**	Tall Shrubland **TS**	Open Tall Shrubland **OTS**
Shrubs 1–2m	Closed Heath **CH**	Open Heath **OH**	Shrubland **S**	Open Shrubland **OS**
Shrubs under 1m	Closed Low Heath **CLH**	Open Low Heath **OLH**	Low Shrubland **LS**	Open Low Shrubland **OLS**
Grasses	Closed Grassland **CG**	Grassland **G**	Open Grassland **OG**	Very Open Grassland **VOG**
Herbs	Closed Herbland **CHB**	Herbland **HB**	Open Herbland **OHB**	Very Open Herbland **VOHB**
Sedges	Closed Sedgeland **CSG**	Sedgeland **SG**	Open Sedgeland **OSG**	Very Open Sedgeland **VOSG**
Ferns	Closed Fernland **CFL**	Fernland **FL**	Open Fernland **OFL**	Very Open Fernland **VOFL**
Climbers	Closed Climbers **CC**	Climbers **C**	Open Climbers **OC**	Very Open Climbers **VOC**

Saline wetlands

Samphire Shrublands – Lake Community 1a

Samphire (*Sarcocornia quinqueflora*) dominated shrublands are found in the gently graded area alongside the water (Figure 155 and Figure 156). This community supports a series of species not commonly encountered on the Swan Coastal Plain such as *Isolepis cernua* var. *cernua* and *Hemichroa diandra* (Figure 157). Further study of these communities may identify more of these uncommon taxa. Of particular interest in this community is *Samolus repens* var. *paucifolius* which is at the southern extent of its range in the study area (Figure 158).

Community description: *Sarcocornia quinqueflora* and *Wilsonia backhousei* Open Low Heath over *Hydrocotyle tetragonocarpa* Very Open Herbland (Figure 156a).

wetland profile

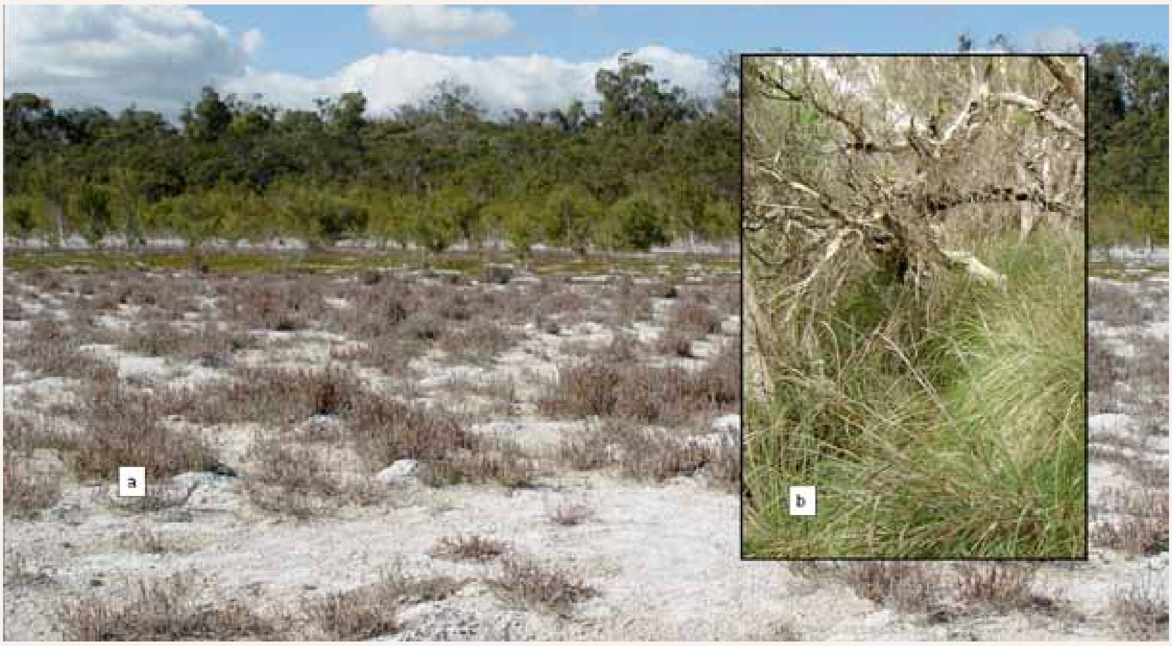


Figure 155. Plant communities visible from the water's edge.
(a) Samphire shrubland on the water margin, to *Melaleuca* forest, then tuart forest.
(b) *Melaleuca* forest underlain by a dense layer of the sedge *Gahnia trifida*, a freshwater community.
Photos – B Keighery/OEPA.

Figure 156. Plant communities on the water's edge, Lake Preston, eastern shoreline.
(a) Samphire heaths.
(b) *Wilsonia backhousei*.
(c) *Hydrocotyle tetragonocarpa*.
Photos – B Keighery/OEPA.

wetland profile

Figure 157. Plant communities on the water's edge, Lake Preston, eastern shoreline.

(a) Samphire heaths.

(b) *Triglochin mucronata* (left) and *Isolepis cernua* var. *cernua* (right).

(c) and (d) *Hemichroa diandra* plant and flowers (male).

Photos – B Keighery/OEPA.

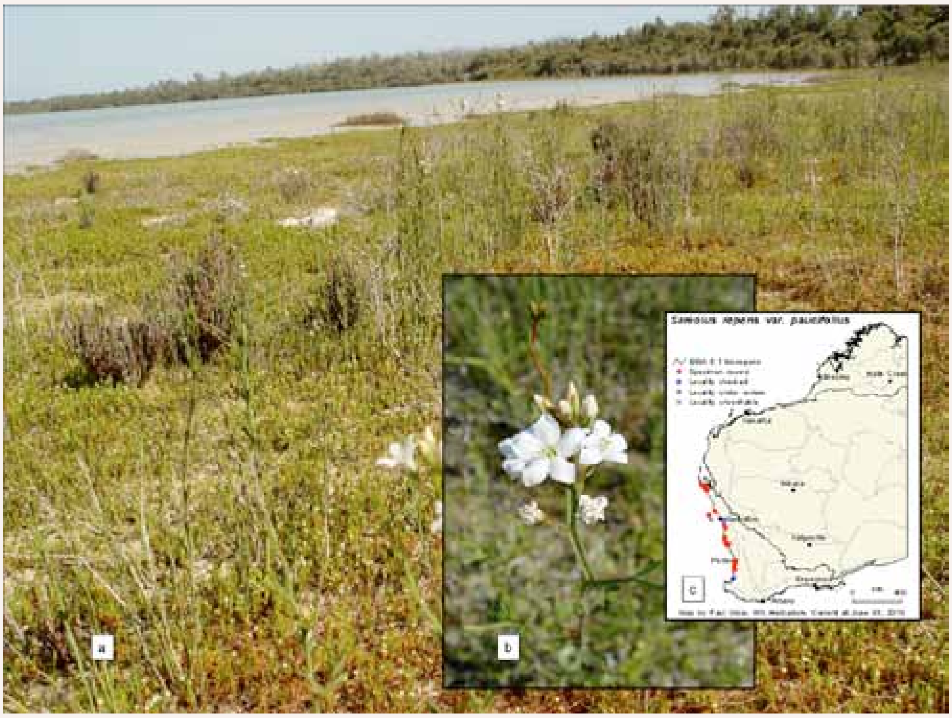


Figure 158. *Samolus repens* var. *paucifolius*. Photos – B Keighery/OEPA.

(a) Water's edge, Lake Preston (western shoreline).

(b) Flowers.

(c) The recorded distribution of *S. repens* var. *paucifolius*, showing Yalgorup Lakes as the most southern location on the plain. Mapping – P Gioia. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

wetland profile

Juncus kraussii Sedgelands – Lake Community 1b

Where the lakes of the study area have a steeper grade and the margins are flooded a *Juncus kraussii* subsp. *australiensis* Sedgeland is found (Figure 159). Generally this community is found on the eastern side of Lake Clifton. Scattered in this sedgeland are *Sonchus hydrophilus* plants (Figure 159b).

Community description: *Juncus kraussii* subsp. *australiensis* and *Baumea juncea* Closed Sedgeland (Figure 159a).

Figure 159. The vegetation on the water's edge, eastern shore of Lake Clifton.

(a) Three zones are distinguished: the lake fringing *Juncus kraussii* subsp. *australiensis* sedgeland, *Melaleuca cuticularis* forest and tuart (*Eucalyptus gomphocephala*) forest.

(b) *Sonchus hydrophilus* is scattered through these communities and is found in many wetland communities of the Southwest as well as a disjunct population in Karijini Gorges (Externally Drained Deserts, Pilbara). This plant is often mistaken for a weed.

Photos – B Keighery/OEPA.

wetland profile

Melaleuca cuticularis Low Forest – Lake Community 2

This community is dominated by the tree *Melaleuca cuticularis* (Figure 160) and sometimes peppermint (*Agonis flexuosa* var. *flexuosa*). This community has an understorey intermediate between that of the communities closer to and further from the waterline which includes the sedges *Gahnia trifida*, *Juncus kraussii* subsp. *australiensis* and *Baumea juncea* and the shrubs *Sarcocornia quinqueflora* and *Wilsonia backhousei*.

Community description: *Melaleuca cuticularis* Closed Low Forest over *Trachymene pilosa* Herbland, and *Gahnia trifida*, *Juncus kraussii* subsp. *australiensis* and *Baumea juncea* Open Sedgeland (Figure 160a).

Community description: *Agonis flexuosa* var. *flexuosa* and *Melaleuca cuticularis* Open Low Forest over *Sporobolus virginicus* Open Grassland, and *Gahnia trifida*, *Juncus kraussii* subsp. *australiensis* and *Lepidosperma gladiatum* Closed Sedgeland.

Figure 160. *Melaleuca cuticularis* Low Forest on the eastern shore of Lake Clifton.
(a) *Melaleuca cuticularis* Low Forest.
(b) *Melaleuca cuticularis* flowers.
Photos – B Keighery/OEPA.

wetland profile

Freshwater wetlands

Melaleuca rhaphiophylla Low Forest - Lake Community 3a

This type of vegetated wetland community occurs on the water's edge of many of the lakes, the margins of the Mixed Shrub Calcareous Flat Wetlands and in various sumplands when the water is predominantly fresh. *Melaleuca rhaphiophylla* is the dominant tree but other co-dominants include peppermint and tuart. A sedgeland dominated by *Gahnia trifida* is found in all known occurrences and this sedge may be accompanied by *Lepidosperma gladiatum* and *Baumea juncea*.

Community description: *Melaleuca rhaphiophylla* Open Forest over *Gahnia trifida* and *Baumea juncea* Closed Sedgeland.

Community description: *Agonis flexuosa* var. *flexuosa* and *Melaleuca rhaphiophylla* Open Low Forest over *Acacia saligna*, *Acacia rostellifera* and *Templetonia retusa* Open Shrubland over *Gahnia trifida* and *Lepidosperma gladiatum* Closed Sedgeland (Figure 161a).

Figure 161. *Melaleuca rhaphiophylla* Low Forest.
(a) *Melaleuca rhaphiophylla* with *Gahnia trifida* and *Lepidosperma gladiatum* (left foreground).
(b) *Gahnia trifida*.
(c) The coastal form of *Kennedia coccinea* scrambles through these wetlands but it also grows in drylands.
Photos – B Keighery/OEPA.

wetland profile

Wet Tuart Forest – Lake Community 3b

At times a community, very similar to that described above, occurs with tuart as the dominant and with no *Melaleuca rhaphiophylla*. This community also occurs on the margins of many of the lakes and in various sumplands within the study area when the water is predominantly fresh. Of particular interest in this community, and that described above, are patches of *Cyrtostylis* and *Corybas* orchids. This community merges with the upslope dryland Tuart Forest to Woodland.

Community description: *Eucalyptus gomphocephala* Woodland over *Agonis flexuosa* var. *flexuosa* Open Low Forest over *Thomasia triphylla* and *Templetonia retusa* Closed Heath over mixed Very Open Herbland, and *Gahnia trifida* Very Open Sedgeland.

Island Vegetation

While most islands will support saline communities dominated by samphires, the large island on Preston Beach Road is unusual in supporting a *Melaleuca lanceolata* Open Low Forest (Figure 162). This location and another on the western side of Lake Preston are the only confirmed record of this species, and of this community, on the mainland Swan Coastal Plain.

Figure 162. *Melaleuca lanceolata* Open Low Forest.

(a) A patch of Low Forest on an island in Lake Preston. This is one of only two populations of this species on the Swan Coastal Plain.

(b) *Melaleuca lanceolata flowers*.

Photos – B Keighery/OEPA.

wetland profile

Mixed Shrub Calcareous Flat wetlands

This wetland plant community is dominated by a series of shrubs and shrub-like trees including: *Melaleuca incana* (Figure 164), *M. viminea* (Figure 163), *M. teretifolia*, *M. cuticularis* (Figure 160), *Acacia saligna*, *Leptomeria ellytes* (Figure 167b&c), *Xanthorrhoea preissii*, *Hakea varia* (Figure 165), *Banksia littoralis* and *Eucalyptus rudis*. These shrubs have an understorey of herbs and sedges including *Brachyscome bellidioides*, *Gahnia trifida*, *Lepidosperma longitudinale* and *Meeboldina cana*. Patches of the native cypress *Actinostrobus acuminatus* (Figure 166) are found in this wetland community.

This community is similar to the wetland communities of the Pinjarra Plain, containing open patches dominated by annually renewed species such as *Wurmbea dioica* subsp. *alba*, *W. monantha*, *Schoenus plumosus*, *Triglochin* species, *Diuris micrantha* (DRF), *Hydrocotyle* species, *Blennospora doleiformis* and *Angianthus preissianus*. While the diversity of species in this plant community is not as high as that in the Pinjarra Plain wetland communities, it is high for a Spearwood Dune community.

This community has been identified as the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain' (Figure 136–167) and appears to be confined to the wetland area to the east of Lake Preston, traversed by Ellis Road and extending to Preston Beach Road in the north. This community has not been identified elsewhere in Yalgorup National Park.

Community description: *Acacia saligna*, *Leptomeria ellytes* and *Xanthorrhoea preissii* Open Heath over *Brachyscome bellidioides* Herbland and *Gahnia trifida*, *Lepidosperma longitudinale* and *Meeboldina cana* Sedgeland.

Community description: *Xanthorrhoea preissii* Open Shrubland over *Melaleuca incana* subsp. *incana* Closed Low Heath over *Gahnia trifida* Sedgeland.

Figure 163. Mixed Shrub Calcareous Flat Wetlands which are the TEC 'Shrublands on calcareous silts of the Swan Coastal Plain'.

(a) A view of the wetlands looking towards a tuart-dominated ridge to the east. During autumn the dominant *Melaleuca viminea* aestivates.

(b) *Melaleuca viminea* leaves and fruit.

Photos – B Keighery/OEPA.

wetland profile

Figure 164. Another view of the Mixed Shrub Calcareous Flat in spring.
(a) *Melaleuca incana* (foreground) and *M. viminea* (mid-ground).
(b) *Melaleuca incana* flowers.
Photos – B Keighery/OEPA.

Figure 165. Another view of the Mixed Shrub Calcareous Flat in spring.
(a) *Hakea varia* shrubs scattered through the community.
(b) *Hakea varia* flowers.
(c) Crusting mosses and lichens on wetland soils.
Photos – B Keighery/OEPA.

wetland profile

Figure 166. An isolated population of the native conifer *Actinostrobus acuminatus* found in the Mixed Shrub Calcareous Flat along Ellis Road. This species is typically found in the clay wetlands on the eastern side of the Swan Coastal Plain and flowers in spring.

(a) *A. acuminatus* plants.

(b) *A. acuminatus* female cones.

(c) *A. acuminatus* male cones releasing pollen when disturbed.

Photos – B Keighery/OEPA.

Figure 167. Another view of the Mixed Shrub Calcareous Flat in spring.

(a) *Melaleuca incana* and *M. viminea* alongside the rare community roadside marker.

(b) *Leptomeria ellytes*, a highly disjunct wetland species in the Yalgorup wetlands.

(c) Fruit of *Leptomeria ellytes*.

Photos – B Keighery/OEPA.

wetland profile

Lake Pollard Wetland Mosaic

Between Lake Pollard and Martins Tank Lake, a series of integrating wetland communities are found. These communities are dominated by tuart, peppermint, *Banksia littoralis*, *Melaleuca cuticularis* and *M. rhaphiophylla* and combinations of these. Understorey species include the shrubs T*empletonia retusa*, *Acacia cyclops* and *Spyridium globulosum* and the sedges *Gahnia trifida*, *Juncus kraussii* subsp. *australiensis* and *Baumea juncea*. While some areas of this mosaic appear similar to the Mixed Shrub Calcareous Flat Wetlands, these wetlands do not support the annually renewed herblands/sedgelands that are typical of the Mixed Shrub Calcareous Flat Wetlands. This community is expected to be a new wetland group, allied to the Mixed Shrub Calcareous Flat Wetlands.

Community description: *Melaleuca cuticularis* and *Melaleuca rhaphiophylla* Open Low Forest over *Templetonia retusa* and *Spyridium globulosum* Open Scrub over *Gahnia trifida* and *Juncus kraussii* subsp. *australiensis* Sedgeland (Figure 168).

Community description: *Templetonia retusa*, *Melaleuca cuticularis*, *Spyridium globulosum*, *Acacia cyclops* and *Melaleuca rhaphiophylla* Closed Scrub over *Baumea juncea*, *Juncus kraussii* subsp. *australiensis* and *Gahnia trifida* Open Sedgeland.

Figure 168. Lake Pollard Wetland Mosaic.
Photo – B Keighery/OEPA.

wetland profile

Profile of a wetland complex: Brixton Street Wetlands

The Brixton Street Wetlands are an amazing place of local, state, national and world renown. It is for their botanical values rather than birds or wetland fauna that the wetlands have this astounding reputation. They are part of Bush Forever Site 387, 'Greater Brixton Street Wetlands, Kenwick', which has the greatest diversity of plants (around 560) of all Bush Forever sites. This is even more astounding when considered in the context of the both the Perth metropolitan region and an area of plant mega-diversity on a world scale. The Brixton Street Wetlands make up just 15 per cent (19 hectares) of the Bush Forever site yet they support around 300 native plants. The diversity of wetlands in this small area supports this diversity of plants and plant communities.

The plant diversity of the wetlands was first comprehensively documented in the late 1980s and early 1990s. During these surveys several presumed extinct species that had not been recorded since the early twentieth century were rediscovered. A number of completely new species were located (for example, *Eleocharis keigheryi*); in fact, new species are still being located, including a new feather flower, *Ptilotus* sp. Brixton in 2010. The information from these surveys contributed to the recognition of the wetland's values as part of the assessment of a proposal to develop land, including the wetlands, for housing. The outstanding values of the wetlands were recognised in this process and the area is now protected and reserved for conservation.

The active, well-informed Friends of Brixton Street Wetlands have been part of the wetland management team since the wetlands' values were first recognised by the local community. Management guidelines for the wetlands were written in 1995 and in 2000 for Bush Forever Site 387 with funding from two community conservation grants from the Minister for the Environment to the Wildflower Society of WA (Inc). The second grant included the production of the information which is part of permanent display panel at the site and reproduced on the following pages. It was prepared in 2004 by the Friends of the Brixton Street Wetlands (text by Bronwen Keighery, Karen Clarke and Mark Brundrett, drawings by Margaret Pieroni and design by Karen Clarke and Mark Brundrett). The information is reproduced in this document with the permission from the Friends of Brixton Street Wetlands.

wetland profile

The Brixton Street Wetlands

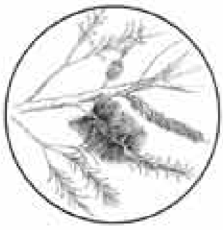
Delicate Treasure

For its size, the Brixton St Wetlands is one of the most diverse sites on the Swan Coastal Plain. It covers only 19 hectares but is a treasure trove of native plants and animals. There are two threatened ecological plant communities and a diverse flora of over 350 different types of native plants including at least 80 types of special significance. A large variety of habitats are present, most in good condition, and these support a diverse array of fauna.

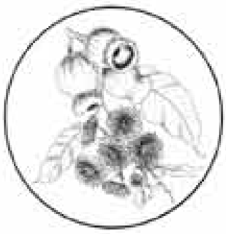
This unique and special place is now protected, saved from development as a housing estate. However, it's a fragile ecosystem and needs careful management to survive. Treat it with care and it will reward you with its many delights.

Looking south over the Brixton St Wetlands in spring

The Brixton St Wetlands is located on the very flat, waterlogged Pinjarra Plain that lies at the base of the Darling Range. Over 97% of the bushland on the Plain's waterlogged soils has been cleared for either agriculture or housing.



Robin Redbreast Bush (*Melaleuca lateritia*)



Marri (*Corymbia calophylla*)

The delicate flowers of Pink Petticoats (*Utricularia multifida*)

Partnerships for Conservation

Government of Western Australia

Department of Conservation and Land Management

Friends of Brixton St Wetlands

Wildflower Society of Western Australia (Inc.) Perth Branch

This display was made possible by a Community Conservation Grant from the Minister for the Environment to the Perth Branch of the Wildflower Society of WA (Inc.) Line drawings are by Margaret Pieroni. Display design by Karen Clarke and Mark Brundrett, May 2004.

wetland profile

The Brixton Street Wetlands

Conservation and Claypans

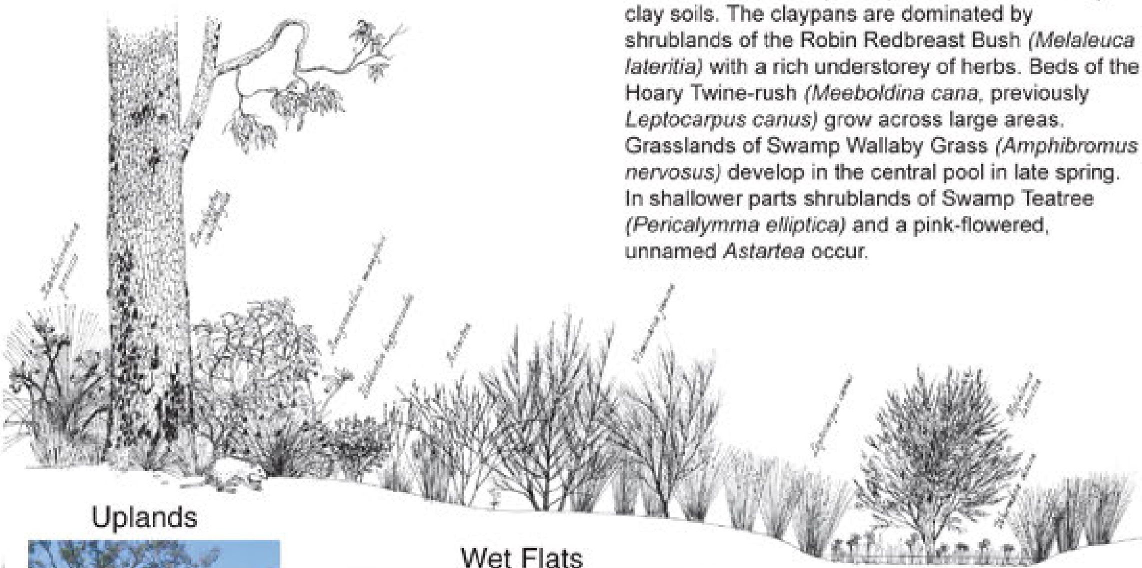
The outstanding conservation values of the Brixton St Wetlands are recognised in many ways. It is now part of the largest area of bushland remaining on the Pinjarra Plain in the Perth region. This continuous area of 126 hectares includes the Brixton Street Wetlands, the University of WA's Yule Brook Reserve, and extends north-east as far as Welshpool Road and Tonkin Hwy. Known as the "Greater Brixton Street Wetlands" this area is protected as a Bush Forever Site.

Three main plant communities occur at the Brixton St Wetlands, the Uplands, Wet Flats and Clay Pans. The Wet Flats and Clay Pans are a mosaic of many smaller plant community types with different plants dominant at different times of the year.

Uplands
These occur on slight rises between the wetlands and support a woodland of Marri *(Corymbia calophylla*, previously *Eucalyptus calophylla)* with an understorey of various shrubs, herbs and sedges.

Wet Flats
The Wet Flats surround the Clay Pans and are a series of low lying flats covered with sheets of water during winter and spring. A tall shrubland of Swish Bush *(Viminaria juncea)* grows on these flats with a rich understorey of shrubs, herbs and sedges. Dense low shrublands occur in the drier areas.

Clay Pans
The Clay Pans contain long-lived seasonal pools and occur in the deeper depressions of the heavy clay soils. The claypans are dominated by shrublands of the Robin Redbreast Bush *(Melaleuca lateritia)* with a rich understorey of herbs. Beds of the Hoary Twine-rush *(Meeboldina cana*, previously *Leptocarpus canus)* grow across large areas. Grasslands of Swamp Wallaby Grass *(Amphibromus nervosus)* develop in the central pool in late spring. In shallower parts shrublands of Swamp Teatree *(Pericalymma elliptica)* and a pink-flowered, unnamed *Astartea* occur.



Uplands

Woodland domianted by Marri (Corymbia calophylla, previously Eucalyptus calophylla) on the low lying rises between the wetlands.

Wet Flats

Swish Bush (Viminaria juncea) shrubland with a rich understorey of shrubs, herbs and sedges.

Clay Pans

Fields of bright green Swamp Wallaby Grass (Amphibromus nervosus) surrounded by clumps of the Hoary Twine-rush (Meeboldina cana, previously Leptocarpus canus) in the central part of the flooded claypans during winter.

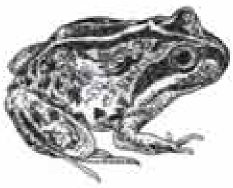
wetland profile

The Brixton Street Wetlands

Frogs and Feather Flowers

Fauna

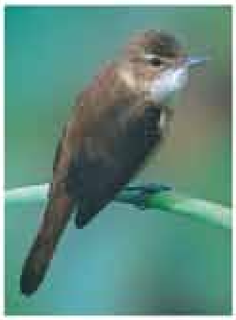
The Brixton St Wetlands support a diverse array of fauna, each depending on different aspects of the vegetation and surface water to provide shelter, food and suitable conditions for breeding. Many of these animals, especially the birds, are present seasonally.



Banjo Frog (*Limnodynastes dorsalis*)

Frogs

The wetlands are a frog paradise. Listen for the Banjo, Moaning, and Quacking Frogs, each named for their distinctive calls. The Crawling Frog is also common.



The Australian Reed-Warbler (*Acrocephalus australis*), a shy bird of reed beds with a beautiful melodious song.

Birds

Over forty bird species have been recorded so far, many such as waders and waterbirds are seasonal visitors during winter and spring.

A beetle with feathery antenna (*Rhipicera femorata*) resting on a Swish Bush (*Viminaria juncea*)

Invertebrates

There is also a large and diverse invertebrate fauna, including crustaceans in the pools and many bizarre and beautiful insects.

Reptiles

Rich in reptiles the wetlands contain the Spiny-tailed Gecko, five species of Legless Lizards, two Dragons, eight Skinks, two Goannas and the Dugite snake.

A Western Bearded Dragon (*Pogona minor*) sunning itself on a warm bare patch of sand

Mammals

The Southern Brown Bandicoot (Quenda) is a locally endangered species that is abundant in the wetlands. It likes the dense, undisturbed bushland for protection from predators.

Flora

Characteristic of the wetlands are carpets of wildflowers of all colours of the rainbow, each wildflower blooming at its own time of the year.

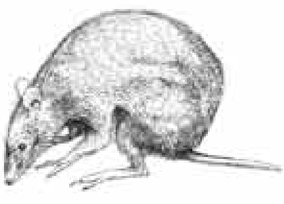
In late spring Feather Flowers of various types form a sea of pink foam across the Wet Flats.

Feather Flowers en masse in the Wet Flats during November.

There are over 20 species of threatened flora present including two aquatic plants that occur only in the clay pans in south-west Western Australia and nowhere else in the world.

Two threatened species are the Stalked Water Ribbons (*Aponogeton hexatepalus*; long lanceolate floating leaves) and Aquatic Pennywort (*Hydrocotyle lemnoides*; small heart-shaped floating leaves). They occur in the seasonal pools of the clay pans. Both flower in early spring and are West Australian clay pan endemics.

Pink Boronia (*Boronia cyrtoides*) from the Marri woodlands



Southern Brown Bandicoot or Quenda (*Isoodon obesulus*)

Fire is the greatest threat to the survival of the many fauna species at the Brixton St Wetlands.

wetland profile

The Brixton Street Wetlands

Friend or Foe?

Numerous people, community groups and government agencies have contributed over many years to making sure the wetlands remain part of our natural heritage:

"......the bandicoots, birds and plants will never know the war that has been waged here so that this could remain just as it is."
Joan Payne, Waterbird Conservation Group.

The Friends of Brixton St Wetlands grew out of the campaign by the Waterbird Conservation Group and others to save the Wetlands in the late 1980s. The Friends coordinate regular guided walks and bushcare activities in the wetlands. Newcomers are always welcome.

1. Bacon and Eggs (Wemia capitata) 2 Flannel Flower (Tribonanthes uniflora), a day pan endemic. 3. Pink Rainbow (Drosera menziesii) 4. Swamp Spider Orchid (Caladenia paludosa) 5. Pink Morning Lily (Chamaescilla glauca), a day pan endemic. 6. Love Creeper (Comesperma volubile)

Further Information

Friends of Brixton Street Wetlands
Phone: 9459 2964

Department of Conservation and Land Management
Phone: 9405 0700

Wildflower Society of WA (Inc.) 9383 7979

City of Gosnells
Phone: 9391 3222

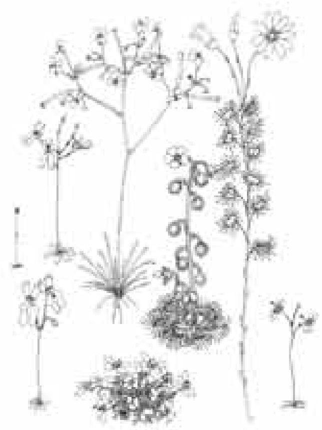
Careful removal of bulbous weeds.

The Brixton Street Wetlands now has a secure future. In 2004 it was purchased by the state government for conservation and put under the management of the Department of Conservation and Land Management (CALM). However, numerous threats still remain. Our actions will determine whether it lives or slowly dies.

We all have a role to play, will you be friend or foe? Please care for the wetlands by observing the following:

* Take only photos, leave only footprints. Please keep to the paths.
* All native flora and fauna are protected by law.
* Dogs disturb both flora and fauna, please leave them at home.
* Report all fires immediately, dial 000.
* Please report any damage or vandalism as soon as possible to CALM on 9405 0700.
* Remember, dumped rubbish and garden waste introduces weeds and diseases.
* Keep cats in at night, that's when they may hunt in the bushland.

A selection of trigger plants and sundews that grow in the area. Trigger plants use a spring loaded "hammer" to transfer pollen onto and off of insects that visit their flowers so that the pollen gets transferred between plants. Sundews trap insects with their sticky leaves then slowly digest their catch to obtain essential food for survival.



A guide to managing and restoring wetlands in Western Australia

Managing hydrology

In Chapter3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Managing hydrology' topic

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When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). 'Managing hydrology', in *A guide to managing and restoring wetlands in Western Australia*, Prepared by J Lawn and A Lam, Department of Environment and Conservation, Perth, Western Australia.

Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Introduction

Managing wetland hydrology is the most important consideration when managing a wetland. A wetland's physical, chemical and biological processes are so closely tied to the natural patterns and fluxes of water that changes to these influence the nature and ecological character of a wetland. Managing a wetland's hydrology is often likely to take the highest priority amongst all of the possible actions needed at a wetland, because it can trigger cascades of ecological impacts; causing, contributing to or amplifying the effects of many common wetland management challenges, such as loss of native plants and animals, poor water quality, weed invasion, acidification, inappropriate fire regimes, algal blooms and nuisance midge. Dealing with these problems without addressing the root cause may achieve little. For some wetland managers, all that will be required is a watching brief to make sure changes aren't likely, while for others managing hydrology will consume most of their time.

This topic outlines the causes of altered wetland hydrology in Western Australia (WA), the effects of altered hydrology, and potential management responses. The topic, 'Wetland hydrology' in Chapter 2 is recommended background reading because it describes the natural hydrology of wetlands, how it influences the plants, animals and water chemistry of wetlands and lists resources that can be used to characterise the natural hydrology of a wetland in WA.

Altered hydrology affects most of the state's land area and is one of the most prevalent and serious threats to WA's wetlands. The hydrology of most wetlands and waterways in WA have been significantly modified since European settlement, particularly in the south-west.[1] Some of the best-known examples of wetland decline in WA are caused by altered hydrology, including the secondary salinisation of Wheatbelt wetlands and the drying of wetlands on the Gnangara groundwater mound in the Perth region. Lesser-known examples include the acidification of wetlands in the South Coast, south-west and in Perth and the coastal plain stretching north and south of it due to drying; and the permanent inundation of previously intermittently inundated wetlands in inland mining regions due to the disposal of water from mine dewatering. An assessment rated the west and the north to be worst affected areas of the state, with the central and eastern regions suffering minor hydrological change with localised instances of major hydrological change[1,2] (Figure 1).

Altered hydrology is a significant challenge for land management in WA. In 2007 the Environmental Protection Authority compared WA's environmental threats and rated altered hydrology as being the second highest priority, on a scale of five, for policy development, management action and investment.[1]

"Alteration of natural water regimes is now recognised as a major contributor to loss of biodiversity and functionality of aquatic and terrestrial ecosystems. It can modify the values of inland waters and lead to other land and water problems including floods and drought-like conditions, waterlogging, salinisation, eutrophication, acidification and erosion. The maintenance of biodiversity and productive land and water systems depends on ecosystem services that in turn rely on maintenance of natural water balances and flow regimes. In severe cases, excessive alteration of natural water regimes leads to widespread loss of whole ecosystems and water supplies."

- Environmental Protection Authority, *State of the Environment Report: Western Australia 2007.*[1]

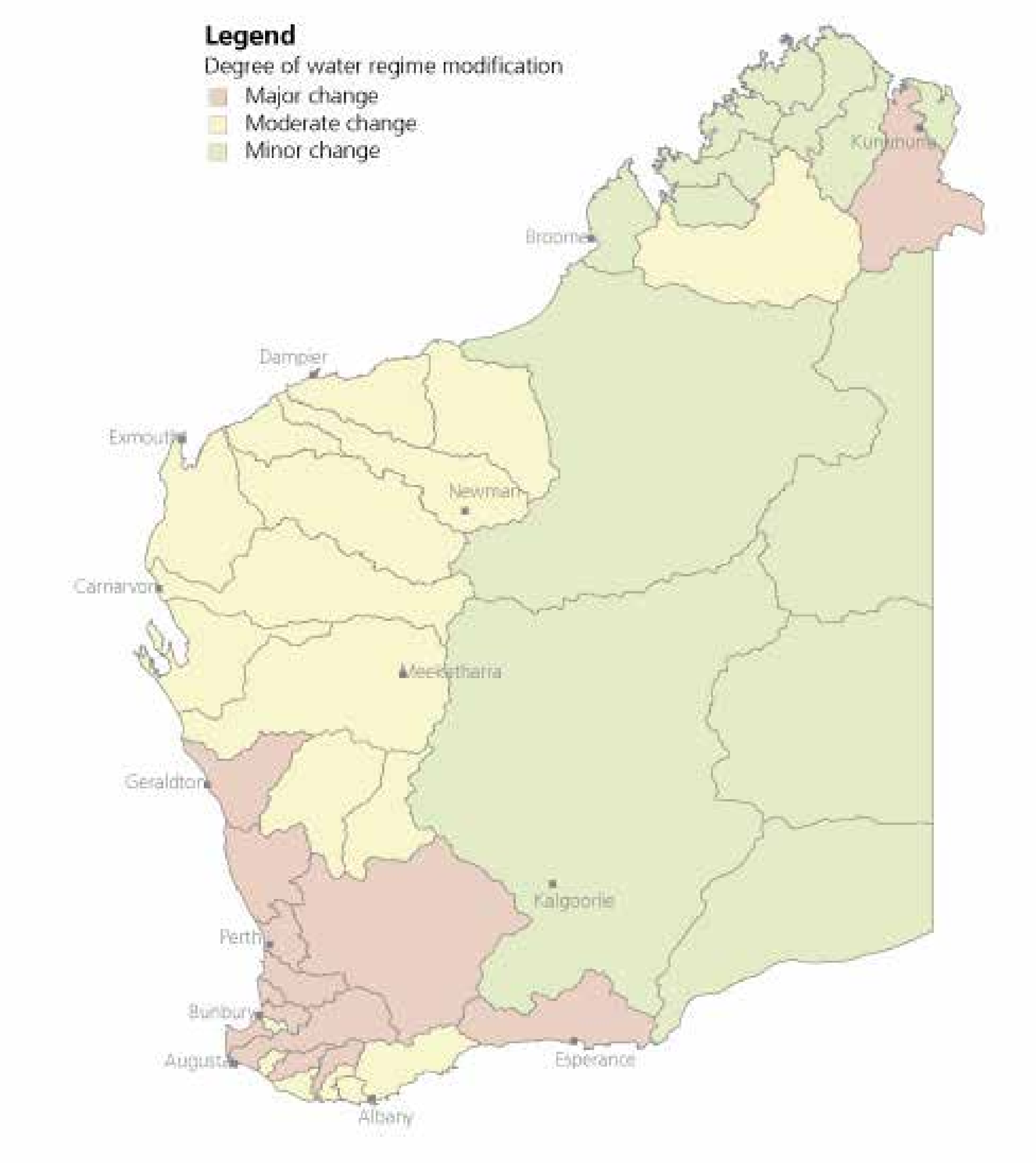


Figure 1. Extent of altered water regimes in WA, by river basins. Image - Environmental Protection Authority.[1]

Despite its high priority for management, altered hydrology and its impacts on WA's wetlands continue to be difficult to address for a number of reasons:

- Australia is one of the highest users of water on a per capita basis in the world.
- Human demand for water is increasing. Water use in WA has tripled in the last twenty-five years[3], increasing the competition between water for human needs and water for the environment.
- Altered wetland hydrology can reflect the wider broadscale change in a catchment. Very large falls or rises in regional groundwater tables are two of the most difficult problems for wetland managers in WA.
- Climate change is causing and will continue to cause severe changes to water availability and patterns in most parts of the state. Wetlands in the south-west of WA in particular are likely to be adversely affected.
- There exists the universal challenge of balancing land development against ecosystem conservation. For example, wetland flats on the coastal plain east and south of Perth have been extensively drained to make them more suitable for pasture and other agricultural uses.
- Water flows through landscapes, so hydrological modifications in one part of the landscape can affect wetlands located a considerable distance away. For example, groundwater dewatering to access minerals can create drawdown in aquifers far beyond the mine site, which can cause groundwater dwependent wetlands to dry beyond natural variability.
- Hydrological change can be intractable (that is, complex and enduring) because it may be ecologically, politically and/or socially difficult to restore the original wetland hydrology. For example, many urban wetlands around the state contain water year-round even though they originally dried out over the dry season, because the people living around them prefer them that way, despite this altering their ecological functions and values.
- Because of economic and social factors, protecting and managing some wetlands often comes at the cost of sacrificing other wetlands. This is the case in many secondary salinised catchments of the Wheatbelt, where the alternative to turning some wetlands into sacrificial drainage basins is to return almost all of the land back to deep-rooted trees, which could only be done at the cost of agricultural production.
- Wetland hydrology is influenced by complex interactions between many factors, including geology, soils, landscape shape, vegetation and climate. Information gaps can result in misunderstanding of the hydrological system, which undermines management decisions. For example, attempts to artificially maintain water levels of some wetlands in WA have had unexpected adverse impacts.
- Historical perceptions about the availability of water and the priorities for water allocation—"the pathological perception of plenty"[4]—are built into our cultural norms, legislation and infrastructure, so while there has been changes in community perceptions there are significant social, technical, commercial and regulatory hurdles to overcome in order to make changes to our water use in the future.
- There has been significant water reform in WA. However, a number of water management Acts are quite old, limiting some potential reforms. For example, the ninety-eight year old Act, *Rights in Water and Irrigation Act 1914*, was written to establish landholders' rights to water in a very early phase of the state's development.[5] It has been recognised as simplistic and out of date with modern requirements, including failing to deal adequately with environmental and social impacts of water use.[6,4] Similarly, legislation for coastal drainage is in need of review.[7]

These complexities mean that managing hydrology in wetlands typically requires much more than good local wetland management. It requires understanding, consideration and management of the effects of cumulative changes in a catchment, each of which viewed on its own may seem insignificant.

One of the biggest challenges facing wetland managers is that on-ground works at the wetland will often yield little improvement in wetland water regime in the long term, especially for those low in the catchment. The landscape-scale hydrological alterations driving altered hydrology of most wetlands means that the vast majority of wetland managers need to embrace the role of advocate, and work with and influence water users, land managers and decision-making authorities across broad landscapes.

Awareness, incentives and regulation are all important and complementary vehicles for change. Encouragingly, there has never been more recognition of the problems nor momentum across so many sectors to address the issues of water management in WA. Wetland managers can capitalise upon and strengthen this momentum by drawing attention to local wetlands of conservation significance, and engaging others to better understand the cumulative effects of their communities upon these wetlands, what values are at threat, and what can be achieved with collective action. The combined voice of wetland managers and other stakeholders can and has produced local, regional and institutional-scale reforms and initiatives in WA, and it is important that wetland managers participate in water planning and water resource management reform processes.

To address the big picture, an integrated approach to land and water management, often referred to as 'catchment management', has been applied to various degrees in WA (linked initiatives include total water cycle management and water sensitive cities). Key elements include cooperation among state and local governments, natural resource management organisations and landholders; involvement of landholders and local communities in identification of issues and solutions; and agreement on common objectives. A more integrated approach to catchment management requires a long-term perspective, and an appreciation that it requires many people and agencies to move beyond their traditional roles.[8] It is increasingly becoming a feature of natural resource management in WA.

However, sometimes a long-term, holistic approach to addressing hydrological issues cannot achieve change quickly enough to protect important wetlands that are under immediate hydrological threat. For wetlands of high conservation priority, a quicker-fix might be necessary, and this usually involves engineering. Engineering solutions have been implemented in several WA catchments, where catchment and landscape management cannot solve hydrological problems within the necessary timeframe. Some examples include artificial supplementation of wetlands with water in response to drying outside of known ranges (for example, at Thomsons Lake in the Perth suburb of Beeliar), and surface water diversions and groundwater dewatering to protect wetlands that are becoming too wet (such as at Toolibin Lake, east of Narrogin in the Wheatbelt and Lake Warden system north of Esperance in the south coast region). Unfortunately, this type of engineering can have downstream impacts and can be expensive. One study estimated that if groundwater dewatering was used to protect just 10 per cent of the Wheatbelt ecosystems threatened by rising saline groundwater tables, it would cost $63–78 million per year.[9]

extra information

Important concepts in wetland hydrology – a primer from the 'wetland hydrology' topic

Some important concepts in wetland hydrology are summarised here. These concepts are described in more detail in the topic 'Wetland hydrology' in Chapter 2.

- **Hydrology** refers to the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere, and its study. Hydrology can be studied at a range of scales (such as hillslope, catchment, regional or global) and from different perspectives (for example, focusing on a particular wetland, a river catchment or a groundwater aquifer) depending on the questions being asked.
- The term **wetland hydrology** is generally used to refer to the movement of water in and out of, and within a wetland.
- The term **hydroperiod** refers to the periodicity (permanent, seasonal or intermittent) of waterlogging or inundation of a wetland. It refers to the potential for water to either inundate a wetland or saturate it without supporting a free standing water column, and the duration of these states. Table 1 shows the wetland hydroperiods recorded in Western Australia.

Table 1. Wetland hydroperiods recorded in Western Australia. Adapted from Semeniuk and Semeniuk (2011)[10]

Periodicity	Hydrotype	
	Waterlogged	Inundated
Intermittent	Not applicable	Intermittently inundated
Seasonal	Seasonally waterlogged	Seasonally inundated
Permanent	Permanently waterlogged	Permanently inundated

- Wetlands with altered hydrology are often described in broad terms such as being 'wetter' or 'drier' than they should be. These descriptions convey the problem in broad terms, which is often all that is needed to initiate some form of management action. However, to fully understand and manage altered wetland hydrology what is needed is an understanding of changes relative to the wetland's natural water regime. The **water regime** of a wetland is the specific pattern of when, where and to what extent water is present in a wetland.[11] The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence (Table 2).[12] This is also referred to as 'hydropattern' in many texts.

Table 2. Features of the water regime of wetlands. Adapted from Bunn et al., (1997).[17]

Feature	Definition
Timing	The timing of a wetland being waterlogged or inundated. Within-year patterns are most important in seasonally waterlogged or inundated wetlands (that is, what time of year) whereas between-year patterns and the variability in timing may be more important to intermittently inundated wetlands.
Frequency	How often wetting and drying occur. Ranging from not at all in wetlands that are permanently inundated (lakes) to wetting and drying many times a year. The rate at which wetting and drying occur can also be important.
Duration	The length of time of waterlogging and/or inundation. Duration in days, weeks or even years, varying within and between wetlands.
Extent and depth	The area of waterlogging or inundation and the depth of the water.
Variability	The degree to which the features mentioned above change at a range of time scales (variability in timing mentioned above). Variability is recognised as a significant part of wetland water regime.

- The wetting-drying cycle encompasses a wetland's natural, cyclic transition between wet and dry conditions. The duration of a single wetting-drying cycle varies between wetlands (with permanently inundated wetlands never, or extremely rarely, drying).
- Surface water reaches wetlands from the **catchment,** an area of land bounded by natural features such as hills or mountains from which surface water flows downslope to a particular low point or sink, where water

extra information

Important concepts in wetland hydrology – a primer from the 'wetland hydrology' topic (cont'd)

collects. Rain and surface water from overland flows and waterways are important natural sources of water for wetlands, particularly **perched** wetlands, which are not connected to groundwater.

- **Groundwater** is water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks. The **groundwater table** (or water table) is the upper surface of groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, it is the surface where the water pressure head is equal to the atmospheric pressure. **Groundwater capture zones** are the area within which any recharge (infiltrating water) eventually flows into the wetland.
- **Groundwater dependent ecosystems** are those parts of the environment, the species composition and the natural ecological processes of which are dependent on the permanent or temporary presence or influence of groundwater. Not all wetlands are groundwater dependent ecosystems (such as perched wetlands and gnammas) and not all groundwater dependent ecosystems are wetlands (such as terrestrial vegetation communities that use groundwater).
- A **water budget** is the balance of all of the inflows and outflows of water over a set period of time. Inflows (inputs) include rainfall, surface water inflows and groundwater inflows. Outflows (outputs) include evaporation, transpiration, surface water outflows and groundwater outflows.
- Wetland water regime is the most important driver of wetland processes, and plays a key role in determining wetland characteristics such as the composition of plant and animal communities.
- The water regime directly affects wetland species. It also affects species indirectly by influencing the characteristics of a wetland including its physical (for example, turbidity), chemical (for example, acidity) and biological (for example, algal blooms) characteristics.
- Wetland water regime is influenced by many factors including climate, landscape shape, geology, soils and vegetation. That is, wetland hydrology is complex and driven at a number of spatial scales.
- Wetland water regime is also dynamic at longer timeframes. Wetlands have responded to changing climate over millennia. For example, Semeniuk and Semeniuk[13] and McHugh[14] have studied changes to Swan Coastal Plain wetlands occurring over thousands of years in response to climate changes.

What causes altered wetland hydrology in Western Australia?

The water regime of a wetland can be altered by anything that affects the movement of water into, out of or within the wetland. Change within a wetland's catchment or groundwater capture zone has the potential to alter wetland hydrology, with the main causes in WA being:

- climate change
- vegetation change
  - large scale clearing and planting of vegetation, vegetation decline
- removing water from wetlands and associated landscapes
  - groundwater bores, surface water pumps, dewatering, subsoil drainage and wetland drainage for land reclamation
- disposing of water (applying, disposing and moving) in wetlands and associated landscapes
  - stormwater disposal, dewatering discharge, deep drainage, irrigating, discharging effluent, discharging tailings
- changing wetlands
  - creating islands, deepening wetlands, puncturing confining layers, obstructing flows with causeways, burning of soils causing the loss of organic matter and subsidence of wetland sediments
- creating water loss
  - creating mining voids, artificial lakes

These drivers of altered hydrology are covered in more detail below.

Both the causes and the impacts of altered hydrology can vary in scale. Localised causes of altered hydrology include a groundwater bore near a wetland or a stormwater pipe discharging directly into a wetland; regional causes include broad-scale vegetation clearing or abstraction of significant volumes of water leading to aquifer-wide decline in water levels; and global causes include climate change. It is important to consider scale in identifying altered wetland hydrology and deciding how to manage it.

The causes of altered hydrology at a wetland can be multiple, complex and may originate far away from the wetland. For example, on the **Swan Coastal Plain**, hydrological change at wetlands is caused by a number of factors, including widespread clearing and urbanisation, climate change and groundwater **abstraction**. These factors are in turn driven by social drivers including economic trends, water pricing, politics and population growth scenarios.[15]

When considering what the causes of altered wetland hydrology might be, it is important to consider the potential linkages between water sources. Water resources in Australia are often classified as either surface water or groundwater, because in some cases the sources are separate. However in WA the connection between surface water and groundwater can be significant, and in many cases, abstraction of groundwater may cause a decline in the surface water resource, and vice versa.[16]

The cumulative effect of changes is critical. For example, modelling demonstrates that the decline in groundwater table in the superficial aquifer of the **Gnangara groundwater system** varies in location but is primarily due overall to declining rainfall, abstraction and pine plantations. This is despite the effect of clearing, which reduces the evapotranspiration of water.

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Abstract: to take, remove, extract

Gnangara groundwater system: the groundwater system formed by the superficial, Leederville and Yarragadee aquifers located in northern Perth, east to Ellen Brook, south to the Swan River, west to the Indian Ocean and north to Gingin Brook

Lastly, a wetland's hydrology may alter naturally, but this usually occurs over longer timeframes than human-induced changes. For example, the build-up of sediments can change the shape of the wetland or modify the conductivity of wetland sediments, and these changes can modify the water regime.[17] Similarly wetland vegetation can influence hydrologic conditions and the physical and chemical environment by slowing water flows, creating new flow paths through the wetland, trapping soil particles and producing peat and other organic sediments.[17]

The following is a summary of the main driving forces of altered regime of wetlands in WA.

Climate change

Climate change is a major threat to wetland values worldwide. Western Australia, and in particular the south-western region of the state, is recognised as one of the regions most vulnerable to the effects of climate change worldwide.

Climate change is widely used to refer to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.[18]

extra information

Climate change defined

Climate change is defined as a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.[18]

The water regime of wetlands can be affected by climate change because it may affect natural patterns of:

- temperature
- evaporative demand
- rainfall.

In most areas of the Kimberley, temperature has increased by up to 0.6 degrees Celsius over the last forty years, but in some areas it has actually dropped by 0.2 degrees Celsius (Figure 2).[19] The temperature in the Pilbara has increased by 0.2–0.8 degrees Celsius. Although predictions vary between climate change models, northern WA is expected to become warmer, with more hot days and less cold nights.[19] Increased average and maximum water temperatures may trigger changes in the sex ratio of species in which temperature influences sex determination, such as turtles and crocodiles.[19]

In some parts of northern WA, including the Canning Basin and West Kimberley[19], increased rainfall has occurred over the period 1950–2000.[20,21] This may possibly be due to raised levels of aerosols from particulate pollution over Asia.[19] In general, this promotes wetter water regimes in the region's wetlands. The rise in sea level that is predicted to occur may also cause seawater intrusion into freshwater wetlands. Modelling predicts that rainfall will reduce slightly in the Kimberley by 2030 compared to the 1930–2007 baseline.[19] Refining climate modelling is an important step towards better managing wetlands in northern WA into the future.

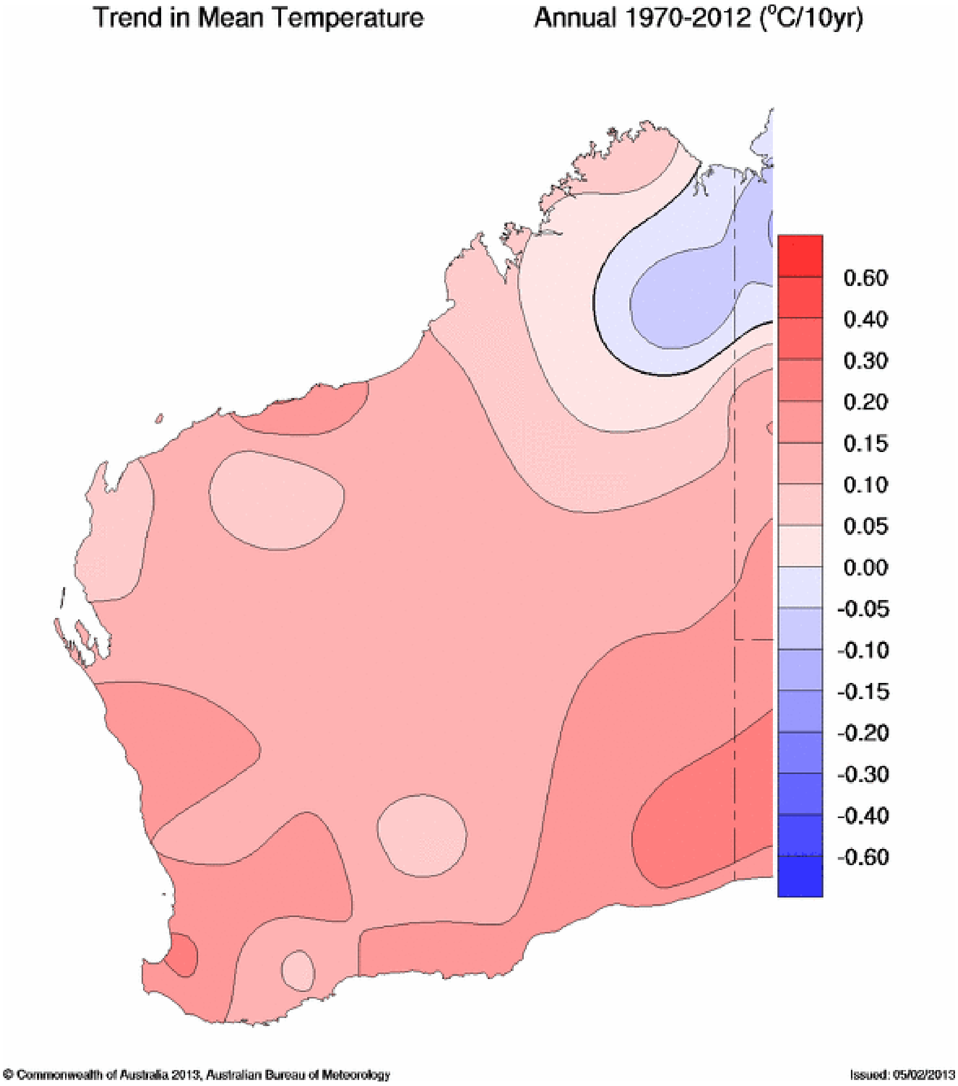


Figure 2. Trends in mean temperature 1970-2012. Image - Bureau of Meteorology.

In contrast, in the south-west of WA, both the annual and seasonal (autumn-winter) rainfall has already decreased significantly since the mid 1970s (Figure 3) and is projected to continue decreasing throughout this century. In fact, the largest reduction in rainfall in Australia has occurred in the northern part of the south-west.[19] The coastal and near coastal region between Geraldton and Albany (which is the study area of the CSIRO south-west WA sustainable yields [SWSY] project) has experienced a 10 to 15 per cent decrease in annual rainfall since about 1975[22], with the decline in autumn and early winter rainfall being the most marked.[22] Already, medium-intensity winter storms (in the range of 10–40 millimetres) which generate much run-off have become less frequent.[23] Runoff has decreased by over half since about 1975.[22] Extreme summer rainfall events have been more frequent since 1970, although there isn't conclusive evidence of the cause.[23]

The south-west is predicted to experience some of the largest reductions in rainfall in all of Australia[19]; projections to 2030 predict a 2–14 per cent reduction (median 8 per cent), over and above the 10–15 reduction that has occurred.[22] Slightly more rain in summer is also likely[19], with the potential for more unseasonal rainfall due to cyclonic activity.[19] Although there is a prediction that extreme rainfall events will become more common on a global scale, modelling with respect to south-west WA is less clear cut[23], with potential implications for the maintenance of processes such as the recruitment of trees.

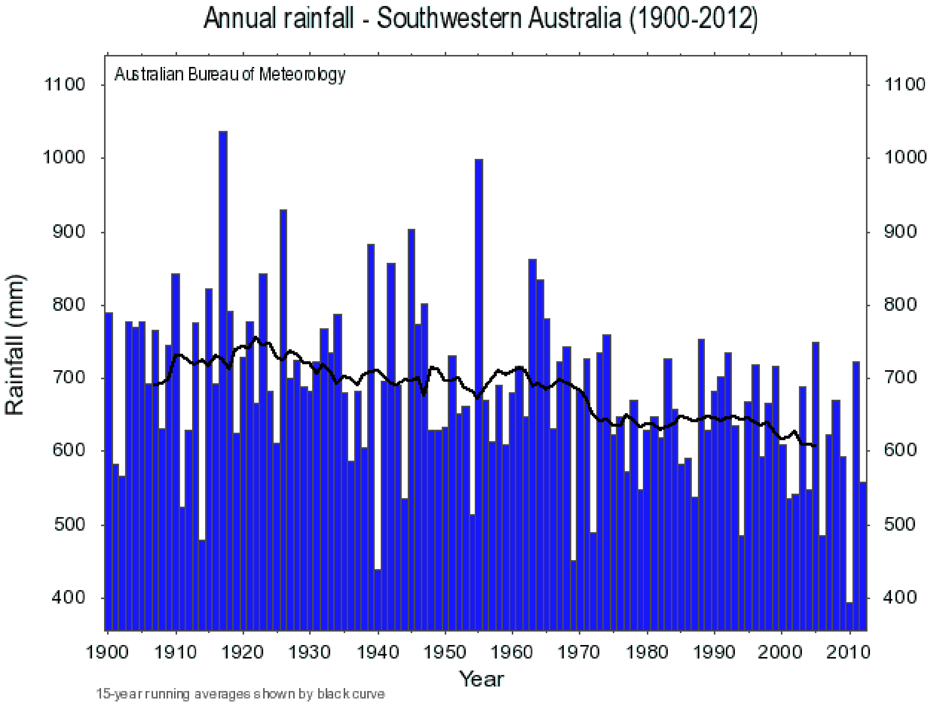


Figure 3. Average rainfall in south-western Australia, with the black line showing the 15 year average. It shows the continuing pattern of declining rainfall in the region. Image – Australian Bureau of Meteorology.

Temperatures have increased 0.4–0.8 degrees Celsius over the last forty years in the SWSY region.[19] Further increases in temperature are predicted: 0.5–2.0 degrees by 2030, compared to the 1960-1990 baseline.[19]

These factors contribute to drier wetland water regimes. All aspects of wetland water regime are likely to be affected (that is, the timing, frequency, duration, extent and depth and variability of water presence). CSIRO has concluded that, in the SWSY study area, 'Wetlands and perennial streams that were relatively abundant in the mid-twentieth century have either decreased or dried out as a result of this change'.[22] It has also predicted that falling groundwater levels are 'likely to result in groundwater dependent ecosystems such as wetlands being impacted'[22], with the potential for about 20 per cent of the area where groundwater dependent ecosystems may occur to experience high or severe stress under the dry extreme future climate modelling scenario in the southern half of the Perth Basin. Modelling indicates that by 2030, groundwater levels are expected to drop by an average of 3 metres within the western Swan Coastal Plain and by at least 3 metres within the Blackwood Plateau.[24]

Vegetation in and around wetlands, waterways and rainforests is likely to be most adversely impacted if drying leads to increased frequency of bushfires.

For information on climate change see:

➤ the DEC website www.dec.wa.gov.au/our-environment/climate-change/index.html

- the Australian Bureau of Meteorology website www.bom.gov.au/climate/change
- the south-west sustainable yields project on the CSIRO website www.csiro.au/en/Outcomes/Climate/Understanding.aspx
- the Indian Ocean Climate Initiative website www.ioci.org.au
- the Intergovernmental Panel on Climate Change (IPCC) website www.ipcc.ch

Changing vegetation

Clearing vegetation

Intact native vegetation in catchments and wetlands uses a significant amount of water and for this reason is important for maintaining the natural wetland hydrological regime. Vegetation clearing has been extensive in WA's urban centres and in areas used for cropping and grazing in the south-west and northern parts of the state.

The Avon Wheatbelt bioregion is one of the most highly cleared catchments in the world, with approximately 93 per cent of original vegetation cleared for cropping.[1] Although much of the cleared area has been planted with crops, compared with **perennial** native vegetation, these **annual** crops tend to use less water, have a shallower root profile, and only be present for part of the year. These features mean less water uptake and transpiration compared with native vegetation, resulting in greater rates of infiltration and aquifer recharge.

In the northern parts of the state, extensive areas of native vegetation have been modified through grazing by livestock and feral animals including camels, goats and horses, which has led to changes to the hydrology of some wetlands.

The presence and condition of dryland vegetation across a wetland's catchment can influence its hydrology by regulating the rates, pathways and amount of water that reaches the wetland. As water flows through bushland, the stems, trunks and plant litter slow its flow and promote its infiltration into soils that are held together by a network of shallow and deep roots. A significant amount of the water percolating through the soil may be taken up by plant roots and **transpired** to the atmosphere. Some water drains through, reaching the water table and recharging the groundwater aquifer. Some is intercepted by plant parts and litter before it reaches the soil, and evaporates. The clearing of native vegetation can impact on wetland hydrology in the following ways:

- Increased runoff on sloped landscapes: removing the stems, trunks and plant litter that slow flows on sloped land means that water has less chance to infiltrate into the soil and reach the wetland slowly through the sub-surface soil.[25] Wetlands downslope of cleared areas tend to receive more water, more quickly, via surface sheet flows. This can result in wetter water regimes as well as more sediment being transported into wetlands.
- Increased infiltration and aquifer recharge on flat landscapes: removing vegetation that intercepts and transpires infiltrating water can allow larger volumes of water to reach the water table. This can result in a rise in the water table and wetter conditions at some wetlands, as well as secondary salinity and acidity.

Changes in vegetation have been widespread in the south-west, and while there are likely to be some further changes in this region, these are likely to be localised. Regulations under the *Environmental Protection Act 1986* introduced in 2004 regulate the clearing of native vegetation, to protect native vegetation while allowing for permitted clearing activities.

One of the emerging considerations in the south-west is the effect of reduced rainfall associated with climate change. Current modelling suggests that the reduced

Perennial: a plant that normally completes its life cycle in two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves, and other plant parts, and then evaporates into the atmosphere as water vapour groundwater recharge associated with reduced rainfall may slow, but not offset, the additional recharge still occurring in many inland catchments of the south-west.[26] Furthermore, the reduction in rainfall can deprive wetlands of the freshwater inputs needed to maintain freshwater communities in the many wetlands undergoing secondary salinity.

In the north of the state, clearing by grazing, and in some areas mining, has been significant in some areas. The reduction in groundcover has significantly altered water infiltration and runoff patterns in affected areas. Currently, clearing of thousands of hectares of native vegetation is underway within the expanded Ord River Scheme near Kununurra, with further clearing proposed in association with the ongoing expansion of irrigation areas and the development of new agricultural zones. The Ord East Kimberley Expansion Project is a state government initiative that will increase the size of the Ord irrigation area to approximately 28,000 hectares of agricultural land. Approximately 14,000 hectares of irrigated farmland has already been developed.

➤ More information on the expansion of agriculture in northern WA is available from the Department of State Development website: www.dsd.wa.gov.au/8161.aspx.

Less well understood is the relationship between vegetation and rainfall. Reduced rainfall has been linked with clearing of native vegetation in areas of WA as well as other parts of Australia and the globe. For example, studies along the "clearing lines" in the eastern Wheatbelt indicate that the removal of vegetation influences rainfall patterns over wide areas. The link between vegetation and rainfall is thought to be related to the micro-relief of the vegetation surface and the air turbulence it causes, producing greater rainfall in vegetated areas.

Researchers from the Centre for Water Research at the University of Western Australia have found evidence that extensive clearing in the south west of WA has caused a 16 per cent reduction in rainfall. Researchers say that clearing of the forested coastal strip region south of Perth, which removed 50 per cent of the native forests between 1960 and 1980, coincided with a 16 per cent reduction in rainfall relative to stationary coastal rainfall. This highlights that not all rainfall decline is attributable to climate change, and land use decisions relating to clearing, revegetation and particularly reforestation will have a bearing on future rainfall patterns. Researcher Dr Mark Andrich cited growing tall native trees including jarrah and karri on vacant coastal land, as well as strategically growing native trees in and around farms, as possible ways to mitigate changes in climate.

Changing fire regimes

European land management practices have led to altered fire regimes across most of Australia. Fire removes above-ground plant parts, and therefore can have a similar effect on hydrology as vegetation clearing. It can promote run-off from sloped landscapes, and increase groundwater recharge on flat areas. As such, changed fire regimes in catchments have the potential to impact on wetland hydrology. Fire within wetland can also have significant effects on hydrology, particularly where sediments with organic matter such as **peat** are burnt, and the **hydraulic conductivity** of the wetland changes.

Tree plantations

Tree plantations (also known as **plantation forestry**) are common across the south-west (notably pines, *Pinus pinaster*, and Tasmanian blue gum, *Eucalyptus globulus*). In most cases, planting trees that consume large volumes of water can lower the water table in two ways: by reducing recharge (the roots take up water before it can percolate to the aquifer) and by using groundwater directly. For example, research by the Department of Agriculture and Food has shown that in an 800 millimetre rainfall zone, blue gum plantations did not allow any part of the annual rainfall to penetrate below 2 metres

Peat: partially decayed organic matter, mainly of plant origin

Hydraulic conductivity: a measure of the ease of flow through a pore space or fractures. Hydraulic conductivity has units with dimensions of length per time (for example, metres per second, metres per minute or metres per day).

Plantation forest: non-irrigated crop of trees grown or maintained so that the wood, bark, leaves or essential oils can be harvested or used for commercial purposes, including through commercial exploitation of the carbon absorption capacity of the forest vegetation depth of the soil profile, leading them to conclude that no recharge occurs in blue gum plantations in these areas.[27]

Gigalitres (GL): one thousand million litres (L); that is, one billion litres

In catchments where clearing has resulted in excess surface and groundwater, plantations may help to return the natural water balance of the catchment. However plantations can also lead to the drying of wetlands which source some or all of their water from the water table. For example, since the 1970s, the Gnangara pine plantations have been responsible in part for groundwater decline in the Gnangara groundwater system, which has resulted in severe drying of some wetlands.[1] The impact of pine plantations on the superficial groundwater aquifer varies, depending upon both the density of the plantation and its location on the mound. In areas where pine plantations were particularly dense they have caused groundwater declines in the order of 3.5 metres in the period 1979–2004.[28]

Factors that can increase the uptake of water in plantation forests include:

- large plantation area
- plantations in valleys and close to wetlands and other aquatic ecosystems
- high tree density
- high leaf cover or density
- no thinning or harvesting of trees
- mature trees with large canopies
- light or medium textured soils
- fresh groundwater
- shallow groundwater.[29]

Infrequently, tree plantations require the application of abstracted groundwater, rather than interception and shallow groundwater use by the trees. For example, proponents of a 900 hectare tropical timber (teak, Indian rosewood and Indian sandalwood) plantation in Beagle Bay, Dampier Peninsula (120 kilometres north of Broome) proposed to abstract 4.5 **gigalitres (GL)** a year from the Broome aquifer for application on the trees.[30]

Finally, water table changes triggered by the harvesting of plantations may cause acidification at nearby wetlands under certain conditions (M Smith, pers. comm.).

Removing water

Water is usually taken for one of three reasons:

- for use
- its presence is preventing the installation of infrastructure in the short-term (such as below-ground pipelines)
- its presence is preventing the land being used for another purpose in the medium to long term (such as mines, agriculture or houses)

Taking water for use

Water is consumed as domestic drinking water, in producing and processing food and other primary produce, extracting minerals, manufacturing, generating energy, watering parks and gardens and in other urban, industrial and agricultural uses. It was estimated that 2,340,000,000,000 litres, or 2,340 gigalitres (GL), of water was consumed in WA in 20053, harvested from a wide range of surface and groundwater sources. Irrigated agriculture (including pasture, horticulture and turf) accounts for 35 per cent of all licensed use in WA. With a growing population and economy, there is increasing pressure on WA's water resources for consumptive uses.1 This growing demand is an increasing threat to wetlands, because any water consumed from or delivered to a wetland's catchment can affect its hydrology. Taking water for use involves either groundwater abstraction or surface water harvesting.

➤ For an overview of WA's water use by sector, see the *State Water Plan.*[3]

Drawdown: the lowering of a watertable resulting from the removal of water from an aquifer or reduction in hydraulic pressure

Cone of drawdown: the depression of the potentiometric surface. Also known as a cone of depression.

Unconfined aquifer: an aquifer close to the land surface which receives direct recharge from rainfall. Its upper surface is the water table. Also known as a superficial, or surficial, aquifer.

Abstracting groundwater for use

Compared with other Australian states and territories, WA relies heavily on groundwater for consumption. It is the only readily available source of water over about 60 per cent of the state. Groundwater is a source of water in all regions of WA. In fact, until the Perth and Southern Seawater desalination plants began supplying water, groundwater provided about two-thirds of the state's water.[31]

At the local scale, abstraction can cause localised cones of depression. The cumulative effect of large amounts of abstraction can be a significant lowering of the groundwater table. These two forms of impact are outlined below.

Drawdown causing localised cones of depression

At the local scale, abstraction can reduce the water in a wetland if it occurs in proximity to it, because it creates **drawdown** in the form of a **cone of drawdown**. In an **unconfined aquifer**, groundwater pumping causes a cone-shaped depression in the water level that expands outwards from the pumping bore until reaching a stable shape (Figure 4). If the cone of depression reaches a wetland, water can be drawn out of the wetland, leading to a direct reduction in water in the wetland (Figure 5). As a guide, the depth of the cone is dictated by the pumping rate, the slope of the cone is dictated by the characteristics of the aquifer medium (storativity and hydraulic conductivity), while the radius is dictated by the duration of pumping. Both small and large abstraction volumes can affect nearby wetlands if not managed appropriately, with the potential to generate adverse effects from abstraction for a small-scale market garden through to a public water supply scheme bore.

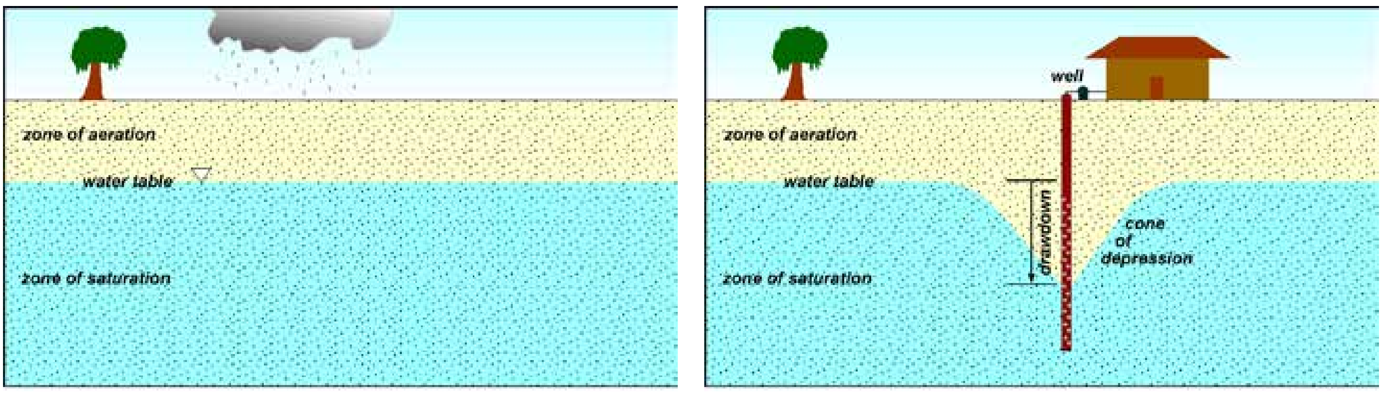


Figure 4. A stylised cone of depression caused by groundwater abstraction in a superficial groundwater aquifer. Image source - http://myweb.cwpost.liu.edu/vdivener/notes/groundwater.htm

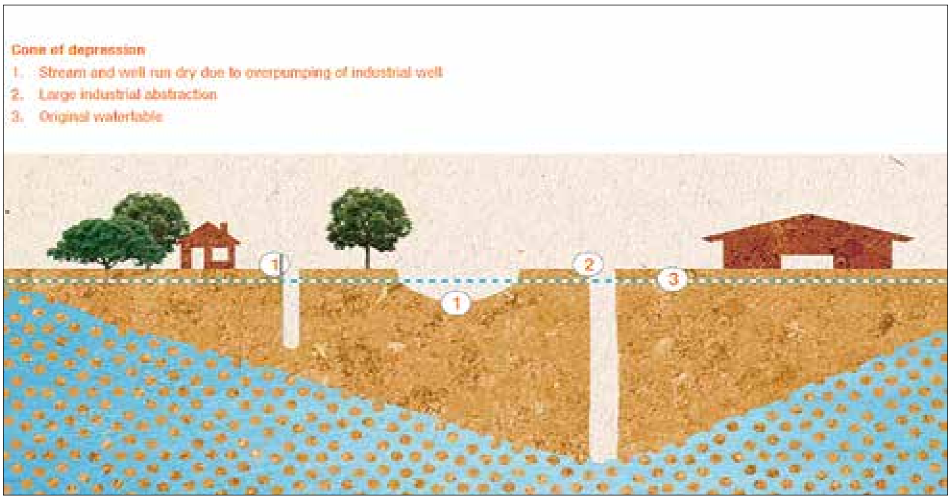


Figure 5. A cone of depression that has lowered the superficial aquifer beyond the base of a stream. Image – National Water Commission.

Confined aquifer: an aquifer deep under the ground that is overlain and underlain by relatively impermeable materials, such as rock or clay, that limit groundwater movement into and out of the aquifer

Regional drawdown of groundwater aquifers

Sustained abstraction of large volumes of groundwater can significantly reduce the amount of water in affected aquifers. Where those aquifers provide water to wetlands, or are connected to those aquifers, wetlands can become drier. The risk of wetland drying caused by groundwater abstraction is particularly prevalent on the Swan Coastal Plain, the south-west, Carnarvon and Pilbara. Groundwater dependent wetlands may be maintained by either superficial or confined aquifers. For example, the significant 'Reedia wetlands' are maintained by groundwater discharge from the Leederville aquifer's Vasse Member.[32]

➤ To find out what aquifers occur below/in proximity to a wetland, refer to the Department of Water's *Hydrogeological Atlas*, available at www.water.wa.gov.au/idelve/hydroatlas/.

➤ To find out more about the state of a particular aquifer, the groundwater webpages of the Department of Water are a good place to start: www.water.wa.gov.au/Understanding+water/Groundwater/default.aspx

➤ For mapping of groundwater dependent ecosystems, see the Bureau of Meteorology's *National Atlas of Groundwater Dependent Ecosystems*: www.bom.gov.au/water/groundwater/gde/.

The most studied example is the Gnangara groundwater system, which is located north of the Swan River in metropolitan Perth. Prior to the operation of the two desalination plants supplying Perth, around 60 per cent of Perth's public water supply was sourced from groundwater, via production bores[33] (Figure 6), with the Gnangara Mound being the main groundwater resource (with the level of abstraction varying in recent years) (Table 3). As well as supplying the people of Perth with a very significant proportion of their 'scheme' water needs (via water service providers such as the Water Corporation), very significant volumes of water from the Gnangara groundwater system are also used for commercial agriculture, forestry and market gardens, and by local government authorities and domestic bore users. The Department of Water estimates that up to a quarter of water abstracted from the Gnangara Mound is done so for domestic use (domestic garden bores are not licensed or metered).[34] The cumulative effects of abstraction, climate change and pine plantations have significantly reduced groundwater in the aquifers that make up the Gnangara groundwater system. Here the deep, **confined** (northern) Yarragadee aquifer, has declined by approximately 50 metres, with most decline centring around Gwelup and Wanneroo.[35] The confined aquifer that overlies it, the Leederville, shows declines of 10 metres, with the largest decline evident around Wanneroo-Pinjar. Above this is unconfined, superficial aquifer. The water table of the superficial aquifer, which most of the 200 wetlands in the area are directly dependent upon for some proportion of their water, has fallen by up to 6.5 metres in areas since the 1970s.[36] Impacts from water abstraction are centred on the Pinjar, Wanneroo, Gwelup and Mirrabooka borefields, with declines of a maximum of 2.4 metres, 2.0 metres, 3.0 metres and 1.5 metres respectively within a six kilometre radius of the borefields.[28] Wetlands that are dependent upon this groundwater have been affected, with the severity of drying differing between wetlands. Water storage in the aquifer has declined by about 500 gigalitres over the last 20 years.[37]

Although the deeper unconfined aquifers are not directly connected to wetlands on the Gnangara Mound, the volume of water stored in them does affect wetlands, as a deficit in the volume of water in a confined aquifer can be transferred to the superficial aquifer because of the hydraulic connection between aquifers. There is downward leakage from the superficial aquifer in locations where the major confining materials are absent from the confining aquifers. The Kardinya Shale separates the superficial aquifer from the Leederville, while the South Perth Shale separates the Leederville from the Yarragadee.[38] When abstraction in the confined aquifers occurs, the decline in the potentiometric heads can cause increased leakage from the superficial aquifer. The increase in leakage can cause water table decline in the superficial aquifer. Groundwater modelling suggests that while the confined aquifer responds to confined abstraction rapidly, the superficial aquifer responds to it slowly.[38] In this way, abstraction of an aquifer can have either a direct or indirect effect on wetlands.

➤ The state of the Gnangara Mound is subject to ongoing monitoring and management. Two key webpages are the Gnangara Sustainability Strategy webpages, www.water.wa.gov.au/gss, and the Department of Water's Gnangara Mound webpage: www.water.wa.gov.au/Understanding+water/Groundwater/Gnangara+Mound/default.aspx#1.

Table 3. 10 year integrated water supply service abstraction history for Gnangara and Jandakot mounds. Source – Department of Water[39]

Year	Jandakot Mound (gigalitres)	Gnangara Mound (gigalitres)	Combined (gigalitres)
2001-02 (dry year)	11.92	153.21	165.13
2002-03	7.8	159.2	167
2003-04	7	151	158
2004-05	5.7	150.3	156
2005-06	5	136	141
2006-07 (dry year)	8.36	160.84	169.2
2007-08	8.5	135	143.5
2008-09	10.8	136.2	147
2009-10	10.8	110.2	121
2010-11 (dry year)	13.3	151.71	165.01

Figure 6. (a) Groundwater, surface and desalinated water sources in the Perth area; and (b) a production bore on the Gnangara Mound, one of many used to source water for the public water supply. Image (a) Water Corporation; (b) Department of Water.

Harvesting surface water

Harvesting water directly from wetlands

The taking of water directly from a wetland can reduce water levels, particularly in wetlands that are not connected to groundwater (in general or at the time of the harvesting). Under the *Rights in Water and Irrigation Act 1914*, areas of the state are either proclaimed water resource areas or not. In those areas that are not proclaimed, the owner or occupier of any land in direct contact with a watercourse or wetland can take water for domestic or non-intensive stock water without a licence under certain conditions; these are known as 'riparian rights'. Permits are required in proclaimed water resource areas, regardless of whether a riparian right to take water exists. Landholders can take water from springs rising to the surface on their land and wetlands wholly on their land, provided the resource is not noticeably or sensibly diminished. The Act does not specify the amount that can be taken under the auspices of riparian rights in unproclaimed areas.

➤ A map of proclaimed surface waters of WA is available from www.water.wa.gov.au/PublicationStore/first/86306.pdf

Compared with groundwater abstraction, the practice and impact of surface water harvesting on WA's wetlands is thought to be less widespread. While not uncommon in Perth's peri-urban areas, most surface water harvesting is in the high-rainfall south-west, and mostly from waterways and dams rather than from wetlands directly. An exception is springs, which are often harvested, usually by excavation to allow greater access to water for on-farm use. Many of the **mound springs** of WA have been excavated to form dams or filled with limestone to create pasture.[40] Intact mound springs are very important **ecological communities**, and across the state, many have been recognised

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Ecological community: naturally occurring biological assemblages that occur in a particular type of habitat by the state and Australian governments as threatened ecological communities. As well as being threatened by surface water harvesting, many mound springs are threatened by groundwater decline, and in the Pilbara, from direct impacts of trampling by managed and unmanaged livestock and feral camels.

extra information

Springs under threat

In the south of the state springs under threat include the following ecological communities:

- Communities of tumulus springs (Organic mound springs, Swan Coastal Plain)
- Assemblages of the organic mound springs of the Three Springs area.

In the north these include the:

- Assemblages of Dragon Tree Soak organic mound spring
- Assemblages of Bunda Bunda organic mound spring
- Assemblages of Big Springs
- Organic mound spring sedgeland community of the North Kimberley bioregion
- Black Spring organic mound spring community
- Assemblages of the organic springs and mound springs of the Mandora Marsh area.

For more information on these threatened ecological communities (TECs), refer to DEC's TEC webpage: www.dec.wa.gov.au/management-and-protection/threatened-species/wa-s-threatened-ecological-communities.html.

(a)

(b)

Figure 7. (a) This dam has been constructed to reduce the impact of livestock on (b) Saunders Spring, Mandora Marsh, Shire of Broome. Water is gravity-fed, while the wetland is protected by fencing. Photos – G Daniel/DEC.

Harvesting surface water flows

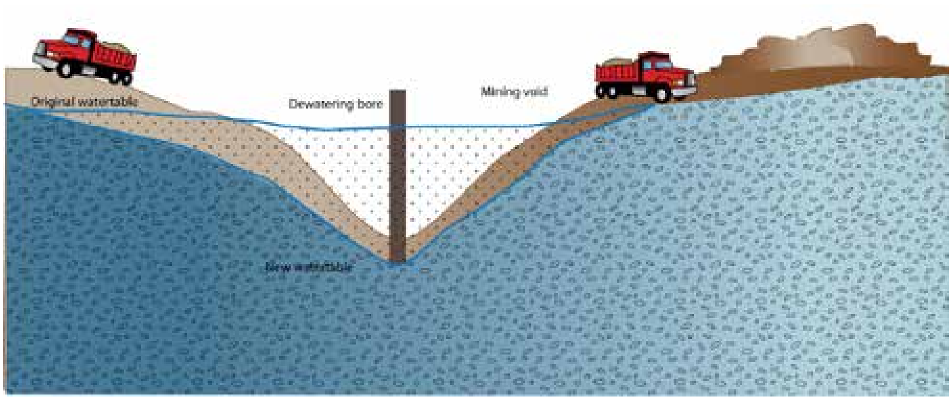
In agricultural catchments, the natural volume of overland flows into wetlands can be reduced if seepage or run-off is harvested by altering flows using **roaded catchments** and other earthworks[41] and directing water into farm water storages such as dams. Historically, much of this water harvesting actually helped to combat the effect of widespread clearing, which makes wetlands wetter than they are naturally. However, with the intensification and diversification of agricultural land uses and the effect of climate change in the south-west, harvesting surface run-off is now potentially depriving many wetlands of their natural inflows. The construction of dams has been linked with a number of environmental changes including major impacts on wetland ecosystem hydrology by altering the timing, magnitude and frequency of water movement.[42] The changes in water movement that a dam creates may threaten the ecological values of wetlands.[42] Similarly, structures to harvest rainwater falling on natural granite outcrops[43] can deprive wetlands on granite outcrops and in the surrounding areas of an important source of water.

Roaded catchment: a catchment where a series of adjacent v-shaped (in cross section) channels are created in the landscape to channel water to a downslope water storage

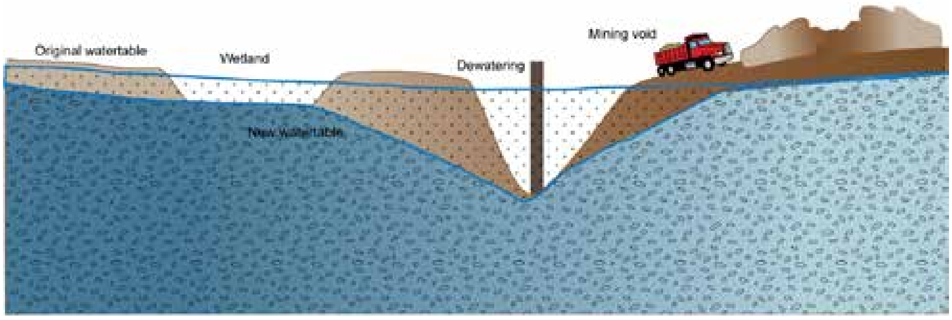
Dewatering: the process of removing underground water to facilitate construction or other activity. It is often used as a safety measure in mining below the watertable or as a preliminary step to development in an area.

Dewatering groundwater

Dewatering involves the removal of groundwater to provide access below the water table. It is a common practice across WA. Dewatering is often a component of mining, as well as when installing underground infrastructure such as pipelines. Dewatering may be achieved by pumping water from groundwater bores in order to draw down the groundwater table (Figure 8a). Alternatively, groundwater that flows into an excavation may be pumped out. Both methods usually result in drawdown of the groundwater table beyond the excavation area. In the case of mining, the groundwater table may need to be lowered by hundreds of metres, and over timeframes of decades. This is the case in a number of operations in the Pilbara.[44] In fractured rock aquifers of the Pilbara, the amount of water abstracted may range from less than 1 gigalitre to 10–40 gigalitres per year.[45] Mine dewatering discharge accounts for an estimated 52 per cent of total water use in the Pilbara, which in 2008 was estimated at 127 gigalitres per year.[45] It is predicted that over the next 20 years, mine dewatering volumes in the Pilbara are likely to increase threefold.[46] Altered wetland hydrology due to dewatering can be caused by either the drawdown itself, or by disposal of unwanted groundwater to wetlands, discussed later. Groundwater drawdown can cause wetlands near the dewatering site to experience drying, if their natural water source includes the superficial aquifer and the cone of depression reaches the wetland (Figure 8b). This has been identified as a risk for wetlands near mines in the south-west, Pilbara[47] and the Mid-West.[48]



(a)



(b)

Figure 8. (a) a groundwater drawdown cone of depression produced by a pump in a mining void; and (b) a groundwater drawdown cone of depression affecting the water regime of a wetland.

Transferring water to aquifers

Aquifer storage and recovery is a process in which water is harvested when it is readily available and pumped into an aquifer for storage, for use in drier times. Distinction is made here between aquifer storage and recovery using water harvested from natural water sources, and managed aquifer recharge using sources such as wastewater, stormwater and dewatering excess, as discussed later in this topic. Aquifer storage and recovery is not widespread in WA, but it has been suggested as a method to replenish hypersaline aquifers (that is, aquifers containing water saltier than seawater) in the eastern Goldfields depleted by abstraction for minerals processing.[49] Water from a large network of salt lakes has been proposed as a potential source of water for replenishment in the eastern Goldfields.[49] The use of water from wetlands to 'replenish' these aquifers would result in sudden and possibly extreme drying of wetlands from which water is sourced.

Draining wetlands

Traditional drainage: open and piped drains

Much of the urban, agricultural and industrial landscapes present today across the south-western coastal areas of WA were made possible through extensive draining, clearing and infilling of wetlands.[50] Much of Perth was built on drained wetlands (for example, the northern Perth area, known as the 'Great Lakes District', shown in Figure 9.

Figure 9. Map of the former Perth wetlands or 'Great Lakes District', constructed from a map by M. Pitt (1979), which itself was reconstructed from a map by John Septimus Roe (1834). Source – Wikipedia (http://en.wikipedia.org/wiki/Perth_Wetlands).

Check: a concrete frame with boards slotting into it, creating a barrier across the drain. The checks are opened or closed by addition or removal of the boards.

Open or piped drains may carry away up to 80 per cent of the rainfall volume in clay catchments and up to 25 per cent in sandy catchments in south-western WA. By rapidly transporting water away, there is less recharge of rainfall to shallow, unconfined aquifers and greater volumes of water are transported and discharged into downstream receiving surface water bodies. Many drains also intersect the groundwater table. Today, much of the south-west coastal zone has networks of drains that intersect the groundwater table to prevent natural winter waterlogging and inundation.[50,51] Broadscale draining of wetlands has particularly targeted the once extensive areas of flat, winter-waterlogged wetlands common to areas of WA's south-west, particularly eastern Swan Coastal Plain and the Scott Coastal Plain, as well as Albany. Water levels in some drains are manually controlled using **checks** and boards, weirs or other devices.

Rural surface drainage of the Swan and Scott coastal plains

Swan Coastal Plain

Most areas of pasture on the eastern side of the Swan Coastal Plain either are or were wetlands[52] that, when intact, had exceptional ecological significance. The remaining intact areas are representative of what was naturally a mosaic of an extensive area of flat, seasonally waterlogged wetlands that were interspersed with shallow, seasonally inundated basins and channels and dryland prior to European settlement. They are described as a "broad, interconnected chain of swamps many kilometres wide". There are a number of accounts of wetland loss and devastation of such areas (including Riggert[53], Seddon[54] and Bekle[55]), and all indicate the significant extent of impact. For example, Seddon reported that between 1955 and 1966, the area of wetland identified as 'shallow freshwater marshland' on the Pinjarra Plain declined in extent from around 8,000 hectares to less than 3,000 hectares, whilst 'deep freshwater marshland' declined from more than 6,000 hectares to less than 1,500 hectares.[54] Rural drainage on the Swan Coastal Plain was reported as extending over 200 kilometres south of Perth, covering an area of 321,000 hectares, and encompassing five gazetted drainage districts: Mundijong, Waroona, Harvey, Roelands and Busselton.

Seasonally waterlogged flats (called **palusplains**) on the Pinjarra Plain occur because of the presence of clay soils interspersed with sandy soils in a very flat landscape bound by scarps.[57] The clay impedes the movement of groundwater both horizontally and vertically, and so rain and runoff collects on the Pinjarra Plain, creating waterlogged conditions until drying occurs in late spring/summer[57], when evaporation exceeds rainfall. In many cases, these wetlands were targeted for use because they offered good prospects for pasture or horticulture due to the water held in their sediment.

extra information

Who is responsible for rural drainage?

Rural drains were created by the Public Works Department and managed by drainage boards from 1900 under the *Land Drainage Act 1900* and subsequently the *Land Drainage Act 1925*. An example of a drainage board was the Benger Drainage Board, which regulated water levels in Benger Swamp between 1918 and 1985.[56] Drainage districts, including those of Albany, Mundijong, Waroona, Harvey, Roelands and Busselton, were gazetted under these Acts. The Public Works Department also developed and managed irrigation channels in irrigation districts proclaimed under the *Rights in Water and Irrigation Act 1914*. Responsibilities associated with drainage were assigned to the Water Authority upon its creation in 1985. The Water Corporation, created in 1996, now has responsibility for the provision of services to the drainage districts as a community service obligation under the service standards imposed by the operating licence issued and regulated by the Economic Regulatory Authority under the *Water Services Licensing Act 1995*. The Water Services Operation Licence No 32 outlines the Water Corporation's sole operational requirement in this regard: "to operate and maintain its rural drainage infrastructure so that the period of inundation to land abutting a drain that forms part of the system shall be a maximum of 72 hours". The Water Corporation has the authority to control connections into their drainage systems. The Water and Rivers Commission, also created in 1996, was given the power in 2000 to provide local bylaws to regulate and control drainage and dewatering that was likely to affect the water in a wetland under the *Rights in Water and Irrigation Act 1914*, but this has not often been exercised. The Department of Water, created in 2006, is now responsible for administering this Act, including drainage governance and reform. More information of the history of drainage governance is available in the *Coastal drainage discussion paper.*[7]

DEC's *Geomorphic Wetlands Swan Coastal Plain* dataset[52] shows that 97 per cent of palusplain on the Swan Coastal Plain has been cleared. Widespread clearing had the effect of increasing the water in the landscape, prompting the installation of rural drains and, over time, extensive and effective rural drainage networks. This is described by Safstrom and Short: "Eventually, after landholders lodged numerous complaints relating to lost crops and property damage, the government addressed the problem of inundation by implementing a network of drains. In 1900, the first Drainage Bill was passed by state parliament. Over the next 70 years, trees on the banks of waterways were removed, lower river reaches were de-snagged, the rivers were straightened and deepened, and systems of interconnecting drains were dug across pastoral lands. Swamps were drained and the flow rate of the river courses increased".[58] The effect of these drains on the hydrology of the wetlands has been variable, but with time a common trend has been the compounding effect of climate change, because of the rainfall-dependent nature of these wetlands. In Pinjarra, for example, there has been 14 per cent less rainfall on average between 1975 and 2008 than in the period 1877–1975. As a result, there is more drying of palusplains than previously.

Scott Coastal Plain

The Scott Coastal Plain occurs on the south coast. It covers a total area of about 105,000 hectares and stretches about 70 kilometres along the coast and 20 kilometres inland, covering Brockman Highway, Stewart Road, Barlee Brook, Donnelly River, the Southern Ocean coastline and the Blackwood River. Private freehold land covers about 42,900 hectares, with the remainder being state forest, national parks/nature reserves, other

Crown land and other minor uses. It consists of predominantly undulating to near flat land. It is an area of deep sediments, with varied soils including coloured deep sands, some deep sandy duplex soils, sandy loams and loams. A significant proportion of the plain has been classified as being wetland, containing a large diversity of wetland types ranging in both size and condition. Wetland types include extensive seasonally waterlogged or inundated areas (palusplain, damplands, sumplands, creeks) and areas of permanent water (lakes, rivers).

Most agricultural or land planning reports tend to refer to 'poorly draining' land that is 'subject to high watertables and waterlogging in winter'. Particularly in the eastern Scott Coastal Plain, this has been attributed to the presence of a coffee rock (iron-oxide cemented layers) or impermeable peaty layer, which serves to slow vertical leakage of groundwater from the superficial aquifer into the Yarragadee aquifer. The water held in these wetlands also provides significant flows to the Scott River and the Hardy Inlet.

Drainage in the Scott River catchment is notable in that it has been designed and installed in an ad-hoc way with little coordination or integrated planning. As it is not a gazetted drainage district, there is no governance structure, meaning that no single organisation is responsible for the management and operation of these networks. It was not until 1984 that the Water Authority was given the power to prohibit drainage works, by amending the *Rights in Water and Irrigation Act 1914*. It is also notable in that it is one of the largest areas where drainage development is still underway. The effect of drainage on the area's wetlands is likely to be variable; for example, large areas of wetland are likely to be drained of water while others are likely to be receiving excess discharge.

Urban subsoil drainage

Subsoil drainage is used to control the maximum height of the groundwater table. It is usually used in urban areas with high groundwater tables, such as areas supporting wetlands, to achieve a vertical separation distance between the groundwater table and infrastructure such as houses. It is used instead of, or in combination with, the use of fill (that is, soil sourced from somewhere other than the location being developed) to ensure that infrastructure and health are not adversely affected by water being present at or close to the soil surface in inhabited areas. It is likely to become used more often, due to urban development in urban centres including Perth and Peel increasingly occurring over more marginal land - areas of wetland and areas where shallow, unconfined groundwater is in proximity to the natural ground surface. It is also likely to become more popular with the land development industry because sourcing and transporting fill to new developments is an increasingly expensive and unsustainable proposition, with the availability of fill becoming more limited, and mining/quarrying for this fill having significant ecological impacts.

Subsoil drainage in urban areas is typically achieved by draining away groundwater using 100 millilitre pipes with slotted holes (perforations). Coarse gravel is laid around the perforated pipes to enable groundwater intake. When groundwater rises to the level of the pipes, they take in water, minimising the vertical distance that the groundwater reaches above the pipes. The pipes are usually laid in road reserves to enable access for maintenance, although in industrial developments they may be installed down the back or sides of lots. The spacing of the pipes influences the degree of drainage achieved. The groundwater is drained to an outlet location. Following installation, subsoil drain infrastructure typically becomes the management responsibility of local government authorities.

Drainage planners design subsoil drainage to specific **controlled groundwater levels** (CGLs). A controlled groundwater level is the **invert** level of a groundwater management conduit such as a drain or channel in metres Australian Height Datum. The CGL is a

Controlled groundwater level: the invert level of a groundwater management conduit such as a drain or channel in metres Australian Height Datum (AHD)

Invert: the level of the lowest portion at any given section of a liquid-carrying conduit, such as a drain or a sewer, and which determines the hydraulic gradient available for moving the contained liquid different depth to the separation distance, which is the actual maximum groundwater level achieved, taking into account the mounding in between pipes. This is an important distinction for infrastructure managers.

Where heavily degraded wetlands and non-wetland areas with a high water table are developed over, there is a need to ensure that urban developments are not affected by high water levels. But this approach can have significant environmental impacts when the drainage is indiscriminate, as the maximum water level of any remaining high conservation value wetlands in the area are also capped, while downstream wetlands (and other ecosystems) may be receiving environments for this drainage discharge.

Stormwater: water flowing over ground surfaces and in natural streams and drains as a direct result of rainfall over a catchment[60]

Recharge: water infiltrating to replenish an aquifer

Impermeable surface: the part of the catchment surfaced with materials, either natural or constructed, which prevent or limit the rate of infiltration of stormwater into the underlying soil and groundwater and subsequently increases stormwater runoff flows. Also referred to as impervious surfaces.

Disposing water: applying and discharging it

Disposing of stormwater in urban wetlands

Stormwater consists of rainfall runoff and any material it picks up in its path of flow. Stormwater is an important source of water for wetlands, and either too much, too little or poor quality stormwater can affect wetlands. In undeveloped catchments, up to 90 per cent of rainfall is absorbed and infiltrated into the earth's topsoil, and there is relatively little stormwater. Particularly when the rainfall event is small, most of the rainfall is infiltrated into the topsoil. Some of it may then slowly reach a wetland by subsurface flows. Some of it is lost to the atmosphere by evaporation from the soil and other surfaces; some is lost to the atmosphere by transpiration by vegetation in the catchment. Some of it reaches the water table, thereby **recharging** groundwater, and slowly reaching downgradient groundwater dependent wetlands in this way. In moderate to large rainfall events, a greater proportion of the water is likely to be stormwater, following natural overland flow paths to receiving wetlands and waterways.

In contrast, in built environments including urban, commercial and industrial areas, as little as 10 per cent of rainfall may infiltrate into the earth because of the extent of paved, **impermeable surfaces** that limit the rate of infiltration of stormwater into the ground.[59] The risk of flooding is significantly increased by the reduction in the vegetated area, and the reduction in permeable surfaces where water can infiltrate, meaning that a lot of water needs to be 'caught' and conveyed to reduce this risk to humans and property. Conveyance to wetlands, waterways and oceans using infrastructure such as pipes and open channels has traditionally been the approach used, and much of the stormwater infrastructure in urban areas around WA is designed to do this (Figure 10). This causes one of two problems for a wetland: either it receives more water than it should, or the stormwater infrastructure bypasses it or provides it with a limited amount and it receives less water than it should. Both pose serious threats to wetlands.

Figure 10. Pipes discharge stormwater directly into Lake Monger, Perth. Photo – L Mazzella/ Department of Water.

Although wetlands receiving stormwater would have naturally received stormwater, they would not have received so much, so quickly. This is because water captured and conveyed from largely developed catchments delivers water to wetlands in greater volumes by bypassing the natural evaporation, transpiration and infiltration pathways in the catchment. Following a large rainfall event, water is captured and conveyed to wetlands and other receiving environments in greater amounts over shorter periods, without the passive water quality treatment that the earth and native vegetation provides. Under these circumstances wetlands can experience:

- increased volume
- increased rate of water rise
- longer duration of the high water level
- potentially less groundwater input
- erosion and sedimentation caused by the entry of water from pipes and open drains
- potentially more water in the dry season.

In Perth and surrounding urbanised parts of the Swan Coastal Plain, and in some other urban centres in WA, stormwater often flows into networks of drains that are also designed to lower the groundwater level, often called main (arterial) drains and branch drains (Figure 11). The intercepted groundwater flows into the drain along with stormwater. In this way, stormwater and groundwater management in the Perth metropolitan area are integrally linked.[59]

Figure 11. A main drain in Baldivis, south of Perth. Photo – J Higbid/DEC.

In some areas, drainage schemes have formally designated the use of wetlands as receiving bodies for stormwater. For example, Yangebup Lake is designated as a 'compensating basin' for the South Jandakot Drainage Scheme, which drains a number of southern Perth suburbs, with an area of 200 square kilometres. The aim of the system is to provide drainage for the urbanised areas and to maintain the water levels in Thomsons Lake, recognised as internationally significant via the Ramsar Convention. The drainage scheme was approved by the Environmental Protection Authority. The scheme was designed so that stormwater could flow directly into Yangebup Lake, North and South Kogolup lakes and Thomsons Lake from residential areas, and through a series of pumps and drains the maximum water levels in each can be controlled. When the water reaches a maximum designated height in Yangebup Lake it is pumped out to Cockburn Sound. It is reported that prior to the 1960s Yangebup Lake was a seasonally inundated wetland, naturally drying out each year.[61] With the water received from the urbanised catchment, it is now permanently inundated. Many wetlands are affected by such drainage schemes in urban areas in the south-west.

In south-western WA, the excess water being delivered by traditional stormwater systems to many wetlands is to some extent being counteracted by the drying effects of climate change and the abstraction of groundwater. This needs to be taken into account when managing stormwater. Stormwater is a precious resource that, with good management, can be an important water management tool. Especially in a drying climate, stormwater can be an important source of water within a wetland catchment that may ultimately reach a wetland, and if it is instead discharged to the ocean or another catchment, affected wetlands may experience a drier water regime.

Secondary salinisation: a human-induced process in which the salt load of soils, waters or sediments increases at a faster rate than naturally occurs

➤ Documents describing drainage schemes in the Perth and Peel area include:

- *Byford townsite drainage and water management plan*[62]
- *Forrestdale main drain arterial drainage strategy*[63]
- *Jandakot drainage and water management plan: Peel main drain catchment*[64]
- *Murray drainage and water management plan*[65]
- *Swan urban growth corridor drainage and water management plan*[66]

Disposing of drainage water in Wheatbelt wetlands

In the Wheatbelt, large areas of agricultural land are degraded, or at risk of degradation, by **secondary salinisation**. One response is the removal of saline waters using a network of deep drains, mole drains, bore siphons and groundwater pumps, directed to valley floors, wetlands and waterways. Affected wetlands are subjected to wetter water regimes (Figure 12), and a new water source which often carries higher salt loads, acid and heavy metals.[67,68] These wetlands are often called 'sacrificial wetlands' as, in effect, they are sacrificed to reduce the impacts upon the surrounding agricultural land. Wetlands that are hydrologically downstream of the receiving wetland can also be affected.

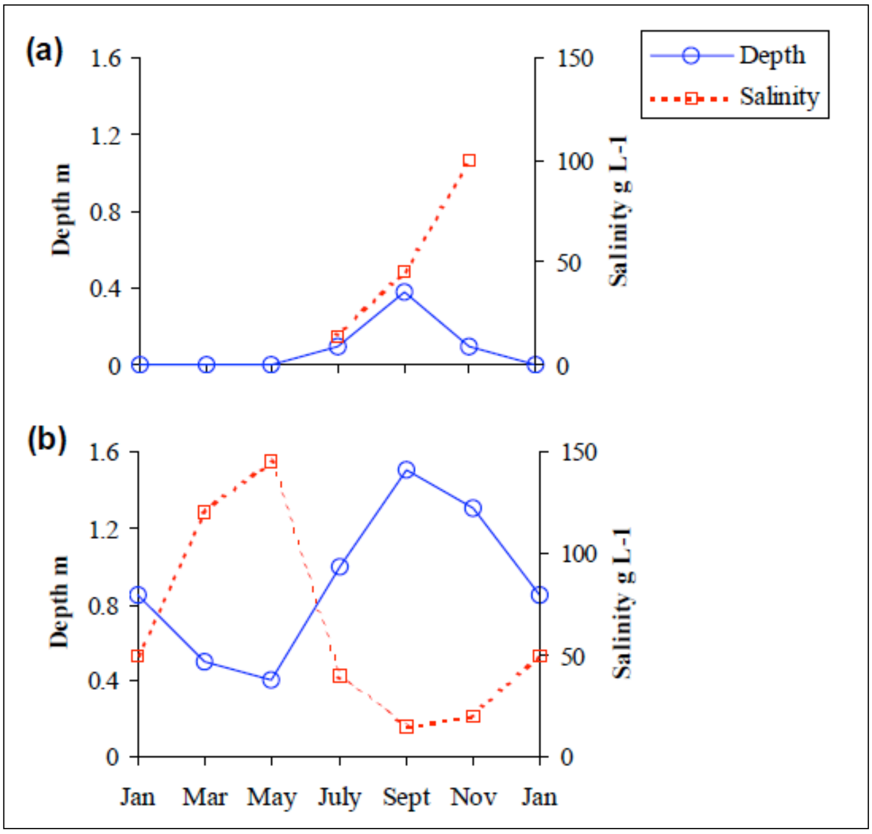


Figure 12. Hydroperiod and salinity patterns in a naturally saline Wheatbelt wetland (a) hydrologically undisturbed, and (b) receiving drainage. Image – Halse (2004).[68]

It is estimated that more than 5,000 kilometres of deep open drains that intercept groundwater have been constructed in the Wheatbelt.[69] Jones et al (2009) describe how 'Some of the saline water removed from these areas is re-used, but the vast majority is discharged into a receiving water body. Often, natural waterbodies, such as basin wetlands, are seen as ideal disposal bodies for this water since they function as natural evaporation basins and are agriculturally unproductive'.[70] Jones et al found that the effect of the disposal of groundwater into wetlands depends on the quality, volume and timing of discharge, and the physical, chemical and biological characteristics of the receiving basin. Drains in the Wheatbelt have been reported to carry from around 8,600–2,592,000 litres per day in spring.[71] When this large quantity of water is discharged into a basin, it is likely to change the timing, frequency, extent and inundation period of the wetland.

The hydrology of many Wheatbelt wetlands have been altered, or are at risk of alteration due to the rising groundwater. The effect of deep drainage upon the hydrology of receiving wetlands compounds these hydrological effects. Adding to this complexity is the potential for less rainfall and different rainfall patterns due to climate change.

➤ Reports describing the effect of deep drainage on wetlands include:

- the topic 'Water quality' in Chapter 3 of the guide, which covers wetland acidification;
- the topic 'Secondary salinity' in Chapter 3 of the guide
- the report, *The potential effects of groundwater disposal on the biota of wetlands in the Wheatbelt, Western Australia.*[70]

Discharging of dewater

Direct discharge to wetlands

Dewatering is the process of removing groundwater to facilitate construction or other activity. It is often used as a safety measure in mining below the watertable or as a preliminary step to development in an area. The water, sometimes referred to as dewater, is sometimes directly discharged into a wetland. This imposes wetter water regimes and introduces a new water source that may be of a different chemical composition, and therefore water quality, to a wetland's natural water sources. Dewatering discharge to wetlands has occurred in the Goldfields and the Pilbara. In the Pilbara, mine dewatering discharge accounts for an estimated 52 per cent of total water use in the Pilbara, which in 2008 was estimated at 127 gigalitres per year.[45] Discharge to salt lakes is commonplace in a number of mining operations in the Goldfields. These salt lakes are typically intermittently inundated, receiving water episodically from rainfall and catchment runoff in times of heavy rainfall, some remaining dry for years and often holding surface water for as little as a few months. A report published by the Department of Water provides some background to their use as dewatering discharge sites: 'The salt lakes of the Goldfields have been the preferred option for the disposal of surplus groundwater (dewatering discharge) produced during mining operations. The lakes are large and flat, providing an expansive surface area for evaporation. Because of the lack of knowledge and understanding of salt lake ecosystems, there was a perception that they were 'barren' and that disposal to these lakes was the most 'environmentally friendly' option for dewatering discharge'.[72] Table 4 is reproduced from this report.

Table 4. Dewatering discharge wetlands in the Goldfields, as listed in Outback Ecology Services (2009).[72]

Discharge lakes in 2009	Discharge lakes, prior to 2009
Lake Carey	Kurrawang White Lake
Lake Way	Lake Fore
Lake Raeside	Lake Tee
White Flag Lake	Banker Lake
Lake Lefroy	Southern Star Lake
Lake Cowan	Lake Miranda
Lake Hope	North Lake Austin
Lake Wownaminya	Lake Koorkoordine
Yarra Yarra Lakes	

Dewatering discharge has been found to generally result in a prolonged wet cycle, with the input of discharge water resulting in permanent localised inundation.[72] Factors that affected the water regime include:

- the rate and volume of water discharged
- bathymetry of the wetland
- the permeability of wetland sediments
- the natural cycles of wetting and drying of the wetland
- the prevailing wind direction, as this can influence movement of the discharge
- the capacity of the wetland and the changes in water levels that occur upon filling.

In addition the discharge has the potential to cause significant water quality impacts. For example, in the Goldfields, hypersaline groundwater is continuously added to many salt lakes, such as Lake Austin, which is naturally intermittently inundated from rainfall.[73] In the Pilbara, the opposite has historically occurred, with fresh groundwater being continuously disposed of into wetlands such as the naturally intermittent, brackish to saline Fortescue Marshes. Both situations can be damaging to the ecology of the receiving wetland. Other contaminant may also be discharged, including metals.

➤ The report, *Development of framework for assessing the cumulative impacts of dewatering discharge to salt lakes in the Goldfields of Western Australia*[72] is a useful summary of the state of discharge in the Goldfields.

➤ *The classification of inland salt lakes in Western Australia*[74] also provides information on discharge characteristics.

Discharge to the superficial aquifer causing mounding

Dewatered groundwater and treated wastewater is sometimes re-injected or allowed to re-infiltrate into a superficial aquifer. This can cause groundwater mounding, that is, a localised dome in the water table, which has the potential to cause wetter conditions in nearby groundwater dependent wetlands. This has occurred at The Spectacles wetlands in the Town of Kwinana. Water quality changes may also occur, due to the addition of a new source.

Irrigating

Irrigation is most widespread in WA's south-west and in specific irrigation areas in the north and mid-west, including the Ord and Carnarvon irrigation areas.[75] The production of fruit and vegetables is the largest component of the irrigated agricultural sector, with dairy and beef pasture, nurseries and turf farms the other major irrigation groups. Irrigation, and low-efficiency irrigation in particular, has the potential to cause wetter water regimes in nearby low-lying wetlands, because water drains beyond the root zone of crops, and flows downgradient through sub-surface soil. Agricultural chemicals can also be transported to wetlands along with this water.[76] Furthermore irrigation salinisation, which currently occurs in the Ord irrigation area and in some of the irrigation areas of the south-west, poses an additional threat to wetlands in these areas.[77] Some, but not all, irrigation is regulated; irrigators generally use groundwater and surface water under licence, though there are some groups in unproclaimed water resource areas that operate without licences. Changes to the regulation of irrigation instigated in the mid-2000s[75] has seen an increase in the efficiency of irrigation.

➤ For more information, see the *Irrigation review final report.*[75]

Discharging effluent

Sewage pumping stations and on-site sewage systems can have localised effects on wetland hydrology. On average, domestic on-site sewage systems dispose of a minimum of 150–200 litres of wastewater per person per day.[78] Septic tanks (underground tanks where sewage is treated to a degree before leaching into the soil) are prevalent in WA. They generally pose a more serious threat to a wetland's water quality than to its hydrology.

Tailings dams

Water used in the mining process is often disposed of in tailings dams, mined-out voids, valleys created by overburden stripping or underground mined areas. Tailings water typically contains toxic substances such as arsenic and heavy metals, and may also be a high temperature. If tailings storage areas are not properly sealed, contaminants may leach into the groundwater and affect wetlands.[79] As with sewage from septic tanks, the input of contaminants to groundwater from tailings dams is generally a greater risk than the change in hydrology associated with the input of water.

Changing wetlands

Mining/deepening/lining/sealing wetlands, creating islands

Since European settlement, physically altering wetlands has been a common wetland 'enhancement' practice in WA. Whether for aesthetic purposes, mining (peat, gypsum, bentonite, marl, salt and algae are just some of the products mined), recreational purposes (such as waterskiing, swimming and fishing) or water-holding purposes (for livestock watering and fire-fighting), these practices result in altered water depth and duration. For example:

- in the case of basin wetlands, deepening may result in a seasonally inundated wetland becoming permanently inundated, by intercepting the groundwater table, or holding a greater volume of water for longer. Excess sediment 'spoil' is often used to create islands in wetlands, which compounds the altered hydrology.
- in the case of flats, deepening tends to involve creating a basin and results in a seasonally waterlogged flat becoming a seasonally or permanently inundated basin
- deepening alters the composition of the sediment and its spatial arrangement and distribution, which affects the water holding capacity of the wetland

Lining wetlands using impervious or low-permeability materials has the effect of artificially retaining surface water in wetlands. Materials that have been employed or proposed to be employed include a polymer proposed to be used at Lake Jualbup in the Perth suburb of Shenton Park (formerly known as Shenton Park Lake, and originally known as Dyson's Swamp). In considering the proposal, the Environmental Protection Authority has concluded that in addition to altering the wetland water regime, and limiting the ability of the oblong turtle population to burrow into the sediment, the installation of a polymer in Lake Jualbup would in effect create a closed system that would result in the concentration of contaminants and nutrients and could lead to odour problems.[80]

Culvert: a conduit used to enable water flow beneath a structure such as a road, causeway, railway or track

Turbid: the cloudy appearance of water due to suspended material

Obstructing flows via roads, causeways and tracks

WA's roads, causeways and tracks act as hydrological barriers in the landscape, changing the route and characteristics of surface and shallow sub-surface flows. As barriers to surface flows, roads can alter the water regimes of surface water fed wetlands. By diverting sub-surface flows to the surface, they can create wetlands where they did not naturally occur. Causeways have been constructed across the beds of a number of large, intermittently inundated wetlands in WA, and can obstruct natural flow paths within wetlands, leading to a change in inundation extent (Figure 13). **Culverts** enable greater hydrological connectivity (Figure 14), but can produce increased flow rates as water is forced through them, causing erosion and sedimentation on the downgradient side, creating **turbid** conditions.

Figure 13. The causeway across Lake McLeod in the Gascoyne region prevents the spread of surface water across the bed of the wetland. Photo - A Lam.

Figure 14. Culverts can enable some degree of water flow beneath barriers such as roads, but they need to be well designed in order to avoid problems such as erosion and sedimentation. Image – Department of Water.

Earthworks and control structures to confine water to wetlands

Some wetlands in regional WA are used for recreational activities such as waterskiing. Many of these wetlands have been altered to improve conditions needed for these activities. In particular, artificially blocking a wetland's natural drainage outlets using earthworks or control structures, so that high water levels are maintained for longer following rain, has made a number of wetlands more suitable for waterskiing. This results in wetter water regimes. This has occurred at Yenyening Lakes, where a gate at Qualandary Crossing was constructed in the early 1900s and has served to dam waters in the lakes for a variety of purposes over time, including waterskiing.[81]

This practice is also carried out for agricultural purposes. Levee banks (human-made ridges or embankments) are often constructed around wetlands to confine water to reduce the size of the wetland and reduce the amount of water that spreads across the land around the wetland. Levee banks sever the natural hydrological connectivity between a wetland and its surrounding landscape - a process which is important for the exchange of material and nutrients. Levee banks are also used to direct flows downstream. This increases the rate of downstream outflow, as water is prevented from spreading out across the land. This delivers more water to downstream wetlands, causing wetter water regimes in them.

Puncturing retarding layers

Excavation near or in wetlands, for purposes such as pipelines, bores and cores, can puncture natural layers in the sediment or soil that retard water leakage and so retain water in wetlands. Many wetlands in WA are perched (not connected to groundwater). In these wetlands, water from rainfall and often from surface flows waterlogs and/or collects as a lens on top an impermeable surface layer (such as heavy clays). Perched wetlands are fairly common in the Wheatbelt, along the eastern side of the Swan Coastal Plain (Pinjarra Plain wetlands), and some of the salt lakes of the Goldfields. If the impermeable layer that contains the water is punctured by excavation, it may, in effect, 'leak', leading to drier water regimes. Some of the activities that require excavation include drilling bores and cores, installing underground pipes, mining and laying building foundations.

Creating water loss

Mining voids

The holes created by excavating mineral ores are called mining voids. In 2003 it was estimated that there were approximately 1800 existing mine voids and more than 150 mines operating below the watertable in WA.[82] Some of these holes dwarf the natural wetlands of WA in dimension, particularly in depth, such as the Muja coal pit in Collie, that is predicted to be 200 metres deep and 400 hectares in area. The extent of impact of these mine voids on the surrounding groundwater environment is largely dependent on the local hydrogeology, as to whether the mine void will act as a groundwater sink or groundwater throughflow cell. In the groundwater sink regime, evaporation exceeds the rate of groundwater inflow into the void and is typical of most hard-rock mines throughout Western Australia.[82] Wetlands down-gradient of mine voids that function as groundwater sinks can experience altered hydrology. Hydrogeological connection of mine voids with important wetlands or groundwater resources is a major consideration in the Pilbara.[82]

Constructing (artificial) lakes

Many water features in urban developments, including those marketed as stormwater treatment constructed lakes, are permanently inundated constructed water bodies with very little native vegetation. These constructed features can be subject to high evaporation rates due to their depth to surface area ratio and where they intercept groundwater, or are topped up with groundwater, they can result in substantial water loss. They often have serious water quality problems, weeds, algal blooms and nuisance insect populations, and if poorly planned, have the potential to generate acid sulfate soils, on-going maintenance and life-cycle costs and flood risks.

➤ For more information see the Department of Water's *Interim Position Statement: Constructed Wetlands.*[83]

Threatened ecological community: naturally occurring biological assemblages that occur in a particular type of habitat that has been endorsed by the WA Minister for Environment as being subject to processes that threaten to destroy or significantly modify it across much of its range

Altering hydrology to manage other wetland problems

Sometimes, hydrology is altered in order to manage other problems, such as poor water quality and nuisance populations of midge and mosquito in wetlands. The decision to manage water quality by altering a wetland's hydrology should be taken with extreme care, within the context of all the management issues at the wetland, by developing a wetland management plan, and ensuring that all legal requirements are met.

One method involves reducing the volume of inflowing water of poor quality. For example, Toolibin Lake, 40 kilometres east of Narrogin, is recognised as an internationally significant wetland, but its condition is threatened by rising groundwater of very high salinity. To mitigate this risk, the natural flow pathways into the wetland have been deliberately modified. This involves diversion of the 'first flush' of water that would normally flow into the wetland with each rainfall event (which carries high salt loads from the catchment) to Lake Taarblin, a downstream wetland. Toolibin Lake receives less salt but also less water, and the downstream wetland receives more water and salt.[84] Later flows that are lower in salt are allowed to flow into Lake Toolibin to help maintain the hydrological balance of the lake.

Another method involves diluting or flushing polluted water with a new, clean water source. For example, freshwater creeks which previously bypassed Lake Towerrinning in the Shire of West Arthur are now diverted into the wetland to dilute nutrients and prevent algal blooms. This approach has implications for the ecology of the freshwater creeks as well as environments downstream of Lake Towerrinning. From a wetland conservation perspective, it is much more sustainable to manage the nutrients entering the wetland.

What effect does altered hydrology have on wetlands?

Altered hydrology can affect wetland water quality, the species and communities present in individual wetlands, the physical and chemical processes in wetlands, regional populations of wetland species, and in the case of drying, it may ultimately result in the loss of wetlands. In practice, it can be difficult to separate out the effects of altered hydrology, because water has such a fundamental effect on wetland species, and physical and chemical conditions in wetlands.

In 2004, a summary of the likely impacts of various threatening processes in the south-west was estimated based on the then current literature and expert assessment by scientists of the (then) Department of Conservation and Land Management. This assessment focused on the number of likely species extinctions that would arise if threatening processes were not managed. Altered biochemical processes associated with altered hydrology were found to be the most significant potential driver of species extinction in the south-west (750 species extinctions).[85]

At the community scale, thirty-seven of the sixty-nine **threatened ecological communities** currently listed by the WA Minister for Environment are wetland communities. Hydrological alteration and climate change are major threats to these communities. It also threatens many wetland communities listed as priority ecological communities.

Table 5 summarises the effects of altered hydrology.

Table 5. A summary of the effects of altered hydrology on wetlands

Change	Increased risks associated with increased drying	Increased risks associated with increased wetting
Changes in water quality	• Altered water chemistry • Acidification • Eutrophication • Altered salinity	• Altered water chemistry • Altered salinity • Eutrophication
Changes in species and communities, in some cases leading to changes in regional populations of species	• Altered species composition • Altered species distribution • Species mortality • Altered species richness • Altered species abundance • Altered community structure	• Altered species composition • Altered species distribution • Species mortality • Altered species richness • Altered species abundance • Altered community structure
Changes in physical and chemical wetland functions	• Altered nutrient cycling • Increased risk of frequent fire, and associated risk of acidification • Altered sediment including desiccation, smaller organic fraction, cracking, oxidation, consolidation	• Altered nutrient cycling • Altered sediment including swelling, flocculation, increased suspension, increased organic fraction, less oxygen leading to reducing conditions
Loss of wetland types and wetlands	• Conversion of wetland types (e.g. permanently inundated wetlands to seasonally inundated) • Loss of wetlands, particularly seasonally waterlogged wetlands	• Conversion of wetland types (e.g. seasonally inundated wetlands to permanently inundated)

Effects on water chemistry and quality

For an organism to inhabit a wetland, the wetland's water regime and water chemistry must suit its needs. Because altered hydrology can alter water regime and chemistry, it can cause changes in the mix of species able to survive at a wetland. What is more, organisms can modify their environment. So to complete the cycle, a change in the mix of wetland species can have impacts on the water regime and water quality. In this way, altered hydrology can cause a series of impacts in wetlands that involve the water regime, water quality and the ecological community (Figure 15).

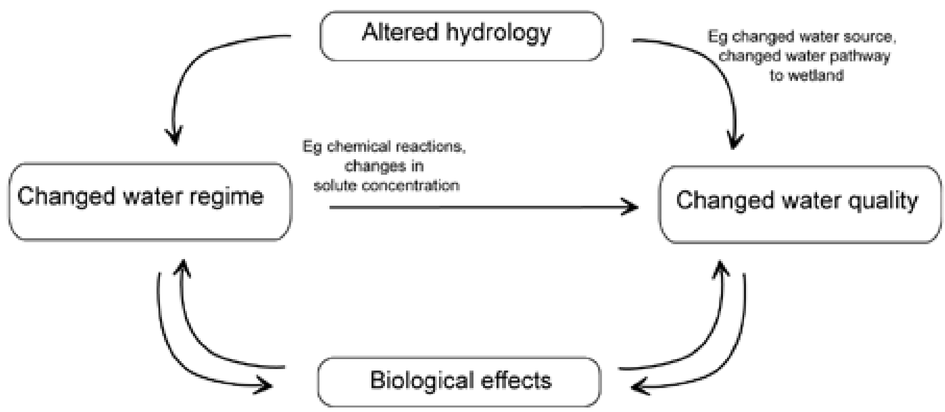


Figure 15. Altered hydrology can produce a range of far-reaching effects because of the interactions between the hydrology, water regime, water quality and biological impacts of wetlands.

If the wetland begins to receive water from a different source, or the proportion of water it receives from each source changes, this can lead to changes in water chemistry. Water sources vary naturally in their composition. For example, groundwater is often rich in minerals, and can vary in salinity from fresh to hypersaline, while rainwater is typically fresh and slightly acidic. Surface water may be derived from rainwater or groundwater, and can pick up both soluble substances (such as salt) and insoluble substances (such as sediment) on its way to a wetland. These differences in composition give rise to variations in characteristics of water such as temperature, salinity, hardness, acidity, nutrients, turbidity, light and dissolved oxygen. A wetland's unique mix of water sources influences its water quality, so any change in sources caused by altered hydrology can cause changes in water quality.

Salty, turbid or acidic water sources are commonly recognised as having potential to degrade the water quality in a wetland that is not naturally salty, turbid or acidic, but fresh, clear, and neutral water can cause problems too. The dilution of natural substances within a natural water source lowers their concentration, and changes the water chemistry in a way that might not suit the resident wetland species (as is occurring at the Fortescue Marshes, Figure 16). Wetland ecosystems are adapted to their own unique mix of water sources, which might naturally include salty, turbid or acidic waters, for example.

The way water leaves a wetland has an influence on the concentration of dissolved substances in the water. Water can leave a wetland through the processes of evaporation and transpiration; processes which leave behind and concentrate compounds such as salt. On the other hand water that flows out of a wetland removes the dissolved substances with the water, and their concentration does not change. Wetlands that are connected to waterways may experience large pulses that flush them, scouring them of sediments or salt, for example. In areas of WA this process isn't as common as in the eastern states of Australia, where it is one of the tools used in wetland management. In this way alterations to hydrology that influence how water leaves a wetland also have the potential to cause changes in water quality that degrade wetlands.

Figure 16. Fortescue Marshes, Pilbara. When fresh groundwater dewatered from a nearby mine was being disposed of in this wetland, the combination of the wetter water regime and continuous fresh water affected the native salt marsh vegetation. Photo – S Halse/DEC.

Acidification of wetlands due to altered hydrology is a major management issue in the south-west of WA. Acidification is a serious threat to wetlands and the primary management aim should be to avoid triggering it, with altered hydrology a key trigger.

Acid sulfate soils: includes all soils in which sulfuric acid is produced, may be produced or has been produced in quantities that can affect the soil properties. Also referred to as acid sulphate soils.

In the case of wetlands containing **acid sulfate soils**, the sulfidic material-containing soils are benign when they remain waterlogged or inundated, but when they are exposed to air, they generate acid which can be released into the wetland. Changes to water regime that involve surface or groundwater drawdown can trigger this process. The acid itself can cause ecological damage. In addition, toxins such as metals and other poisons such as arsenic remain bound in wetland soils under neutral conditions, but they become soluble and toxic when conditions become acidic. Below are some examples of alterations to hydrology leading to acidification:

- excavation of peat-based wetlands in the City of Stirling in Perth for urban development generated acidic groundwater, which became contaminated with arsenic as a result[86]
- inland peat wetlands in the south-west have become acidic because of dewatering and peat mining (for example, Lake Cowerup in the Lake Muir-Byenup Lagoon Ramsar site[87])
- wetlands receiving drainage constructed to combat rising groundwater in the Wheatbelt are suffering the effects of acidity and salinity.

Nutrients may also increase with drying. For example, drying of peat releases nutrients, particularly organic nitrogen.[88]

Not only can changed water regimes generate contaminants, they can also move existing contaminants into wetlands. Secondary salinity in the Wheatbelt is also caused by altered water regimes moving existing salt into new places. Rising water tables wet previously dry parts of the soil profile, mobilising salt and bringing it to the surface. The combination of saltier and wetter (waterlogged) conditions affects wetlands.

➤ The management of altered hydrology in the Wheatbelt is also addressed in the topic 'Secondary salinity', in Chapter 3.

Groundwater drawdown in near-coastal superficial aquifers may allow seawater intrusion into the aquifer.[89] This may result in seawater entering wetlands that previously received groundwater.

When vegetation is cleared and land is developed over or put into agricultural production, shallow sub-surface flows are often re-routed to the surface, increasing the proportion, amount and flow speed of water delivered to wetlands as surface water. This water may gather contaminants as it flows overland to the wetland, without the filtration provided by flowing slowly through the soil. In addition, its increased flow speed may allow it to collect and deliver extra sediments and organic material to wetlands. In this way, the load of manufactured chemicals, the turbidity and nutrient content of a wetland's waters can be increased. If large amounts of extra sediment are delivered, sedimentation can cause changes to wetland shape, which may bury wetland organisms and/or result in further changes to the water regime.

Changes to water regime and/or water quality may leave dead vegetation or animals in the water column. Decomposition of this organic material by bacteria and other organisms consumes oxygen, resulting in low levels of dissolved oxygen in the water column. This can affect the health of aquatic plants and animals, including fish, and can cause further deaths of wetland organisms.

➤ The effects of altered hydrology on water quality is discussed in the topic 'Water quality', also in Chapter 3.

Effects on populations, communities and species

Thresholds: points at which a marked effect or change occurs

As established in the topics 'Wetland ecology' and 'Wetland hydrology' in Chapter 2, when seeking to determine how species may be affected by altered water regimes, an understanding of their water requirements is critical.

Some of the key points about water requirements include:

- Species have **water requirements**: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence.
- Water requirements are driven not only by the water needed by a species, but also the chemical environment of water, such as the levels of oxygen, carbon dioxide, light, salt and acidity in water.
- Water absence and presence also drives physical processes in sediments. For example, the cracking and swelling of clays in response to drying and wetting that is important for some wetland plants and animals (such as planigales, which are very small carnivorous marsupials); the consolidation of sediments on drying that provides habitat for rushes and sedges; and the development of peat, and impairing peat fires, that provides a refuge for desiccation and fire-sensitive species.
- Species employ a range of adaptations that enable them to cope with particular water regimes. These include physiological, behavioural and reproductive adaptations or traits. For example, in wetlands that dry, smaller animals develop desiccation resistant/tolerant resting eggs before dying (such as many microcrustaceans); plants develop seeds, algae and bacteria develop spores and cysts; larger animals go into aestivation or dormancy in the wetland sediment (including some fish, crayfish, molluscs and turtles) or migrate to another site (including crocodiles and other reptiles, frogs, birds, mammals, many insects); and plants use groundwater where it is within reach.
- Boom and bust cycles are a natural part of the population dynamics of many wetland species in WA. Many of the species that inhabit WA's wetlands are quite resilient to year-to-year hydrological change over their normal wetting-drying cycles (for example, seasonal or intermittent waterlogging/inundation).
- In highly altered landscapes, the ability of individuals and populations of plants and animals to cope with natural amounts of variability in water regime can be compromised by the additional stressors (such as salinity, fragmentation, excess nutrients, weeds, fire and so on). Human-induced change is escalating population and ecosystem level stress, threatening wetland biodiversity in the south-west[15] and other areas of WA.
- The study of water requirements goes under many names including environmental water requirements, ecohydrology and hydroecology.

For an organism to live at a wetland, the wetland's water regime and water quality must suit its requirements. Altered hydrology can impact on both of these factors, and can result in organisms' requirements not being met.

An aspect of the water regime (frequency, duration, depth, extent, seasonality, rate, variability) may be particularly important for an individual's survival or reproductive success. So may an aspect of water quality (such as salinity, acidity, nutrients, oxygen, turbidity, light or temperature). Since altered hydrology can impact on any combination of these, there is a large chance that altered hydrology will affect a wetland's suitability for a range of organisms. Conditions beyond an organism's tolerance, or **threshold**, can cause declining health, dispersal to more suitable habitat, or death.

Drought and flood can naturally cause such conditions to occur. However, human changes to the environment have greatly impaired the natural capacity of many species and communities to recover from drought[90] and flood, particularly in areas impacted by intensive land and water use. For example, at Lake Gregory, prolonged inundation triggered by a cyclone resulted in drowning and death of the wetland's trees. Seedlings sprouted but regeneration was limited by cattle grazing of the seedlings. Lake Gregory's trees are vital to maintaining waterbird breeding levels at the wetland.[91] Animals may also be directly affected: land uses can create barriers and hazards to migration to remaining suitable habitats during drought, particularly for animals such as frogs, tortoises, quendas, rakali, fish, snakes and lizards; and when they coincide with bust cycles of a population, they can have catastrophic consequences for the population. The loss of the mosaic of wetland and dryland in natural landscapes means that those species with poor dispersal abilities will be disadvantaged.

Decline in condition of vegetation

A decline in condition of plants often occurs with altered water regime. Wetland plants establish under the conditions that suit their anatomy and physiology, and when the conditions change, their condition can decline, in very rapid (days) to very long-term (decades) timeframes, depending on the change and their ability to adapt to it. Decline in the vigour of a plant is usually evident as yellowing, browning, wilting or dead foliage. In the case of drying, dropping leaves or branches can help plants to survive by reducing

extra information

Studies of the water requirements of WA's wetland species

Knowledge of water requirements is based upon deduction, observation, and studies. Some of the local studies are listed below. There are also a large number of studies of the water requirements of WA's waterways, available from the Department of Water website www.water.wa.gov.au.

Wetland vegetation has been much more intensively studied than fauna. However, even with this level of study, scientists generally cannot make absolute or definitive statements about the response of a particular species in different wetlands. As described by Horwitz, Sommer and Hewitt[92], the degree of response depends on the magnitude, rate and duration of water level increase or decrease, the historic changes in water levels, the specific site conditions (soil stratigraphy, etc.), habitat type and species in question, the influence of disturbance impacts (fire, etc.), and finally the condition of the vegetation. Resilience of a community may be site-specific, rather than species-specific, stemming from historical adaptations.[93]

Generalised understandings of a species response can be refined at a particular wetland using a range of investigations, including measurements of water potential and sapflow sensors to quantify a plant's water use.

Methodologies

- *Approach to determination of ecological water requirements of groundwater dependent ecosystems in Western Australia*[94]

Kimberley

Riparian studies that include wetland species in the Kimberley include:

Water regime for wetland and floodplain plants. A source book for the Murray-Darling Basin[95] (includes some species found in WA wetlands including *Eucalyptus camaldulensis*)

Pilbara

Riparian studies that include wetland species in the Pilbara include:

- *Environmental water report series, report no. 17: Determining water level ranges of Pilbara riparian species*[96]
- *Environmental water report series, report no. 20: Determining water level ranges of the lower De Grey River*[97]
- *Environmental water report series, report no. 22: Determining water level ranges of Lower Robe River*[98]
- *Climate, management and ecosystem interactions in the Pilbara: tree water use at Millstream National Park, WA*[99]
- *Waterlogging and salinity tolerance in riparian and floodplain trees and shrubs in the Pilbara region* (in preparation)
- *Water requirements of the riparian tree Melaleuca argentea in the Pilbara* (in preparation)

extra information

Studies of the water requirements of WA's wetland species (cont'd)

Swan Coastal Plain

- *Draft Ecological character description of the Becher Point Wetland Ramsar Site*[100]
- *Gnangara mound ecohydrological study. Final report to the Western Australian Government, Department of Water. Report No. CEM2010-20*[101]
- *Study of the ecological water requirements of the Gnangara and Jandakot Mounds under section 46 of the Environmental Protection Act*[102]
- *Ecological water requirements for selected wetlands in the Murray drainage and water management plan area*[103]
- *A guide to emergent plants of south-western Australia*[104]
- *Identification of the wetland plant hydrotypes on the Swan Coastal Plain, Western Australia*[105]
- *Wetlands of the Swan Coastal Plain: The effect of altered water regimes on wetland plants*[106]
- *Ecological character description of the Forrestdale and Thomsons Lakes Ramsar Site, A report to the Department of Environment and Conservation*[107]

Unpublished

- *Turquoise Coast Development Jurien Bay: Assessment of likely impacts of drawdown on groundwater dependent ecosystems*[108]

South-west WA

- *Determination of ecological water requirements for wetland and terrestrial vegetation – southern Blackwood and eastern Scott Coastal Plain*[109]
- *A summary of investigations into ecological water requirements of groundwater-dependent ecosystems in the South West groundwater areas*[110]
- *South West Yarragadee – assessment of vegetation susceptibility and possible response to drawdown*[111]
- *Relationship between water level, salinity and emergent and fringing vegetation of the Muir-Byenup wetlands*[112]
- *Ecological character description of the Muir-Byenup System Ramsar Site, South-west Western Australia: report prepared for the Department of Environment and Conservation*[113]
- *Ecological character description of the Lake Warden System Ramsar Site, Esperance Western Australia: a report by the Department of Environment and Conservation*[114]
- *Environmental water requirements of wetlands in the Torbay Catchment, South Coast Region.*

Unpublished

- *The south-west Yarragadee Blackwood groundwater area project: Assessment of fauna in relation to groundwater dependent ecosystems and ecological water requirements*[115]
- *South West Yarragadee proposal: Assessment of drawdown impacts upon fauna*[116]

their water needs. Some species may show signs of stress sooner than others, or plants in one area or zone of the wetland may show signs of distress first. While it is possible to make generalisations about the response of a species to wetland water regime changes, there is variability amongst individual plants and sites.

Some wetland trees, such as the moonah *Melaleuca preissiana* (a paperbark that occurs in the south-west of WA), may alter their root system distribution and attempt to elongate their roots to follow water down the soil profile when the groundwater table declines. Certain conditions are needed, with a slow rate of change one of the most important factors in addition to the magnitude of change. A range of studies by Professor Ray Froend and others (including Froend et al[106], Groom et al[117], Froend and Loomes[94], and Sommer, Froend and Paton[118]), have demonstrated the importance of rate of change for trees and other Swan Coastal Plain wetland plant species. For example, it has been found that at slow rates of change, moonah can be fairly resilient to altered groundwater regimes, responding over many decades. Figure 17 shows the risk of impact for wetland vegetation, based upon research done in WA. Trees are often long-lived (for example, moonah can be hundreds of years old), and can provide a long-term indication of conditions. When mature trees die due to altered conditions, they are sometimes replaced with new recruits that are better able to cope with the conditions if they develop root morphologies suitable to the new water regime.

Precautionary principle: where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation[123]

Banksia tree species have a dimorphic rooting system consisting of a central thick sinker (tap) root and subsurface lateral roots from which smaller sinker roots may arise.[119] *Banksia littoralis* is a wetland tree in coastal and near-coastal south-west WA that has been declining in abundance, with poor seedling recruitment.[117,120] It was one of two *Banksia* species looked at in a recent study into response to water decline. The study found that the maximum rate of root elongation was 18.2 mm day^{-1} but that this rate was not achievable when plants were unable to meet their water requirements once the groundwater table fell below the rooting depth of the plants. It confirmed that the response of phreatophytic *Banksia* to rapid water table decline depends on the availability of other water sources, and the rate of groundwater table decline.[121]

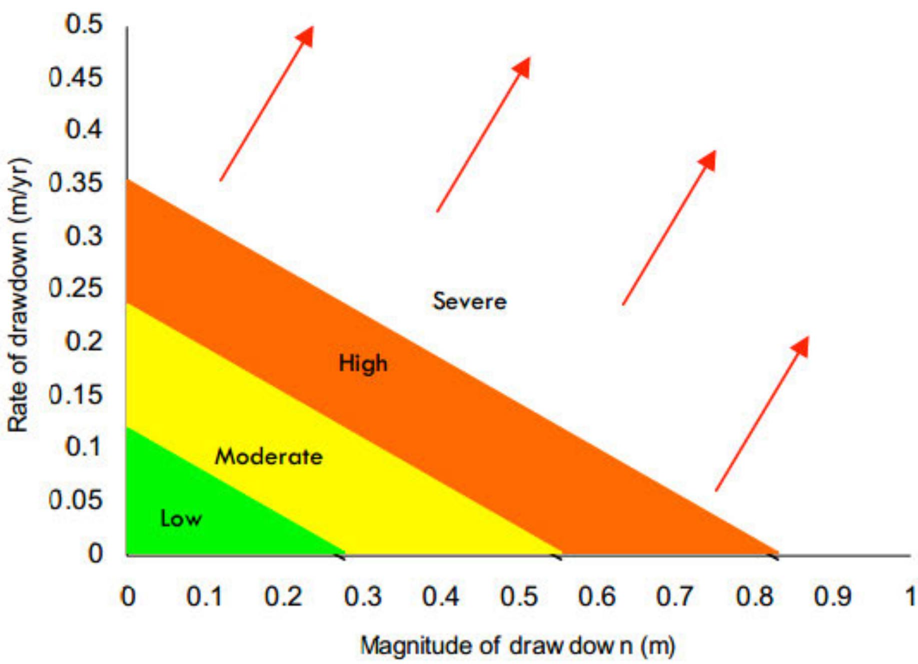


Figure 17. Risk of impact categories for wetland vegetation (trees, shrubs, sedges) based on cumulative rate and magnitude of groundwater level change (drawdown). Source - image in Sommer and Froend[101], citing Loomes and Froend (2004).

It is important to note that the risk categorisation in Figure 17 is a guide to the risk of impact. There are a number of sites where decline has occurred even though the drawdown was within the low risk of impact category (for example, at Lake Yonderup[122]). This highlights the importance of understanding individual wetlands and applying the **precautionary principle** in decision-making. Extrapolating known responses to new sites involves risks, and expertise and site-specific knowledge is generally advisable. As researchers (Horwitz, Sommer and Hewitt[92]) describe, the degree of response depends on the magnitude, rate and duration of water level increase or decrease, the historic changes in water levels, the specific site conditions (stratigraphy, etc.), habitat type and species in question, the influence of disturbance impacts (fire, etc.), and finally the condition of the vegetation. Resilience of a community may be site-specific, rather than species-specific, stemming from historical adaptations.[93] Generalised understandings of a species response can be refined at a particular wetland using a range of investigations, including measurements of water potential and sapflow sensors to quantify a plant's water use. Sophisticated methods of studying tree water use, such as Zim probes, are now being employed in some areas (for more information, see www.foresthealth.com.au).

Plants also respond to too wet conditions in a variety of ways, depending upon their anatomy and physiology. Generally speaking, where the duration or depth of inundation is beyond the tolerance of plants, there are a minimum of two key problems: the plant cannot get enough oxygen, and secondly the lack of oxygen in the soil creates reduced soil conditions that lead to the development of toxic compounds that can affect plants. When the oxygen supply to roots is reduced, respiration and photosynthesis rates are reduced. Plants may wilt, drop leaves and branches, and ultimately die if the duration of inundation is sustained. Plant species respond differently to sustained inundation, and indeed, individual plant responses can vary depending on site-specific factors and degree of adaptations such as shallow root systems, aerenchyma, pressurised gas flow, adventitious roots, loss of stomata and floating leaves (described in the topic 'Wetland ecology' in Chapter 2).

Vegetative reproduction: a type of asexual reproduction found in plants. Also called vegetative propagation or vegetative multiplication.

Suckering: growing roots laterally under the soil, which project shoots to emerge in a new location away from the base of the parent plant

Changes in species distribution and abundance within a wetland

Changes in water regime can change species distribution within a wetland. Where changes are beyond the capacity of individual plants to adapt, vegetation sometimes responds to wetter conditions by shifting to drier areas of the wetland, or to drier conditions by shifting to wetter areas of the wetland. This is because under the new hydrological conditions, the new location meets their water requirements better than their original location (Figure 18). As well as colonising new locations by growing from seed, sedges and rushes can expand **vegetatively i**n the preferred direction by growing extra rhizomes, roots and shoots. Some wetland trees, such as sheoaks (*Casuarina* species), can also expand vegetatively, by growing roots horizontally under the ground, or **suckering.** However, many wetland shrubs and trees can only shift locations through the germination and establishment of seedlings in the new location.

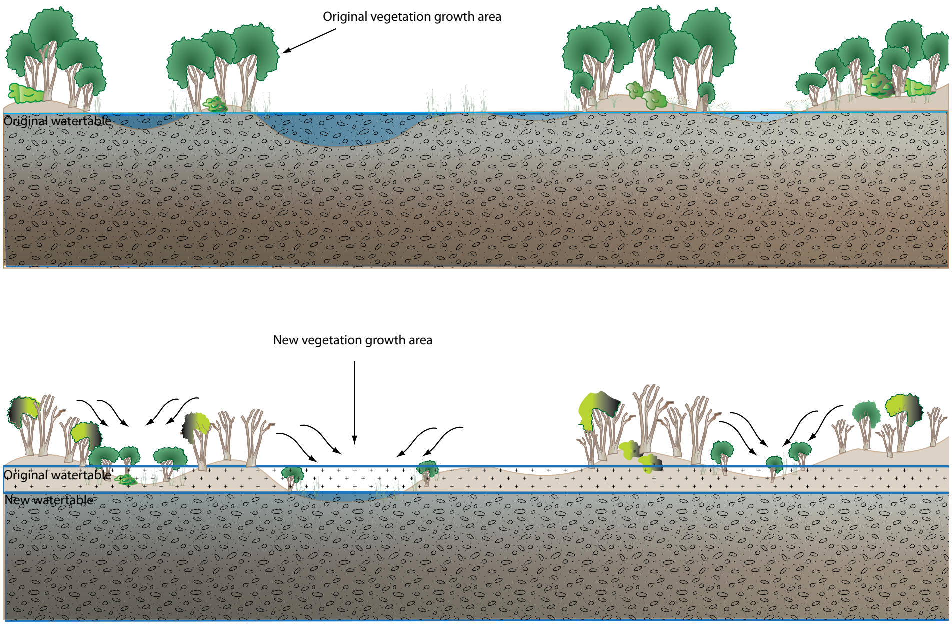


Figure 18. Within a wetland, plants sometimes germinate or otherwise colonise drier locations (often upslope) in response to wetter water regimes, or wetter locations (downslope) in response to drier water regimes, in areas that best suits its water requirements. In basin wetlands, this may involve colonising a different part of the bank. In wetland flats, this may involve movement to localised mounds or depressions.

Of course, vegetation may only shift within a wetland if there is:

- another location that meets its water requirements and other conditions such as suitable soil type)
- an area available for colonisation
- seeds or vegetative parts that are able to reach that location.

If these conditions aren't met, species may become locally extinct at the wetland.[106] In a number of wetlands on the Swan Coastal Plain, for example, swamp paperbarks (*Melaleuca rhaphiophylla*) are being replaced with flooded gums (*Eucalyptus rudis*) trees. Forests and woodlands dominated by the swamp banksia (*Banksia littoralis*) are becoming rare, due to the combined effect of wetland drying, Phytophthora dieback and more frequent fires.[120] If fauna rely on the species for habitat, they may also be lost. The process in which wetland plants are replaced by dryland plants is known as 'terrestrialisation'.

At some wetlands, flood events are required for the establishment of stands of trees, including some species of wetland paperbarks and eucalypts. Changes to the frequency of flood events can therefore influence the success of recruitment. This may lead to long-term changes in the structure and composition of wetland ecosystems.

Species composition: the species that occur in a community

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Loss of species from a wetland, changes in species composition

Altered hydrology can change the mix of species (**species composition**) present at a wetland. Species differ in their capacity to tolerate changes in wetland water regime, with some species more sensitive to changes in water regime and water quality than others. More sensitive species may decline, while more tolerant species may increase in abundance. This may be short, medium or long term, depending upon the changes that have occurred and the resilience of the species to variability.

Species of mammals, birds, reptiles, frogs, fish, invertebrates, fungi, plants and bacteria may all be affected. Altered hydrology can lead to invasion by new species (both native and introduced), as the new water regime provides suitable conditions where they did not exist before. For example, simpler, less diverse aquatic invertebrate communities may be present in drier years, with richer and more diverse assemblies returning under more normal conditions if they are able to reach the wetland. Or, as has happened in many Wheatbelt wetlands, much more pervasive change has occurred, where seasonally drying, freshwater wetlands dominated by rushes, sedges, submerged plants and charophytes have become permanently inundated, saline wetlands that are dominated by **benthic microbial communities.**[124,125] The seed banks of the plants may have disappeared from many of these wetlands.[125]

Some species have times in their lifecycle at which they are most sensitive to alterations. For example, adult frogs may be able migrate to more suitable wetlands but if, when they spawn, the water levels dry rapidly, tadpoles will not be able to mature past their aquatic phase (Figure 19). In these ways, altered water regime can have significant impacts on a wetland's species composition.

Figure 19. The water in this wetland near Mandurah, in the Peel region, receded before these tadpoles could mature into adult frogs. Photo – J Lawn/DEC.

The ways in which altered wetland water regime may affect an individual include:

- by altering cues for hatching/germination of eggs, seeds, spores and cysts. These include the depletion of eggs and seed banks due to too frequent flooding and drying, or the loss of their viability due to age given unsuitable conditions to hatch or germinate
- by reducing the ability of animals to develop into adults, reproduce and maintain resilience to disease
- by reducing the ability of plants to grow, maintain new growth, periodically flower and set seed, and maintain resilience to disease and other factors

To complicate matters further, altered hydrology can also have a range of indirect effects, because it can disrupt normal biological interactions such as pollination, predation, herbivory and symbiosis. Even if a species is itself able to tolerate the new hydrological conditions, it may be impacted indirectly through the decline of another species on which it depends. Altered hydrology may also bias the outcome of competition between two species, particularly if the new conditions favour one species more than another. Cascading effects on habitats and food webs may be triggered.

The compounding effect of drought in combination with ongoing climate change is of particular concern. An example comes from a study of **invertebrates** in **gnammas** (granite rock outcrops) of the Wheatbelt by researcher Dr Brian Timms.[126] Granite rock outcrops are important habitats for small aquatic fauna, including many **endemic** species. They support a rich and diverse range of species and have particular conservation value for rotifers, microcrustaceans, oligochaetes and midges.[127] They are important because they are seasonally inundated, 'freshwater islands' in areas where wetland plants and animals are seriously threatened by sustained waterlogging or inundation and secondary salinisation. These wetlands fill by rainfall, typically in winter, and persist for several weeks or sometimes months, depending on their size, shape and when the rainfall occurs. Their inhabitants are well adapted to this seasonality by being able to disperse (insects), having a drought-resistant stage such as a resting egg (such as rotifers and copepods) or silk-encased larvae (some midge).[127] The water regime is of paramount importance to the invertebrate community structure of gnammas. Of concern is the decrease in rainfall of between 2 and 10 per cent in much of the Wheatbelt over the last forty years. Generally being active dispersers, the insects inhabiting these gnammas are relatively buffered in drier times. However, the very small crustaceans such as cladocerans and ostracods need water for periods of time in order to complete their life cycles. In considering whether the changing climate has affected this, Dr Timms concluded that, given that all crustaceans and almost all insects completed their life cycles in the drought year of 2010 at most study sites, there isn't conclusive evidence yet of invertebrate communities in the study area being affected. However, in considering the predictions of a further decrease of 2–5 per cent in rainfall, Dr Timms predicts that life cycles may be disrupted and diversity affected. In considering the most affected northern gnammas, where many species did not complete their life cycles in the drought year of 2010, Dr Timms notes that it is not known how often the failure of many species to complete their life cycles can occur before local extinction takes place, and indeed whether it has already taken place in some areas.

Some **obligate wetland species** have a low tolerance for altered hydrology and are more likely to show a decline in condition if a wetland begins to dry, and are therefore useful as 'indicator species' of altered hydrology (Figure 20). Dryland obligate species can be used in a similar way to indicate wetter water regimes. Many **facultative wetland plants**, which can also occur in drylands, are likely to tolerate a wide range of water regimes. They are less likely to be affected by altered hydrology, and therefore more expertise and more supporting evidence is generally required when using them to infer that a wetland's hydrology has been altered.

Invertebrate: an animal without a backbone

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyungar origin.

Endemic: naturally occurring only in a restricted geographic area

Obligate wetland species: species that are generally restricted to wetlands under natural conditions in a given setting

Facultative wetland plants: plants that can occur in both wetlands and dryland under natural conditions in a given setting

Figure 20. The endangered Dunsborough burrowing crayfish, *Engaewa reducta*, is one of the endangered species of burrowing crayfish that inhabit WA's south west and south coast. They burrow into damp soils each year once surface water dries out and resurface with the onset of rains. With a drying climate the soils of many of their wetland habitats are drier for longer. Photo – K Rogerson/DEC.

➤ For additional detail on wetland species' water regime tolerance, see the topic 'Wetland ecology' in Chapter 2.

Changes in population distributions

Species with the ability to disperse may show significant population-scale changes in distribution in response to large-scale altered hydrology and climate changes. Waterbirds may breed less frequently in wetlands subject to reduced water. Migratory birds may also be affected by disruptions to the synchronicity of migration and prey flushes[131], that is, changes in the timing of environmental cues to migrate and during migration that may have effects on migratory birds.

The Swan Coastal Plain has been recognised as playing a significant part in the life cycle of many WA birds, playing a part in life-supporting systems that is out of all proportion to its size.[54] Researcher Dr Stuart Halse has considered the effect of climate change on waterbirds, and predicts that the proportion of the State's waterbirds using northern Australia will increase and the Swan Coastal Plain will probably become less important as a summer drought refuge, as well as a breeding area. Southern specialists such as chestnut teal are most likely to be affected by climate change. Dr Halse also considers it possible that some species of waterbird characteristic of the north are likely to extend their ranges southwards with increased summer rain.[26]

Extinction of species

Large-scale changes to hydrology in a region can endanger species. In particular, warmer, drier conditions predicted under many climate change scenarios will pose a significant threat to a number of WA's wetland species, particularly flora of shallow freshwater claypans, salt-intolerant species, cool-adapted species, species with poor or flood-dependent dispersal mechanisms, and groundwater dependent species, such as aestivating fish, some frogs, burrowing crayfish.[132]

Many species of frogs in the south-west are potentially at risk. For example, the climatic habitats of the white-bellied frog (*Geocrinia alba*), yellow-bellied frog (*Geocrinia vitellina*) and sunset frog (*Spicospina flammocaerulea*) are predicted to disappear completely with an increase of annual temperatures of 0.5 degrees Celsius.[133]

Initiatives such as ClimateWatch are collecting information on the population of particular species to understand how changes in temperature and rainfall are affecting their behaviour. WA animals studied in the initiative include the oblong turtle and a number of frogs. It uses citizen science, enabling every Australian to be involved in

case study

When peat wetlands dry out: a case study of Lake Wilgarup

As peat forms in places that rarely dry out, drier water regimes at peat wetlands can cause great damage:

Firstly, the plants and animals are exposed to drier conditions.

Secondly, the drying of the peat can trigger acidification, affecting sensitive species.

Thirdly, the wetlands may become more susceptible to fire. Peat does not occur in places that normally become dry enough to burn, yet dried peat, being dry organic matter, is flammable. In general, the species at peat wetlands are not adapted to fire and are more likely to be killed by it. Peat fires at wetlands are difficult to extinguish, and can burn underground for weeks, or even months. For wetlands undergoing drying and acidification, resilience in the event of fire can be low, with the potential for the loss of the original ecological community.

Lastly, burning or overheating of sediment due to fire can result in the loss (volatilisation) of organic material, cracking and/or erosion, further exposing the remaining sediment to air and potentially triggering the release of significant amounts of stored acidity. Cracks as deep as 1 metre have been recorded in organic sediments.[128]

In addition to these impacts, peat smoke contains compounds which are toxic to humans, so the burning of peat wetlands can be a serious human health issue.[129]

Drying, acidification and fire has occurred at Lake Wilgarup, a peat wetland on the Gnangara Mound in the City of Wanneroo. A progressively drier water regime was causing declines in the condition of dense stands of paperbarks (*Melaleuca rhaphiophylla*) within the wetland. A fire in January 2005[130] killed much of these stands, and the population has not regenerated because of a combination of drier water regimes and changed soil conditions after the fire, including the drying of organic sediments and severe acidification due to oxidation of acid sulfate soils. Dense recruitment by flooded gums (*Eucalyptus rudis*), which tolerate drier water regimes, is now replacing the paperbarks (Figure 21).

Figure 21. A dense stand of flooded gums (*Eucalyptus rudis*) are recruiting under the dead stags of paperbarks (*Melaleuca rhaphiophylla*) at Lake Wilgarup on the Gnangara Mound. The paperbarks were killed by fire, and were unable to regenerate because of drier water regimes. Photo - R Susac/DEC.

collecting and recording data that will help shape the country's scientific response to climate change. ClimateWatch was developed by Earthwatch with the Bureau of Meteorology and The University of Melbourne. The website is www.climatewatch.org.au.

extra information

Species vulnerable to climate change in the south-west of WA

A collaborative project coordinated by Murdoch University concluded that the species most vulnerable to climate change in the south west are anticipated to be:

- Species of seasonally inundated or waterlogged wetlands whose life cycles, survivorship and reproduction may be adversely affected by premature wetland drying and change in seasonality.
- Freshwater turtles which depend on permanent moisture, regular winter rainfall and temperatures to determine sex of offspring e.g. western swamp tortoise *Pseudemydura umbrina* and side-necked tortoises (family Chelidae).
- Species that breed in autumn because the change in timing of seasonal rainfall and temperature triggers may not allow them to complete life cycles (e.g. tadpoles may not have time to develop into adult frogs).
- Species of cold climates, mostly with south coast distributions, which will lose suitable habitat due to increasing temperatures e.g. the rare sedge *Reedia spathacea* and disjunct south-eastern Australian wetland sundew species *Drosera binata.*
- Species which are endemic, have restricted range, are already endangered or threatened, for example, Albany pitcher plant *Cephalotus follicularis*, sunset frog *Spicospina flammocaerulea*, white-bellied frog *Geocrinia alba*, hairy marron *Cherax teniumanus*.

For more information, see the report *Climate change and Western Australian aquatic ecosystems: impacts and adaptation responses.*[132]

Effects on wetland soils

The types of sediments that develop, and their rates of accumulation can be determined, in part, by a wetland's water regime. For example, in wetlands with permanent inundation or waterlogging, it is not uncommon for peat to develop, over long periods of time. Peat is the product of wetland plants that have only partially decayed/ decomposed. In wetlands with inundation and other conditions suitable for diatoms (a type of algae), the sediment may be dominated by their remains: tiny glass-like cell walls of silica; this sediment is known as diatomaceous earth, which slowly builds up over time. In inundated wetlands, abundant populations of charophytes, molluscs and other invertebrate fauna can leave behind shells and deposits, which over time, can form carbonate sediment. Drier water regimes may reduce the extent to which these types of sediments accumulate, and with increased potential for fire, they are at greater risk of losing peat and other organic sediments through combustion (as discussed in the earlier case study 'When peat wetlands dry out: a case study of Lake Wilgarup').

Drying of wetlands that contain acid sulfate soils can generate acids and trigger serious changes to wetland soils. These are described earlier and also in the topic 'Water quality' in Chapter 3.

➤ Detailed case studies of changes to wetlands and wetland soils arising from climate changes are provided in the article, *The response of basin wetlands to climate changes: a review of case studies from the Swan Coastal Plain, south-western Australia.*[13]

Hysteresis: the condition that caused a shift from one state to another does not necessarily result in a shift back to the first state when the condition is simply reversed

Limits of acceptable change: variation that is considered acceptable in a particular component or process of the ecological character of the wetland, without indicating change in ecological character that may lead to a reduction or loss of the criteria for which the site was Ramsar listed

Effects on wetland ecosystems

The changes to water quality, soils, species and communities can have cumulative effects on wetland ecosystems. Changes may be evident as a gradual change; this is known as 'proportional response' and describes a progressive decline in ecosystem processes with changes in water regime.[94] An abrupt change or regime shift can signal the occurrence of a 'step change' or 'threshold change', this is when little change is evident until a particular threshold is reached and rapid and extensive changes follow. It describes a non-linear response to a relatively small change in the external stressor.

The response of the wetland to altered regime can inform the potential management response. For example, for those wetlands where the **hysteresis** model of non-linear change applies, reversing the external stressor does not result in the original wetland ecology being restored.

The concept of defining '**limits of acceptable change**' can be useful for wetland managers seeking to identify the water requirements needed to maintain a wetland's ecological character (Figure 22A). In addition to defining absolute minimums and maximums, it is important to consider other aspects, such as baseline shifts, number of peak events and seasonal shifts (Figure 22 B–D).

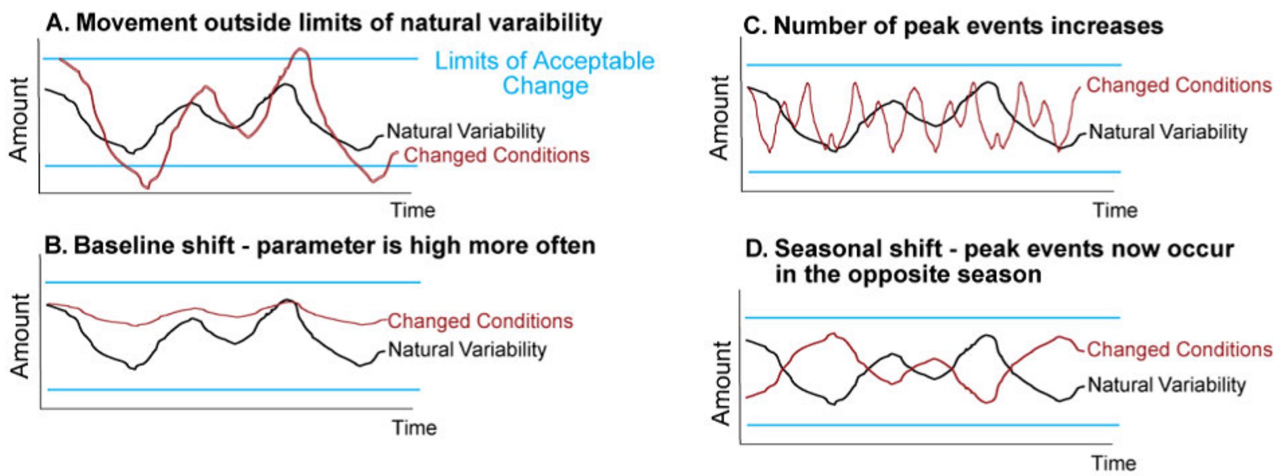


Figure 22. Limits of acceptable change. Source – Hale and Butcher (2007).[134]

Limits of acceptable change have been defined for a number of Western Australia's internationally significant wetlands recognised via listing under the Ramsar Convention. Table 6 is an excerpt of the limits of acceptable change defined for Thomsons and Forrestdale Lakes in southern metropolitan Perth.

➤ A factsheet on limits of acceptable change is available from the Australian Government website: www.environment.gov.au/resource/limits-acceptable-change-fact-sheet

Table 6. An excerpt of some of the limits of acceptable change defined for Forrestdale and Thomsons Lakes, internationally significant wetlands located in Perth's southern suburbs. Source – Maher and Davis, 2009.[107]

Components and processes	Baseline condition and range of natural variation where known (range with average in brackets)	Limits of acceptable change
Annual minimum water depth	Typically falls to around 0.5 m below the lake bed level. **Permanent water** (in most years): • Thomsons: 1972–1977 and 1989–1995 • Forrestdale: 1972–1982 and 1989–1993 **Annual drying** (in most years): • Thomsons: 1978–1988 and 1996–present • Forrestdale: 1983–1988 and 1994–present	• At the sediment surface (wet years), or up to 0.5 m below the lake bed levels (medium years), or 0.5–1.0 m below the lake bed surface (dry years) (DoE 2004) for 3–4 consecutive months annually. • Always <1.0 m below the sediment surface (DoE 2004). • Not 0.5–1.0 m below the sediment surface for longer than 4 consecutive months more than once every ten years or for 2 consecutive years (Froend et al 1993).
Annual maximum water depth	**1952–2005**: Thomsons Lake 38–371 cm (139 cm) Forrestdale Lake 45–266 cm (129 cm) **1980–1999** (decades before and after Ramsar listing): Thomsons 38–206 cm (105 cm) Forrestdale 47–187 cm (103 cm)	• >0.9 m (DoE 2004) for 2 months during spring. • > 1.6 m at least once every 10 years (for invertebrates) • No less than 0.5 m more than once every 10 years (Froend et al 1993). • No greater than 2.5 m for 2 consecutive years (Froend et al 1993).
Period of inundation/ drying	**1972–2005**: Thomsons 5–12 months (9.6 months) Forrestdale 5–12 months (9.9 months) **Drying phase 1 (1980s)**: Thomsons 7–10 months (8.6 months) Forrestdale 9–12 months (10.2 months) **Drying phase 2 (mid-1990s to 2005):** Thomsons 5–9 months (7.3 months) Forrestdale 5–9 months (6.8 months)	• > 6 consecutive months annually (Balla and Davis 1993; Briggs and Thornton 1999). • Preferred earliest drying by April (wet year), Feb–Mar (medium year) or January (dry year) (DoE 2004). • Permanent water present for not more than 2 consecutive years in every ten years (Crome 1988; Halse et al. 1993; Davis et al. 2001).

Loss of wetlands

Complete, sustained drying beyond natural variability can lead to the loss of areas of wetlands and entire wetlands. The terrestrialisation of wetlands into dryland is a natural phenomenon that can occur due to natural processes and conditions, but the potential scale and rate of human-induced terrestrialisation, in already very altered landscapes, may have much larger ramifications for biodiversity and groundwater quality.

Wetlands are the ecosystems most vulnerable to climate change in the south-west of WA

A collaborative project coordinated by Murdoch University concluded that the ecosystems most vulnerable to climate change in the south west are anticipated to be:

- shallow, seasonally wet (waterlogged or inundated) surface water dependent wetlands
- groundwater dependent wetlands, especially where water abstraction is also occurring, such as the Swan Coastal Plain.

For more information, see the report *Climate change and Western Australian aquatic ecosystems: impacts and adaptation responses.*[132]

Recognising the signs of altered hydrology

There are observable changes in wetland ecosystems that can indicate a change in wetland hydrology and water regime. The observations take various forms, but do not have to involve direct numeric measurement. Given that most WA wetlands naturally go through cycles of wetting and drying, detecting a relatively slow or subtle change in water regime is likely to require observations over several years (or even decades). Wetland ecosystems with greater natural variability in their hydrology or longer wetting-drying cycles will require observations over longer time periods. The ecological and hydrological time lags between disturbance to the groundwater regime and an ecological response vary.

General observations

A person familiar with a wetland will often notice hydrological changes, or their biological symptoms, without measuring their observations. Regular visitors to a wetland might notice such signs as:

- in wetlands with surface water, sustained trends in patterns of movement of the waterline (which signifies extent and depth of water) (such as over a number of years)
- a decline in the condition of wetland vegetation evident as yellowing, browning, wilting or dead foliage in vegetation
- population declines or explosions of particular plants or animals, including weeds and feral animals
- new types of plants or animals appearing, or familiar plant species appearing in new parts of the wetland
- changes in the sediments, such as deep cracking in clays, beyond what normally happens in drought.

Care should be taken when attributing any observed ecological effects to altered hydrology or any other cause, because altered hydrology is only one of many environmental factors that might affect wetland organisms. Some other factors include diseases, fire, predators, herbivores, competition, nutrients, weed invasion, salinity or other pollutants. If altered hydrology is suspected to be the cause of decline in ecosystem condition, then further information should be sought to confirm it, and to investigate its potential links with other potential degrading processes.

Aside from general observations, information can be gained in several ways, including:

- talking with people who are familiar with a wetland over a number of years
- viewing sequences of aerial photographs, which can show changes in the distribution of perennial wetland vegetation, sediments or the water line over a number of years. Internet sources of aerial photography include Google EarthTM and Landgate's map viewer (www.landgate.wa.gov.au/bmvf/app/mapviewer).
- viewing old photographs of the site
- reading oral histories and history books, which can be an important source of information on past vegetation structure, land use, fauna populations and water regime of the wetland (see below)
- looking at long-term data on water levels from a variety of sources (see below)
- examining rainfall records, which can be used to understand general trends in an area. Rainfall records are available for most locations in the state from the Bureau of Meteorology website through tools such as 'Climate data online': www.bom.gov.au/climate/data/index.shtml.

extra information

Historical information on wetland water levels

Sources of information on wetland water levels include:

- The Department of Water's water information network. Its records are available online at the water information resources catalogue: http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp
- Hydrographs are available for many sites, available at http://kumina.water.wa.gov.au/waterinformation.wrdata/wrdata.cfm
- Reports from the South West Wetlands Monitoring Program, available via the DEC library: http://science.dpaw.wa.gov.au/conslib.php (authors 'Lane' and 'Halse').
- Reports online, and in public libraries, state government libraries, and the repositories of regional natural resource management (NRM) organisations.

extra information

Oral histories

Oral histories can provide a wealth of information on conditions in wetlands following European settlement, but prior to monitoring.

For example, Clohessy describes how: "Oral histories compiled by the Gwelup Progress Association provide an interesting account of the historical horticultural activities that dominated the Gwelup area for about 90 years until the commencement of urbanisation in the 1970s. The City of Stirling was identified as 'swamp land that people could crop three times a year' and was generally thought to be a productive horticultural precinct. The presence of peat in the City of Stirling was identified long before the onset of urbanisation and was crucial to the horticultural productivity of the area. Sand-dominated landscapes were considered 'worthless' as there was no irrigation in the area prior to the late 1930s and 1940s, making it difficult to produce a consistent crop on these nutrient poor sands. Upon the construction of irrigation bores, horticultural activities expanded to the 'sanded land', which was also much cheaper and easier to work than the 'swamp land' as horses and machinery could be used (Moore 2001).

Farming practices associated with horticultural activities in the Gwelup area comprised the burning of peat (Moore 2001) and the use of fertilisers. The burning of peat may have released significant amounts of stored acidity, perhaps adversely affecting the quality of groundwater prior to the onset of urbanisation. Fertiliser use during this horticultural era contributed to the presence of elevated nutrient concentrations in groundwater in combination with the commencement of unsewered urban development (Barber et al. 1993). Nitrate concentrations in the lower half of the Superficial aquifer, where production bores are screened, have declined since".[135]

Relevant oral histories include:

- *Forrestdale: people and place*[136]
- *Oral histories documenting changes in Wheatbelt wetlands*[137]
- *Oral histories of Wanneroo wetlands: recollections of Wanneroo pioneers, changes that occurred between European settlement and the 1950s*[138]
- *Recollections of the Beeliar wetlands*[139]

For more sources, see the WA Branch of the Oral History Association of Australia website: www.ohaa-wa.com.au/ and the Royal Western Australian Historical Society Inc: http://histwest.org.au/?page=links.

Monitoring water levels

Monitoring the levels of surface water and groundwater provides data on some of the most important aspects of the water regime that affect wetland ecology. Monitoring water depth through time at various points within a wetland provides information on the depth, extent, duration and timing of inundation or waterlogging.

Monitoring the surface water depth of wetlands that are inundated can be carried out by installing a depth (or staff) gauge and measuring the depth of water in relation to the depth gauge. A gauge should be positioned so that wetland water levels can be measured when they are at their lowest and highest; in drying wetlands, some gauges have been left stranded by water level declines. In some cases, it may be appropriate to carry out a lakebed sediment bathymetric survey to determine the lowest lakebed level, so that surface water staff gauges can be installed in the most appropriate locations, as occurs in monitoring of some wetlands on the Gnangara and Jandakot mounds.[140] In wetlands that are seasonally waterlogged, neutron probes may be useful for monitoring moisture content.

Groundwater can be monitored using monitoring bores, also known as piezometers, to measure the depth of water in the bore. The installation of the bores needs to be carefully considered in order to get the information required, particularly the location, screens and configuration of the bore network. The bores should be positioned up-gradient and down-gradient of the wetland so that both horizontal and vertical groundwater flow can be measured. For wetlands fed by the superficial aquifer, it may be useful to install the groundwater monitoring bores in clusters of three: shallow (screened at the water table), intermediate (screened approximately half way through the superficial aquifer) and deep (screened at the base of the superficial aquifer). It is also important that the flow components of the regional groundwater system in the vicinity of the wetlands are known. Neutron probe access tubes, for monitoring unsaturated zone moisture content, may also be installed adjacent to monitoring bores.

Changes may influence the timing (season or month) of the driest or wettest conditions, or the rate of change in water depth or extent. Water regimes can be characterised using a range of parameters that define features of the water regime (timing, frequency, duration, extent, depth and the variability in these). The water regime parameters used might vary between wetlands, because a parameter that is meaningful to describe one water regime may be irrelevant in another. For example, 'season of maximum inundation' might be a meaningful parameter to define a seasonally inundated wetland, but is irrelevant for a wetland that could contain surface water in any season, or for a wetland that naturally experiences waterlogging but not inundation.

Some of the parameters used to characterise water regimes at wetlands are:

- timing (season or month) of driest/wettest conditions
- frequency of driest/wettest conditions
- duration of driest/wettest conditions
- maximum and minimum depth of inundation or waterlogging
- extent (area and location) of inundation or waterlogging
- rate of change in water depth or extent

In all wetlands there is natural variation in water regime. This means that water regime parameters are best described by a range of values rather than a definitive value. For example, the recorded maximum water depth of a seasonally inundated wetland might vary 'between *X* and *Y* metres' in a ten year period. When characterising the water regime, the extremes should be recognised as natural to the wetland, unless there is evidence to suggest that the extremes have been caused by altered hydrology. The natural variability should therefore be taken into account when deciding whether a wetland's water regime (and therefore its hydrology) has been altered.

> *'When Europeans arrived in Australia… they called the dry times 'drought' and the wet times 'flood' and the times of perfect pasture growth 'normal'. The extremes were regarded as aberrations of the 'normal' conditions. However, as records show, extremes of wet and dry are not abnormal – they are part of the natural pattern.'*
>
> -Brock et al. (2000)[141], p. 2.

Quadrat: a plot (often square) that is marked, either temporarily or permanently, to facilitate counts of plants in a given area

➤ For additional detail on monitoring, see the topic 'Monitoring wetlands' in Chapter 4.

Monitoring vegetation or other biological indicators

Photo monitoring can provide a good visual record, where a rigorous record of change is not required. If time or money is not available for the quantitative monitoring of vegetation and other wetland parameters, photo points may be useful in determining if changes are occurring. Photo points are simple, fast and relatively cheap to establish. The drawback of photos is that they only provide an indication that a change is occurring or has occurred and may not enable that change to be quantified. Small, incremental changes may be difficult to detect in photos, and it may take a number of years before change is noticeable, by which time remedy or reversal may be difficult to achieve.

Similarly, examination of aerial maps and photographs from monitoring points over time are simple methods of identifying change.

➤ For a guide to photo points for monitoring purposes, see the *Land for Wildlife* program's Wildlife Note No. 9 *Photographic monitoring of vegetation*.[142]

➤ Google Earth www.google.com/earth supplies a free software program that provides online access to aerial photography covering WA. Some areas have many years of aerial photography (time series), which can assist with identifying vegetation change.

➤ Aerial photography can be viewed and purchased from Landgate's Map Viewer www.landgate.wa.gov.au/bmvf/app/mapviewer/ and NearMap www.nearmap.com.

To detect the degree and rate of the change associated with water regime, vegetation monitoring may consider characteristics such as:

- extent
- species composition
- structure (height class and dominance); and
- vegetation density (percentage cover)

Common measures include stem diameter at breast height (DBH); species richness; crown health; species cover and abundance; weediness index; regeneration index; stem condition; presence/absence of seedlings; and presence/absence, density and foliage cover of understorey species. Monitoring programs need to be designed carefully to detect and record change accurately and to establish any correlations with water regime changes. **Quadrats** are a standard monitoring tool.

➤ For additional detail on monitoring, see the topic 'Monitoring wetlands' in Chapter 4.

➤ More guidance on composition, structure and density changes are provided in 'Managing wetland vegetation' in Chapter 3.

Technology now offers opportunities to monitor vegetation in new ways, making use of aerial photography and high-resolution digital airborne imagery to detect indications of canopy change, water use and plant health. These techniques may be suitable for large, complex wetlands or those in remote or inaccessible areas.

➤ For more information, see CSIRO www.csiro.au/Organisation-Structure/Divisions/Land-and-Water/Environmental-Earth-Observation.aspx.

Understanding the potential for, and the impact of, altered hydrology

Models are often used to simulate hydrological systems, and predict the effect of changes. A **groundwater model** is a simplified representation of a groundwater system and it captures and synthesises all of the known information, and where information is not known, identifies any assumptions being made about how the system is thought to work. Groundwater models may be conceptual, analytical or numeric. Conceptual models are used as visual tools to display the relationships between parts of the groundwater system. They may be simple or more complex, such as shown in Figure 23. Numeric models assign actual quantities to each part of the system. Perth regional aquifer modelling system, or PRAMS, is a regional model of Perth's groundwater (Moora–Mandurah). It is used by the Department of Water to manage groundwater in the region and to help predict cause and effect under different scenarios (for example, more or less groundwater abstraction). The Peel-Harvey and south west models are referred to as PHRAMS and SWAMS respectively.

While regional groundwater models tend to be useful in understanding regional trends, they are often unsuitable for use at the scale of individual wetlands. In the case of PRAMS, its calibration and resolution are based on a 500 by 500 metre grid size and therefore cannot provide detailed information for local scale management objectives, such as managing individual wetlands, which require smaller grid sizes, higher resolution conceptual models and higher quality calibration. To gain a better understanding of the role of the Gnangara groundwater system's effect on wetlands, the Department of Water have developed local area models (LAMs) at a refined level of detail (50 to 100 metre grid) for five wetlands/wetland sites (Lake Mariginiup, Lake Nowergup, Melaleuca Park, Lake Bindiar and Lexia). These local area models provide quantitative tools to assess land and water use impacts on the environment and groundwater systems. These local area models will be used to refine and improve PRAMS so that the impact on wetlands due to changes in the superficial aquifer can be determined.

Modelling of surface water-groundwater interaction sometimes involves the coupling of surface hydrological models with groundwater models.

Models are often used to help determine the potential environmental impacts of proposals assessed by the Environmental Protection Authority under the *Environmental Protection Act 1986*. It is important to be aware that models reflect the information they are based on, and it is possible for them to be wrong. For example, if a model is based upon one year's monitoring data, its predictive capability about how a system works over the long term and how it may respond to events is likely to be extremely limited. Important factors include the type of model used and its suitability for the task at hand, the assumptions built into the model, the integrity of the data, calibration and the stated uncertainty of its outputs.

➤ For more information on groundwater modelling, see the *Australian groundwater modelling guidelines.*[144]

➤ The eWater toolkit www.toolkit.net.au/Default.aspx is a source of software tools and information related to the modelling and management of water resources provided by the eWater Cooperative Research Centre.

➤ For more information on local area models, see the reports listed under 'Local area modelling' at: www.water.wa.gov.au/sites/gss/reports.html.

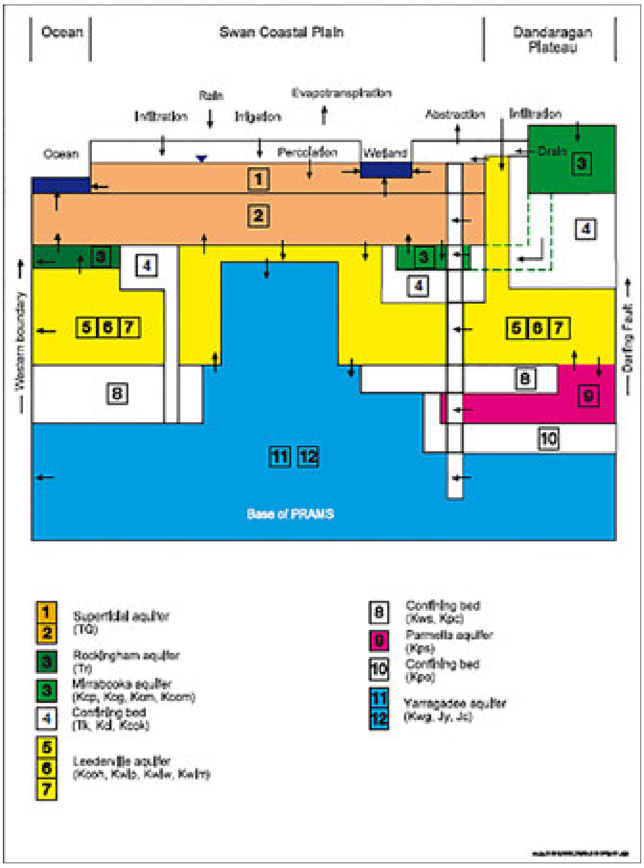


Figure 23. A conceptual hydrogeological model of the Perth groundwater system. Image – Department of Water.[143]

At the wetland scale, the complexity of groundwater flows can be compounded by the complexity of wetland sediments. For example, Figure 24 shows the wetland sediment profile of Lake Mariginiup on the Gnangara Mound, in the suburb of Mariginiup north of Perth. In winter/ spring, groundwater flows into the wetland on its eastern side, then up to 92 per cent is removed by evapotranspiration; a small amount is recharged to groundwater from the western side of the wetland.[145]

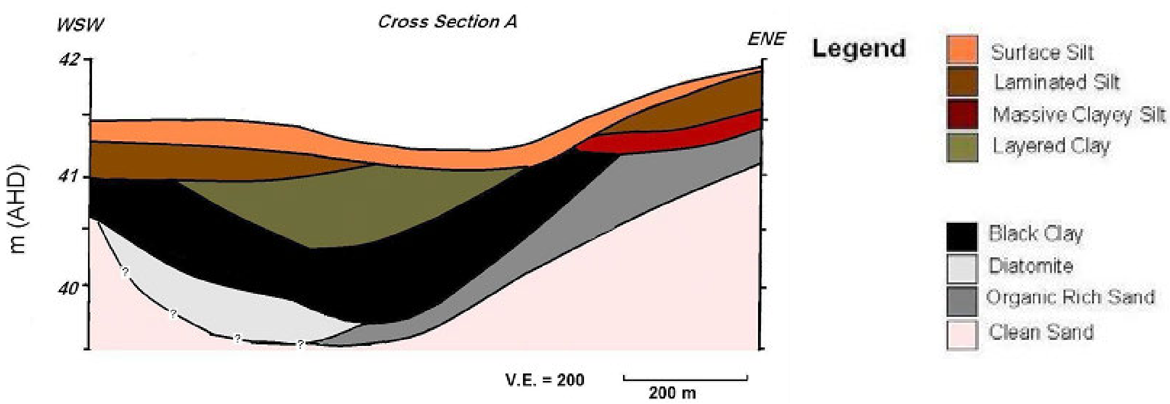


Figure 24. In many wetlands, the sediment is not uniform across the wetland, such as those of Lake Mariginiup, represented here in cross-section. Image – Department of Water.[63]

Notwithstanding this, models can help us to analyse a lot of complex information and to draw conclusions about broad trends. Examples are the:

- South West Sustainable Yields Project, which models the potential effects of climate change on wetlands between Geraldton and Albany (Figure 25). Predictions have been developed of the potential effects of drying upon wetlands under a number of different potential future climate scenarios. These predictions are an important tool for people involved in natural resource management at subregional to regional scales. At the scale of individual wetlands, however, predictions should be used with care. For more information, see www.csiro.au/partnerships/SWSY.

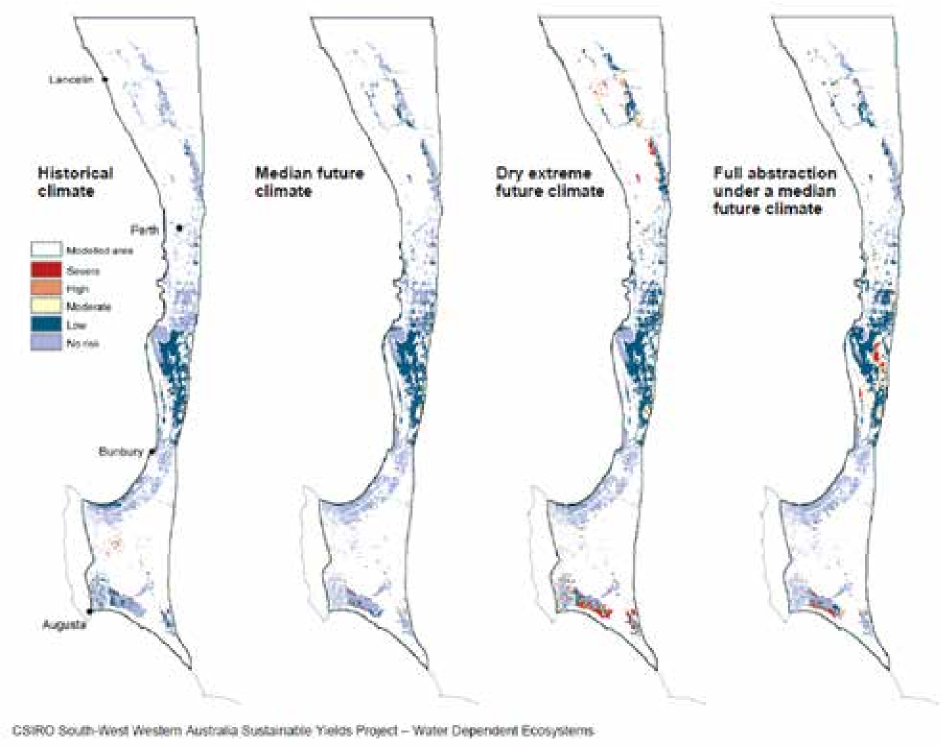


Figure 25. Modelled predicted impacts of climate change on wetlands of south-west WA, based on different climate and abstraction scenarios. Image – CSIRO.

Managing hydrology in wetlands

First and foremost, deciding how best to manage altered hydrology at a particular wetland requires an understanding of the wetland's hydrology (including catchment and aquifer, where relevant).

Once this is established, an important decision is the level or levels at which to take action. The various levels at which to operate range from on-ground works or local scale works through to involvement in sub-regional or regional initiatives, plans and policies. The appropriate level of action will depend on the circumstances. In most cases, the actions that yield the biggest effect on managing a wetland's hydrology do not involve on-ground work. The existing approved land and water uses, competing demands for land and water use, legislative controls, available funding, conservation priorities, likelihood of success of on-ground works and so on all need to be weighed up when deciding how best to act.

It might be within the power of one person or an organisation to effectively tackle altered wetland hydrology, if the cause is localised. However, managing a wetland's hydrology usually requires a catchment- and aquifer-scale approach. As well as improving outcomes for wetland ecosystems, such an approach may also improve outcomes for natural dryland ecosystems, as well as farming systems and infrastructure, because hydrology can affect all of these things, not just wetlands. These gains, however, do not come easily and quickly. It can be challenging to align the priorities of all of the relevant people and organisations to develop a suitable approach to manage a landscape and its hydrology. Managing at this scale requires a big-picture approach and a long-term vision to achieve ecosystem health and productive landscapes that meet human needs. Determining and agreeing on an appropriate approach may take years, implementing

Ensuring you have sound expert input

Before embarking on on-ground activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate.

On-ground actions to manage wetland hydrology should generally only be taken after a management planning process has been completed and a management plan prepared, however basic it may be. This process should determine what actions are legal, feasible, cost-effective and without adverse side effects. For guidance on wetland management planning, see the topic 'Wetland management planning' in Chapter 1.

Where on-ground action involves hydrological interventions, it is likely that the input of a qualified hydrologist or hydrogeologist, and in some cases, an engineer, will be needed.

It is also essential to make sure you have all the necessary legal approvals. Guidance is provided in the following sections and in the topic 'Legislation and policy' in Chapter 5.

the approach will take more years, and waiting for the hydrological outcomes can take decades. These improvements might be too late to save wetlands of high conservation priority which are at immediate risk of degradation due to altered hydrology.

To deal with wetlands of high conservation priority that are under immediate hydrological threat, a quicker solution than catchment and aquifer-scale management is required. In these cases, engineering solutions are often considered, as a way to take immediate pressure off a high-value ecosystem. Some approaches include earthworks to modify surface flows, groundwater pumping to lower water tables, and artificial supplementation of water levels. These options require large investments of time, commitment and money, and require expertise from a number of fields. They are usually only used where a wetland's conservation values are well-documented, and its conservation priority is well-justified and accepted. Due to the investment levels required, government is normally involved.

For social, economic or ecological reasons, it may not be possible or appropriate to restore every wetland to its original hydrology. In these cases, it might be better to accept the altered hydrology and where appropriate, shift focus from restoring hydrology to maintaining a functioning, if changed, ecosystem.

Lastly, it is important to acknowledge that it is possible that reinstating the natural water regime might not restore the wetland ecosystem present before the change to the water regime, or might have unintended outcomes. This is potentially the case at Lake Warden, where lowering the water level in the wetland to natural levels appears to have dramatically increased the wetland salinity.

Table 7 provides a summary of the major causes of altered hydrology in Western Australia, and how their impacts may be mitigated. In some cases, the only mitigation measure is to avoid the activity that causes hydrological change.

Table 7. Potential responses to altered hydrology.

Cause	Potential management responses		
Aim: to maintain hydrological processes in healthy wetlands			
	• maintain wetland vegetation and surrounding dryland vegetation	• avoid any earthworks, drainage, pumping, clearing or plantations that might alter flows into or out of the wetland	Page 57
	• avoid placing abstraction bores near the wetland, or borefields upgradient of wetlands that rely on groundwater.	• monitor wetland condition	
	• influence proposals in planning phase	• influence legislation, policy or plan	Pages 57 - 63
Aim: to avoid water rise in wetlands			
New proposal to dewater or clear	• influence proposal in planning phase	• influence legislation, policy or plan	Pages 57 -63
Dewatering	• aquifer reinjection of dewater (managed aquifer recharge)	• alternative uses of excess dewater	Pages 65 - 66
Aim: to manage water rise in wetlands			
Clearing	• maintain native vegetation	• large scale revegetation	Pages 66 - 72
	• large scale deep-rooted perennial cropping/plantations	• landscape drainage modifications	
	• surface water inflow diversions	• wetland dewatering	
	• groundwater pumping		
Aim: to manage water decline in wetlands			
New proposal to take water	• influence proposal in planning phase	• influence legislation, policy or plan	Pages 57 - 63
Existing use of water	• ensure water is allocated to wetlands at a sub-regional scale	• employ water use efficiencies	Pages 72 - 87, 89 - 91, 93 - 94
	• deter illegal/unapproved use of water	• recycle water	
	• use alternative water sources - desalination - alternative groundwater aquifers - stormwater and rainwater	• recharge groundwater	
	• avoid abstracting near wetlands	• minimise drawdown of wetlands via best practice abstraction	
	• artificial supplementation		
Dewatering	• use alternative to dewatering	• design and operate dewatering to minimise impacts	Pages 88
Plantation, vegetation	• design, operate and modify tree plantations	• modify natural vegetation	Pages 92 - 93
Aim: to manage water balance			
General development	• use well-designed culverts in existing wetland causeways	• do not install new causeways	

Cause	Potential management responses		
New proposal for urban development	• influence proposal in planning phase	• influence legislation, policy or plan	Pages 57 - 63
	• infiltrate water into the soil throughout the catchment in small rainfall events, rather than directing it into pipes or open drains	• use well-designed public open space, road reserves and wetlands to receive stormwater in moderate to large rainfall events by overland flow paths across vegetated surfaces	Pages 85 - 87, 95 - 97
	• adequately separate sub-soil drainage systems from wetlands		
Urban development	• Retrofit urban environment		Pages 85 - 87

Maintaining hydrological processes in healthy wetlands

Prevention is better than cure. It is easier to maintain hydrological processes than to reverse altered hydrology. If a wetland's hydrology is still largely intact, then the following actions will help achieve good hydrological management:

- maintain wetland vegetation and surrounding dryland vegetation
- avoid any earthworks, drainage, pumping, clearing or plantations that might alter flows into or out of the wetland
- avoid placing abstraction bores near the wetland, or borefields upgradient of wetlands that rely on groundwater
- monitor wetland condition.

Influencing legislation, policies and plans to protect wetland hydrology

Government policies, plans and legislation form the basis for permitting or prohibiting activities that can alter hydrology, and therefore they can strongly influence wetland hydrology. They can determine the nature of land use or water use, so influencing their formulation or their revision can be more effective than on-ground works to maintain or restore natural wetland hydrology.

The community has an important role in setting political agendas and raising government awareness of wetland conservation issues. While specific government agencies are assigned responsibilities for wetland conservation by the state government, government agendas and programs are frequently influenced by community concerns and opinions. Some government committees include community representatives to facilitate greater consideration of community opinions when developing policy and making decisions. For example, the Wetlands Coordinating Committee (described later) and a number of its sub-committees include representatives of the voluntary conservation movement and wetland scientists from universities and the private sector.

Agencies of both the Western Australian and Australian governments publish documents that guide water management in the spheres of land use planning, environmental protection and water resources. Influencing the positions established by government, and ensuring that these positions are mirrored in decision-making processes, can be effective. Most policies, strategies, and position statements developed by government agencies or committees are released in draft form for public comment. Submissions made during this time are usually considered through a formal process and a response is made to each substantive point raised. Submissions with well defined and explained points make it easier for the agency or committee to respond. Most agencies publish guidelines for preparing submissions. The response to submissions is sometimes published. Some agencies or committees will invite community input before a draft is prepared, in the form of a workshop or survey. Invitations may be extended on a random basis or to known representative community members.

extra information

Gnangara sustainability strategy: an example of public participation

The Gnangara sustainability strategy (GSS) is a cross-government initiative working on an action plan to ensure the sustainable use of water for drinking and commercial purposes and to protect the environment. The consultative approach taken seeks to address land, water and biodiversity issues on the Gnangara system through a transparent, cooperative framework for the benefit of all groundwater users.

The draft GSS was released for public comment on 6 July 2009 for an eight week period concluding on 31 August 2009. Sixty-two submissions were received, consisting of 1179 comments. A further 136 comments were made on Appendix 1 - Gnangara groundwater system zone plans. All comments received during the public submission period for the draft GSS have been collated and analysed. The analysis of public submissions is available from the GSS website, and together with a final strategy has been delivered to the Western Australian State Government for consideration in December 2009. Further consultation is taking place on some elements of the strategy.

For more information see www.water.wa.gov.au/sites/gss/index.html.

Broad policy development can also be initiated by government in response to an issue raised by the community through individual or group lobbying to the responsible Cabinet Minister. The community response to a specific plan or proposal can also contribute to broader policy development on an issue.

Changing the way water is managed, referred to as *water reform*, has been high on the state and Australian Government agenda. In particular, the National Water Initiative (NWI), of the National Water Commission, is guiding nation-wide reforms. The NWI represents a shared commitment by governments to increase the efficiency of Australia's water use, leading to greater certainty for investment and productivity, for rural and urban communities, and for the environment. The WA Government signed the NWI in April 2006. WA's water reform agenda is aimed an ensuring there is enough water for long term economic and social needs in a changing climate as well as ensuring the environment is protected. Improved water planning and water allocation processes and outcomes are key tenets of water reform.

Table 8, Table 9 and Table 10 outline some of the key studies, state plans and legislation that determine how wetland hydrology is influenced by water and land use in WA. More information on water allocation process is provided in the below section entitled 'Ensuring water allocated to the environment in water allocation plans provides for wetland water requirements'.

➤ More details on water reform progress are available from www.water.wa.gov.au/Future+water/Water+reform/default.aspx#1.

➤ More information on policies and legislation relevant to the protection of wetland water regimes is available in the topic 'Legislation and policy' in Chapter 5.

➤ Information on the roles of state and Australian government agencies is provided in the topic 'Roles and responsibilities' in Chapter 5.

Table 8. Regional water studies

Study	Geographic scale	What it establishes	More information
Northern Australia Water Futures Assessment	Kimberley, north and east from Broome across northern Australia	The information needed to inform the development and protection of northern Australia's water resources, so that development is ecologically, culturally and economically sustainable	www.environment.gov.au/topics/water/water-information/northern-australia-water-futures-assessment

Table 9. Some of the plans, licenses and approvals that have an influence on wetland hydrology (see also Table 11, page 97)

Type of plan	Geographic scale	What it establishes	Lead organisation	More information
Regional water plans	Regional	The region's water allocation; water use efficiency; water service provision; waterways, drainage and floodplain management.	Department of Water	www.water.wa.gov.au/Future+water/Resource+management/Regional+water+planning/Overview/default.aspx Currently, there are four regional plans covering the Kimberley, Pilbara, Perth-Peel and South-west regions.
Water allocation plans	Regional	How much water is allocated to wetlands	Department of Water	www.water.wa.gov.au/Managing+water/Allocation+planning/default.aspx See also the below section 'Ensuring water allocated to the environment in water allocation plans provides for wetland water requirements'.
District water management strategies	District	Whether the area is capable of supporting urban development, and if so, how water in the landscape will be managed	Department of Water	www.water.wa.gov.au/Managing+water/Water+and+land+use+planning/default.aspx www.water.wa.gov.au/Managing+water/Urban+water/Strategies+and+management+plans/default.aspx#1
Strategic water issue plans	Variable	Variable	Variable	For example, the ***Gnangara Sustainability Strategy*** is a cross-government initiative: www.water.wa.gov.au/sites/gss/gss.html
Development proposals	Local	How a development is designed, constructed and operated	Department of Planning, Environmental Protection Authority	

Type of plan	Geographic scale	What it establishes	Lead organisation	More information
Licenses to take water	Local	How much water can be taken and under what conditions	Department of Water	www.water.wa.gov.au/Business+with+water/Water+licensing/default.aspx
Wetland management plans	Local	How a wetland is managed	Land manager; third party on behalf of/with consent of land manager	Seek from the land manager.
Strategic regional plans (various names)	Regional	What vision and priority is given to wetlands in a region by the group/community	Natural resource management organisations	Northern Agricultural Catchments Council www.nacc.com.au *Regional Natural Resource Management Strategy, Northern Agricultural Region of Western Australia* Perth Region NRM www.perthregionnrm.com *The Swan Region Strategy for Natural Resource Management* Rangelands NRM WA www.rangelandswa.com.au *Rangeland NRM Strategic Plan 2012-2015* South Coast Natural Resource Management Inc. www.southcoastnrm.com.au *Southern Prospects 2011-2016* South West Catchments Council www.swccnrm.org.au *Draft South West Regional Natural Resource Management Strategy 2012-2020* Wheatbelt NRM www.wheatbeltnrm.org.au *Wheatbelt Strategic Plan 2010-2012*

Table 10. WA Acts covering water resources management

Act	Purpose
Country Areas Water Supply Act 1947	Provides for the protection of public drinking water source areas in rural areas and the regulation of clearing control areas.
Environmental Protection Act 1976	Provides for the prevention, control and abatement of pollution and for the conservation, preservation, protection, enhancement and management of the environment.
Land Drainage Act 1925	Provides for the constitution and abolition of drainage districts.
Metropolitan Water Authority Act 1982	Authorises the provision of certain drainage works and coordinates drainage services.
Metropolitan Water Supply, Sewerage and Drainage Act 1909	Provides for the protection of public drinking water source areas in the metropolitan area.
Rights in Water and Irrigation Act 1914	The principal legislation for the allocation and management of use of water resources.
Water Agencies (Powers) Act 1984	Provides many of the works and other powers of the Minister for Water and the Department of Water.
Waterways Conservation Act 1976	Provides for the conservation and management of certain waters and associated land and environment.

Influencing proposals and decisions in the planning phase - avoiding or mitigating impacts

Decision-making processes often have a public consultation phase built-in. Community input during these phases can be a very effective way to influence a decision-making authority's determination of a proposal (a decision-making authority, or DMA, is a public authority empowered by legislation to make a decision in respect of a proposal). Raising issues early in the planning process is most effective, as it provides the proponent with more opportunity to address an issue or modify a proposal during the earlier stages of planning.

Planning development and new infrastructure can require considerable investment and the later in the process an issue is raised, the less likely it will be that the proponent will want to, or be able to afford to change the proposal.

A decision-making process that can involve considerations of wetland hydrology is the environmental impact assessment process. Where proposals that are likely to result in a significant effect on the environment, these need to be referred to the Environmental Protection Authority (EPA) under Part IV of the *Environmental Protection Act 1986*. For example, where an application for a water licence being sought under the *Rights in Water and Irrigation Act 1914* would have a significant effect on the environment the Department of Water must inform the EPA, and the impact of the licence would be considered by the EPA during its environmental impact assessment process.

As shown in Figure 26, the EPA requires proponents of land and water use proposals to seek to avoid impacts to the environment.

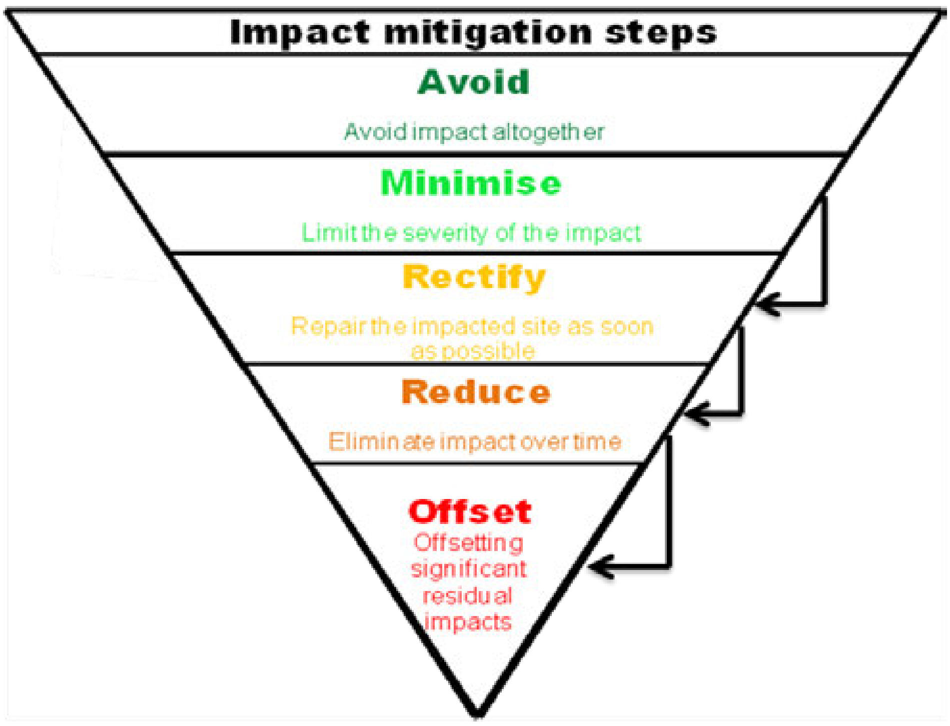


Figure 26. The EPA's decision framework. Avoiding environmental impact is the primary objective of environmental impact assessment. Image – R Pybus/DEC, adapted from EPA (2006).[146]

Via the environmental impact assessment process, the Government of Western Australia has established the water to be allocated to wetlands and other groundwater dependent ecosystems on Perth's Gnangara and Jandakot mounds.

In 1986 the EPA assessed the Water Corporation's proposal to abstract groundwater from the Gnangara Mound for public water supply and provided advice to the Minister for the Environment. In 1988, the Minister for the Environment approved the proposal, subject to conditions, to ensure that the wetlands (and other groundwater dependent environments) would be protected. These conditions were applied under the provisions of the *Environmental Protection Act 1986* and published in Ministerial Statement No. 021. These conditions established water level criteria for a number of wetlands. These wetlands are commonly referred to as 'Ministerial criteria sites' and they were chosen to represent the range of wetlands across the mound. The water level criteria were established through the determination of ecological water requirements. Typically, the way water was 'allocated' to wetlands was to identify a minimum water level permissible at each wetland below which the water should not fall (either surface or groundwater). The Ministerial conditions for the Jandakot Mound were first established in 1992 in Statement No. 253.

The impacts of abstraction are chiefly measured through compliance with environmental conditions that are monitored at Ministerial criteria sites. Compliance reporting is published by the Department of Water. The Ministerial conditions have been revised a number of time since 1986, in part because of the compounding effect of climate change and pine plantations on groundwater levels (the amendment of conditions is provided for under section 46 of the Act). Since 1997, the then Water and Rivers Commission (now Department of Water) has been subject to the Ministerial conditions. A review of the Ministerial conditions was completed in 2008 and most recently the requirements have been established in Ministerial Statement No. 819[147] for the Gnangara Mound, and Ministerial Statement No. 688[148] for the Jandakot Mound.

➤ For water level data for selected wetlands on the Gnangara and Jandakot mounds, see http://kumina.water.wa.gov.au/waterinformation/ewp/ewp.cfm.

Other water supply projects approved with Ministerial conditions under the *Environmental Protection Act 1986* include the Exmouth and Kemerton water supply.

The environmental impact assessment process grants members of the community specific rights to have concerns and views regarding proposals taken into consideration. These rights are generally applicable where a proposal is formally assessed, however, the EPA may request targeted public input into proposals that are assessed informally and that do not have to undergo a full assessment.

The types of submissions and appeals an individual may make include:

(i) a submission to the EPA during the public submission period of a project proposal undergoing environmental impact assessment

(ii) an appeal against decisions, recommendations and orders issued in respect to the environmental impact assessment process and applications to clear native vegetation to the Minister for Environment.

Appeal rights include the right to appeal:

- the decision of the EPA not to assess a proposal
- the content or recommendations of an EPA report.

The following appeals are only available to the proponent of the proposal:

- conditions imposed on a proposal by the Minister
- an order imposed on a proponent by the Minister following a breach of conditions.

➤ More information on public participation in decision making processes is available in the topic 'Legislation and policy' in Chapter 5.

➤ Information on the roles of decision making authorities is provided in the topic 'Roles and responsibilities' in Chapter 5.

Accepting hydrological change and managing the new conditions

It will not always be possible, practical or appropriate to reinstate the wetland's hydrology, or even to know what it was. Some of the reasons for this include:

- The remediation tools and techniques available are not effective enough to reinstate the original hydrology and vegetation.
- Wetland conservation may be a lower priority than the management goal for which the hydrology was altered (for example, water supply, urban development).
- The influence of a changing climate on wetlands cannot be mitigated directly through on-ground management.
- New ecological or social values have developed at the wetland as a result of the altered hydrological conditions. For example, at Lake Yangebup drainage inputs have caused increased water levels, and the lake now supports a significant population of diving birds.
- Irreversible change has occurred. For example, Lake Gnangara, which has undergone drying over more than twenty years, severe and sustained acidification, and a complete change in the ecological community; and some wetlands in the WA Wheatbelt.[125]

In such cases, management might involve accepting the wetland's new state, making modifications to reduce (rather than cease) the impacts of the land use, or a combination of the two.

More broadly, there are some basic principles that can be applied to assist wetland ecosystems to adjust to new hydrological conditions. These include:

- Preventing excessive or sudden hydrological changes, to allow plants and animals to 'migrate' if possible.
- Increasing the resilience of wetlands by reducing other stressors, and managing other threats to the integrity of wetland ecosystems. Under changed hydrological conditions, wetlands are likely to be less resilient to other threats, for example, the effect of too frequent fire if a wetland is drying, particularly if there is a risk of acidification. Similarly, other threats could reduce the capacity of wetland ecosystems to cope with altered hydrology.
- Improving the biological connectivity between wetlands in the landscape, through a planning process that supports ecological corridors and land uses that are sympathetic to nature conservation.

What not to do: make wetlands deeper if they dry out

Landowners can understandably become upset when wetlands dry out beyond their natural water regime. There are many instances of landowners excavating wetland soil to make a deeper wetland that intercepts groundwater. There are many potentially significant impacts in doing this including:

- a high potential to cause the acidification of soils and water due to disturbance of acid sulfate soils
- direct harm to species inhabiting the soils including aestivating turtles, fish, frogs, plants, macroinvertebrate egg banks and wetland plant seed banks
- changes in habitat due to changes in the topography of the site
- loss of wetland sediment, which is habitat for species
- alteration of the ecological character of the wetland, due to the loss of sediment biogeochemical processes
- alteration of wetland sediment, potentially increasing the loss of water from the wetland due to loss of retarding layers such as clay and important soil stratigraphy such as layers of sand and clay
- exposure of groundwater, increasing transpiration of the superficial aquifer and potentially affecting other nearby wetlands and waterways

Digging out wetlands may constitute environmental harm under the *Environmental Protection Act 1986*. Authorisation is typically required to carry out such actions, as outlined in the topic 'Legislation and policy' in Chapter 5.

Prioritisation processes

Often the regional scale of altered hydrology means that it is likely that it will not be possible to tackle altered hydrology at every wetland. Prioritisation is typically required to decide which wetlands should receive intervention measures and which will miss out. In areas where the risks of altered wetland hydrology are high, prioritisation processes can help to focus management efforts where they will have most effect. Prioritisation processes usually entail an identification of:

- wetland values
- threatening processes
- potential to address threats.

An example of sub-regional wetland prioritisation process is the *Buntine-Marchagee Natural Diversity Catchment Recovery Plan: 2007–2027.*[149]

A drying climate in the south-west and further pressures on water resources are realities that must be taken into consideration in wetland management. The draft *Gnangara Sustainability Strategy*[150] recognises that some of the legally required water levels for wetlands on the Gnangara Mound (via ministerial conditions) are no longer achievable. It is generally agreed that new standards need to be set, against which to monitor management of the groundwater resource.[150] This will require accepting that many Gnangara Mound wetlands will inevitably become drier and some will transition to dryland environments. Minimising further exacerbations to wetlands adjusting to new, drier conditions will involve designing ways to abstract groundwater that protect the most sensitive locations.

extra information

Climate change adaptation: what the buzz words mean for wetlands

There are two main categories of human responses to climate change: mitigation and adaptation. Both types of response help to reduce the risks of climate change.

Mitigation involves actions that are intended to reduce the magnitude of our contribution to climate change. It includes strategies to reduce greenhouse gas sources and emissions and enhance greenhouse gas sinks.

Adaptation consists of actions undertaken to reduce the adverse consequences of climate change, as well as to harness any beneficial opportunities. Adaptation actions aim to reduce the impacts of climate stresses on human and natural systems.

At the scale of a region's wetlands, adaptation strategies include:

- identifying, protecting, managing and planning for climate change refuges
- maintaining and creating connectivity of habitats and landscapes
- using technological and engineering solutions to sustain important threatened ecosystems
- translocating fauna to other habitat, where assessments indicate this is appropriate
- increasing resilience by reducing other stressors
- effective monitoring of change and timely and appropriate responses
- establishing incentives to promote improved conservation management on private lands.[151]

For more information, see the *Climate change and Western Australian aquatic ecosystems, impacts and adaptation responses, 2011 report card*[19]

Avoiding water rise in wetlands

Wetlands and interconnected drainage network systems are not appropriate discharge outlets for dewatering. Methods used to avoid water rise in wetlands include:

- aquifer reinjection of dewater
- alternative uses of excess dewater

Reinjecting aquifers with dewater (managed aquifer recharge)

Where conditions are suitable, aquifer reinjection of dewater offers an alternative to direct discharge into wetlands. It has been employed in the Pilbara, where it was pioneered at the Yandicoogina mining operation by Rio Tinto Iron Ore. Via five re-injection bores,16,500,000 litres (0.0165 gigalitres) a day of excess water has been reinjected into the Yandicoogina aquifer since 2006, avoiding what had been the standard regional practice of discharging surplus water into surface ecosystems such as waterways.[152] The project was recognised as leading practice, winning the 'Management of water resources – commercial project' category at the 2007 Western Australian Water Awards. This aquifer reinjection is considered to be a form of **managed aquifer recharge.**

Managed aquifer recharge: recharging an aquifer under controlled conditions to store the water for later abstraction, to achieve environmental benefits or to mitigate the impacts of abstraction

Using surplus dewater rather than discharging it to wetlands

Mining proponents are required to use dewatering volumes to mitigate any environmental impacts in the first instance. That is, where dewatering is creating a deficiency for a wetland or other ecosystem, the priority is for the dewatering to be used to mitigate this. Water needs of the mine and mining camp are the second and third priorities. Where surplus water still exists following these needs being met, it is now required of proponents of mining operations to consider alternatives to discharge to the environment.[153] There is now a mandate for the analysis of the potential for appropriate alternative uses of dewatering surplus in sectors such as irrigated agriculture, industry or recreational or social needs in the community.

Managing water rise in wetlands

Methods used to manage water rise in wetlands include:

- large-scale native revegetation of dryland and wetland
- planting of deep-rooted perennial crops
- modifying landscape drainage patterns
- controlling surface water inflows
- wetland dewatering
- groundwater pumping
- draining into low value ecosystems to protect high value ecosystems

Managing water in agricultural catchments can entail retaining and replanting native vegetation and modifying landscape drainage patterns. In productive agricultural catchments, it is not always viable to revegetate catchments to the extent needed to improve wetland hydrology. The significant resources need to alter catchment flows by means other than revegetation means that a limited number of priority wetlands and priority catchments are the focus of recovery actions by state government.

The 'Natural Diversity Recovery Catchments' program developed under the State Salinity Strategy is a landscape-scale program aimed at protecting areas with high natural diversity that are threatened by rising water tables and salinisation, and focusing especially on wetlands. So far, six Natural Diversity Recovery Catchments exist:

- Buntine-Marchagee
- Drummond
- Lake Bryde complex
- Lake Muir-Unicup
- Lake Warden
- Toolibin Lake.

A central aim of salinity and landscape-scale water management in these catchments is to achieve integration between nature conservation and sustainable agricultural practices[149] (Figure 27).

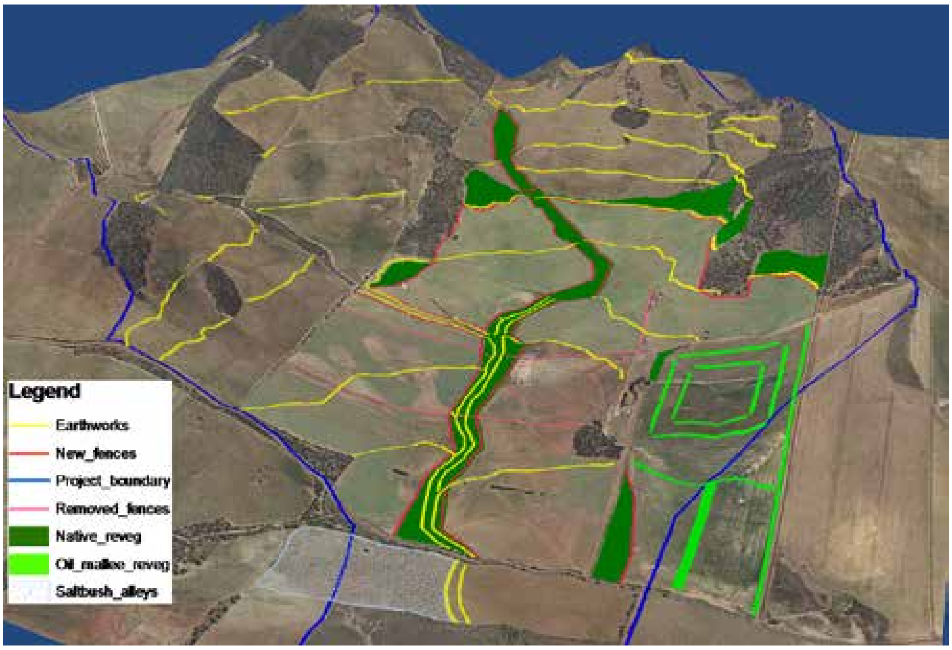


Figure 27. Integrated water management at the landscape scale in agricultural catchments has a positive effect on reducing salt, nutrient and sediment export to downstream wetlands. Engineering and biological options are integrated to optimise gains in water management (surface and groundwater) and agricultural productivity in this 800-hectare demonstration area in the Buntine-Marchagee. Note the elevations are exaggerated. Image – R Dawson/DEC.

Oil mallee: multi-stemmed eucalypt planted on agricultural land, with the stems arising from an underground root mass known as a lignotuber. Stems can be harvested for products such as eucalyptus oil.

➤ Information on DEC's Natural Diversity Recovery Catchments can be found at DEC's website.[154]

Another major state government program, which focuses on landscape-scale salinity management more broadly, is the Engineering Evaluation Initiative led by the Department of Water. It examines a range of potential mitigation options including deep drains, groundwater pumping and surface water management, safe saline water disposal and regional drainage planning.

➤ More information on the Engineering Evaluation Initiative is available from the Department of Water website.[155]

Retaining and replanting native vegetation

Native vegetation uses water, and retaining vegetation is a cost-effective way of maintaining existing water use. It also slows surface flows in the catchment, and understorey vegetation can be just as important as trees in regulating flows. Native vegetation also helps to maintain biodiversity. It can be achieved by fencing off remnant vegetation from livestock (Figure 28).

While not offering a magic bullet to landscape-scale watertable rise in agricultural settings[156], replanting native vegetation can also be beneficial (Figure 29). For maximum effectiveness the extent needed and location is best determined in consultation with hydrologists, based on an analysis of recharge characteristics in a catchment. As a rule, trees are best planted in recharge areas; discharge plantings rarely reclaim saline areas; responses are generally confined beneath the planting; and plantings of extensive areas of a landscape are required to significantly reduce watertables.[157] Perennial crop plantations such as **oil mallees**[158] can achieve nature conservation and sustainable agricultural objectives under the right conditions.[159] A number of government and non-government programs provide funding and labour for fencing of native vegetation and covenanting of protected remnants.

In some circumstances, the government offers farmers cost-sharing arrangements to revegetate areas to improve water use and contribute to recharge control. This is the case in the 140,000 hectare Lake Bryde Natural Diversity Recovery Catchment, where more than 400,000 native species plants have been planted on private property and reserves, and more than 500 hectares of remnant vegetation have been fenced off. These actions are complemented by a large scale surface water management project.

➤ For more information on funding, labour and other assistance see the topic 'Funding, training and resources' in Chapter 1.

➤ Analysis of the uptake of water by trees is outlined in reports such as *Hydrological impacts of integrated oil mallee farming systems*.[159]

➤ Revegetation case studies, such as those provided at www.dec.wa.gov.au/management-and-protection/land/salinity/revegetation.html?showall=&start=1 highlight useful information.

Figure 28. Fencing off native vegetation can be a cost-effective measure for hydrological management. Photo – G Mullan/DEC.

(a)

(b)

Figure 29. (a) oil mallee eucalypts, on right of photo, a prospective commercial crop, growing alongside traditional crops in the Buntine-Marchagee catchment; and (b) mixed shrubs and trees have been chosen in this location within the Buntine-Marchagee catchment for their resilience, structural diversity and genetic integrity. Photos – G Mullan/DEC.

Contour banks: mounds of earth which follow hillslope contours to arrest flowing water and allow infiltration

Grassed waterway: a vegetated channel which directs water flow paths. The vegetation slows surface flows.

Retaining and replanting trees

Deep-rooted trees are proving useful in lowering high groundwater in some areas of the south-west. For example, blue gum (*Eucalyptus globulus*) plantations are attributed with reducing the unnaturally high water levels in some wetlands in the south coast of WA associated with widespread clearing of native vegetation for cropping and grazing. In the West Poorrarecup area, for example, it was found that some wetlands were showing improvements in condition as a result of nearby plantations[27], while other wetlands had dried up[160], although it is not clear whether these had formed due to the high groundwater following clearing.

Modifying landscape drainage patterns

Simple modifications can often be made to water flow paths to lessen the impacts of altered hydrology on wetlands. Increasingly, farmers are using mulching and earthworks to increase water uptake, slow the flow of water through the landscape, promote infiltration and reduce erosion and sedimentation. This might simply involve the reinstatement of the original lie of the land by removing artificial structures such as drains or levee banks. Other measures include **contour banks**[161], **grassed waterways** (G Mullan 2009, pers. comm.)(Figure 30), and cropping practices that leave stubble and mulch in place such as conservation tillage. These works can also improve farming outcomes, as healthy catchments are more productive. Any works should be undertaken with caution, because manipulating hydrology can often have unexpected impacts. Changes to landscape drainage patterns may be subject to regulation under the *Soil and Land Conservation Act 1945* and the *Environmental Protection Act 1986*. For more information, see the 'Legislation and policy' topic.

Figure 30. A landholder inspects a constructed grassed waterway in full flow in the Buntine-Marchagee catchment. The grassed waterway is part of the landscape-scale integrated water management approach. Photo – K Stone.

Controlling surface water inflows

Structures that bypass or divert some of the surface water flows are used in some high value wetlands, such as Toolibin Lake. A surface water diversion channel is used at Toolibin Lake to regulate the amount and quality (specifically, salinity) of the surface water that enters the wetland. The diverted flows are sent to the sacrificial wetland, Lake Taarblin. However, in the last decade, the management criterion for salinity levels at the wetland inlet has rarely been met, and as a result, the wetland bed has been largely free of surface water for an extended period[162] which creates another suite of problems for the wetland. Large rainfall events can play an important role at such sites, for example, an intense rainfall event on 12 December 2012 resulted in 0.013 gigalitres (13,000,000 litres) entering via the diversion weir, with the majority slowly evaporating over six weeks.[163]

Changes to surface water inflows may be subject to regulation under the *Soil and Land Conservation Act 1945* and the *Environmental Protection Act 1986*. For more information, see the 'Legislation and policy' topic.

Dewatering wetlands

Lowering wetland water levels by directly removing surface water is a management response that, due to its expense, is an intervention measure for wetlands of high conservation significance. Because of the need to dispose of the water, significant downstream impacts are possible. It can necessitate the construction of an evaporation basin or the sacrifice of other wetlands to receive the discharge. This is particularly harmful when the water is of a different salinity (or similarly different in its water chemistry).

Lake Wheatfield in the Lake Warden Ramsar system in Esperance is dewatered and the discharge is released into Bandy Creek. Dewatering removes excess water from the wetland generated from increased catchment runoff caused by clearing 85 per cent of the catchment's native vegetation to allow for agricultural land uses. Lake Wheatfield is hydrologically connected to Lake Warden. Prior to dewatering, "beach" areas needed by migratory and resident waders had been significantly reduced and bird numbers recorded in biannual monitoring showed steep declines. The dewatering successfully controls water levels (Figure 31) and available wader habitat. However, the alteration of water levels has contributed to increased salinity levels, a serious management issue.

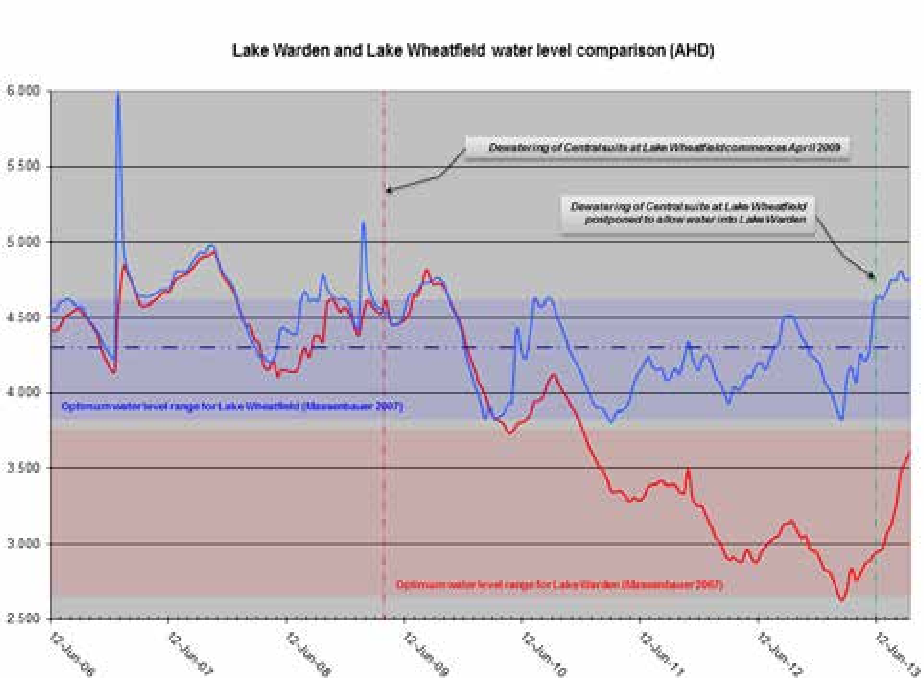


Figure 31. Hydrological response to management interventions for Lake Wheatfield (blue) and Lake Warden (red). Measurements are in metres AHD. Image: J Lizamore/DEC.

➤ Dewatering of wetlands may be subject to regulation under the *Soil and Land Conservation Act 1945* and the *Environmental Protection Act 1986.* For more information, see the 'Legislation and policy' topic.

Pumping groundwater

Groundwater pumping to lower the groundwater discharging into wetlands is a management response that, due to its expense to establish and operate, and potential complexities, is an intervention measure for wetlands of high conservation significance. It is a measure that 'buys time' to allow longer-term measures to be put in place. It isn't always an option, particularly when the hydrogeological setting is not suitable. Groundwater pumping is being used to help manage groundwater levels at Toolibin Lake, although in the past technical problems have resulted in two periods where many groundwater pumps have been out of commission.[85] Groundwater pumping may be subject to regulation under the *Environmental Protection Act 1986.* For more information, see the 'Legislation and policy' topic.

➤ For a general review of the considerations involved in groundwater pumping, see the report, *A review of groundwater pumping to manage dryland salinity in Western Australia.*[164]

Draining into low value ecosystems to protect high value ecosystems

Inland drainage should result in an overall environmental benefit.[165] Any proposal to install inland drainage should avoid wetlands and other ecosystems of high conservation value. Wetland mapping and a number of studies and policies have been developed to aid land managers and decision making authorities to identify wetlands of high conservation value in the Wheatbelt and other areas where deep saline drainage is being used to manage waterlogging and salinity. These resources include:

- *Wheatbelt basin and granite outcrop wetland evaluations* dataset
- *Evaluating the conservation significance of basin and granite outcrop wetlands in the Avon natural resource management region: Stage One Assessment Method*[166]
- *Evaluating the conservation significance of basin wetlands within the Avon Natural Resource Management region: Stage Three Assessment Method*[167]
- *Policy framework for inland drainage*[165]

Minimising water decline in wetlands

Minimising water decline in wetlands can be achieved by selecting a suite of strategies, such as:

- ensuring water allocated to the environment in water allocation plans provides for wetland water requirements
- using desalinated water
- using less water
- preventing illegal water use/ loss of unused water
- prioritising water for the environment over aesthetic uses such as artificial lakes
- reusing (recycling) more water
- harvesting alternative water sources (desalination, deep aquifers and coastal superficial aquifers)
- recharge aquifers through managed aquifer recharge
- developing alternative water sources
- choosing abstraction locations to avoid wetlands
- minimising drawdown near wetlands via abstraction depth, rate and timing
- minimise subsoil drainage effects on wetlands
- avoiding or minimising dewatering impacts near wetlands
- artificially recharging wetland with dewater
- maintaining wetland water levels artificially
- reducing drawdown caused by plantation trees
- modifying current vegetation

These are outlined below.

Ensuring water allocated to the environment in water allocation plans provides for wetland water requirements

The *Rights in Water and Irrigation Act 1914* provides the legislative basis for the planning, regulation, management, protection and allocation of water resources in WA, including the identification and management of water for ecosystems.[168]

Under the RIWI Act, the right to the use and control of all groundwater (artesian and non-artesian) is vested in the 'Crown', that is, the state of WA. No person can access or use groundwater except in accordance with the rights and obligations conferred under the RIWI Act (or another law).[34] The Minister for Water has delegated responsibility to the Department of Water for administering the Act through the preparation of **water allocation plans** and the administration of water entitlements and water rights. Unlike many other jurisdictions in Australia, there are no **held environmental water** entitlements in WA.[168]

The decisions made by the Department of Water when a **water licence** is applied for under sections 5C and 26D of the Act are guided by water allocation plans. Water allocation plans are non-statutory, but provide important guidance on the water **allocation limits** within a particular geographic area, how much water is assigned for the environment–the **environmental water provision**–and the **sustainable yield** that

Water allocation plan: a plan that determines and licenses how much groundwater or surface water can be taken from a region for domestic or commercial purposes without adversely affecting ecological, recreational and cultural values

Held environmental water: water available under a water access right, a water delivery right or an irrigation right for the purposes of achieving environmental outcomes

Water licence: a formal permit which entitles the licence holder to 'take' water from a watercourse, wetland or underground source under the *Rights in Water and Irrigation Act 1914*

Allocation limit: annual volume of water set aside for consumptive use from a water resource

Environmental water provision: the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements.

Sustainable yield: the amount of water that can be taken from a water resource system (expressed as an extraction regime) without causing unacceptable impacts on the environment can be taken. There are currently twenty water allocation plans in place, covering 80 per cent of WA's water use (Figure 32). This includes four groundwater water allocation plans under development.[168]

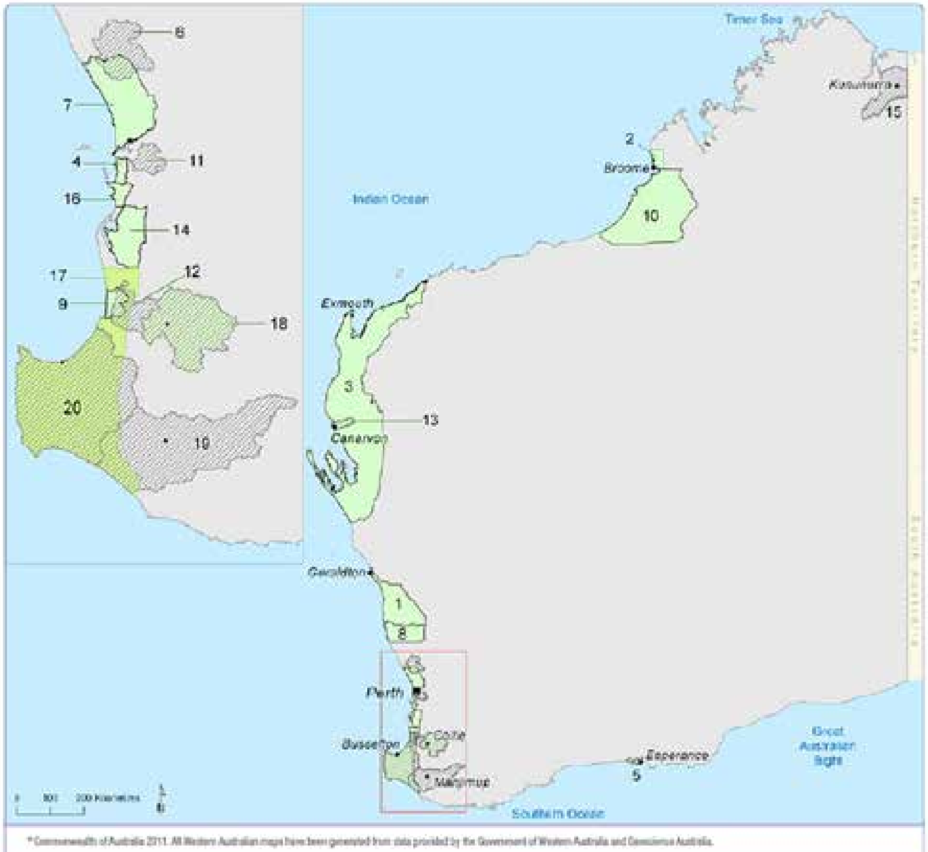


Figure 32. Water management plan areas in WA. Image – National Water Commission 2011.[170]

Environmental water requirement: the water regime needed to maintain the ecological values (including, assets, functions and processes) of water-dependent ecosystems at a low level of risk

The Department of Water is required to consider environmental needs for water in accordance with *Statewide policy no. 5 – Environmental Water Provisions Policy for Western Australia.*[171] Plans are required to state the regimes, levels, volume or thresholds required for environmental water, that is, their **environmental water requirement,** and how this has been determined, to what extent it will be achieved through the environmental water provision and how it will be monitored. In developing water allocation plans, the Department of Water carries out pre-planning assessments to determine what water the environment requires.

Environmental water provisions are then established for each resource and implemented through the setting of allocation limits and through system specific management rules and trigger levels. These may relate to attributes of the groundwater regime such as flux or flow, level (in unconfined aquifers), pressure (in confined aquifers) and water quality. An objective of the Gnangara allocation plan, for example, is to 'Protect groundwater-dependent ecosystems from direct impacts associated with abstraction'[36] and a maximum allowable depth to groundwater (summer and/or spring maximum) below valuable groundwater dependent ecosystems is applied. High value groundwater-dependent ecosystems that may be affected by abstraction may have local area policies applied to them. The department develops these additional requirements to protect high value areas or areas at high risk of impact. Trigger and response criteria may also apply to some sites.[36]

Draft water allocation plans are released for pubic comment, and this is the best time for stakeholders to examine how the plan ensures a wetland's water requirements are met. Plans are approved by the Minister for Water and apply for a seven-year period, with ongoing interim evaluation. Taking the opportunity to comment on these plans through the public consultation process, or becoming involved with a stakeholder committee on water planning, are two ways to advocate for the maintenance of wetland hydrology at a big-picture level.

➤ The process for stakeholder participation, are explained in the report *Water allocation planning in Western Australia: a guide to our process.*[172]

➤ A review of environmental water management in WA has been produced by the National Water Commission in 2012, entitled *Australian environmental water management: 2012 review.*[168]

➤ A report card on how well WA carries out water planning was produced by the National Water Commission in 2011[170]: www.nwc.gov.au/?a=19805.

➤ The current allocation plans for various areas of WA are available on the Department of Water website at: water.wa.gov.au/Managing+water/Allocation+planning/default.aspx.

➤ Potential reforms of WA's water allocation process are outlined in the report *Proposed Water Resources Management Act background discussion paper*.[6]

The importance of participating in the water allocation planning process

A water allocation plan includes:

- objectives for the plan
- water allocation limits (as volumes)
- water for the environment (as volumes or regimes)
- water licensing policies
- arrangements for implementing and evaluating the plan.[173]

Ensuring the full range of stakeholders participate in the water management planning process is important in ensuring that the public participation process represents the views of all Western Australians. To this end, the Department of Water has published a short guide entitled *How to make a submission on a water allocation plan during the public comment period*[174] available from www.water.wa.gov.au/PublicationsStore/first/99163.

Using less water

Across Australia and globally, individuals, groups and governments are acknowledging the precious nature of our freshwater resources, and changing behaviour to reduce water use.

Using less water is important across all sectors including mining, industry, agriculture and domestic. Even in those areas where there is too much water in the landscape, freshwater is still a scarce resource and needs to be used efficiently.

Perth is now saving more than 100 gigalitres (that is, 100 billion litres) of scheme water each year[175] (that is, water from the integrated water supply scheme, which does not account for water harvested from rainwater tanks, groundwater bores and so on). Over the past five years, savings work out to about 8 per cent per person.[175] 'Waterwise' campaigns and water pricing that better reflects the true cost of water use have contributed to changing behaviour. However, the Water Corporation reports that the average water use per person was 132,000 litres in the 2012–13 financial year, making Perth one of the highest water using cities in not only Australia, but the world. Regulation of water use is still critical, for example, the two-day-a-week sprinkler roster in Perth, which accounts for slightly more than half of the 100 billion litre saving in scheme water; and which tackles one of the key issues for water use in residential areas, "Western Australia's most extensive and expensive irrigated crop, the suburban lawn".[54] In addition to more efficient use of scheme water, another important initiative is reducing the volume of groundwater abstracted via garden groundwater bores; there are an estimated 169,200 domestic garden bores taking groundwater from the superficial aquifer in Perth, and the Department of Water estimates that up to a quarter of water abstracted from the Gnangara Mound is done so for domestic use.[176] The Department estimates that approximately 73 gigalitres of groundwater was abstracted using domestic garden bores in the Perth metropolitan area in 2010.[177] Although unlicensed and not metered, they are subject to some control via the sprinkling restrictions and controls on their use near high value wetlands.

In WA, the Department of Water and the Water Corporation have sought to reduce water use via 'Waterwise' campaigns. The Water Corporation has published a target to reduce water use by 15 per cent/125 kilolitres of scheme water used per person per year in Perth by 2030.[175]

Similarly, in the Kimberley, Pilbara, Great Southern and Goldfields regions, water efficiencies achieved through the 'Regional Integrated Water Efficiency Program' are estimated to have saved 4.5 gigalitres of water in its first full year.[175]

In 2007 the Minister for Water Resources established the requirement for all local governments to prepare and implement water conservation plans that conserve groundwater and improve water use efficiency.

Through the massive cultural shifts in water use taking place, there is evidence that Western Australians do value wetlands and other water-dependent ecosystems, and embrace the sense of place that makes Western Australia unique. George Seddon, author of *Sense of Place, a response to an environment: The Swan Coastal Plain, Western Australia* wrote that, on arriving from Victoria, "I was ill-prepared for Western Australia, and I think this must be a common experience. Even the West Australians whose families have been here for three and four generations are ill-prepared in some basic ways, because our primarily British background is still apparent in our attitudes towards the way we use the environment; and in nothing so much as our attitude to water. Centuries of water-riches makes it hard to grasp our water-poverty and its implications, although these are better-understood in Western Australia that they are in the coastal cities of eastern Australia. In Perth (and Adelaide) the aridity of this most arid of continents is a part of one's consciousness".[54]

Ongoing reductions in water use will continue to be needed, in order to help offset increasing population and, in larger areas of WA, the increasing drying associated with climate change. Climate models indicate a possible further 8 per cent reduction in surface water yields (for example, from dams) by 2030 in a median scenario.[175]

➤ Significant potential still exists to reduce water use in WA. Support and incentives for individuals, businesses and local government abounds. The role of individuals and groups in bringing about improved water use of individuals, businesses and local governments through corporate citizenship should not be underestimated.

➤ For more information, see the:

WA Water Awards: www.awa.asn.au/awards/wa/

Department of Water's website: www.water.wa.gov.au/Managing+water/Water+efficiency/default.aspx

Water Corporation's website: www.watercorporation.com.au/about-us/the-way-we-work/our-strategies

Preventing illegal water use and loss of water

Prevent illegal water use

The right to take groundwater or surface water is primarily granted by way of a licence by the Department of Water under sections 5C and 26D of the *Rights in Water and Irrigation Act 1914*. Allocation limits define how much water can be taken by those with a licence, and how much water is reserved for the environment. When people take water without a licence, or take more water than is allowed for in their licence, this reduces the water left for the environment. Details about licences are publicly available via a spatially-based dataset called *The Water Register*, available from www.water.wa.gov.au/ags/WaterRegister. Details about the operating strategies that form part of the terms and conditions of a licence to take water (for example, the abstraction regime and methods used to minimise impacts on wetlands) may be available to the public, subject to Freedom of Information applications.

The Department of Water has increased the metering of water use. As outlined in Strategic Policy 5.03 *Metering the taking of water*[178], this increased regulation is required because unmetered use of water resources may lead to overuse, which could have unacceptable impacts on the local ecological, economic and social values of an area. In recent years the Department has increased its compliance and enforcement activities. This includes an increased on-ground presence of compliance officers visiting properties to speak with licensees, survey water use, check meter readings, monitor daytime sprinkler bans and ensure that operations are in accordance with conditions on licences. The Department's compliance enforcement unit monitors metering readings submitted to it and audits selected licensees to assess compliance with all aspects of their licences.

The Department of Water has signalled that illegal water use is not tolerated. It issues directions, infringement notices and takes action to prosecute those in breach of the law. In recent years it has successfully prosecuted a number of illegal water users. These include a grower in the suburb of Gnangara who took more than 79 million litres (0.079 gigalitres) more water than he was entitled to, and a vegetable grower in the suburb of Wanneroo who illegally took water and tampered with a state-owned water meter to prevent the meter flow wheel from accurately measuring how much water was taken from the ground.

➤ For more information on metering on the Gnangara Mound, see the Department of Water's website: www.water.wa.gov.au/Understanding+water/Groundwater/Gnangara+Mound/Gnangara+Mound+metering+project/Project+background/default.aspx

➤ Compliance and enforcement information is available at: www.water.wa.gov.au/Business+with+water/Water+licensing/Compliance+and+enforcement/default.aspx#1

Prevent the unnecessary loss of water from wetlands and aquifers

Uncapped artesian bores are a source of water loss in areas of WA, particularly the Pilbara. Decommissioning or recommissioning these bores is effective at preventing unnecessary water loss. For example, during phase 2 of the Carnarvon artesian basin rehabilitation project, finished in September 2010, fourteen controlled bores were drilled and twenty-eight free-flowing bores were decommissioned. This saved 8 gigalitres of water from being lost across the plan area. Pressure heads increased in most areas as a result. In 2011, the Department of Water identified eight free-flowing bores that require capping as part of finalising the Carnarvon Artesian Basin rehabilitation project. The aim is to cap these bores and/or license any use from them.[179]

Feral animals including camels, horses and goats can consume significant volumes of water from natural and artificial water sources, and controlling their numbers can be important in significant and sensitive wetlands. For example, in droughts, large herds of over one hundred camels may congregate on available water, and in addition to depleting the surface water, they can cause overgrazing, trampling, pugging and fouling of wetlands.

➤ For more information on feral animal control, see the topic 'Introduced and nuisance animals' in Chapter 3.

Converting open irrigation channels to piped channels reduces seepage and evaporative losses. Harvey Water has been carrying out this conversion in the Harvey Water Irrigation Area (made up of the Harvey, Waroona and Collie irrigation zones). Harvey Water gets water from seven Darling Scarp dams controlled and maintained by the Water Corporation. It uses delivery infrastructure made up of a network of channels and pipes: 83 kilometres of lined channels, 172 kilometres of unlined channels and 430 kilometres of pipeline with a total of 1 536 supply points. Harvey Water states that the conversion of open channels to pipelines is leading to water efficiency savings of approximately 17 gigalitres (that is, 17 billion litres) per year due to water not being lost through seepage and evaporation. Harvey Water has stated its aim is to convert the remainder of the system, which is a mix of soil and concrete lined channels to pipes. The initial conversion of channels to pipelines, known as the Harvey Pipe Project, was the inaugural winner of the WA Water Awards and the WA Engineering Excellence Award in 2006.

➤ For more information see the Harvey Water website: www.harveywater.com.au.

Prioritising water for the environment over aesthetic uses such as artificial lakes

The creation of permanently inundated water bodies in urban settings is generally not supported by state government. This is particularly the case when they require the exposure of groundwater through excavation, which exposes the groundwater to evaporation and can change local hydrological patterns, affecting nearby natural wetlands and ecosystems (as well as posing a risk of acid sulfate soils). The same principle applies to artificial water bodies that are created by preventing water from infiltrating through the use of a lining or layer that slows or prevents infiltration of stormwater into groundwater. Similarly, the modification of wetland type, such as converting a seasonally waterlogged basin into a seasonally inundated basin, is not supported.

➤ This position is outlined in the *Decision process for stormwater in WA*[180] and the *Interim position statement: Constructed lakes*.[83]

Reusing (recycling) more water

Currently the vast majority of water used in WA is discharged to the ocean or other receiving environments, or lost to evapotranspiration (for example, in the case of water put on gardens). Recycling reduces the need to take more water from the environment. WA now recycles around 21 gigalitres (21 billion litres) of water a year.

Wastewater recycling

Recycled water is usually treated wastewater which is further treated to varying qualities that is 'fit for purpose' for its intended use. Wastewater is the spent or used water from a community. It comes from domestic, commercial and industrial sources, and it is 99.97 per cent water because the greatest volume comes from showers, baths and washing machines. The rest is dissolved and suspended matter. Once treated, it can then be used for:

- irrigation of sports grounds, golf courses and public open spaces
- industrial processing
- groundwater replenishment
- toilet flushing/clothes washing/garden watering
- environmental benefits (for example, maintaining wetlands)
- irrigation of food crops
- irrigation of non-food crops (for example, trees, woodlots, turf, flowers)
- construction/dust suppression

In 2012 13.6 per cent of wastewater was recycled. Generally, there is a much higher percentage of recycling in regional areas, with some towns recycling 100 per cent of their wastewater.[175] The Water Corporation is involved in approximately 50 water recycling schemes in WA to irrigate parks, gardens, golf courses, sports grounds and other open spaces. The Water Corporation has published a target to recycle 30 per cent of all wastewater in WA by 2030.[175] As well as expanding water recycling in current types of uses, such as in new industrial areas including Neerabup and East Rockingham, the Water Corporation is looking at the potential irrigation of vineyards and other horticulture, and at the potential use of dual reticulation. Dual reticulation, or 'third pipe systems', have two separate pipes deliver drinking and non-drinking water into homes and commercial/industrial in new developments. The non-drinking pipe water source may be recycled water, greywater, stormwater or groundwater.[175] Dual reticulation schemes are likely to be most viable for new developments in regional areas where scheme water supply is scarce and augmentation is costly. They are also expected to be viable for the irrigation of public open space and for large scale industrial developments. The Water Corporation works with local governments to identify all non-drinking water alternatives to scheme water use for the irrigation of public open space for new developments. Some pilot programs are in place, and a dual reticulated scheme is being considered for Karratha to irrigate residential gardens as well as public open space. Greywater recycling is a good way to return water back to the environment.

➤ For more information, see:

Department of Water's website: www.water.wa.gov.au/Managing+water/Recycling/Waterwise+community+toolkit/Non-drinking+water+sources/default.aspx

Water Corporation's website: www.watercorporation.com.au/about-us/the-way-we-work/our-strategies

Alternative water source options for landowners and developers are outlined at: www.watercorporation.com.au/Home/Builders%20and%20developers/Subdividing/Non%20drinking%20water%20options

Sewerage recycling

Sewer mining is also a potential future recycling method. Sewer mining is the process of extracting, treating and using wastewater before it reaches a wastewater treatment plant. Sewer mining is not practiced widely in Perth as groundwater is often a cheaper alternative. It may become a more attractive option with groundwater sources becoming fully allocated.[181] The Water Corporation states that this water source is under investigation, with several sewer mining proposals being assessed and the corporation potentially interested into looking into more opportunities in the future. The Town of Vincent has announced that it is investigating sewer mining as a potential water source for the Hyde Park lakes (www.vincent.wa.gov.au/Services/Environment_Sustainability/Green_Initiatives/Sewer_Mining).

Sewer mining: the process of extracting untreated wastewater from the sewerage network and treating it on-site in a treatment plant for reuse

Mine dewatering surplus

With over 200 licences to take water for dewatering and dewatering volumes exceeding 300 gigalitres per year, the use of this water as a resource is significant. Water generated via mine dewatering is required first and foremost to mitigate any environmental impacts and secondly for mine site uses. Historically water left over following this has been disposed of via aquifer injection or discharge to wetlands or watercourses over and above their needs. Now there is a stronger push to use any surplus left following these uses in a way that harnesses water as a resource, such as in other mining operations or sectors such as irrigated agriculture, industry or recreational or social needs of the community. The Department of Water has established this position and how opportunities for doing so may be facilitated in *Strategic Policy 2.09: Use of mine dewatering surplus*.[153]

Harvesting alternative water sources

Desalination

Almost half of Perth’s scheme water needs, about 150 gigalitres (150 billion litres) of water a year, is now supplied by the Perth Seawater Desalination plant and the Southern Seawater Desalination plant. The use of these alternatives to dams and groundwater is likely to be the most important water supply action taken to date to improve water security for the wetlands of the Gnangara Mound in Perth.

The Water Corporation has published a target of developing up to 100 gigalitres of new water sources.[175] Although desalination is identified as a cornerstone of Perth’s water supply, it is not considered by the Water Corporation to be a sole solution. It estimates that to rely solely on desalination for Perth’s needs would necessitate ten new 50 gigalitre desalination plants by 2060. This would entail significant public and/or private investment in capital; a six-fold increase in energy use over current levels and a doubling in water bills.[181]

Stormwater and rainwater harvesting

Stormwater and rainwater harvesting is a viable form of water reuse in some areas of Australia. However, stormwater high in the catchments is a natural source of water for wetlands lower in the catchment, and should be infiltrated into the groundwater or take flow paths that mimic their natural flow to wetlands wherever possible (outlined in the sections ‘Infiltrating stormwater at-source in urban catchments’ and ‘Using overland flow paths for stormwater entry into wetlands’). Excess stormwater at the bottom of the catchment offers more of an opportunity for harvesting.

Drainage in the region around Perth removes more water than all the bores in the superficial aquifer in the same area. A study published in 2008[182] found that the median annual discharge of stormwater from the Perth and Peel metropolitan regions was estimated as 120 gigalitres with approximately 67 per cent from the Swan-Canning catchment (exclusive of Avon and Helena rivers; and Ellen, Jane and Susannah brooks), 16 per cent from the coastal main drains (Carine, Herdsman and Subiaco) and 17 per cent from the Peel's main drains. This stormwater volume is equivalent to approximately two Mundaring Weirs at full storage capacity (63.6 gigalitres) or two and a half Perth Seawater Desalination plants (45 gigalitres). This is also greater than the potential volume from rainwater harvesting of the region's residential roofs. Some local governments collect stormwater from drains and use it locally for irrigation purposes.

Abstract groundwater from deep aquifers and coastal superficial aquifers

Abstraction from the superficial aquifers has a direct effect on wetlands fed by superficial groundwater. Because of these direct impacts, deep aquifers are increasingly considered more appropriate sources. For example, the Department of Water is working with the Water Corporation to investigate opportunities for, and the possible effects of, increasing the proportion of water abstracted from the confined aquifers relative to that abstracted from the superficial aquifer of the Gnangara groundwater system.[36] The Water Corporation has stated that in relation to Perth's water needs, the superficial inland (that is, not coastal) aquifers are now relied upon only in the very driest of years and only for about 10 per cent of supply needs.[183] It has outlined that by 2022, around half of Perth's scheme water will come from secure deep groundwater sources. This is proposed to be coupled with replenishment of the Leederville and Perth Yarragadee aquifers with recycled water (see next section for more detail), and the development of coastal superficial groundwater schemes to use water that currently flows naturally into the ocean at Eglington and Yanchep.[183]

Recharging aquifers through managed aquifer recharge

Managed aquifer recharge (MAR) is the purposeful recharge of an aquifer under controlled conditions to store the water for later abstraction, to achieve environmental benefits or to mitigate the impacts of abstraction. It can be achieved by injection by a bore or series of bores, or by infiltration using infiltration ponds or trenches.

The Department of Water is primarily responsible for administering managed aquifer recharge via the *Rights in Water and Irrigation Act 1914* (the *Environmental Protection Act 1986* may also be triggered under certain circumstances). The Department of Water recognises the potential to use MAR to recharge an aquifer near a valued wetland to maintain the wetland's water levels, while either recovering water elsewhere within the aquifer or connected aquifers where impacts would be minimal, or not seeking recovery of any of the water.[184]

The Department of Water's list of potential sources of water for MAR includes but is not limited to:

- groundwater drawn from other aquifers
- water from streams, lakes or dams
- treated wastewater sourced from industrial sites or sewerage treatment plants
- dewatering excess from mine sites or construction sites
- excess stormwater or stormwater redirected from existing drainage systems
- excess agricultural runoff.[184]

Groundwater replenishment

Groundwater replenishment is one form of managed aquifer recharge. Groundwater replenishment has been announced by the Government of Western Australia as the next new climate independent water source for Perth. This follows a three year trial which involved treating 3.3 gigalitres (3.3 billion litres) of recycled wastewater to drinking water standards before injecting it 120–220 metres below the ground, into the confined Leederville aquifer underlying the Gnangara Mound[185] (Figure 33).

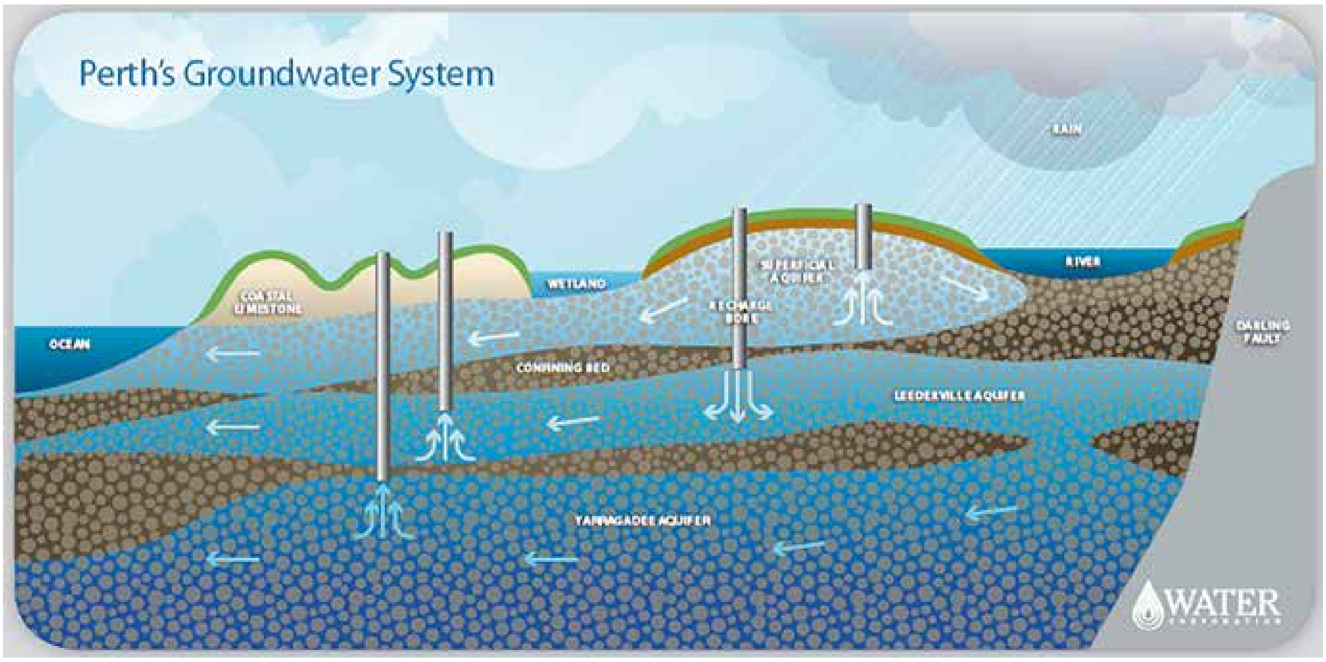


Figure 33. Replenishment of the Leederville aquifer will help to reduce pressure on the wetlands of the Gnangara groundwater system. Image source – Water Corporation[186]

The effects of this groundwater replenishment may potentially be two-fold. Firstly, the replenishment of the Leederville aquifer may reduce the downward flow of water from the superficial aquifer, which is the direct source of water for many groundwater fed wetlands. While replenished water is unlikely to move into shallow groundwater (because the pressure is not sufficient enough to allow upward movement of the recycled water into the superficial aquifer) the recharge increases groundwater pressure in the Leederville aquifer, reducing the downward flow of water from the superficial aquifer.

Secondly, this groundwater replenishment will provide an alternative water supply source, thereby reducing abstraction of the remaining groundwater. This will reduce drying of wetlands fed by the Gnangara groundwater system, by reducing the net amount of water abstracted from it. Groundwater replenishment will initially supply seven gigalitres (7 billion litres) of water a year. The Beenyup replenishment site has the potential to recycle up to 28 gigalitres annually, enough to supply 140,000 households with drinking water each year. By 2060, groundwater replenishment could contribute 115 gigalitres each year by recycling water from Perth's four major wastewater treatment plants. Groundwater replenishment could account for up to 20 per cent of Perth's total yearly drinking water supply.[187]

It is thought that the water will undergo natural filtration for up to 30 years before extraction. The Water Corporation has reviewed the trial, involving more than 62,000 water samples and 254 health guidelines, and published a report stating that recharge of highly treated recycled water into the confined Leederville aquifer does not pose any risk to the environment nor to public health.[187]

Other benefits of Perth's groundwater replenishment scheme are that it is cheaper and uses about half the energy of a desalination plant.

➤ For more information, see:

Department of Water's website: www.water.wa.gov.au/Managing+water/Managed+aquifer+recharge/default.aspx

Water Corporation's website: www.watercorporation.com.au/water-supply-and-services/solutions-to-perths-water-supply/groundwater-replenishment

Recharge aquifers to moderate water level decline

Re-injecting treated wastewater into aquifers has been suggested[188,189] as a way to moderate water level decline on the Gnangara Mound and seawater intrusion from the coastal side. Groundwater from the Gnangara Mound ultimately flows to the coast. Injecting treated wastewater at the coast has been suggested, in order to create a barrier that prevents the intrusion of seawater into the aquifer from the coastal side. It would also allow groundwater to bank up behind the barrier of injected water and increase the water level in the superficial aquifer. This may lessen the degree to which groundwater dependent wetlands dry.

The CSIRO Perry Lakes Aquifer Replenishment Study proposed to divert treated water from the Subiaco wastewater treatment plant to underground filtration galleries on the western side of the Perry Lakes (west lake and east lake), with the aim of creating localised groundwater mounding, to help to increase wetland water levels.[190,191] A trial has been carried out over 18 months at CSIRO Floreat to understand the likely water quality outcomes. The Town of Cambridge has published its decision not to proceed with the replenishment scheme at this time, citing the determination that significantly higher ongoing costs are required to operate the system along with the possibility of further unforeseen risks.[192]

CSIRO is currently conducting preliminary investigations into the potential to recharge the surficial aquifer system in coastal locations in the Cockburn, Kwinana and Rockingham local government areas with treated wastewater. Investigations encompass the costs and environmental risks of enabling heavy industry to access appropriately treated water recharged to the aquifer. Potential benefits may include a reduced risk of seawater intrusion, improved throughflow to coastal wetlands and provision of irrigation water for local government.

➤ For more information on the project, see www.australianwaterrecycling.com.au/projects/recycled-water-for-heavy-industry

Developing alternative water sources

The Water Corporation has published a target of developing up to 100 gigalitres of new water sources.[175]

It has provided a summary of current positions regarding some of the alternative/novel water sources that have been considered to date, including:

- Water from the Kimberley

  An independent expert panel commissioned by the Government of Western Australia evaluated the technical and financial viability of bringing water from the Kimberley to Perth and found the project was high risk, high cost and generally impractical. These findings are presented in the report, *Options for bringing water to Perth from the Kimberley: an independent review.*

- Cloud seeding

  Cloud seeding is the process of artificially generating rain by implanting clouds with particles such as silver iodide crystals. After extensive testing, the CSIRO has determined that cloud seeding is unlikely to be effective in much of Australia. Concerns have also been raised about the long term environmental effects of using silver iodide crystals.

➤ For more information and links to relevant reports, see the Water Corporation's website:
www.watercorporation.com.au/home/faqs/water-supply-and-services/why-dont-you-build-the-kimberley-pipeline-or-canal

www.watercorporation.com.au/home/faqs/water-supply-and-services/is-cloud-seeding-a-viable-solution-to-perths-water-supply

Positioning abstraction bores away from wetlands and configuring them to minimise drawdown

The most effective way to reduce the impacts of drawdown on ecosystems is simply to extract less water. For example, harvesting less water from a wetland for self-supply can lead to immediate changes in wetland hydrology. Extracting less water can be achieved by using water more efficiently, using alternative water sources or changing land use.

Where abstraction is required, abstraction bores should be positioned away from wetlands, so that the groundwater drawdown cone, also known as the 'cone of depression', does not reach them. In addition to helping protect wetlands, this can minimise the risk of causing acidification due to drawdown in areas of potential acid sulfate soils.

As well as position bores away from wetlands, hydrogeologists may be able to design a configuration of abstraction bores that further reduces impacts. For example, depending on the area's hydrological characteristics, it may be preferable to position many bores over a wide area, rather than drawing a lot of water from a single bore. This may spread the impacts, reducing the drawdown depth and the magnitude of the impact at any one point.

Domestic garden bore scale

The Department of Water generally does not support the installation and use of domestic groundwater bores in the vicinity of significant wetlands in the Perth area, as outlined in Operational policy 5.[17] *Metropolitan domestic garden bores*.[177] This is reflected in the mapping of suitable and unsuitable areas for new domestic garden bores within the *Perth Groundwater Atlas*[193] (Figure 34).

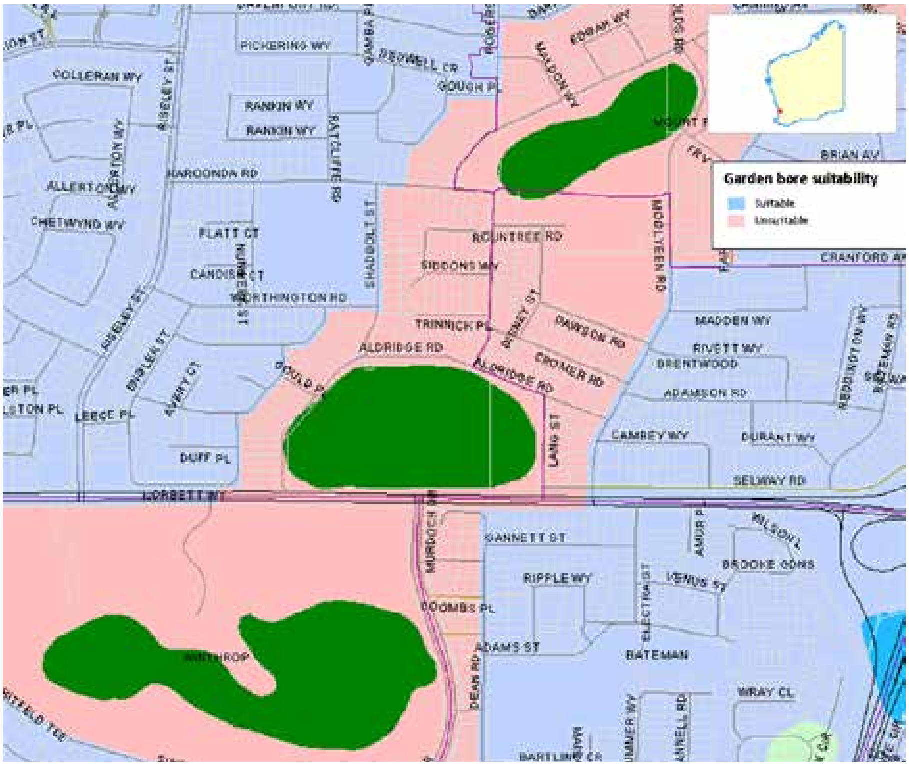


Figure 34. This excerpt from the *Perth Groundwater Atlas* dataset shows that areas around significant wetlands, such as the conservation management category wetlands Blue Gum Lake, Booragoon Lake and Piney Lake, are designated (via pink shading) as unsuitable for installing groundwater bores because of the potential impacts on the wetlands. Image – excerpt of the *Perth Groundwater Atlas*, Department of Water.[193]

Commercial-scale

Licences to take water are administered by the Department of Water under sections 5C and 26D of the *Rights in Water and Irrigation Act 1914*. When a water licence is applied for, the decisions made by the department are guided by water allocation plans (as described earlier in this topic) and these are particularly useful in taking into account the cumulative impacts of abstraction. However, each licence application is also assessed with regard to the location of proposed abstraction points near wetlands. For example, on the Gnangara Mound, in response to declining groundwater levels across the plan area, the department has developed an internal policy to limit or restrict use of groundwater in environmentally sensitive areas (*Internal Allocation Note – Managing abstraction in areas of declining water levels affecting groundwater-dependent ecosystems on the Gnangara Mound,* Department of Water 2005).[36] This policy helps departmental officers to assess water licence applications in areas where groundwater-dependent ecosystems are at high risk of impact from abstraction. Refusal to grant a licence may occur if the application is considered environmentally unacceptable or unsustainable.

➤ The process, and opportunities for stakeholder participation in water allocation planning, are explained in the report *Water allocation planning in Western Australia: a guide to our process*.[172]

Drinking water production bores scale

To ensure the protection of groundwater-dependent ecosystems in the vicinity of production wells, the Department of Water works with the Water Corporation each season to reduce public water supply abstraction in areas that can have a significant impact on wetland hydrology and other groundwater dependent vegetation. Bores are classified as most (environmental) sensitivity, medium sensitivity and least sensitivity, and managed accordingly. This approach has been implemented at a number of production bores on the Jandakot and Gnangara mounds, with some Gnangara bores being turned off for several years due to their impact on declining water levels, and concern regarding impacts on groundwater dependent vegetation.[194]

Minimising drawdown near wetlands via abstraction depth, rate and timing

Minimise magnitude and rate of abstraction to minimise drawdown depth

It is critical to minimise the abstraction rate in order to limit the depth of drawdown experienced by wetlands. As a guide, the depth of the cone of drawdown is dictated by the pumping rate, the slope of the cone is dictated by the characteristics of the aquifer medium (storativity and hydraulic conductivity), while the radius is dictated by the duration of pumping. Determining a depth of drawdown should be guided by the environmental water requirements of the wetland species and using knowledge of potentially acidic locations or layers in the soil. The risk of impact is likely at 30 centimetres or more, but in many wetlands the impact of drawdown is highly likely at less than 30 centimetres (Figure 35).

Making drawdown as gradual as possible may allow the wetland ecosystem to adapt to some degree to the water level decline. Sudden groundwater drawdown events can lead to the death of wetland vegetation that draws water from the water table, because the roots are suddenly left with no access to the water table. In contrast, slow groundwater drawdown increases the chance for individual plants, particularly trees, to extend roots in pursuit of the declining water table, and survive. Similarly it allows for intervening recruitment events, with young trees potentially able develop root morphologies that are more adapted to the new conditions.

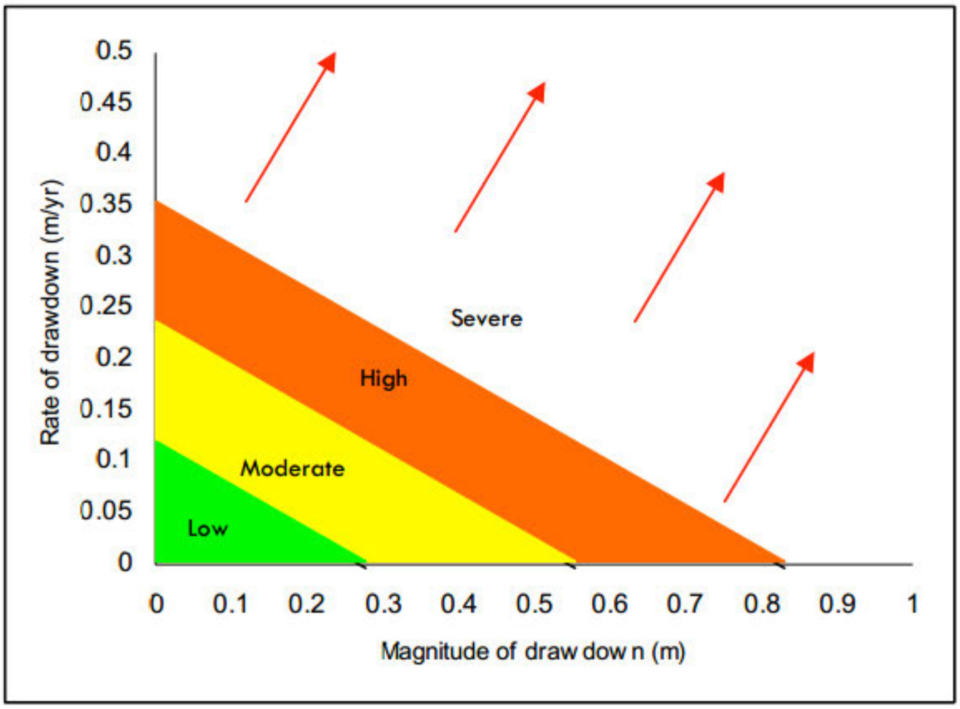


Figure 35. Risk of impact categories for wetland vegetation based on cumulative rate and magnitude of groundwater level change. Source - image in Sommer and Froend[101], citing Loomes and Froend (2004).

Manage drawdown timing (season, duration or frequency)

In combination with managing the drawdown depth, managing the season, duration and frequency of water abstraction may lessen the impacts of drawdown on wetlands. For example, in a permanently inundated wetland, dry season drawdown, in combination with natural decline in the surface water level, may result in drying and triggering acidification of acid sulfate soils. In such systems it may be preferable for drawdown to occur when the wetland water level is highest. As this is often when water is less needed (for example, by horticultural operations during the winter/wet season), storage may potentially be of use where feasible and legal.

Another key consideration is the time when plants and animals will be least sensitive to water loss. This timing can vary, depending on the suite of plants, animals and other life in the wetland. For example, if a wetland's waterbirds need a high spring water level to breed, drawdown should not occur from or near that wetland in spring. Similarly, if wetland plants rely heavily on groundwater over the dry season, then drawdown should occur over the wet season when rainwater is available as an alternative water source.

➤ Broad-scale risk maps have been compiled by DEC for several coastal regions of WA where a high or moderate probability of ASS occurrence has been identified. This risk mapping of acid sulfate soils is available via the DEC website: www.dec.wa.gov.au/management-and-protection/land/acid-sulfate-soils/ass-risk-maps.html

Infiltrating stormwater at-source in urban catchments

Maintaining stormwater infiltration 'at-source' is an important tool for maintaining the water regime of wetlands located in urban environments. In essence, at-source infiltration seeks to replicate the natural process of rainfall percolating into the soil at, or very close to, the location that it has fallen in the catchment, giving rise to the term at-source (Figure 36). In comparison, traditional drainage systems capture and pipe or drain stormwater to a point of discharge such as a wetland or the ocean, often distant from its point of capture.

Figure 36. Vegetated swales and flush kerbs capture and infiltrate rainfall along the length of this road in The Glades, Byford. Photo – courtesy www.newWAterways.org.au.

At-source infiltration helps to mimics the natural catchment flows including:

- peak flows into wetlands
- seasonality of flows into wetlands
- discharge pathways into wetlands
- water quality entering wetlands
- annual frequency of flows into wetlands
- level and duration of inundation of wetlands.

By doing so, it achieves three critical outcomes:

1. all other things being equal, it contributes to the management of the water balance in urban catchments, helping to maintain the normal volume of water to reach those wetlands that are naturally groundwater fed. This is where sound water planning is critical, because the balance depends on managing decreased groundwater levels due to abstraction and climate change with increased runoff due to clearing and impervious surfaces.

2. it reduces the velocity at which water flows into wetlands. The flow of water reaching the wetland by groundwater is moderated compared to higher-velocity surface flows running off impervious surfaces.

3. it improves the quality of water flowing into wetlands and has a strong influence on the natural water chemistry that shapes the character a wetland. The percolation of water through the aquifer removes certain dissolved and particulate materials. The water chemistry also changes as it moves through the aquifer, for example, 'picking up' dissolved ions and salts.

At-source infiltration is possible in catchments with permeable soils, such as sand, that readily allow water to infiltrate. This is the case for large areas of the Swan Coastal Plain

(Moore River–Dunsborough), including the Quindalup, Spearwood and Bassendean Dunes. At-source infiltration requires land that is permeable, that is, not covered with concrete or other impermeable materials. However, it is aided by structural devices such as soakwells, infiltration basins and trenches, swales, pervious paving and flush kerbs.

Using overland flow paths for stormwater entry into wetlands

In moderate to large rainfall events, stormwater would naturally flow into those wetlands that are low in the catchment. To mimic natural flow paths, this water should reach wetlands by overland flow paths across vegetated surfaces, rather than by discharge of pipes or drains. Overland flow paths benefit wetlands by helping to maintain water regime and water quality.

The placement and design of these overland flow paths must, however, consider potential impacts on infrastructure through which they pass if there is potential for flooding to occur.

Minimising subsoil drainage effects on wetlands, using alternatives

Subsoil drainage needs to be well designed in order to minimise the effect on any nearby wetlands. In particular, subsoil drainage needs to be separated (horizontally) from the wetland to ensure normal interaction of the groundwater table with the wetland is maintained. The drawdown curve of each pipe is limited by factors such as the size of the pipe, the hydraulic conductivity of the soil and the hydraulic head (that is, regional recharge). A number of factors are assumed when calculating the likely drawdown, including the uniformity of the soil hydraulic conductivity in a soil layer (such as in a sand layer or in a clay layer) in all directions. As important as the drawdown curve of each pipe is the number and therefore the spacing of pipes in a development near a wetland.

Alternatives to subsoil drainage are available, and include alternative construction methods, a number of which are more common in the eastern states of Australia. Very deep controlled groundwater levels are likely to require 'sump and pump' infrastructure.

The state government has formally established new standards for the management of groundwater levels in new urban developments. These standards are outlined in documents including *Better Urban Water Management*[169] and the *Stormwater Management Manual for Western Australia.*[59] These standards address many objectives, including the protection of high conservation value wetlands. These standards establish the expectation that the condition/health of these wetlands will be maintained or improved during land development by not altering the groundwater regime by greater than normal climatic variances.[195] Proposals to modify the groundwater levels via the installation of controlled groundwater levels (CGLs) must demonstrate that they meet this criterion. The Department of Water is responsible for approving controlled groundwater levels, and it has outlined the considerations required when setting CGLs in the document *Water resource considerations when controlling groundwater levels in urban development*.[195] Sub-soil drainage setbacks are one way of minimising the effect upon wetlands. The land development industry is required to carry out both pre- and post-development monitoring and report upon their adherence to what was proposed and predicted, as outlined in *Water monitoring guidelines for better urban water management strategies/plans*.[196]

➤ The subsoil drainage policy of the Department of Water is outlined in the document *Water resource considerations when controlling groundwater levels in urban development guidelines*[195]

Avoiding or minimising dewatering impacts near wetlands

Use alternatives to dewatering

There are alternatives to dewatering near wetlands. Driven pile construction, sheet piling and slurry walls can avert the need for dewatering associated with various types of construction. Trenchless technologies for installing or repairing underground cables and pipelines, such as microtunnelling, avoid the need for open trenching or dewatering.

➤ The Australasian Society for Trenchless Technology website (www.astt.com.au) is a source of information on potential alternatives to trenching and dewatering.

Design and operate dewatering to minimise impacts

Dewatering techniques differ in their potential to affect nearby wetlands. For example, an array of dewatering well-points or spears connected to a common suction pump or vacuum extraction system is a technique that can have a larger radius of influence than sumps with submersible pumps at their base.[197]

Carrying out works when the watertable is lowest in summer can reduce the depth and/or size of the dewatering footprint and rates. Using groundwater recharge trenches to constrain the lateral extent of the cone of depression by creating a hydraulic barrier between the wetland and the cone of depression is another important technique. Examples of this can be found in the Pilbara.[184]

Dewatering is regulated via groundwater abstraction licences from the Department of Water, except if an exemption applies. If a hydrological impact assessment shows that impacts are likely, dewatering management plans may be required as a condition of licence. The Department of Water must inform the Environmental Protection Authority if a water licence being sought under the *Rights in Water and Irrigation Act 1914* would have a significant effect on the environment. As outlined in the Department of Water's *Western Australian water in mining guideline*[198] and the *Strategic policy 2.09: Use of mine water surplus*[153], water generated by mining dewatering operations must first be used for the mitigation of environmental impacts. This involves ensuring that water is returned to the environment, through injection back into the aquifer or augmenting reduced environmental flows of groundwater-dependent wetlands. This is usually enforced via conditions of the licence.

➤ *Dewatering of soils at construction sites*[199] outlines how the Department of Water assesses impacts of dewatering associated with construction.

DEC also has requirements for proposed dewatering in proximity to wetlands. The document *Treatment and management of soils and water in acid sulfate soil landscapes*[197] (section 5.3.9) states that dewatering must not alter the wetland water level or water quality of valuable wetlands (such as conservation and resource enhancement management category wetlands). Proposals to dewater within 500 metres of a valuable wetland must implement a range of management measures to protect the wetland. These include:

- baseline laboratory analysis of wetland water quality data, capturing seasonal variation
- baseline water level monitoring
- water level and water quality monitoring during dewatering
- a range of monitoring, mitigation and remediation measures in the event of changes in water quality or water level.

Adding wetland water artificially using dewater

Managed aquifer recharge can be used to minimise the impacts on wetland water regimes. Abstracted groundwater may be re-injected into aquifers that are connected to a wetland to allow the recharge water to flow naturally into the wetland, rather than being discharged directly into it. This is being done at several mine sites in the Pilbara and is also becoming an alternative method of disposal at construction sites.[184]

Adding wetland water artificially using harvested stormwater/ rural drainage

Harvested stormwater and rural drainage water represents a considerable resource.

For example, drainage in the region around Perth removes more water than all the bores in the superficial aquifer in the same area. A study published in 2008[182] found that the median annual discharge of stormwater from the Perth and Peel metropolitan regions was estimated as 120 gigalitres with approximately 67 per cent from the Swan-Canning catchment (exclusive of Avon and Helena rivers; and Ellen, Jane and Susannah brooks), 16 per cent from the coastal main drains (Carine, Herdsman and Subiaco) and 17 per cent from the Peel's main drains. This stormwater volume is equivalent to approximately two Mundaring Weirs at full storage capacity (63.6 gigalitres) or two and a half Perth Seawater Desalination plants (45 gigalitres). This is also greater than the potential volume from rainwater harvesting of the region's residential roofs.

Key considerations are cost of installing and maintaining infrastructure and the quality of the water harvested.

Adding wetland water artificially using groundwater

Artificial maintenance of water levels can be achieved by pumping groundwater into a wetland. It is usually very expensive, and therefore has been used relatively sparingly in order to achieve a particular management purpose at high conservation value wetlands (for example, to maintain waterbird habitat or to prevent acidification).

Artificial maintenance has been undertaken in several wetlands on the Swan Coastal Plain suffering from drying, with varying degrees of success. It is an extreme hydrological intervention, and itself carries a risk of unintentional ecosystem degradation. Designing an appropriate program of supplementation depends on an accurate understanding of local and regional hydrology, and its interaction with ecology. Unfortunately, information of this detail is often lacking, or can easily be incorrectly interpreted because of its complexities. The below case study provides two examples of water level maintenance, one considered to be acceptable and one that is thought to have contributed to ecosystem decline.

case study

Artificial supplementation of water levels at Lake Nowergup and Lake Jandabup: a tale of two wetlands

Artificial supplementation at Lake Nowergup

Lake Nowergup in the City of Wanneroo is thought to be the deepest wetland on the Gnangara Mound. Part of the lake is located within Lake Nowergup Nature Reserve, which is managed by DEC. Water levels at the wetland have been falling since the 1970s in line with regional water levels across the mound, and have been artificially supplemented using water from the Leederville aquifer since 1989. To maintain water levels, the lake is supplemented with approximately 1.2 gigalitres of water per year, sourced from the Leederville aquifer, at a cost of about $50,000 per year.[140] The purpose of this supplementation has been to assist in meeting a legislated minimum peak water level in spring. The absolute spring minimum peak for Lake Nowergup is 16.8 metres Australian height datum (AHD), with a preferred spring minimum peak of 17 metres AHD, with no more than two years in six where this is not achieved (Figure 37). This water level was designed to support the wetland's role in providing habitat for waterbirds, as well as other wetland fauna and vegetation. In the first few years, the minimum water level criterion was met using groundwater pumped from the Leederville aquifer. However, as regional water table levels continue to decline, more water has been needed to ensure the minimum water level is reached each year.

In autumn 2002, despite artificial supplementation, wetland vegetation on the western side of the wetland died suddenly. On inspecting the hydrographs (data collected from monitoring bores, graphed to show patterns and trends over time) for the western side of the wetland, artificial supplementation was identified as a likely cause. The hydrographs showed that as soon as supplementation ceased after the minimum water level criterion was reached each spring, water would drain quickly through permeable limestone on the western side of the wetland, until the wetland water was at a similar level to the regional water table. Although the wetland trees had been experiencing the same peak water level every spring, the autumn minimum was falling lower each year. With every year, the seasonal fluctuation in water levels increased. By 2002 when the tree deaths occurred, the water level fell nearly 3 metres in six months.[200] This is compared with normal seasonal fluctuations of up to 1 metre on the Gnangara Mound. It is thought that if wetland levels had been allowed to decline gradually (along with the regional water table), then the trees may have had some chance to adjust to the gradually drier conditions. However, if this had occurred, other species would not have had their water requirements met, and processes such as acidification could occur.

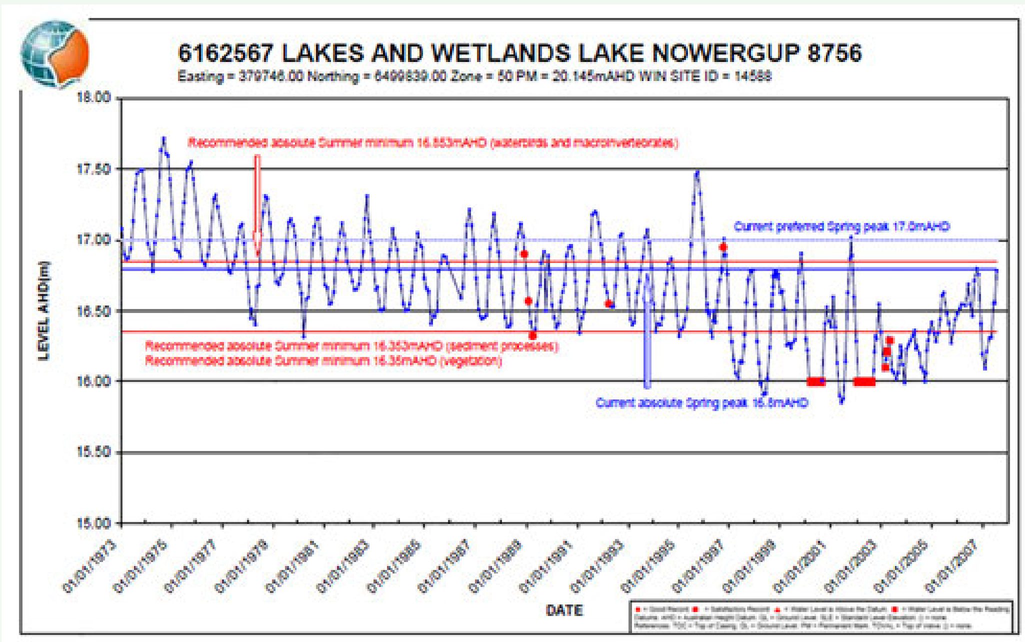


Figure 37. Hydrograph showing water level changes at Lake Nowergup. Image – Department of Water.

case study

Water is currently pumped into the wetland all year round. If pumping is stopped, water levels decline rapidly. The current pumping regime tries to approximate a rate of rise/fall that is closer to what would naturally, historically have occurred. In 2009/10 the management approach was to target a spring peak of 16.5 m AHD and a summer minimum of approximately 15.9 m AHD. However, it has been acknowledged that these targets would not meet the legislated criteria or the environmental water requirements for the wetland, but that the volume of supplemented water required to meet these levels and the high cost of providing such a large quantity of water was deemed prohibitive.

A local area hydrogeological model of the Nowergup area was developed by Sinclair Knight Mertz[201] in 2009 and a detailed study of the wetland's hydrology[202] was carried out in 2011 by the Department of Water. On the basis of this study, it has been recommended that the current artificial maintenance regime should be continued, but it should be re-assessed as part of the next Gnangara groundwater allocation plan review (scheduled to occur in 2016). It was also recommended that a revised spring peak minimum criteria of 16.2 m AHD be proposed under section 46 of the *Environmental Protection Act 1986* and that it be achieved by gradually reducing it by 0.1 metres per year from the 2009 spring peak of 16.5 m AHD.[202] Additional recommendations, including recommendations regarding the regional groundwater level and allocations in the Wanneroo groundwater area and Nowergup subarea were also made in the report.

This experience is a lesson that wetland managers must understand the local hydrogeology, and think broadly about what the ecological implications are, before taking management actions that will affect a wetland's hydrology.[203,194,204] A review of the program's success to date found that:

"Artificial maintenance requires:

- a management regime that considers not only static water levels, but also rates of water level rise, rates of fall, inter-annual variation or fluctuation and the quality of the water being used
- sufficient knowledge of the hydrogeological system to achieve appropriate water levels, rates of change and water quality requirements.

Artificial maintenance is practical only in a very limited number of situations as it requires a management regime that meets environmental objectives and that is feasible in terms of implementation and cost."[202]

Artificial supplementation at Lake Jandabup

Lake Jandabup on the Gnangara Mound has also been artificially supplemented using water from the superficial aquifer: sporadically since 1989 and more consistently since 1999. A decline in the groundwater table had caused the wetland to dry and acidify, and macroinvertebrate populations in the wetland were severely affected. To maintain water levels, the lake is supplemented with approximately 1.2 gigalitres of water per year. The cost of supplementing the wetland has been estimated at almost $9 million over a ten-year period.[92]

Assessments of the supplementation have been positive. In 2009, researchers concluded that "The recovery has been sound, with the return of aquatic macroinvertebrate communities in less acidic waters, despite the resulting water chemistry and community structure being somewhat different to the original".[92] While artificial supplementation has been successful in preventing further acidification events in the wetland to date[205] Sommer and Horwitz found that artificial augmentation diminished the seasonal signal in macroinvertebrate composition and caused some taxa to increase in abundance or to appear in the wetland for the first time, which they coined as 'augmentation beneficiaries'.[206]

Sommer et al[207] found that: 'Artificial supplementation can be appropriate under certain circumstances (as the successful example of Lake Jandabup has shown). However, one must be very aware that such a management strategy is trying to solve one problem whilst exacerbating another *[groundwater decline].* Because of this, wetland supplementation schemes in Perth should be supported by somewhat more rigorous scientific backing than they appear to be at the present time.'

More recently, with the Gnangara Mound's continued falling water levels, it has been reported that the artificial supplementation regime is not keeping up.[208]

Designing, operating and retrofitting tree plantations to minimise drawdown

Unlike abstraction bores which can be switched on and off, the rate at which plantation trees use water is not easily controlled. The interception of rainfall, extent of runoff, and groundwater extraction rate and location can only be coarsely managed in the planning phase. Factors include carefully choosing the location of the plantation (higher vs. lower elevations), the species planted and the density of trees, the plantation design (blocks vs. strips, perpendicular vs. parallel to the contour) and phasing of planting, in order to influence the location of drawdown, and the rate of drawdown over time. The decision-making authority for plantation proposals is the relevant planning authority, typically local government.

While water access entitlements can be granted for the purposes of irrigated agriculture, plantation water use cannot be regulated under the *Rights in Water and Irrigation Act 1914*. The background discussion paper of the proposed Water Resources Management Act states that the interception of water by plantations is proposed to be regulated in areas where high levels of water use (not where plantations assist with salinity and land management).[6] Proposed plantations with the potential to cause significant environmental impacts may be referred for environmental impact assessment under Part IV of the *Environmental Protection Act 1986*.

Thinning or harvesting of a plantation may alleviate drawdown. However, commercial and legal constraints often apply. For example, in the Gnangara groundwater area, the pine plantations are managed in accordance with the *Wood Processing (Wesbeam) Agreement Act 2002* which commits the state government to provide wood to the Wesbeam plant until 2029.[29] In some circumstances environmental constraints may also apply; for example, some plantations are used by native cockatoos. The Gnangara pines are a key food source for Carnaby's black cockatoo, *Calyptorhynchus latirostris,* during the non-breeding season (January-June). As part of implementing the Gnangara Sustainability Strategy, the Forest Products Commission is investigating the potential of modifying harvesting strategies within the constraints of the acts to assist in increasing recharge to the Gnangara system.[36]

Using wastewater on plantations is also being investigated, for example, by the Water Corporation in the south coast.

➤ The report *Plantation forestry and water management guideline*[29] provides a brief overview the Department of Water's role in the management of plantation forestry.

➤ A number of studies on the Gnangara pine plantation were undertaken for the Gnangara Sustainability Strategy and are available from the strategy website: www.water.wa.gov.au/sites/gss/reports.html

Modifying current vegetation

Forest management, by selectively removing crowded trees, controlling re-growth and gradually replacing introduced species of trees with native species is a form of catchment thinning trialled in the Wungong Catchment.

➤ For more information, see the Wungong Catchment Trial in which forests were subject to thinning: www.watercorporation.com.au/water-supply-and-services/ongoing-works/wungong-catchment-trial.

Burning native vegetation removes plants which would otherwise intercept and transpire water, and allows increased infiltration of rainfall to the aquifer. It has been suggested as one of the ways to increase aquifer recharge on the Gnangara Mound, therefore helping to balance the impacts of groundwater drawdown on wetland water regimes.

This option is being investigated by CSIRO and DEC, however there are serious concerns regarding the impact on the burnt ecosystems, as well as human health and safety.[190]

Replacing introduced planted trees which have a high water demand, such as pines, with native vegetation such as Banksia woodland also has the potential to increase groundwater recharge. Active revegetation may not be necessary, as some areas of pines which were killed by wildfire have regenerated into moderately diverse native vegetation.[190]

Retrofitting rural drainage networks to drain less water

Retrofitting open rural drains to export less water from an area is technically feasible. It is generally a case of making them shallower and wider so that they do not intercept groundwater and drain it away (known as exfiltration), or so they intercept groundwater less deeply than before. Drains require a consistent grade, so changes to the base level of the drain (the invert level) would need to be made across the entirety of the drain and its network to allow it to function. Changes of this nature will mean that the maximum groundwater level won't be 'capped' as much as before. It may also mean land needs to be provided in order to widen the existing drainage channel. While technically feasible in some areas, the impacts of higher maximum groundwater levels to landholders and infrastructure in the catchment area needs to be part of a feasibility assessment when work of this nature is being considered, and the capacity of the drain to provide protection from floods needs to be retained.

Installing water control structures in wetlands to increase water

Boards, weirs and gates are used in many rural and metropolitan wetlands to control water levels. This may be an option in wetlands that are connected to a defined channel by way of an inlet (originating from a waterway or drain) or an outlet (flowing to a waterway or drain). Many such devices were installed many years ago, and their original purpose was usually not to maintain the natural water regime of wetlands. The reasons varied from enhancing conditions for waterskiing and other recreational opportunities to improving conditions for agriculture in or near wetlands. Yenyening Lakes, Lake Towerrinning and Benger Swamp are just some of the affected wetlands.

In recent decades, water control structures have been employed in a number of wetlands to ensure enough water is maintained in them to protect or reinstate conservation values. Lake Mealup, West Pinjarra, is one such wetland, as outlined below. This form of structural control provides an option for managing many wetlands in urban areas that form part of the arterial drainage network but which are being impacted by drying.

This form of structural control needs to be designed so as to ensure that the wetland is not affected by large volumes and high speed (velocity) flows or water that is significantly different in chemistry or of poor quality. This form of structural control can also have serious effects on downstream environments, such as waterways or connected wetlands, because their hydrology is likely to be altered. Structural controls may also be physical barriers to fauna such as fish. For these reasons proposals may be subject to environmental impact assessment under Part IV of the *Environmental Protection Act 1986*. Furthermore, detaining water can be a serious safety hazard and structures generally need to be designed by a suitably qualified engineer.

case study

Installing weirs to combat the acidification of Lake Mealup, West Pinjarra

Declining water levels in Lake Mealup culminated in the annual drying of the wetland each year from 1994 until 2012. This is thought to be due to a combination of reduced rainfall and a reduction in surface water flowing into the wetland, due to the closure of a shallow channel that had previously connected the wetland to the Water Corporation's Mealup Main Drain. Signs of drying and acidification were abundant: the pH dropped from 7 to below 3, algal blooms were common, waterbirds were less common and the invasive introduced bulrush *Typha orientalis* expanded to cover 80 per cent of the wetland. The Lake Mealup Preservation Society worked to secure the involvement and collaboration of many people and organisations in order to halt Lake Mealup's ecological decline. Studies confirmed the presence of actual acid sulfate soils. Approvals and funding were sought and provided to divert drainage flows from the Mealup Main Drain into Lake Mealup by way of a variable height weir on the drain. The first diversion of drain water was carried out in June 2012. The pH has stabilised at 7 and the signs of life are reappearing, with frogs and waterbirds evident. A close eye is kept on the wetland's water chemistry, with fortnightly monitoring of pH, oxygen reduction potential and dissolved oxygen. More information on this project is available from the topic 'Roles and responsibilities' in Chapter 5.

Figure 38. The dry sediment in an area of Lake Mealup, showing signs of acidification prior to the diversion of drainage flows into the wetland.
Photo – H Bucktin/DEC.

Figure 39. The adjustable height weir, receiving flows diverted from the Mealup Main Drain.
Photo – H Bucktin/DEC.

Figure 40. Lake Mealup, full in August 2012. Photo – R Rose.

case study

Managing both water rise and decline: urban catchments

Urban water encompasses all water that enters urban catchments, including stormwater, groundwater, water present in ecosystems such as wetlands, wastewater, scheme water and other sources of drinking water.

While one of the principles of urban water management is to retain natural drainage systems and protect ecosystem health, when areas are urbanised the natural catchment hydrology can change through the:

- clearing of vegetation (increasing the amount of water)
- creation of vast expanses of impermeable surfaces including buildings, roads, car parks (increasing the amount of water)
- taking of water for domestic, commercial and industrial purposes, and then discharging it to the ocean (reducing the amount of water)
- redirection of stormwater (increasing water in some areas, and reducing in others)
- development occurring over some wetlands (reducing natural flood storage).

Because these activities can offset or compound each other, managing urban catchments can be complex. Similarly, the effects on wetlands can be complex. The example below demonstrates how multiple threats can interact (Figure 41).

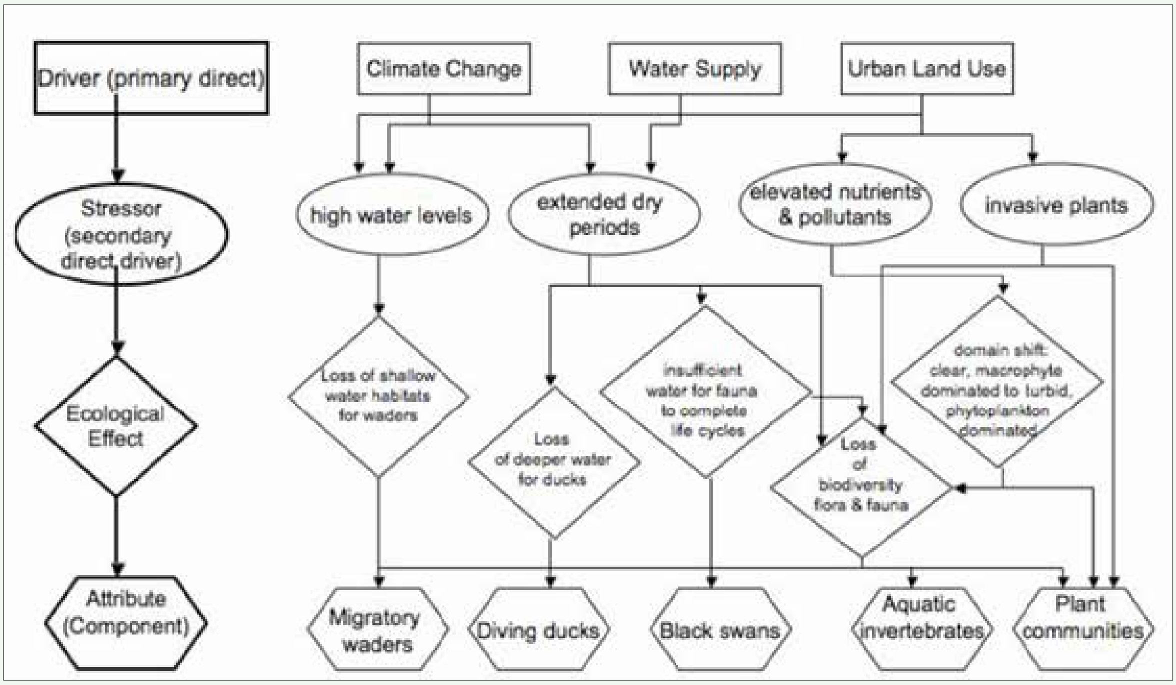


Figure 41. The interaction of different threats at Forrestdale and Thomsons Lake, in Perth's southern suburbs. Source: Maher and Davis 2009.[107]

New urban catchments offer the best opportunities for managing urban water. Being intensively developed, the economies of scale are suitable to design, install and manage the water management infrastructure needed to balance the needs of the environment with the protection of humans and infrastructure from stormwater, groundwater and wastewater. The extent to which best practice water management is achieved in urbanising areas is largely attributable to the development industry, and in turn, the ability of government to regulate the industry, enforce technical standards and foster best practice through incentives, to ensure water and environmental protection. As corporate citizens, companies in the development industry may voluntarily seek to improve standards, but market forces driven by profit margins and consumer choices heavily influence the willingness of companies to do so. Ultimately, the cost of poor management affects everyone in the community, not just those purchasing real estate. Industry and non-industry recognition of the companies that are achieving best

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practice or developing innovative approaches is one method of increasing consumer awareness of the environmental footprint of their new house or a new commercial or industrial district.

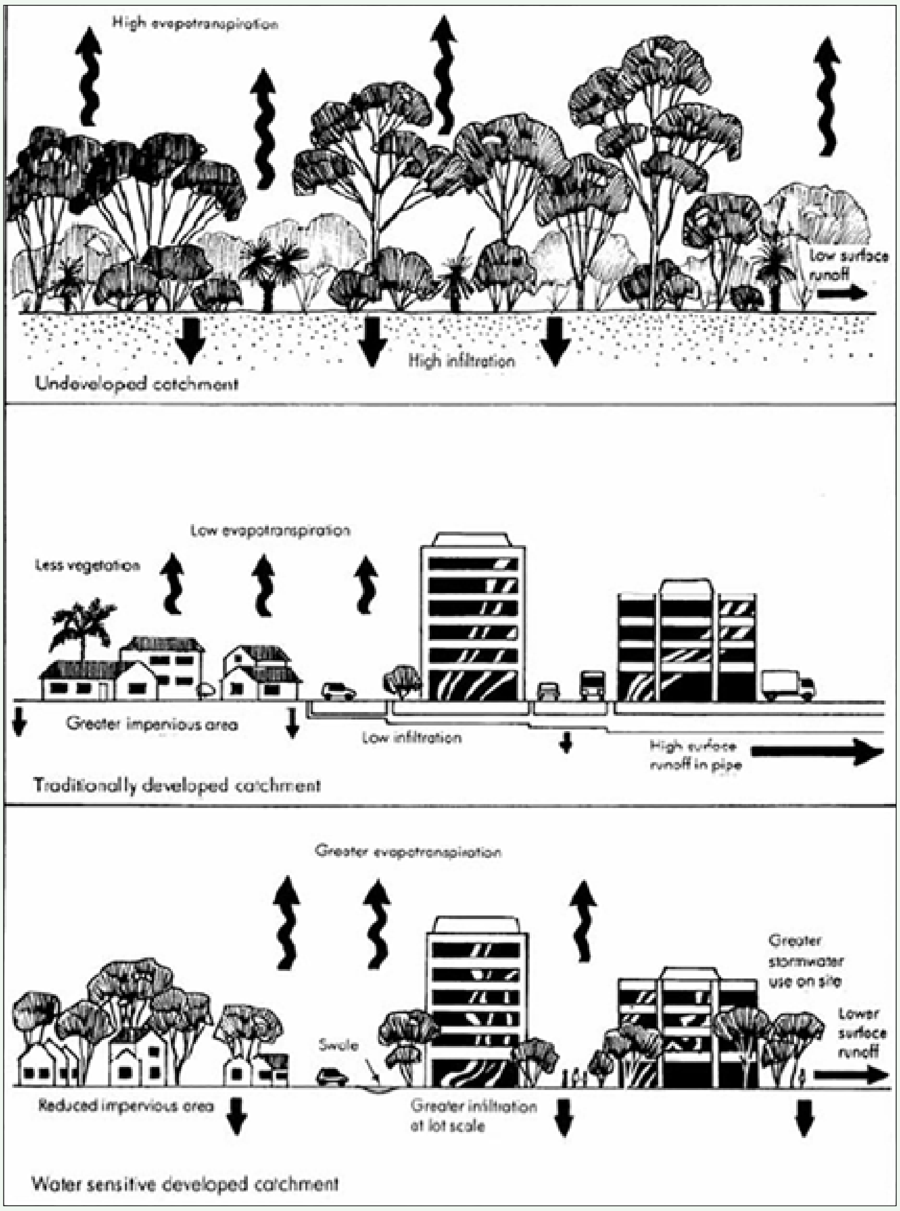

Figure 42. Water in natural catchments (top) traditionally-developed urban areas (middle) and urban areas where water-sensitive urban design has been applied (bottom). Diagram from the *Stormwater management manual for Western Australia.*[59]

Urban water should mimic the natural wetland water regime of conservation value wetlands, including:

- peak flows into wetlands
- seasonality of flows into wetlands
- discharge pathways into wetlands
- water quality entering wetlands
- annual frequency of flows into wetlands
- level and duration of waterlogging or inundation of wetlands.

Stormwater is a precious resource that, with good management, is an essential water management tool. Especially in a drying climate, stormwater is almost always an important source of water for a

case study

wetland. In urban catchments, good stormwater design maintains the natural wetland water regime. In new urban developments, this objective is a requirement of stormwater design. In older areas, where traditional stormwater design often resulted in wetlands receiving too much, too little or very poor quality stormwater, infrastructure can be retrofitted to improve the hydrology of wetlands in the catchment. Retrofitting is the process of installing or undertaking additional or alternative stormwater management devices or approaches in an existing developed area.

Maintaining the pre-development water regime of wetlands can be achieved by designing stormwater systems that mimic stormwater flows before development, including:

- infiltrating water throughout the catchment in small rainfall events, rather than directing it into pipes or open drains
- using well-designed public open space, road reserves and wetlands to receive stormwater in moderate to large rainfall events by overland flow paths across vegetated surfaces
- adequately separating sub-soil drainage systems from wetlands

Stormwater design in new developments is governed by policies that take into account the significant environmental values of water, including:

- *Better Urban Water Management*[169]
- *Stormwater Management Manual for Western Australia*[59]
- *Decision process for stormwater management in WA*[180]
- *Towards a water sensitive city: the urban drainage initiative – Phase 2*

Resources include:

- New WAterways: a resource for urban water management in Western Australia. The website is www.newwaterways.org.au.
- Australian National Hydropolis Conference: www.hydropolis.com.au/papers.htm

Regulatory control of urban water management is via plans that establish water management at increasing finer scales of land development, from the district scale down to individual lots (Table 11). The development of these plans is typically triggered by proposals to rezone or develop large areas of land.

➤ For more information on the water planning process for urban developments, see:

the Department of Water's webpage on water and land use planning: www.water.wa.gov.au/Managing+water/Water+and+land+use+planning/default.aspx

the guidance note, *Water management reports in the land planning process.*[209]

Table 11. Urban water management plans that determine urban water management outcomes

Geographic scale	Land planning tool	Associated water planning report	What the water planning report establishes
Regional	Regional or sub-regional strategy, regional or sub-regional structure plan or region scheme	Regional water management strategy	Likely areas for land use change that may impact the use and management of water resources
District	District structure plan, local planning strategy, region scheme amendment	District water management strategy	Whether the area is capable of supporting urban development, and if so, how water in the landscape will be managed
Local	Local planning scheme amendment, local structure plan	Local water management strategy	How the proposed urban structure will address water use and management
Local	Subdivision proposal	Urban water management plan	How the final urban form will use and manage water
Local	Condition of development approval	Wetland management plan	How a wetland is managed, including wetland hydrology

Glossary

Abstract: to take, remove, extract

Acid sulfate soils: includes all soils in which sulfuric acid is produced, may be produced or has been produced in quantities that can affect the soil properties. Also referred to as acid sulphate soils.

Allocation limit: annual volume of water set aside for consumptive use from a water resource

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Catchment: an area of land which is bounded by natural features such as hills or mountains from which all surface runoff water flows downslope to a particular low point or 'sink' (a place in the landscape where water collects)

Check: a concrete frame with boards slotting into it, creating a barrier across the drain. The checks are opened or closed by addition or removal of the boards.

Climate change: a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.[18]

Climate change adaptation: actions undertaken to reduce the adverse consequences of climate change, as well as to harness any beneficial opportunities

Climate change mitigation: actions that are intended to reduce the magnitude of our contribution to climate change, including strategies to reduce greenhouse gas sources and emissions and enhance greenhouse gas sinks

Community: a general term applied to any grouping of populations of different organisms found living together in a particular environment

Cone of drawdown: the depression of the potentiometric surface. Also known as a cone of depression.

Confined aquifer: an aquifer deep under the ground that is overlain and underlain by relatively impermeable materials, such as rock or clay, that limit groundwater movement into or out of the aquifer

Contour banks: mounds of earth which follow hillslope contours to arrest flowing water and allow infiltration

Controlled groundwater level: the invert level of a groundwater management conduit such as a drain or channel in metres Australian Height Datum (AHD)

Culvert: a conduit used to enable water flow beneath a structure such as a road, causeway, railway or track

Dewatering: the process of removing underground water to facilitate construction or other activity. It is often used as a safety measure in mining below the watertable or as a preliminary step to development in an area.

Drawdown: the lowering of a watertable resulting from the removal of water from an aquifer or reduction in hydraulic pressure

Ecological community: naturally occurring biological assemblages that occur in a particular type of habitat

Endemic: naturally occurring only in a restricted geographic area

Environmental water provision: the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements.

Environmental water requirement: the water regime needed to maintain the ecological values (including, assets, functions and processes) of water-dependent ecosystems at a low level of risk

Facultative wetland plants: plants that can occur in both wetlands and dryland under natural conditions in a given setting

Gigalitres (GL): one thousand million litres (L); that is, one billion litres

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyungar origin.

Gnangara groundwater system: the groundwater system formed by the superficial, Leederville and Yarragadee aquifers located in northern Perth, east to Ellen Brook, south to the Swan River, west to the Indian Ocean and north to Gingin Brook

Grassed waterway: a vegetated channel which directs water flow paths. The vegetation slows surface flows.

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater capture zone (wetland): the area within which any recharge (infiltrating water) eventually flows into the wetland

Groundwater dependent ecosystems: those parts of the environment, the species composition and the a term used to describe ecosystems which derive part or all of its water from groundwater

Groundwater model: a simplified representation of a groundwater system and it captures and synthesise all of the known information, and where information is not known, identifies any assumptions being made about how the system is thought to work

Groundwater table: the upper surface of groundwater in an unconfined aquifer (top of the saturated zone). In technical terms, the surface where the water pressure head is equal to the atmospheric pressure.

Held environmental water: water available under a water access right, a water delivery right or an irrigation right for the purposes of achieving environmental outcomes

Hydraulic conductivity: a measure of the ease of flow through a pore space or fractures. Hydraulic conductivity has units with dimensions of length per time (for example, metres per second, metres per minute or metres per day).

Hydrology: the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere

Hydroperiod: the periodicity (permanent, seasonal, intermittent) of waterlogging or inundation of a wetland

Hysteresis: the condition that caused a shift from one state to another does not necessarily result in a shift back to the first state when the condition is simply reversed

Impermeable surface: the part of the catchment surfaced with materials, either natural or constructed, which prevent or limit the rate of infiltration of stormwater into the underlying soil and groundwater and subsequently increases stormwater runoff flows. Also referred to as impervious surfaces.

Invert: the level of the lowest portion at any given section of a liquid-carrying conduit, such as a drain or a sewer, and which determines the hydraulic gradient available for moving the contained liquid

Invertebrate: an animal without a backbone

Limits of acceptable change: variation that is considered acceptable in a particular component or process of the ecological character of the wetland, without indicating change in ecological character that may lead to a reduction or loss of the criteria for which the site was Ramsar listed

Managed aquifer recharge: recharging an aquifer under controlled conditions to store the water for later abstraction, to achieve environmental benefits or to mitigate the impacts of abstraction

Mound spring: an upwelling of groundwater emerging from a surface organic mound

Obligate wetland species: species that are generally restricted to wetlands under natural conditions in a given setting

Oil mallee: multi-stemmed eucalypt planted on agricultural land, with the stems arising from an underground root mass known as a lignotuber. Stems can be harvested for products such as eucalyptus oil.

Palusplain: a seasonally waterlogged flat wetland

Peat: partially decayed organic matter, mainly of plant origin

Perched: not connected to groundwater

Perennial: a plant that normally completes its life cycle in two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Plantation forest: non-irrigated crop of trees grown or maintained so that the wood, bark, leaves or essential oils can be harvested or used for commercial purposes, including through commercial exploitation of the carbon absorption capacity of the forest vegetation

Precautionary principle: where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation[123]

Recharge: water infiltrating to replenish an aquifer

Roaded catchment: a catchment where a series of adjacent v-shaped (in cross section) channels are created in the landscape to channel water to a downslope water storage

Quadrat: a plot (often square) that is marked, either temporarily or permanently, to facilitate counts of plants in a given area

Secondary salinisation: a human-induced process in which the salt load of soils, waters or sediments increases at a faster rate than naturally occurs

Self-supply water: water sourced on-property by landholders

Sewer mining: the process of extracting untreated wastewater from the sewerage network and treating it on-site in a treatment plant for reuse

Species composition: the species that occur in a community

Stormwater: water flowing over ground surfaces and in natural streams and drains as a direct result of rainfall over a catchment[60]

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Suckering: growing roots laterally under the soil, which project shoots to emerge in a new location away from the base of the parent plant

Sustainable yield: the amount of water that can be taken from a water resource system (expressed as an extraction regime) without causing unacceptable impacts on the environment

Threatened ecological community: naturally occurring biological assemblages that occur in a particular type of habitat that has been endorsed by the WA Minister for Environment as being subject to processes that threaten to destroy or significantly modify it across much of its range

Thresholds: points at which a marked effect or change occurs

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour

Turbid: the cloudy appearance of water due to suspended material

Unconfined aquifer: an aquifer close to the land surface which receives direct recharge from rainfall. Its upper surface is the water table. Also known as a superficial, or surficial, aquifer.

Vegetative reproduction: a type of asexual reproduction found in plants. Also called vegetative propagation or vegetative multiplication.

Water allocation plan: a plan that determines and licenses how much groundwater or surface water can be taken from a region for domestic or commercial purposes without adversely affecting ecological, recreational and cultural values

Water budget: the balance of all of the inflows and outflows of water

Water licence: a formal permit which entitles the licence holder to 'take' water from a watercourse, wetland or underground source under the *Rights in Water and Irrigation Act 1914*

Water regime (wetland): the pattern of when, where and to what extent water is present in a wetland. It includes the timing, duration, frequency, extent, depth and flow, and the variation in these features over time.

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Water table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone). Also known as the groundwater table.

Wetland hydrology: the movement of water into and out of, and within a wetland

Wetland water regime: the pattern of when, where and to what extent water is present in a wetland. It includes the timing, duration, frequency, extent, depth and flow, and the variation in these features over time.

Wetland water budget: the difference in volume between the inputs (water sources) and outputs of water over a set period of time

Personal communications

Name	Date	Position	Organisation
Margaret Smith	14/07/2009	Hydrologist	Department of Environment and Conservation, Western Australia
Gavan Mullan	17/08/2009	Recovery Catchment Officer	Department of Environment and Conservation, Western Australia

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A guide to managing and restoring wetlands in Western Australia

Wetland weeds

Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Wetland weeds' topic

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Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Ecosystem services: the processes by which the environment produces resources that provide benefits to humans, e.g. flood and disease control, clean air, waste recycling, plant pollination[2]

Introduction

Weeds pose a serious threat to Western Australia's environment, society and the economy. Weeds threaten primary production, and the biodiversity and conservation values of Western Australian ecosystems.[1] They impact severely on agriculture and biodiversity by competing with crops and out-competing native plants and degrading habitat. The cost to Australian agriculture alone of managing weeds is estimated to be over $4 billion a year and in Western Australia, as much as 20 per cent of annual production costs.[2]

The cost of weeds from loss of biodiversity and **ecosystem services** is likely to be of a similar magnitude.[2] At present, environmental weeds are generally not managed to the same extent as agricultural or pastoral weeds.

In recognition of existing and potential impacts of weeds, in 2001 the Western Australian Government released *A Weed Plan for Western Australia*[1] to coordinate effective weed management across the state. The *State of the Environment Report: Western Australia 2007* further highlights the significance of weeds by identifying them as a number one priority for management.[2]

What is a weed?

In general terms, a **weed** can be defined as 'a plant that requires some form of action to reduce its harmful effects on the economy, the environment, human health and amenity, and [the term weed] can include plants from other countries or other regions in Australia or Western Australia.[2]

This topic focuses on '**environmental weeds**', which refers to plants that become established in natural ecosystems, altering natural processes and leading to the decline of the communities they invade.[3,1]

Naturalised: plants that spread and persist outside of their normal range of distribution

Where do weeds come from?

Most Western Australian weeds originate from South Africa, Europe, Asia and America, brought in by early settlers as ornamental garden plants or for aquaculture, pastoral and agricultural production.[4,5] It is estimated that about two thirds of the weeds now established in Australia originated from gardens[2] (see Figure 1). Some weeds were also introduced unintentionally transported in soil, in water and in animal fur and feed.

However, not all weeds originate from other countries. Some Australian native species have become **naturalised** outside their normal range of distribution and are considered weeds when they disrupt the structure and diversity of other native plant communities.

Figure 1. Native to South Africa, arum lily *(Zantedeschia aethiopica)* was first introduced as a garden plant and is still used in the floriculture industry. It is a major wetland weed that is very difficult to eradicate once established.
Photo – B Huston/DEC.

Weed distribution in Western Australia

About 10 per cent of Western Australia's flowering plants are introduced weeds and these comprise more than half of the recognised weeds in Australia. It is estimated that of the 1,233 identified weed species in WA, around 55 per cent are classified as environmental weeds, most of which (around 800 identified species) are found in the Swan Coastal Plain **bioregion** (see Figure 2).[2] Over 300 identified weed species occur in the South West region and between 100 and 200 identified species occur in parts of the Goldfields, Mid West, Pilbara and Kimberley regions. Weed numbers in the central desert area of WA is low in comparison, with less than 30 identified species.[2]

Bioregion: a territory defined by a combination of biological, social and geographic criteria rather than by geopolitical considerations; generally, a system of related, interconnected ecosystems[1]

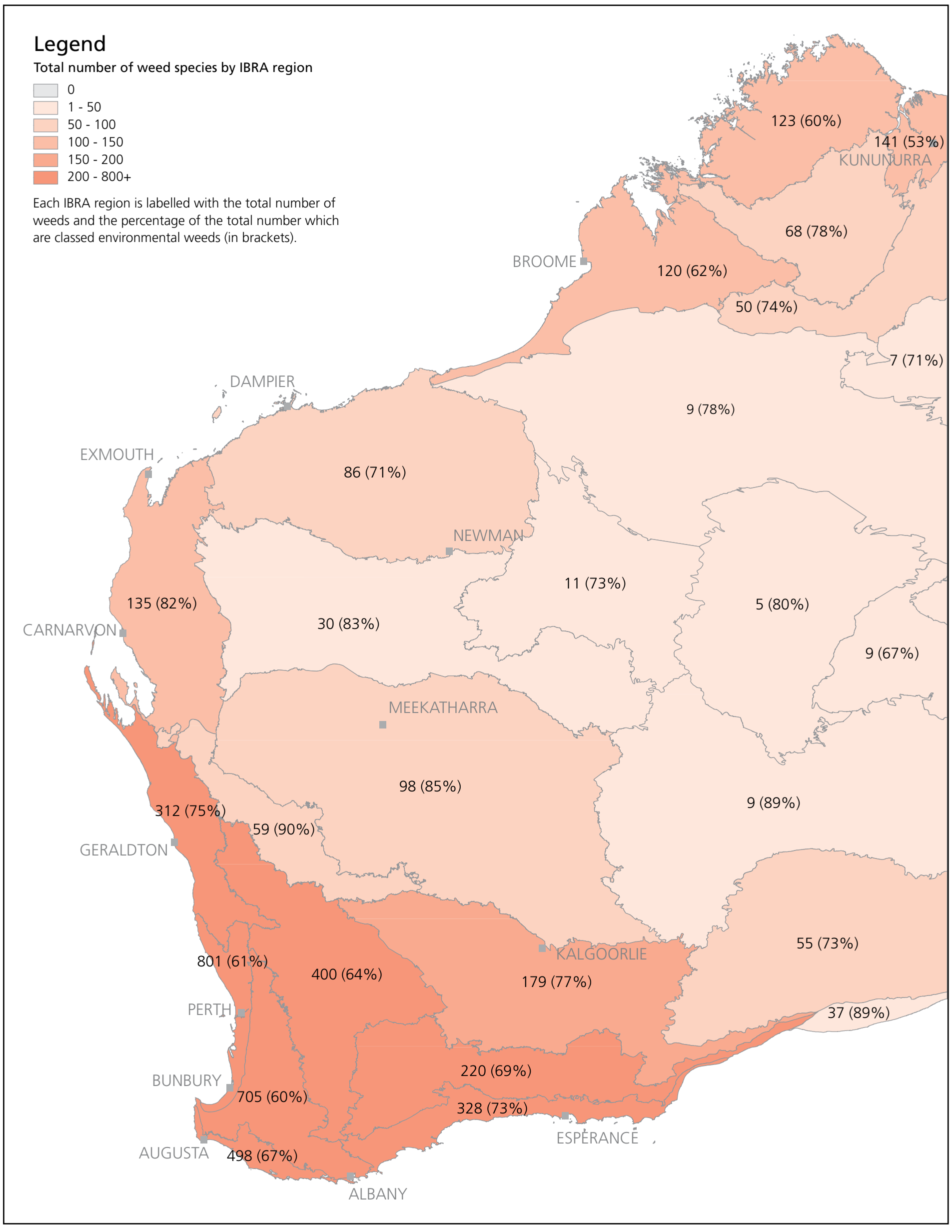


Figure 2. Total number of weed species found per bioregion and percentage that are environmental weeds (in brackets). Source: *State of the Environment Report: Western Australia 2007*.[2]

What causes weeds to occur and spread in wetlands?

In the south-west of Western Australia, weeds have invaded almost every wetland.[5] Weeds that flourish in wetlands often have broad tolerance limits to nutrients, pH, salinity and hydrological regimes and many are '**disturbance opportunists**', responding positively and rapidly to habitat disturbance. Understanding how weeds spread is essential in preventing them from becoming established in wetlands, and managing existing infestations.

Wetlands are vulnerable to weed invasion where there is disturbance of the soil and native vegetation, leaving the soil bare and ideal for germination of weed seeds. Disturbed edges of wetlands are most at risk from weed invasion, for example where they are located within or adjacent to highly disturbed landscapes such as housing settlements, parklands, paddocks, road verges and tracks.

When a wetland is disturbed, space and light conditions increase, creating favourable conditions for weed growth. Disturbance events in wetlands may be natural or resulting from human activities. Natural events in wetlands such as drying and wetting, drought and fire can lead to mass germination of many weed species.

Human activities that contribute to the introduction and spread of weeds include altering hydrology, clearing native vegetation, dumping garden waste, livestock access and vehicle movement (see Figure 3). Frequent fires and spread of dieback in urban wetlands and surrounding bushland also favour weed invasion and establishment.

Figure 3. (below) Weeds are introduced and spread around wetlands by many means including (a) dumping of garden waste such as prunings, lawn clippings and soil, (b) grazing livestock, and (c) vehicles in wetlands. Photos – T Bell/DEC.

(a)

Figure 3. (continued)

(b)

(c)

In comparison to disturbed areas, intact, undisturbed densely vegetated areas are more resilient to weed invasion as weeds are less able to get a foothold and compete for light, moisture and nutrients[5] (see Figure 4).

Figure 4. Wetlands with an intact understorey and few disturbances are more resilient to weed invasion. Photo – J Higbid/DEC.

Once established, weeds can very quickly dominate and degrade natural ecosystems by out-competing and replacing native plants, which may not be able to maintain their dominance or territory as a result (see Figure 5).

Figure 5. The understorey of this wetland has been completely replaced with kikuyu grass (*Pennisetum clandestinum*). Photo – T Bell/DEC.

Weeds can also occur in inundated areas of wetlands in which introduced aquatic plants can cover water surfaces and shade out submerged native aquatic plants and animals.[6] Aquatic weeds can be introduced into wetlands through disposal of ornamental aquatic plants from ponds or aquariums into wetlands or waterways and drains that feed into them (see Figure 6).

Seed dispersal mechanisms: the means by which plants distribute their seeds, for example via wind, water, birds and insects

The rate of weed invasion in wetlands depends on the type and level of disturbance(s) and the growth and reproductive characteristics of the weed. Other factors that influence weed invasion include climate, season, soil type, water and nutrient availability, extent, type and condition of native vegetation and presence of seed dispersal mechanisms.

Characteristics that give weeds a competitive advantage over many native species and assist in their spread include production of large numbers of highly viable seeds, multiple **seed dispersal mechanisms**, seed dormancy, underground storage organs and the ability to germinate and spread rapidly.[5] The absence of predators and diseases that would otherwise keep weeds in check in their countries of origin also provides a competitive advantage.[7]

Figure 6. Salvinia (*Salvinia molesta*) is a free-floating fern and a serious aquatic weed that forms dense masses on the water surface. It was originally introduced from South America as a pond ornamental. Photo – K Tripp/Shire of Wyndham East Kimberley.

Whilst many weeds are introduced to wetlands due to human activities, some invade by themselves through the dispersal of seed and vegetative propagules (see Figure 7). Weeds have a variety of adaptations that can help them disperse more effectively, such as sticky, hooked or light weight seeds that are ideal for catching a ride in fur, wool, clothing, wind or water. Some seeds are ingested by animals and birds and deposited in faeces in a different location.

Figure 7. Pasture grasses are common wetland weeds. Kikuyu grass (*Pennisetum clandestinum*) is spreading from this horse property across a firebreak into the vegetation of an adjacent wetland. Photo – T Bell/DEC.

Humans can assist in spreading weeds by transporting seeds attached to shoes, clothing or vehicles or by dumping soil fill (containing weed seeds or vegetative material), garden prunings or lawn clippings in and around wetlands. Wetland weeds generally produce large numbers of highly viable seed that are easily spread. For example, a major wetland weed, pampas grass (*Cortaderis selloana*), produces up to 100,000 seeds per flower plume, which are readily spread over long distances by wind and water[5] (see Figure 8). Bridal creeper, blackberry, olive tree and Japanese pepper have seeds encased in fleshy fruits that are rapidly dispersed by birds and foxes.[5]

Figure 8. Producing around 100,000 seeds per flower head, pampas grass (*Cortaderia selloana*) seeds are easily spread by wind and can travel for long distances. Photo – T Bell/DEC.

What effects do weeds have on wetlands?

Weed invasion poses a serious threat to the biodiversity and conservation values of wetlands and can disrupt key ecosystem functions.[5] The development of native seedlings can be hindered by the competition created by weeds for light, nutrients and moisture. This can lead to displacement of native plants and loss of biodiversity due to degradation and simplification of the wetland plant community. Weeds can also increase fire risk by increasing fuel loads in summer, contribute to soil erosion problems, reduce native fauna habitat and reduce overall ecosystem resilience[5] (see Figure 9).

Figure 9. Weeds can pose a serious fire risk in wetlands, particularly during summer when annual weeds die off, increasing fuel loads. Photo – Environmental Protection Branch/Fire and Emergency Services Authority.

Weeds can also contribute to reduction in water quality of wetlands, which in turn can lead to midge problems, algal blooms, loss of natural invertebrate communities, displacement of native species and a reduction in aesthetic and recreational values. Heritage values can also be affected by weeds, for example where traditional Aboriginal bush tucker plants are displaced or watering holes and camping sites are degraded.[5] The control of weeds is therefore essential for the long-term protection, management and restoration of wetlands.

Weed impact at a glance

The impact of environmental weeds on wetlands can be significant where they compete with native vegetation, inhibiting growth and natural regeneration. This can result in:

- loss of biodiversity as weeds replace native plants
- loss of habitat and food source for wetland birds and other fauna (e.g. replacement of native shrubs and groundcovers with grasses)
- increased fire risk
- increased erosion risk (e.g. bank erosion)
- altered nutrient recycling
- altered soil quality
- reduced water quality (e.g. reduction of light and oxygen from aquatic weeds)
- loss of aesthetic amenity and recreational value
- increased management costs.

The control of weeds is therefore essential for the long-term protection, management and restoration of wetlands.

Broadleaf: plants that possess relatively broad flat leaves rather than needle-like leaves

Succulent: plants which have specialised fleshy, soft and juicy tissues designed for the conservation of water e.g. cacti

What types of weeds affect wetlands?

To control wetland weeds successfully, it is vital to understand the different types of weeds that exist and how (and when) they grow, reproduce and spread. Without this knowledge, weed control measures may not be effective and may result in wasted time, money and effort. Inappropriate weed control may also result in direct or indirect damage to native flora and fauna and can exacerbate the weed problem.

Weeds can be divided into three broad types: non-woody weeds, woody weeds and aquatic weeds. Non-woody weeds are weeds with a non-woody green stem (i.e. are herbaceous), woody weeds have a woody stem and aquatic weeds are those that grow partly or wholly submerged in water.

Non-woody weeds

Non-woody weeds refer to weeds with a non-woody green stem. They include grasses, **broadleaf** herbs, rushes and sedges, **succulents**, ferns, some vines and plants that develop specialised underground storage organs known as bulbs, corms and tubers.

extra information

Weed life cycles and reproduction

Weeds have either an **annual**, **biennial** or **perennial** life cycle. Most wetland weeds are annual species, which means they normally complete their life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts). Biennial weeds normally complete their life cycle within two years while perennial weeds, often the most invasive type of weed, normally live for two or more growing seasons.

Weeds reproduce sexually through the production of seed, or asexually (or vegetatively), in which parts of the parent plant (e.g. spores, rhizomes, stolons, bulbs, tubers, corms and buds) detach and generate new individuals. Some weeds reproduce both sexually and asexually.

Life form: the shape or appearance of a plant that mostly reflects inherited or genetic influences

Grasses

Grasses can be one of the most serious and difficult weeds to control in wetlands. Once established, they can spread very quickly, smothering native vegetation, and in the case of many annual grasses (which die off during the summer months), significantly increasing wetland fuel loads and fire hazard. Many grasses are also extremely resilient and can re-sprout after damage from trampling, grazing, drought or fire.

Grasses are highly successful colonisers due to their specialised **life forms** and reproductive strategies. Understanding the growth and reproductive strategies of grass weeds is essential in order to identify the most appropriate control methods and how and when they are best applied.

Annual grasses

Completing their life cycle within a year, annual grasses produce seeds which can be dispersed very efficiently by one or more means including wind, water, native and domestic animals and vehicles. Individual plants may produce hundreds or thousands of seeds, which can remain dormant in the soil, waiting to germinate when conditions are favourable. Minimising soil disturbance, which exposes buried weed seeds, is a key strategy in controlling the germination and spread of annual weeds.

Fire can also trigger germination of dormant seeds, with the resulting bare soil and increased light and nutrient availability following a fire providing ideal conditions for grasses to become established.[5]

Examples of annual grass weeds that grow in wetlands include (see Figure 10):

- annual veldt grass (*Ehrharta longiflora*)
- barb grass (*Parapholis incurva*)
- fountain grass (*Pennisetum setaceum*)
- great brome (*Bromus diandrus*)
- blowfly grass (*Briza maxima*)
- rye grass (*Lolium* spp.)
- shivery grass (*Briza minor*)
- wild oat, bearded oat (*Avena fatua, A. barbata*).

Figure 10. (below) Examples of annual grass weeds that grow in wetlands. Photos – (a) and (b) R Randall/Western Weeds; (c) L Fontanini and KC Richardson; (d) A Ireland and KR Thiele; (e) L Fontanini; (f) J F Smith. Images (c)–(f) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) annual veldt grass (*Ehrharta longiflora*)

(b) bearded oat (*Avena barbata*)

(c) great brome (*Bromus diandrus*)

(d) blowfly grass (*Briza maxima*)

(e) shivery grass (*Briza minor*)

(f) annual barbgrass (*Polypogon monspeliensis*)

Perennial grasses

Perennial grasses can survive for several or more years, often producing highly viable seed each year that can be spread by wind, water, native and domestic animals and vehicles. Perennial grasses also reproduce **vegetatively** from **stolons**, **rhizomes** and occasionally corms, which store energy reserves that allow the plant to survive during dormancy or extreme conditions such as fire or drought. Stolons are stems that usually run horizontally along the soil surface and rhizomes are stems that are buried underground. Both types of stems have dormant buds that can produce new roots and shoots and allow rapid lateral (sideways) growth of plants, particularly after fire.[5] Perennial grasses are either summer or winter growing, forming tussocks or mats that can quickly smother native plants.

Vegetative reproduction: a type of asexual reproduction found in plants. It is also called vegetative propagation or vegetative multiplication

Examples of perennial grass weeds that grow in wetlands include (see Figure 11):

- African lovegrass (*Eragrostis curvula*)
- buffalo grass (*Stenotaphrum secundatum*)
- couch (*Cynodon dactylon*)
- kikuyu (*Pennisetum clandestinum*)
- paspalum (*Paspalum dilatatum*)
- perennial rye grass (*Lolium perenne*)
- perennial veldt grass (*Ehrharta calycina*)
- phalaris (*Phalaris aquatica*)
- sweet vernal grass (*Anthoxanthum odoratum*)
- tambookie grass (*Hyparrhenia hirta*)
- yorkshire fog (*Holcus lanatus*).

Tall (or giant) perennial grasses:

- African feather grass (*Pennisetum macrourum*)
- bamboo (*Bambusa* spp.)
- elephant grass (*Pennisetum purpureum*)
- fountain grass (*Pennisetum setaceum*)
- giant reed (*Arundo donax*)
- pampas grass (*Cortaderia selloana*).

Figure 11. (below) Perennial grass weeds that grow in wetlands. Photos – (a) JF Smith; (b) V English/DEC; Trevor Hall/DEEDI © The State of Queensland, Department of Employment, Economic Development and Innovation (Trevor Hall), 1995; (c) L Fontanini; (d) R Randall/ Western Weeds. Image (a) and (c) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) fountain grass (*Pennisetum setaceum*)

(b) buffel grass (*Cenchrus ciliaris*)

Figure 11. (continued)

(c) Yorkshire fog (*Holcus lanatus*)

(d) giant reed (*Arundo donax*).

Grass growth forms

Grasses fall into one of three descriptive growth forms; tussock, stoloniferous or rhizomatous. Understanding the different growth forms is a key consideration when deciding on the best control methods for specific weeds.

Tussock grasses

Tussock grasses are the most common grass growth form, usually forming dense, erect clumps that can create large fuel loads as they age and die off (see Figure 12). They reproduce by seed and/or by sprouting new shoots located at the base of the plant. Most annual grasses are tussock forming, such as annual veldt grass (*Ehrharta longiflora*), fountain grass (*Pennisetum setaceum*) and wild oat (*Avena fatua*). Examples of perennial tussock grasses that can occur in wetlands include pampas grass (*Cortaderia selloana*), perennial veldt grass (*Ehrharta calycina*) and tambookie grass (*Hyparrhenia hirta*).

Figure 12. Example of a tussock grass (perennial veldt grass, *Ehrharta calycina*). Photo – R Cousens/Western Weeds.

Stoloniferous grasses

These grasses possess specialised stems called stolons that store energy reserves and spread laterally across the soil surface, sprouting new shoots and roots. Stoloniferous grasses also produce seed, which in combination with reproduction by runners, makes them extremely invasive, particularly where moist, fertile soils are present. Examples of species that can occur in wetlands include kikuyu (*Pennisetum clandestinum*), couch (*Cynodon dactylon*) and saltwater couch (*Paspalum vaginatum*).

Rhizomatous grasses

Rhizomatous grasses spread laterally by means of special underground stems called rhizomes, which sprout new roots and shoots as they grow. Like stoloniferous grasses, rhizomatous grasses can also reproduce by seed, making them extremely invasive. Rhizomes store energy reserves and being underground, they are protected from extremes in climate (e.g. during drought or fire), allowing them to re-sprout vigorously if the above ground portion of the plant is damaged or killed. They are highly invasive, particularly where moist, fertile soils are present. Examples of species that can occur in wetlands include giant reed (*Arundo donax*), perennial veldt grass (*Ehrharta calycina*) and kikuyu (*Pennisetum clandestinum*). Some grasses, such as kikuyu, produce both rhizomes and stolons.

extra information

Native grasses that look like weeds

Western Australia has many species of native plants that can be mistaken for weeds. Native grasses are particularly prone to mistaken identity (see Figure 13). For this reason, it is essential to accurately identify weed species before implementing a weed control program.

(a) **(b)**

Figure 13. The weed tambookie grass (a) (*Hyparrhenia hirta*) is sometimes mistaken for native kangaroo grass (b) (*Themeda triandra*). Photos – P Hussey/Western Weeds.

➤ For additional detail on weed identification see the section 'Sources of more information on managing weeds in wetlands' at the end of this topic.

Broadleaf herbs

As with grass weeds, it is important to distinguish between annual and perennial herbs as this helps to determine the most appropriate management and control strategy.

Annual herbs

Most annual herbs in south-western Australia germinate with the first rains of autumn and set seed and die during the following summer months.[8] However, in wetlands, some annual weeds germinate when water levels drop during spring and set seed the following autumn. Other species are more opportunistic, sometimes germinating, flowering and setting seed more than once a year when conditions are favourable.[8] Examples of common annual herbs that can occur in wetlands include (see Figure 14):

- blackberry nightshade (*Solanum nigrum*)
- bushy starwort (*Symphyotrichum squamatum*)
- flaxleaf fleabane (*Conyza bonariensis, C. parva*)
- Paterson's curse (*Echium plantagineum*)
- tall fleabane (*Conyza sumatrensis*)
- white bartsia (*Bartsia trixago*)
- wild radish (*Raphanus raphanistrum*).

Figure 14. (below) Annual herb weeds that grow in wetlands. Photos – (a) SM Armstrong, KC Richardson and JF Smith; (b) R Randall; (c) G Byrne and KC Richardson; (d) J Dodd and R Knox; (e) L Fontanini, KC Richardson and JF Smith; (f) S M Armstrong. Images (a) – (f) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) blackberry nightshade (*Solanum nigrum*)

(b) flaxleaf fleabane (left, *Conyza bonariensis* and right, *Conyza parva*)

Figure 14. (continued)

(c) white bartsia (*Bartsia trixago*)

(d) Paterson's curse (*Echium plantagineum*)

(e) wild radish (*Raphanus raphanistrum*)

(f) bushy starwort (*Symphyotrichum squamatum*)

Perennial herbs

Perennial herbs have a life cycle of two or more years. Depending on species, they can reproduce by seed, stolons and rhizomes. Examples of perennial herbaceous weeds that can occur in wetlands include (see Figure 15):

- castor oil plant (*Ricinus communis*)
- dock (*Rumex* spp.)
- gentes herb (*Canna x generalis*)
- pennyroyal (*Mentha pulegium*)
- sorrel (*Acetosa vulgaris*).

Figure 15. (below) Perennial herbs that grow in wetlands. Photos – (a) I Morley/DEC; (b) G Keighery/Western Weeds; (c) JF Smith (d) J Dodd and KR Thiele; (e) R Knox; (f) K Brown/DEC. Images (c) – (e) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) curled dock (*Rumex crispus*)

(b) fiddle dock (*Rumex pulcher*)

(c) canna hybrid (*Canna* spp.)

(d) castor oil plant (*Ricinus communis*)

(e) pennyroyal (*Mentha pulegium*)

(f) blue periwinkle (*Vinca major*)

Sedges

Sedges are also classed as herbs or graminoids and refer to the grass-like species from the plant families including Juncaceae and Cyperaceae. The 'bulrush' refers to plants within the family Typhaceae (see below). Native sedges perform a vital role in wetlands, controlling erosion, maintaining water quality and providing habitat. However there are some species (both native and introduced) that can become invasive weeds in wetlands. Examples of weed species of sedges that can occur in wetlands include (see Figure 16):

- jointed rush (*Juncus articulatus*)
- spiny rush (*Juncus acutus*)
- tiny rush (*Juncus microcephalus*).
- budding club-rush (*Isolepis prolifera*)
- bunchy sedge (*Cyperus polystachyos*)
- club-rush (*Isolepis hystrix*)
- dense flat sedge (*Cyperus congestus*)
- divided sedge (*Carex divisa*)
- umbrella sedge (*Cyperus eragrostis*).

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath is generally not split, there is no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Figure 16. (below) Examples of rushes that are weeds that occur in wetlands. Photos – (a) GJ Keighery and JF Smith; (b) K Brown/DEC; (c) J F Smith; (d) K Bettink/DEC; (e) GJ Keighery and JF Smith; (f) BA Fuhrer. Images (a), (c), (e) and (f) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) bulrush (*Typha orientalis*)

(b) sharp rush (*Juncus acutus*)

(c) dense flat sedge (*Cyperus congestus*)

(d) *Isolepis hystrix*

Figure 16. (continued)

(e) bunchy sedge (*Cyperus polystachyos*)

(f) capitate rush (*Juncus capitatus*)

Typha

One of the most aggressive weeds of Western Australian wetlands is the introduced species *Typha orientalis*, a native of eastern Australia[9] (see Figure 17). The native species, *Typha domingensis*, is often mistaken for the introduced species, and both are commonly referred to as 'bulrush'. *Typha orientalis* is generally taller, with wider leaves and flower heads. The leaf blade of *T. domingensis* does not exceed 8 millimetres in width while the leaf blade of *T. orientalis* can be up to 14 millimetres wide (although exceptions exist making it difficult to distinguish between the two). Spreading from rhizomes, once established, *T. orientalis* rapidly forms a dense monoculture, suppressing all other vegetation. With each seed head producing up to 300,000 seeds, control is very difficult once established and requires vigilance for several years. *Typha* infestations can be linked to excessive nutrients within wetlands and/or altered hydrology whereby changes in wetland natural wetting/drying cycles can favour their establishment and dominance over native aquatic vegetation.

Figure 17. (below) (a) The introduced bulrush (*T. orientalis*) has formed a dense monoculture in Lake Mealup; (b) introduced typha seeds covering the soil surface; (c) seeds are easily spread by the wind. Photos – (a) N Landmann/DEC; (b) and (c) T Bell/DEC.

(a)

(b)

(c)

Weeds with corms, bulbs and tubers

This group of weeds possesses specialised underground fleshy storage organs known as corms, bulbs or tubers. These organs allow them to flourish in nutrient deficient soils or die back and enter a state of dormancy when conditions are extreme, such as during fire or drought.[8] Many species have spread from gardens, where they have been grown as ornamentals (for example arum lilies and freesias). Dumping of garden waste and soil in or near wetlands has assisted their spread and establishment. Their seed and underground reproductive structures can also be spread by water, wind, animals and by other human activities. Fire can also play a role in stimulating sprouting of dormant corms in the soil, which can remain viable for many years, in some cases longer than seed.

Figure 18. Two-leaf cape tulip (*Moraea miniata*) cormels. Photo – R Knox/Western Weeds.

The competitive advantage these weeds possess as a result of their underground storage organs, diverse reproductive strategies and ability to spread is considerable and, as such, they are a highly invasive and persistent group of weeds. Once established, they are extremely difficult to eradicate, particularly if a bank of dormant corms or bulbs has built up in the soil (see Figure 18). As a result, follow-up control may need to be undertaken for some years. Table 1 compares the differences between corms, bulbs and tubers.

Table 1. Comparison of life cycle and reproductive strategies of corms, bulbs and tubers

Type	Location of storage organ	Typical life cycle	Reproduction
Corms	Swollen underground stems or stem bases	Summer dormant, sprouting from corms in autumn. Produces one or two daughter corms annually	• Daughter corms • Cormels (small corms formed around the parent corm) • Axillary buds (that form new plants when the main growing shoot is removed) • Seed
Bulbs	Swollen underground leaf bases	Summer dormant, sprouting new leaves in autumn. Perennials produce one or two daughter bulbs annually	• Daughter bulbs • Bulbils (small bulbs formed at base of leaves or on underground stems, form new plants when detached) • Seed
Tubers	Swollen underground stems or roots, forming dense tuberous root mats	Usually summer dormant, re-sprouting in autumn	• New shoots arising from rhizomes • Seed

Examples of weeds with corms, bulbs and tubers that can occur in wetlands include (see Figure 19):

Corms

- freesia (*Freesia alba x leichtlinii*)
- harlequin flower (*Sparaxis bulbifera*)
- one-leaf cape tulip (*Moraea flaccida*)
- two-leaf cape tulip (*Moraea miniata*)
- watsonia (*Watsonia meriana*)

Bulbs

- belladonna lily (*Amaryllis belladonna*)
- soursob (*Oxalis pes-caprae*)
- three-cornered garlic (*Allium triquetrum*)

Tubers

- asparagus fern (*Asparagus aethiopicus*)
- arum lily (*Zantedeschia aethiopica*)
- bridal creeper (*A. asparagoides*)
- bridal veil (*A. declinatus*)

Figure 19. (below) Examples of cormous, bulbous and tuberous weeds that occur in wetlands. Photos – (a) L Fontanini; (b) A Shanahan/DEC and R Knox; (c) R Randall; (d) JP Pigott and R Randall; (e) R Randall; (f) KC Richardson and KR Thiele. Images (a) – (f) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

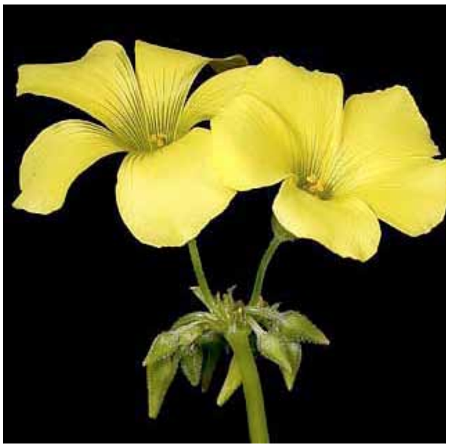
(a) three-cornered garlic (*Allium triquetrum*)

(b) two-leaf cape tulip (*Moraea miniata*)

(c) watsonia (*Watsonia meriana*)

(d) bridal creeper (*Asparagus asparagoides*)

(e) harlequin flower (*Sparaxis bulbifera*)



(f) soursob (*Oxalis pes-caprae*)

Woody weeds

Woody weeds are perennial weeds with woody stems including shrubs, trees and some vines. Most woody weeds reproduce by seed and some have a further advantage of being able to re-sprout from stems or branches (for example, after fire or lopping) or by means of a suckering root system (that is, re-sprouting from lateral roots). Woody weeds such as some vines can be problematic in wetlands when they form dense, impenetrable thickets which shade out and prevent germination of native species (see Figure 20). Removal of large woody weeds can be problematic, resulting in damage to surrounding vegetation, spread of seeds and secondary invasion of other weeds when light availability and temperature are increased following their removal (see Figure 21).

Figure 20. Passion vine (*Passiflora foetida*) infestation at Windjana Gorge. The fruits of this species are readily eaten by birds and mammals and distributed widely throughout the Kimberley. Passion vine dominates and smothers native vegetation, creating a higher fuel load in fire-sensitive ecosystems. Photo – L Williams/Environs Kimberley.

Figure 21. Coffee bush (*Leuceana leucocephala*) infestation along the foreshore of Roebuck Bay (Ramsar wetland). Spread by cattle and through water and soil movement, this species easily invades and dominates areas that have a history of disturbance. Photo – L Williams/Environs Kimberley.

Management and control of woody weeds should take into account re-sprouting/ suckering ability, risk of spreading seed and damage to surrounding vegetation, and secondary weed invasion. Examples of woody weeds that can occur in wetlands include (see Figure 22):

Trees

- athel pine (*Tamarix aphylla*)
- coral tree (*Erythrina* spp.)
- date palm (*Phoenix dactylifera*)
- poplar tree (*Populus* spp.)
- willow (*Salix babylonica*)

Small trees and shrubs

- buckthorn (*Rhamnus alaternus*)
- edible fig (*Ficus carica*)
- flax leaf paperbark (*Melaleuca linariifolia*)
- Japanese pepper (*Schinus terebinthifolia*)
- lantana (*Lantana camara*)
- olive (*Olea europaea*)
- sweet pittosporum (*Pittosporum undulatum*)
- Sydney golden wattle (*Acacia longifolia*)
- tagasaste (*Chamaecytisus palmensis*)
- taylorina (*Psoralea pinnata*)
- victorian tea tree (*Leptospermum laevigatum*)

Vines

- blue periwinkle (*Vinca major*)
- dolichos pea (*Dipogon lignosus*)
- Japanese honeysuckle (*Lonicera japonica*)
- morning glory and coast morning glory (*Ipomoea indica, I. cairica*)

Figure 22. (below) Examples of woody weeds that occur in wetlands. Photos – (a) I Morley/DEC and A Fairs/DEC; (b) TC Daniell and M Hancock; (c) KC Richardson; (d) L Fontanini; (e) KC Richardson; (f) K Bettink/DEC; Images (b) – (e) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) common fig (*Ficus carica*)

(b) Sydney golden wattle (*Acacia longifolia*)

(c) victorian tea tree (*Leptospermum laevigatum*)

(d) sweet pittosporum (*Pittosporum undulatum*)

(e)) athel pine (*Tamarix aphylla*)

(f) morning glory (*Ipomoea indica*)

extra information

Natives behaving like weeds

Some species of native wetland plants can behave like weeds if the wetlands in which they grow naturally are disturbed, or they are introduced (or spread) into areas outside of their natural range. Like weeds, these natives are opportunists that can take advantage of disturbed conditions, rapidly colonising areas to the exclusion of other native species. Native plants such as bracken fern (*Pteridium esculentum*) can form dense monocultures that alter the structure and diversity of wetland ecosystems (see Figure 23). Other examples of natives that can behave like weeds include:

- golden wreath wattle (*Acacia saligna*)
- native typha (*Typha domingensis*)
- marsh club-rush (*Bolboschoenus caldwellii*)
- white cedar (*Melia azedarach*).

Figure 23. (below) Photos – (a) T Bell/DEC; (b) A Ireland and J Smith. Image (b) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

(a) Bracken fern (*Pteridium esculentum*) is an opportunist species.

(b) It can form dense thickets that smother out other native understorey vegetation.

Legislation and weeds

Declared plants in Western Australia

Plants that pose a serious threat to agriculture are declared under the *Agriculture and Related Resources Protection Act 1976*. Any landholder with declared plants on their property is required to control them at their own expense. For a complete list of declared plants in Western Australia, see the Department of Agriculture and Food WA website (www.agric.wa.gov.au).[10]

Weeds of national significance

Through the National Weeds Strategy framework, the Australian Government has identified twenty weeds of national significance (WONS). Due to their invasiveness, impacts and potential for spread, these weeds pose a serious threat to agriculture, forestry and the environment. Landowners with WONS on their property are responsible for their management at their own expense. A full list of WONS and management guidelines are available at www.weeds.gov.au.[11]

Aquatic plants: a plant that grows for some period of time in inundated conditions and depends on inundation to grow and, where applicable, flower

Aquatic weeds

Native aquatic plants perform vital functions in wetlands; they bind the sediment, provide habitat for aquatic fauna and help maintain optimal water quality. However, when some species (native and introduced) become highly abundant under certain conditions, they can severely alter wetland ecology.

➤ For additional detail on in the role of aquatic plants in wetlands, see the topic 'Wetland ecology' in Chapter 2.

Aquatic plants include plants that float with roots trailing in the water surface (floating aquatics) and those that are fully or partly submerged in the water with roots attached to the sediment (submergent aquatics). Introduced species of aquatic plants can enter wetlands in a number ways, for example, directly from disposal of pond, dam and aquarium plants and waste into wetlands, or indirectly via waterways and stormwater drains that feed into wetlands. Birds and other animals can also transport seed and plant material from backyard ponds or dams into wetlands.

Prolific growth of aquatic weeds is often a symptom of elevated levels of nutrients in the water or sediments, which can cause an increase in plant growth. If the right conditions occur, such as increased light intensity and water temperature in combination with high nutrient levels, an explosion in plant growth can occur. Factors that contribute to elevated nutrient levels may include the discharge of nutrient-rich stormwater into wetlands, uncontrolled livestock access or leaching of fertiliser from nearby agricultural areas and urban gardens and lawns. Elevated light intensity and water temperature in wetlands can result from a reduction in shading due to clearing of wetland vegetation such as overhanging trees.

➤ Algal blooms are also a symptom of elevated nutrients in wetlands. This is discussed in more detail in the topic 'Water quality' in Chapter 3.

A common feature of aquatic weeds is their ability to form a dense layer, or 'mat', above or below the water, blocking out light and depleting the water body of oxygen.[6] This can lead to the death of fish and other aquatic life and shading out of native aquatic plants. Salvinia (*Salvinia molesta*) is an example of an aquatic weed that forms a dense mat on the water surface, shading the water beneath it and restricting growth of algae and submerged aquatic plants (Figure 28). This prevents air entering the water body and subsequent deoxygenation can kill fish and other organisms.[6,12] Salvinia is listed as a declared plant in Western Australia and a WONS.

Serious aquatic weeds include (see Figure 24):

- alligator weed[2,3] (*Alternanthera philoxeriodes*)
- arrow head[3] (*Saggitaria montevidensis*)
- Brazilian water milfoil[3] (*Myriophyllum aquaticum)*
- Canadian pond weed[3] (*Elodea canadensis*)
- fanwort[2,3] (*Cabomba caroliniana*)
- horsetails[3] (*Equisetum arvense*)
- hydrocotyle[3] (*Hydrocotyle ranunculoides*)
- lagarosiphon[2,3] (*Lagarosiphon major*)
- leafy elodea[3] (*Egeria densa*)
- saggitaria[3] (*Saggitaria platyphylla*)
- salvinia[2,3] (*Salvinia molesta*)
- strap weed (*Vallisneria australis*)
- watercress (*Rorippa nasturtium-aquaticum*)
- water hyacinth[1,3] (*Eichhornia crassipes*)
- water lettuce[3] (*Pistia stratiotes*).

1 Appears on '100 of the World's Worst' invasive species list
2 Weed of National Significance
3 Declared in WA

Figure 24. (below) Examples of aquatic weeds that occur in wetlands. Photos – (a) BA Fuhrer; (b) R Knox and WA Herbarium; (c) R Knox and J Dodd; (d) R Davis; (e) AGWEST; (f) DJ Edinger. Images (a) – (f) used with permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 6/11/2009.

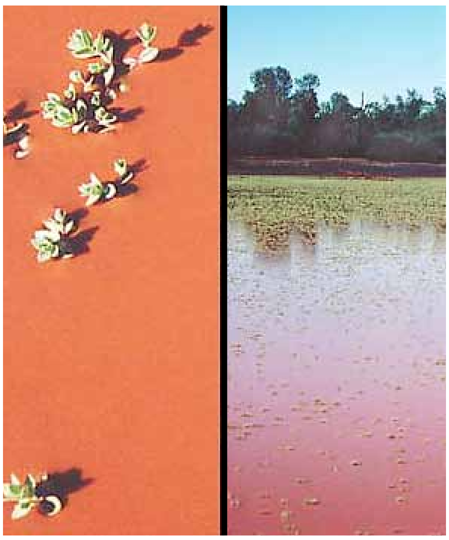
(a) *Crassula natans*

(b) water hyacinth (*Eichhornia crassipes*)

(c) hydrocotyle (*Hydrocotyle ranunculoides*)

(d) watercress (*Rorippa nasturtium-aquaticum*)

(e) water lettuce (*Pistia stratiotes*)



(f) common starwort (*Callitriche stagnalis*)

Priority wetland weeds for management in Western Australia

The Department of Environment and Conservation has identified weeds that are priorities for management in WA regions to protect environmental assets from the threat posed by established weeds and to allow more effective use of available resources for management. Priority wetland weeds are summarised in Table 2. Priority weeds for control have been determined according to their ecological impact, invasiveness, current and potential distribution and feasibility of control.

Table 2. Priority wetland weeds for management in Western Australia by region

(K Agar 2009, pers. comm.); based on Keighery G and Longman V (2004). ***The naturalised vascular plants of Western Australia 1: Checklist of environmental weeds and distribution in IBRA regions,*** Plant Protection Quarterly, Volume 19 (1), 2004)

Common name	Scientific name
Swan Region	
Athel pine	*Tamarix aphylla*[1,2,3]
Baboon flower	*Babiana angustifolia*
Blackberry	*Rubus* spp.
Brazilian pepper	*Schinus terebinthifolius*
Bulrush	*Typha orientalis*
Burrgrass	*Cenchrus echinatus*
Castor oil plant	*Ricinus communis*
Clubrush	*Isolepis hystrix*
Couch	*Cynodon dactylon*
Crassula	*Crassula natans* var. *natans*
Date palm	*Phoenix dactylifera*
Divided sedge	*Carex divisa*
Fern cotula	*Cotula bipinnate*
Haas grass, tribolium	*Tribolium uniolae*
Harlequin flower	*Sparaxis bulbifera*
Pampas grass	*Cortaderia selloana*
Parrot's feather or brazilian water milfoil	*Myriophyllum aquaticum*
Pond stonecrop	*Crassula natans* var. *minus*
Robust pennywort	*Hydrocotyle ranunculoides*
Sagittaria	*Sagittaria platyphylla*
Salvinia	*Salvinia molesta*[2,3]
Slender thistle	*Carduus pycnocephalus*
Sparaxis	*Sparaxis bulbifera*
Spiny rush	*Juncus acutus*
Sweet pittosporum	*Pittosporum undulatum*
Taro	*Colocasia esculenta* var. *esculenta*

Common name	**Scientific name**
Water hyacinth	*Eichhornia crassipes*[1,3]
Wavy gladiolus	*Gladiolus undulates*
South West Region	
African feather grass	*Pennisetum macrocouru*
Athel pine	*Tamarix aphylla*[1,2,3]
Blackberry	*Rubus* spp.
Brazilian pepper	*Schinus terebinthifolius*
Bulrush	*Typha orientalis*
Burrgrass	*Cenchrus echinatus*
Castor oil plant	*Ricinus communis*
Clubrush	*Isolepis hystrix*
Couch	*Cynodon dactylon*
Date palm	*Phoenix dactylifera*
Divided sedge	*Carex divisa*
Harlequin flower	*Sparaxis bulbifera*
Kikuyu	*Pennisetum clandestinum*
Puccinellia	*Puccinellia ciliata*
Salvinia	*Salvinia molesta*[2,3]
Spiny rush	*Juncus acutus*
Water hyacinth	*Eichhornia crassipes*[1,3]
Watercress	*Rorippa nasturtium-aquaticum*
Midwest Region	
African love grass	*Eragrostis curvula*
Athel pine	*Tamarix aphylla*[1,2,3]
Bulrush	*Typha orientalis*
Burrgrass	*Cenchrus echinatus*
Castor oil plant	*Ricinus communis*
Clubrush	*Isolepis hystrix*
Couch	*Cynodon dactylon*
Cyperus	*Cyperus* spp.
Date palm	*Phoenix dactylifera*
Divided sedge	*Carex divisa*
Feather top	*Pennisetum villosum*
Harlequin flower	*Sparaxis bulbifera*
Kikuyu	*Pennisetum clandestinum*
Morning glory	*Ipomoea cairica* and *I.indica*

Common name	Scientific name
One-leaf cape tulip	*Moraea flaccida*
Paspalum	*Paspalum dilatatum*
Salvinia	*Salvinia molesta*[2,3]
Spiny rush	*Juncus acutus*
Water hyacinth	*Eichhornia crassipes*[1,3]
Waterbuttons	*Cotula coronopifolia*
Watercress	Rorippa nasturtium-aquaticum
Pilbara Region	
African love grass	*Eragrostis curvula*
Athel pine	*Tamarix aphylla*[1,2,3]
Butterfly pea	*Clitoria ternatea*
Castor oil plant	*Ricinus communis*
Cotton palm	*Washingtonia filifera*
Cyperus	*Cyperus involcratus*
Date palm	*Phoenix dactylifera*
Parkinsonia	*Parkinsonia aculeata*
Stinking passion flower	*Passiflora foetida*
Bulrush	*Typha orientalis*
Goldfields Region	
Annual barbgrass	*Polypogon monspeliensis*
Athel pine	*Tamarix aphylla*
Blackberry nightshade	*Solanum nigrum*
Blue pimpernel	*Lysimachia arvensis*
Bulrush	*Typha orientalis*
Couch	*Cynodon dactylon*
Tamarisk	*Tamarix ramossisima*
Toad rush	*Juncus bufonius*
Kimberley Region	
Castor oil plant	*Ricinus communis*
Couch	*Cynodon dactylon*
Giant rubber bush	*Calotropis gigantea*
Mimosa, giant sensitive plant	*Mimosa pigra*
Mint weed	*Hyptis suaveolens*
Morning glory	*Ipomoea* spp.
Paragrass	*Urochloa mutica*
Parkinsonia	*Parkinsonia aculeata*

Common name	Scientific name
Rosella	*Hibiscus sabdariffa*
Rubber bush	*Calotropis procera*
Rubbervine	*Cryptostegia grandiflora*
Salvinia	*Salvinia molesta*
Stinking passion flower	*Passiflora foetida*
Water hyacinth	*Eichhornia crassipes*
Windmill grass	*Chloris virgata*
Zornia	*Ziziphus mauritiana*
Warren Region	
African feather grass	*Pennisetum macrocourum*
Athel pine	*Tamarix aphylla*[1,2,3]
Blackberry	*Rubus* spp.
Brazilian pepper	*Schinus terebinthifolius*
Bulrush	*Typha orientalis*
Burrgrass	*Cenchrus echinatus*
Castor oil plant	*Ricinus communis*
Clubrush	*Isolepis hystrix*
Couch	*Cynodon dactylon*
Date palm	*Phoenix dactylifera*
Divided sedge	*Carex divisa*
Harlequin flower	*Sparaxis bulbifera*
Kikuyu	*Pennisetum clandestinum*
Puccinellia	*Puccinellia ciliata*
Salvinia	*Salvinia molesta*[2,3]
Spiny rush	*Juncus acutus*
Water hyacinth	*Eichhornia crassipes*[1,3]
Watercress	*Rorippa nasturtium-aquaticum*
Wheatbelt Region	
Annual barbgrass	*Polypogon monspeliensis*
Blackberry nightshade	*Solanum nigrum*
Blue pimpernel	*Lysimachia arvensis*
Couch	*Cynodon dactylon*
Spiny rush	*Juncus acutus*
Tamarisk	*Tamarix parviflora*
Toad rush	*Juncus bufonius*
Bulrush	*Typha orientalis*

Common name	Scientific name
South Coast Region	
African love grass	*Eragrostis curvula*
African scurfpea	*Psoralea pinnata*
Arum lily	*Zantedeschia aethiopica*
Blackberry	*Rubus* spp.
Blue periwinkle	*Vinca major*
Cotton bush	*Gomphocarpus fruticosus*
Couch	*Cynodon dactylon*
Hedera	*Hedera helix*
Lantana	*Lantana camara*
Lesser canary grass	*Phalaris minor*
Morning glory	*Ipomoea indica*
Myrtleleaf milkwort	*Polygala myrtifolia*
Nutgrass	*Cyperus rotundus*
Pampas grass	*Cortaderia selloana*
Sagittaria	*Sagittaria platyphylla*
Saltwater couch	*Paspalum vaginatum*
Salvinia	*Salvinia molesta*
Senecio	*Senecio angulatus*
Sparaxis	*Sparaxis bulbifera*
Spiny rush	*Juncus acutus*
Stinkwort	*Dittrichia graveolens*
Sweet pittosporum	*Pittosporum undulatum*
Sydney golden wattle	*Acacia longifolia*
Three-cornered garlic	*Allium triquetrum*
Bulrush	*Typha orientalis*
Water couch	*Paspalum distichum*
Water hyacinth	*Eichhornia crassipes*
Watercress	*Rorippa nasturtium-aquaticum*
Watsonia	*Watsonia meriana* var. *bulbifera*
Wavy gladiolus	Gladiolus undulates

1 Appears on ‘100 of the World’s Worst’ invasive species list
2 Weed of National Significance
3 Declared plant in Western Australia

Key techniques for managing weeds in wetlands

Once established, weeds can be extremely difficult to eradicate and require consistent and sustained effort over time to bring them under control. Where infestations are severe, it may not be possible to completely remove weeds and ongoing efforts must instead focus on containment to prevent further spread. Before embarking on a weed control program, some guiding principles should first be considered to ensure success and avoid wasted time, money and effort.

Despite the very best intentions, weed control programs almost always fail if vital information about the weeds and site conditions are not taken into account. It can also be easy to underestimate how much time may be required for follow-up weed control and therefore initial plans may need to be scaled back once all the information is taken into account to ensure a successful result. To fail to plan is to plan to fail!

Aim of weed control

The weed control strategies presented in this topic are aimed at protecting and conserving wetland values, particularly biodiversity. Weed control measures that have the potential to have direct or indirect adverse effects on biodiversity should be carefully considered before being implemented. For example, the use of certain herbicides that are extremely effective in controlling particular weeds may have unacceptable impacts on non-target native plants and/or wetland animals. Similarly, the removal of weeds that provide habitat for native fauna may result in fauna losses due to predation, exposure to the elements and removal of food sources.

In such cases, weed management measures may need to be modified, or perhaps even abandoned if damage to the environment is at a level considered to be detrimental to biodiversity conservation aims. Where negative impacts are likely, but at a manageable level, it is important to assess which native species are likely to be affected, what the level of impact will be, how impacts will be managed and the pros and cons of these impacts versus the long-term benefits to biodiversity.

Ideally, a weed control program should form part of an overall wetland management plan to ensure that weed control activities not only meet wetland management goals but are undertaken at the most appropriate time in conjunction with other wetland management activities, including encouraging native vegetation regeneration. A wetland management plan will assist in identifying priority wetland management actions and where, when and how these should be undertaken. For example, in some situations, weed control may not be the highest priority for management where other issues pose a higher threat to wetland biodiversity values.

➤ For additional detail on wetland management planning, see the topic ‘Wetland management planning’ in Chapter 1.

Weed management versus weed eradication

It should be noted that weed management does not necessarily imply complete and permanent removal of every single weed in a given area. In many cases, complete removal of weeds is not feasible or desirable for many reasons; for example, limited resources, increased potential for erosion or other adverse environmental impacts.

Prevention is the key

The best strategy for controlling weeds is to prevent weeds from becoming established in the first place and to act quickly following any new weed invasions. Once weeds have become established, weed control should ideally start in the least affected areas and move towards the most affected areas.

Consideration of the causes of weed infestations may identify other factors that may need to be addressed prior to, or simultaneously with, weed control. For example, where excess nutrients are stimulating growth of aquatic weeds, removal of the source or implementation of measures to ameliorate the impacts of nutrients may need to be undertaken as a matter of priority.

Guiding principles to prevent weeds from becoming established in wetlands include:

Prevent introduction of weeds from wind and water:

- Identify where weeds could be transported from via wind and water and implement measures to reduce the risk of invasion (for example, undertaking weed control in nearby paddocks or road verges).
- Remove known aquatic weeds from nearby garden ponds, drains or dams.
- Restore native dryland vegetation adjacent to wetlands and establish **shelterbelts** around property boundaries (using fast-growing **indigenous/local provenance** dryland plants) to stop weeds from blowing in or entering via runoff to act as a barrier to weed invasion.

Prevent introduction of weeds from human and livestock movement:

- Prevent or minimise access to wetlands via vehicles, livestock and humans.
- Before entry onto properties and/or wetland vicinity, clean weed seeds from vehicles, machinery, tools, pets and livestock, clothing and boots.
- Prevent disposal of garden prunings or lawn clippings from gardens into or around wetlands.
- Protect wetland vegetation from grazing, disturbance and clearing by fencing off areas of native vegetation.
- Prevent direct disposal of aquatic plants from ponds, dams or aquaria into wetlands, waterways or drains.

Reduce susceptibility of the site to weed establishment:

- Avoid disturbing existing native vegetation as this is where weeds will invade.
- Reduce or eliminate sources of nutrients entering wetlands that could stimulate the growth of weeds (for example, by ensuring fertiliser applied to gardens, lawns and paddocks does not leach into wetlands).
- Reduce fuel loads and risk of fire (and hence growth of weeds following an unplanned fire).

Early detection and control:

- Undertake regular monitoring to check for new weed infestations and remove them as soon as possible.

Indigenous: a species that occurs at a place within its historically known natural range and that forms part of the natural biodiversity of a place

Local provenance: indigenous plants propagated from collections from locations as close as geographically (in terms of habitat) practicable to the location where the propagated plants are to be planted. This ensures that genetic integrity is maintained

Shelterbelts: belts or rows of trees and shrubs planted to provide protection against prevailing winds

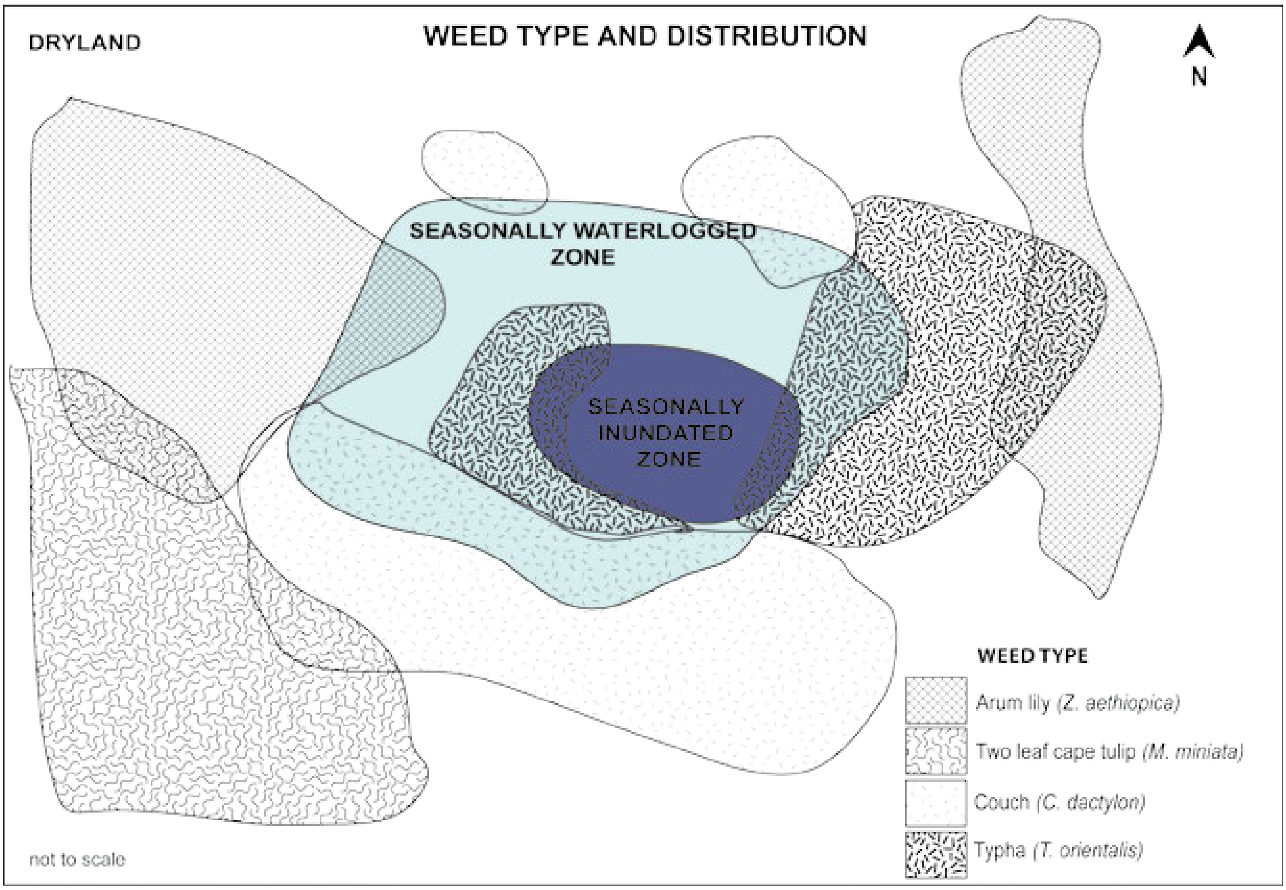
Weed identification is the key to successful weed control

For weed control to be successful, it is essential to accurately identify weed species to ensure that the most appropriate control methods are chosen. This will also minimise the risk of mistaking 'weedy' looking native plants as weeds! For additional detail on weed identification see the 'Sources of more information' section at the end of this topic

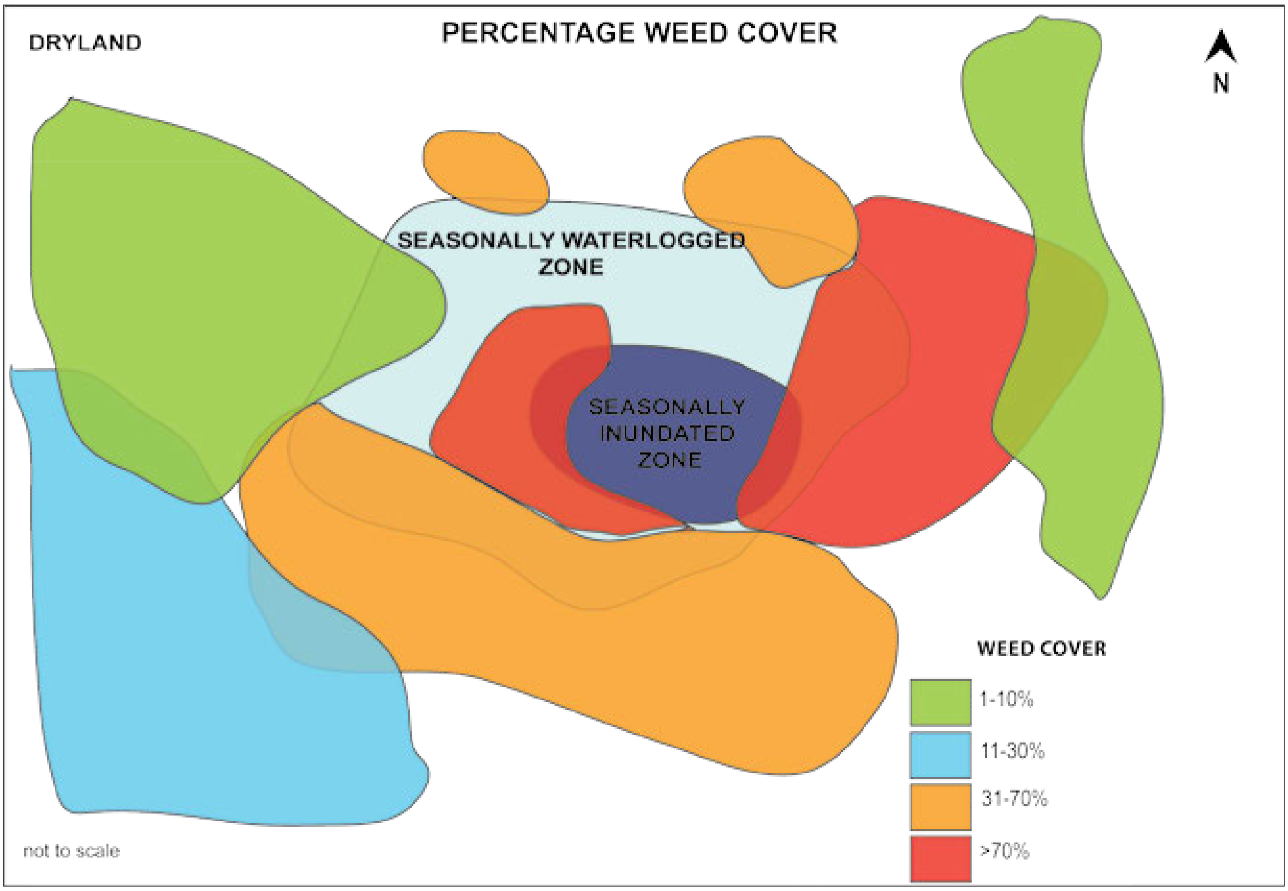
Weed mapping

Mapping individual weed species can assist in prioritising weeds for control. Ideally, weed mapping should be done in conjunction with mapping wetland vegetation communities to identify areas of native vegetation that are priorities for preventing and/or controlling weed invasion. Vegetation maps can be overlain with a weed map to show where serious weeds occur, extent of infestations (distribution and percent cover) and the rate and direction in which they are spreading. Not all weeds need to be mapped, just those that have the most serious, or potential for serious impacts on the site (see Figure 25). An aerial photo of the site provides a good basis for developing vegetation and weed maps to ensure that maps are to scale and important features in and around the wetland are incorporated.

Figure 25. (below) Examples of simple wetland weed maps which overlay an aerial photograph of the wetland and a wetland vegetation condition map – (a) weed type and distribution and (b) percentage weed cover.



(a)



(b)

Weed mapping can also help identify how and from where weeds are spreading, or have the potential to spread into the wetland area. For instance, tracks through the wetland or adjacent paddocks may be the source of highly invasive grass (pasture) weeds such as couch (*Cynodon dactylon*) and kikuyu (*Pennisetum clandestinum*). Similarly, agricultural or stormwater drains that are connected to wetlands may be the source of aquatic weeds. If weeds originate from neighbouring properties, working with neighbours in a joint effort to control weeds will ensure a more effective long-term outcome and better use of resources.

Mapping can also identify other areas of the wetland that are disturbed (or at risk from disturbance), or influenced by other factors that promote weed invasion. High fire risk areas can also be identified, which may be a critical factor in determining priority areas for weed control. Consideration of other factors such as climate, season, topography, wetland hydrology and fauna communities will also assist in deciding where, when and how weed control efforts will be most effective.

A weed map does not need to be complicated and requires only a few items including an aerial photograph of the wetland or property (on a size A4 or A3 sheet, at a scale of between 1:1,000 and 1:2,000 is ideal, depending on the size of the wetland), plastic overlay sheets and permanent marker pens.

➤ Aerial photographs may be sourced from local government authorities (councils or shires) or landcare centres. Rural landholders can source them from the Small Landholder Information Service (Department of Agriculture and Food, www.agric.wa.gov.au). Alternatively, Google Maps can also be useful for printing out reasonable quality aerial photos at no cost.

Mapping one weed at a time is the simplest approach (and remember, not all weeds need to be mapped, just those that present the greatest threat to the wetland). Many weeds grow in distinct zones. Use easily distinguishable features on the aerial photograph to assist in determining the boundaries of weed infestation zones (such as large trees, tracks, fence lines, inundated areas and so on). The boundary around each zone should be drawn on the plastic sheet (overlaying the aerial photograph) using the marker pens, indicating the name of the weed(s) in each zone. It can also be helpful to estimate the per cent of weed cover for each weed species, indicated using a colour code. For example:

- light infestation (i.e. weed forms 1–10 per cent of ground cover) = green
- light – medium infestation (i.e. weed forms 11–30 per cent of ground cover) = blue
- medium – heavy infestation (i.e. weed forms 31–70 per cent ground cover) = orange
- heavy infestation (i.e. weed forms greater than 70 per cent ground cover) = red.

Once the map is completed, this can be used to overlay a vegetation condition map to determine the highest priority areas for control. Small isolated patches of serious weeds in relatively undisturbed areas of native vegetation are usually the highest priorities for weed control (that is, following the weed control principle of working from the least weed affected areas, outwards towards the worst affected areas). Overlaying the weed map over the vegetation condition map is also useful for highlighting particular associations between certain weed species and plant communities or soil types.

➤ The step-by-step instructions used by DEC officers to map weeds are available at www.dec.wa.gov.au/monitoring/standard-operating-procedures.html

➤ For additional detail on wetland vegetation mapping, see the topic ‘Managing wetland vegetation’ in Chapter 3.

The basic principles of a weed management program

- Prevent spread, or further spread, of serious weeds into areas of intact vegetation.
- Avoid disturbing intact vegetation as this can lead to weed invasion.
- Work in areas that have the capacity to regenerate (i.e. where native vegetation can recover and grow back naturally following weed control).
- Develop a weed management plan (incorporating weed and vegetation condition maps to identify priorities for weed control).
- Control weeds as soon as they appear, working from areas least affected towards areas most affected.
- Where possible, revegetate disturbed or degraded areas that harbour serious weeds and that continue to provide a source of seed that can spread into other areas. Although this is a lower priority than protecting the least invaded areas of vegetation, it should be incorporated into long-term weed control program actions.
- Undertake a social program to educate neighbours and others contributing to the spread of weeds, and encourage their active participation in the solution.

How much weed control and when?

Resources and timing

The size of the area, amount of weeds to be controlled and rate of control should be dictated by the resources available and the rate at which natural regeneration or revegetation is expected to occur following removal of weeds. This will ensure that weed control measures and follow-up weed control is manageable, and bare areas left by weed control will be colonised by native plants and not the next crop of weeds. The best time to control weeds is as soon as possible after invasion, while numbers are low. Once weeds have become established and a major infestation results, weed control is much more difficult and costly in terms of time, labour and money.

Planning and prioritisation

In order to achieve successful outcomes, a detailed implementation plan is essential. The plan should identify priority weeds for control, how weeds will be controlled, when weeds will be controlled, and required materials, labour and costings for each phase of the weed control program. Details for follow-up weed control should be also be included, as well as requirements for ongoing monitoring of the site.

Prioritising weed species for control should take into account their invasiveness, distribution and impacts on the wetland. Prioritisation of weeds can be assisted by undertaking a weed map of the site, identifying the areas or zones where control should occur (discussed in more detail under the heading 'Weed mapping'). The plan may need to be modified if unexpected events occur, such as fire, disease or reduction in the level of resources (for example, available time and money) to undertake planned activities. In the case of a fire, weed control may need to be diverted to areas that have been burned to minimise the risk of major weed infestation post fire. Growth of annual grasses and weeds with bulbs and corms can be especially vigorous post fire and therefore weed control should be undertaken as soon as germinants start to appear (see Figure 26).

Figure 26. Weed control should be undertaken as soon as weed germinants appear following a fire. Photo – N Hamilton/DEC.

Table 3 provides an example of a basic weed control implementation plan (note: different weed species require control at different times of the year and a weed control implementation plan should reflect this).

Follow-up

With most weed control programs, it is necessary to weed the site more than once to get the weed population(s) under control. When weeds are killed (for example, by spraying) or physically removed (for example, digging out or hand pulling), this can create conditions that stimulate further germination of weed seeds, corms or bulbs lying dormant in the soil. For weed control to be successful, follow-up weeding is essential to ensure the new batch of weeds does not become established and out-compete regenerating native plants or seedlings.

Weed succession

Sometimes the removal of one type of weed can encourage the growth of other weed species, so follow-up weed control may need to employ a different strategy to the initial control. Follow-up weeding will need to be ongoing and for several years at least, depending on the site conditions, weed species present and rate and success of regeneration or revegetation. Progressively less follow-up weeding should be required once native plants are regenerating well and at a rate faster than weeds can become re-established.

Most weed species maintain a soil seed bank for at least several years, and others will continue to re-invade until re-established native vegetation has reached sufficient density. A program of at least three years will be required to achieve maintenance level management; in almost all cases, weed control maintenance will need to continue over the long term (at least 10 years), unless the original disturbance mechanisms have been arrested, and adjacent weed sources controlled.[5]

In some instances, it may be more effective to manage weeds at a local catchment scale, especially if they originate from outside the property boundary. Working with neighbours or the local government council in a joint effort to control the most problematic weeds in a local area may be a more effective use of resources, and increase the likelihood of success in the long term.

Table 3. Basic weed control implementation plan

				Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Activity	**Who**	**Cost**	**Hours**	**2009**	**2009**	**2009**	**2009**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**	**2010**
Weed mapping	Mary	$ -	4																
Mark zones for control	Mary	$ -	1																
Order native seedlings, fertiliser	Mary	$150	2																
Purchase chemical, backpack/ sprayer	Mary	$300	2																
Book spray contractor	Mary	$-	0.5																
Weed control zones 1 and 2	Contractor	$250																	
First follow-up weed control	Contractor	$100																	
Revegetation* zones 1 and 2	Mary	$ -	10																
Second follow-up weed control	Mary	$ -	4																
Third follow-up weed control	Mary	$-	4																
Monthly monitoring of weeds and native seedlings	Mary	$ -	6																
TOTAL		$800	33.5																

*Note: In some situations, weed control may need to be continued for several years before revegetation (or natural regeneration) can occur.

The big picture

Finally, proposed or existing weed management programs should be considered in view of the ecosystem as a whole to avoid causing more harm than good. For example, there may be instances where weeds are not causing significant impacts on biodiversity (and are not likely to in the future) and removal of these weeds may result in more aggressive weeds replacing them. This is especially critical in situations where follow-up weed control and/or regeneration or revegetation is unlikely to occur or may be unreliable (for example, due to limited labour or resources, other difficulties such as site access etc).

extra information

Benefits of weeds in wetlands

In some circumstances, weeds may provide a source of food or habitat for native fauna and a corridor for them to move safely from one area to another. Ideally, weed control should be undertaken gradually to allow fauna time to find alternative habitat and followed up with revegetation with native species. Weeds can also play an important role in reducing nutrients and sediments from entering wetlands and affecting water quality. In this situation, interim soil stabilisation and/or sediment trapping methods may be required between weed removal and natural regeneration or revegetation.

Weed control methods

This section outlines the main methods of control of wetland weeds and when they are best used. The weed control methods include:

- manual control
- mechanical control
- suppression
- barriers
- flame and steam weeding
- biological control
- controlled grazing
- chemical control
- integrated weed control.

To achieve best results, one method or a combination of methods (integrated weed control) is often the best approach, depending on the type and extent of the weed problem, site conditions and available resources (for example, time, labour, money).

Table 4 summarises the control options for the major types of wetland weeds. These are discussed in more detail in the following sections.

Table 4. Control options for major types of wetland weeds

Weed type	Control options
Annual grasses	Small infestations: • Hand pull or dig up entire plant prior to seed set (note: crowning may be a better option where pulling up or digging out weeds is difficult or causes major soil disturbance); and/or • Flame or steam weed (note: first assess the level of risk for causing fires, especially in peat areas). Larger infestations: • Mow or slash prior to seed set; and/or • Apply recommended herbicide early in the growing season when plants are small (3–5 leaf stage). Use a grass-selective herbicide if grass is growing amongst native vegetation and ensure native grasses will not be damaged.
Perennial grasses	*Tussock grasses* Small infestations: • Remove entire plant prior to seed set, or when dealing with larger areas or difficult-to-remove plants, use a knife to cut through roots below crown tissue at the base of the stem (removing all dormant buds at the base). Larger infestations: • Mow or slash after the flower head has emerged but prior to seed set. Slashing is most effective when followed up with herbicide treatment. *Stoloniferous or rhizomatous grasses* Small infestations: • Hand weeding is not recommended due to the difficulty in removing all stem and root material and the resulting soil disturbance; • Flame or steam weeding; follow-up treatments may be required; and/or • Solarisation; for summer active plants in moist soil. Larger infestations: • Weed barriers; constructed or through revegetation; • Shading out through revegetation; and/or • Apply recommended herbicide during the growing season when plants are small.
Broadleaf herbs	Small infestations: • Hand pull or dig up entire plant before seed set; and/or • Flame or steam weeding. Larger infestations: • Mow or slash after flower head has emerged but prior to seed set; and/or • Apply recommended herbicide during the growing season before flowering when plants are small and actively growing.
Corms, bulbs and tubers	Small infestations: • Remove entire plant (usually early in the growing season, before seed set), ensuring no bulbils or daughter corms are left in the soil. Larger infestations: • Undertake repeated mowing or slashing after flower head has emerged but prior to seed set to avoid spreading seed. Slashing is most effective when followed up with herbicide treatment; and • Apply recommended herbicide at the correct stage of lifecycle, usually just before or just on flowering (this can vary depending on the species, seek expert advice).
Woody weeds	Small infestations: • Remove entire plant (hand pull, digging out). Larger infestations: • Apply recommended herbicide using most appropriate technique, i.e., foliar spray, cut and paint, basal bark spraying, scrape and paint, stem injection, stem and leaf wiping.

Manual control

This includes hand pulling and digging, crowning, and hand removal of aquatic weeds. Manual control methods are useful where there may be concerns about the impact of machinery or herbicides on the environment, and where there are smaller areas of weed infestation. Where appropriate, manual control may be more effective when combined with herbicide application to minimise soil disturbance.

Hand pulling and digging

This method can be used with success where weed numbers are low, where weed control is taking place in a localised area and if the weeds are easy to pull or dig up. It may be the preferred method where weeds are growing amongst sensitive areas of vegetation, where other methods of removal may cause an unacceptable level of disturbance or risk damage to native plants. The keys to success are to ensure that hand pulling and digging is done prior to the weeds seeding and that all of the plant material that is capable of germinating or regenerating is removed from the soil. This includes seed pods and capsules, roots, bulbs, corms, tubers, rhizomes and stolons. In the case of weeds with bulbs and corms, following removal of the parent bulb/corm, the remaining soil must be carefully checked to ensure that any daughter bulbs or corms are not left behind as these can sprout and grow rapidly to form a secondary infestation. If bulbs and corms are present, they must be bagged and removed from the site together with the immediately surrounding soil. It should be noted that soil disturbance from hand pulling and digging can encourage weed seeds to germinate; therefore, follow-up weed control is likely to be required.

Crowning

This technique is useful for weeds that can re-sprout from structures beneath the soil, such as crowns, corms and rhizomes, and clumped or tufted fibrous root systems. A knife or other sharp object is inserted at an angle into the soil and the roots are severed to enable the plant to be removed. It is essential to remove the section the roots attach to, the '**crown**', as this can re-sprout if left in the ground.

Hand removal of aquatic weeds

Floating and submerged aquatic weeds are often best removed by hand to avoid damage to native aquatic vegetation and risks associated with using herbicides in wetlands. Floating aquatic weeds can be harvested by hand, using long-handled rakes for instance, and collected plant material stored in bags for solarisation, composting or landfill disposal. Use of bunds may be useful for larger areas to prevent aquatic weeds from entering 'weeded' out or uninfested areas.

Mechanical control

Mechanical removal is suited to managing large areas of weeds, inaccessible areas due to thick infestations and for aquatic weeds. Methods include mechanical slashing, mowing, cutting, cultivation, scraping and harvesting.

Crown: the region of compressed stem tissue from which new shoots are produced, generally found near the surface of the soil

Slashing, mowing and cutting

In the case of areas completely dominated by annual grasses, this option provides the added advantage of reducing fuel load and hence fire risk when weeds die off over summer. This method is suitable for areas in which native vegetation is not present or is growing in isolated patches that can be avoided, thereby minimising damage from machinery. Slashing and mowing should be done before seed set, to avoid spreading seed around the site. This method does not usually kill weeds straight away, but it serves to deplete their energy reserves and prevent seeding.

Slashing and mowing may need to be repeated several times over the year following if regrowth occurs. This method can be used in combination with chemical control, by spraying regrowth with an appropriate herbicide following slashing and mowing. Using heavy machinery to control weeds should be considered very carefully as it has the potential to compact wetland soils (see Figure 27). This soil damage can in turn make it harder to revegetate the area, reduce the habitat of soil dwelling and burrowing animals, and alter drainage patterns.

Figure 27. Slashing bulrush (*Typha orientalis*) at Forrestdale Lake. Stems are sprayed following slashing to prevent regrowth. Photo – T Bell/DEC.

case study

Salvinia and native bulrush control in Lily Creek Lagoon, Kununurra

Approximately 135 hectares in area, Lily Creek Lagoon in Kununurra is part of the Ramsar wetland site that encompasses Lakes Kununurra and Argyle. It is directly connected to Lake Kununurra, the supply dam for the irrigation area and environmental flows to the Lower Ord River. The township of Kununurra wraps around Lily Creek Lagoon, which is an important habitat for migratory birds, freshwater crocodiles and numerous species of fish. It also provides an attractive backdrop and recreational area for the town.

A small infestation of salvinia (*Salvinia molesta*) was first discovered by a local resident in May 2000. It was immediately identified to be of major concern due to its potential to completely smother the water body and cause damage to the native aquatic ecosystem. It is also of concern as this is the only current infestation in the north of WA and establishment could see it spread through the use of boat trailers to the pristine waterways of the Kimberley.

The control and eradication process of salvinia has been a joint effort of the Shire of Wyndham-East Kimberley, Ord Land and Water, Water Corporation, Department of Water, Department of Environment and Conservation, Department of Agriculture and Food and Save Endangered East Kimberley Species. The initial short-term goal was to contain the isolated infestation, preventing it from spreading throughout Lily Creek Lagoon, Lake Kununurra and Lower Ord River. The long-term goal was for complete eradication due to the serious nature of the weed and the small scale of the infestation.

Several different methods have been used over the past nine years to eradicate salvinia. Initial controls involved the containment of the weed through a boom fence and the manual removal of the bulk of the salvinia where possible. This was followed up by spraying with Roundup Biactive®, and installation of more boom fences (see Figure 28).

The floating boom fences, which are partly submerged beneath the surface to about 35cm depth, are designed to trap salvinia and prevent it from spreading to uninfested areas. Initially one boom fence was used for containment, with more booms being installed later to create additional holding cells. The holding cells served two functions, to trap salvinia that was regenerating from small pieces missed hiding in the native typha stands, and to trap any new plants entering the lagoon from the drain leading into it.

The major difficulty of salvinia being trapped within dense stands of native typha made access for control and removal very difficult. A clearing permit was obtained to remove a small area of native typha in order to allow greater access to the salvinia infestations. The most successful strategy for controlling native typha was mechanical removal with follow up spraying of regrowth. An excavator was used to remove approximately 600 square metres of native typha, which created an open water area which allowed access for eradication of salvinia. Removal of native typha was undertaken outside the breeding season of the swamp hen, which relies on the dense stands for nesting.

Given the total area of native typha within Lily Creek Lagoon is approximately 72 hectares, the loss of this small section has prevented salvinia from invading the remaining native typha in the lagoon, which would have been disastrous. Its removal from the control area improved the effectiveness of the salvinia control as only several small clumps have since been found and these were easily removed by hand.

Monthly monitoring is undertaken to ensure any new infestation are identified and eradicated early. No salvinia has been found since October 2007 and therefore it is likely that it has been eradicated. Lilies and other aquatic plants have regrown in the control area effectively rehabilitating it. If by October 2009 no salvinia is found, the area will be declared clear of salvinia and monitoring frequency will be reduced.

A pamphlet was produced for the community describing salvinia and the threat it poses to the environment, industry and lifestyle. A media campaign was also run, with articles in local papers, radio interviews and displays at the Kununurra Show, natural resource management field days and conferences. Signs have also been erected at the site informing the public of the salvinia quarantine area.

case study

Figure 28. (below) (a) Salvinia monitoring and collection; (b) salvinia trapped within stands of native typha; (c) salvinia containment area using boom fences. Photos – D Pasfield/Ord Land and Water.

(a)

(b)

(c)

Cultivation and scalping

Cultivation is generally not recommended for weed control in a bushland or wetland environment as it involves breaking up the weeds and turning the soil. This can spread weed seeds and other plant parts capable of regenerating, damage native plants and create conditions that favour secondary weed invasion, such as increased space and light. This method may be useful in large, degraded areas where there is no native vegetation present or as a pre-cursor to direct seeding, which requires a completely weed free environment.

Follow-up weed control after direct seeding a cultivated site needs to be vigilant to prevent establishment of the next weed crop that is guaranteed to emerge. This may best be achieved by using an appropriate selective herbicide, and when planting native seedlings a thick layer of mulch can be applied to suppress secondary weed growth.

Scalping involves slicing off the top layer of soil which contains the weeds and weed seeds, leaving the surface bare in preparation for revegetation. Scalping can be done by hand using a sharp shovel for small areas, or with a tree planting machine or road grader for larger areas. Once again, follow-up weed control is important to deal with secondary weed growth which may out-compete establishing native vegetation.

Aquatic weed harvester

In situations where aquatic weeds dominate large wetlands (particularly lakes) and where hand harvesting, spraying or other weed control options are not feasible, aquatic weed harvesters can be used to remove large amounts of weeds. These machines can be purchased in Australia and have been used with varying degrees of success in Western Australia. An aquatic weed harvester typically has large cutting blades that cut the weed above the sediment layer (see Figure 29). Harvesters remove submerged aquatic weeds such as introduced or native typha and floating aquatic weeds such as salvinia. The disadvantage with aquatic weed harvesters is they are expensive to purchase and they can cause damage to native aquatic vegetation and disturb the sediment layer, causing increased turbidity and re-suspension of nutrients or other pollutants. Harvested weeds must be disposed of appropriately to avoid causing odour or other problems (such as leaching of nutrients) from decomposition of plant material.

Figure 29. Aquatic weed harvester removing native typha and salvinia. Photo – K Tripp/Shire of Wyndham East Kimberley.

Weed suppression

Weed suppression methods aim to suppress conditions that favour weed establishment such as soil disturbance and increased light, nutrients and space. Weeds can be suppressed by smothering, mulching, solarisation and drowning.

Smothering and mulching

Depending on the site and type of weeds present, using thick layers of mulch or other materials, including carpet or weed matting, can be very useful in discouraging weed growth. The layers of mulch or matting effectively reduce light and thus prevent weeds from **photosynthesising**. For very aggressive or persistent weeds, conveyor belt rubber is excellent as it forms an impenetrable layer which can be removed once weeds have completely died off. The smothering technique is particularly useful in areas that are dominated by weeds and have no native plants present, where very vigorous and invasive weeds such as couch (*Cynodon dactylon*) and kikuyu (*Pennisetum clandestinum*) are present, or in situations where use of chemicals or other methods are unsuitable.

Solarisation

This method involves covering weeds with ultraviolet-resistant black plastic sheeting and making use of the sun's energy to kill weeds and weed seeds. This method is useful for treating summer-growing grasses in highly disturbed areas during summer, where the soil is moist. The time taken to kill weeds will depend on the weed species, season applied and intensity of the sun. A minimum of four weeks is usually required. Follow-up chemical control may be required, particularly in the case of stoloniferous or rhizomatous grasses such as kikuyu (*P. clandestinum*) and couch (*C. dactylon*), which may re-sprout following treatment. Plastic bags can also be used to sterilise weeds that need to be removed from the site and disposed of, thus reducing the chance of spreading seed or plant parts that can re-sprout. This usually involves placing weed seed heads that have been removed into black plastic bags and placing these in the sun until all plant parts are 'cooked' before disposal.

Drowning

This method can be effective for **emergent** aquatic weeds such as *Typha orientalis*. The plant is drowned by cutting the shoot below the water surface. This may need to be repeated several times over a season to completely kill the plant. There may be insufficient water depth for this method to be effective in killing weeds growing near the water's edge.

Barriers

Natural and constructed physical barriers can be effective weed control measures.

Revegetation

Dense native vegetation can provide an excellent natural weed barrier and therefore weed control programs should include restoration of native vegetation wherever possible. Native vegetation not only competes with weeds for light, nutrients and moisture, it provides a physical barrier which can prevent the entry of wind and water borne seeds into sensitive areas (see Figure 30).

Constructed weed barriers

These can be very effective by providing a physical obstacle that prevents the spread of turf grass or pasture (for example, couch, kikuyu, buffalo grass) from lawn areas or paddocks into sensitive natural areas. The barriers are constructed along the boundary of the area to be protected by digging a trench at least 50–60 centimetres deep and placing materials such as weed mesh or rubber conveyor belt vertically into the ground as a barrier to stop rhizomes from creeping through. The trench is backfilled and, where appropriate, concrete kerbing (or similar) may be placed on top to provide a 'mowing'

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Emergent: a plant that is protruding above the surface of the water or, where a water column is not present, above the wetland soils (as distinct from floating or submerged plants)

Figure 30. Couch (*Cynodon dactylon*) and kikuyu (*Pennisetum clandestinum*) are unable to penetrate a dense stand of the native sedge *Baumea articulata*. Photo – T Bell/DEC.

Figure 31. Concrete kerbing provides an ideal weed barrier, preventing grass weeds from nearby lawn areas from invading newly revegetated areas. Photo – D Moort/City of Rockingham.

edge and further barrier for stolons creeping across the soil surface (see Figure 31). Pedestrian footpaths can also be used as an effective barrier.

Controlled grazing

In certain circumstances and with proper management, controlled grazing can be used to keep weeds, particularly pasture grasses, under control. It must only be used when grazing is a legal activity and does not have the potential to cause environmental harm. It is important to be aware that grazing is a form of clearing (due to its impact on native vegetation) that is subject to regulations of the *Environmental Protection Act 1986*. Furthermore, grazing should not be introduced to areas where it has not previously occurred. Activities such as increasing the stocking rate on native pastures or grazing regenerated areas may constitute clearing of native vegetation and will require a clearing permit if an exemption does not apply.

➤ For additional detail on clearing regulations and managing livestock in wetlands, see the topic 'Livestock' in Chapter 3.

Grazing is most suited to situations in which livestock access can be strictly controlled within specific areas. Controlled grazing can have multiple benefits including:

- reducing weed biomass, making follow up spraying more effective
- reducing weed competition with native plants
- preventing weeds from flowering and setting seed
- reducing fire risk
- providing a feed source for livestock.

Livestock should not be allowed to roam freely throughout wetlands as they can cause significant damage to native vegetation, spread weeds and dieback, foul water bodies, damage banks and cause soil erosion. Ideally, grazing should be limited to short 'crash grazing' episodes, best done during dry times so that livestock can access margins of the wetland without damaging banks or native vegetation. Livestock movement can be very effectively managed using portable electric fencing.

Pasture grasses such as kikuyu (*Pennisetum clandestinum*), couch (*Cynodon dactylon*), wild oat (*Avena fatua*) and African love grass (*Eragrostis curvula*) are palatable to most livestock so they can be very efficient at keeping them under control. However, weed seeds can be spread in manure so it may be necessary to place livestock in holding yards for a few days before moving them into other areas. Care should be exercised to ensure weed species present are not toxic to livestock (for example, cape tulip (*Moraea* spp.), Paterson's curse (*Echium plantagineum*)). Where appropriate, follow-up spraying after grazing provides for more complete weed control, particularly where grazing is intended as a short-term measure only.

Fire

The use of fire to control weeds in wetlands is generally not recommended, due to the complex behaviour and impacts of fire. Fires can cause a range of problems in wetlands, including the risk of exacerbating weed problems and endangering native plants and animals and starting underground peat fires. The use of fire requires careful consideration and a thorough understanding of the impact of fire on weed populations and wetland ecology and should only be undertaken by those with expert knowledge and the necessary authorisations.

Figure 32. After a fire, bare soil, increased light availability and nutrients in the soil provide ideal conditions for germination of weeds. Photo – T Calvert/DEC.

Inappropriate use of fire (for example, too frequent, too hot, wrong time of year) can lead to loss of habitat and native species diversity, and pose a risk to people and property (see Figure 32). Wetlands and bushland experiencing fires that are too frequent or intense can result in native species decline and the area becoming dominated by weeds. Although fire can be a useful tool in stimulating regeneration of native vegetation, not all weeds are fire sensitive and some may actually flourish after a fire. Where unplanned wildfires do occur, this can provide a window of opportunity to control a range of weeds that germinate in response to fire (as weed germination is often faster than native vegetation and therefore the weeds are easy to find and treat).

The invasion of annual grass weeds is of particular concern as increased soil nutrients, light and space availability after a fire favour their rapid germination and spread, out-competing regenerating native plants. Grasses such as perennial veldt grass (*Ehrharta calycina*) and African lovegrass (*Eragrostis curvula*) are common examples of weeds which flourish after a fire. These weeds can dramatically alter wetland vegetation composition in the long term if left unchecked.

Use of controlled managed burns (for example, spot or mosaic burns) may be appropriate under certain circumstances: for instance, in controlling large and difficult weeds such as introduced bulrush (*Typha orientalis*) or pampas grass (*Cortaderia selloana*). The aim of a controlled managed burn is to burn only the desired area in a manner that minimises damage to the environment, people and property. Weed control following fire must be vigilant in order to kill newly germinated weeds as soon as they appear. Where appropriate, follow-up spraying is a very effective as a post-fire control strategy.

Controlled burns require a permit

It is important to seek expert advice before undertaking any controlled burns in or around a wetland or property. A permit from the local government authority is required before undertaking any burning on rural properties. Many local government authorities enforce a total fire ban during the summer - early autumn period and fines are applicable if burning is undertaken at this time.

Flame and steam weeding

These methods involve the use of extreme heat to kill non-woody weeds by rupturing plant cell membranes, thus rendering the plant unable to retain moisture and causing it to die off. These methods are best suited to annual grasses and herbs. Repeat applications may be required as only the leaf/stem material is killed and the roots are left intact, meaning plants may re-sprout.

Flame weeding is done using a portable unit, usually comprising of a gas bottle (liquefied petroleum gas or propane) and hand wand. Vehicle mounted units can be used for larger jobs. A direct flame or infra-red burner is applied to the weeds using a hand wand until the plant leaves are severely wilted (not burnt). Flame weeders should be used with extreme caution in fire risk areas. Although flame weeding is not yet widely used in Australia, it has been used successfully for many decades in Europe for weed control on organic farms and on hard surfaces in urban areas.

Steaming involves delivery of pressurised heated water directly onto plant leaves using a hand wand or similar apparatus. Some local government authorities in Western Australia have used steam weeding to control weeds on road verges or footpaths, where use of chemicals is undesirable due to pedestrian use, or where the weeds occur within environmentally sensitive areas. Repeated applications may be needed, particularly on mature perennial weeds.

Biological control: the control of an introduced plant or animal by the introduction of a natural predator or pathogen, usually bacteria, viruses or insects, or by biological products such as hormones

Although both these methods hold promise as alternatives to herbicides, more research is required to fully assess their effectiveness on a range of weed types and conditions.

Biological control

Many introduced plants that have become environmental weeds in Western Australia are not a problem in their native environment, due to the presence of natural competitors such as insects, herbivores and pathogens that keep their numbers and growth under control. **Biological control** of weeds refers to the introduction of predators or pathogens that will attack and debilitate weeds without becoming pests themselves or adversely affecting native flora and fauna, agricultural crops and livestock. The aim of biological control agents is not necessarily to eradicate a weed but to reduce its population to a more manageable level.

The use of biological control agents for environmental weeds is not yet widespread due to the huge costs involved in conducting research and testing of the agent. Additionally, not all weed species are suitable for biological control. Although relatively few environmental weeds have been subject to biological control programs in Australia, examples of some that have include skeleton weed (*Chondrilla juncea*), salvinia (*Salvinia molesta*), bridal creeper (*Asparagus asparagoides*), blackberry (*Rubus ulmifolius*), cape tulip (*Moraea* spp.), water hyacinth (*Eichhornia crassipes*) and Paterson's curse (*Echium plantagineum*).

- For more information on biological control of weeds, contact the Department of Agriculture and Food or see www.agric.wa.gov.au.

Chemical control

In some situations, use of herbicides is the most cost-effective, practical and efficient means of controlling weeds. Herbicides can be used as the sole means of controlling weeds or in combination with other methods. Two major advantages of using herbicides are that weeds can be selectively targeted where necessary, and soil disturbance is kept to a minimum. Disadvantages of using herbicides are their toxic nature and potentially harmful effects on humans, livestock and the environment if used incorrectly. Use of herbicides around wetlands in particular needs careful consideration and care due to the risks of chemicals contaminating the water and damaging or killing aquatic life. At present, Roundup Biactive® is the only registered herbicide for use near water in Australia. If herbicides are to be used, application methods that have the least potential for damaging non-target species should be considered first, for example, cut stump, wiping or injecting instead of spraying, which has the potential for spray drift related impacts.

When using herbicides, it is essential to apply the correct herbicide, in the right dose, at the right time, using the correct application method. Use only registered herbicides, follow manufacturer's instructions on the label, and wear the appropriate protective clothing during handling. All registered herbicides are labelled with important information to assist in selecting the correct product and give the recommended application methods and dose. Labels also provide safety and poisoning information and recommended disposal methods.

extra information

Legal obligations for herbicide users

The *Pesticides Act 1999* provides for the registration of herbicides, labels and containers.

In Western Australia, anyone who uses herbicides is bound by the Health (Pesticides) Regulations 1956. These regulations were developed to provide protection for the applicator, the public and the environment from misuse of pesticides and herbicides. Herbicide labels are written in accordance with the regulations and therefore any herbicide user has a legal obligation to read and follow instructions on the label. The label provides directions for use, and for the protection of the environment, information about storage and disposal, recommendations for personal protective equipment and information about the weeds that can be treated.

Despite the provision of these details, many environmental weeds are not listed for use on herbicide labels and therefore an off-label permit may be required. The Department of Agriculture and Food has obtained a minor use off-label permit for a number of herbicides to be used specifically on environmental weeds in non-crop areas (including wetlands and bushland) until March 2017. This permit (PER13333) provides for the use (by any person in Western Australia) of a herbicide product in a manner other than that specified on the approved label of the product. However, persons who wish to use herbicide products in ways other than those specified on the approved label, must read and follow the permit instructions. For more information see www.apvma.gov.au/permits.[13]

Ideally, all herbicide users should undertake training in correct preparation, handling, application, transport and storage of herbicides. Although there is currently no legal requirement for herbicide users (other than paid contractors) to undertake training in the use of herbicides, legislation for use of chemicals is under review and this may change in the future.

Wetting agent: a substance that helps water or other liquid to spread or penetrate (also known as a surfactant or penetrant)

➤ For additional detail on herbicide use, products available, safety and environmental considerations and recommended herbicides for weeds see 'Sources of more information' at the end of this topic.

Use of herbicides in and around wetlands

The use of herbicides in and around wetlands should be undertaken with great caution, and only as a last resort, when non-chemical weed control methods are not realistic or viable. There is potentially a great risk to aquatic life if herbicides enter wetlands or waterways. Of particular concern is the impact of herbicides and associated **wetting agents** on frogs. Studies have shown that tadpoles and mature frogs have been found to be extremely sensitive to these chemicals, which may cause damage to their skin and gills, resulting in death (see Figure 33).

Figure 33. Frogs and tadpoles are extremely sensitive to certain herbicides and wetting agents. Seek advice from organisations such as the Department of Environment and Conservation or Department of Agriculture and Food before using herbicides in and around wetlands where frogs are present. Photo – C Mykytiuk/DEC.

Tips on reducing environmental risks associated with herbicide use near wetlands

Adapted from Cooperative Research Centre for Australian Weed Management's Introductory Weed Management Manual.[7]

- Use only herbicides that are registered for use in wetlands and/or are documented to have low toxicity to aquatic organisms (for example, Roundup Biactive®, Fusilade®).
- Apply herbicide at the recommended rate.
- Ensure that weeds are treated at the appropriate time (when surface water levels are low) to reduce the need for repeated follow-up treatments.
- Mix herbicides with a coloured dye to mark areas that have been sprayed.
- Avoid using wetting agents, as many of these are more toxic to wetland fauna than the actual herbicide.
- If contractors are to be used for herbicide application, ensure they follow procedures to minimise risks to wetland fauna.
- If possible, treat weeds close to water bodies progressively rather than in one large-scale operation, to minimise risks to wetland fauna, and to reduce erosion and habitat loss where weeds are binding the soil or providing habitat.
- Mixing of chemicals and cleaning of equipment should be done away from the wetland and in a location where any accidental run-off will not directly enter the wetland.
- Wherever possible, direct the spray away from water bodies, when there is no wind.
- When spraying around drains that feed into wetlands, move upstream when spraying rather than downstream to aid dilution of any contamination and to avoid creating a 'slug' of herbicide entering the wetland.
- Spray only when rain is not expected for several days.
- Check with the local government authority to find out what regulations apply for the application of herbicides near wetlands.

The only herbicide registered for use around wetlands at present is Roundup Biactive®, which is a broad spectrum, non-selective herbicide reported to be 100 times safer for frogs than the original Roundup formulation.[14] To minimise potential impacts on frogs, the use of herbicides should be avoided between late autumn and early spring, when egg-laying, hatching and subsequent dispersal of juvenile frogs takes place. Timing may vary between species, so it is important to seek expert advice for assistance in identifying frog species present in wetlands, and to confirm the timing and duration of their breeding cycles before herbicide application takes place.

Fusilade®, a selective grass-specific herbicide (commonly used to control annual and perennial veldt grass, kikuyu, couch and water couch) has been tested in Western Australia and found to be highly effective in removing introduced grasses. Care should be taken when using Fusilade® and the stronger preparation Fusilade Forte® in and around wetlands as recent studies have shown that it can have a negative effect on native seed germination.[15] Fusilade® is slightly soluble in water and has low toxicity to aquatic organisms. To minimise risk of negative impacts on wetland flora and fauna, always follow the manufacturers instructions on the label and apply carefully to target weeds, avoiding contact with the soil, water and non-target species as much as possible.

How herbicides work

Herbicides kill weeds by disrupting essential biochemical processes within the plant. Herbicides act in two ways, either via direct contact with plant surfaces (for example, leaves and stems) or when translocated through the plant's circulatory system. There are different types or herbicides including **selective**, **non-selective**, **residual**, **non-residual** and **pre-emergent**.

Non-synthetic herbicides

There are a number of **non-synthetic** herbicides on the market that may be effective against a range of weeds. These herbicides contain active ingredients such as pine, cinnamon and clove oils, petroleum or mineral oils, acetic and pelargonic acid or potassium salts. Many of these products such as those containing acetic acid or pelargonic acid are designed to 'burn' foliage, causing dessication of plant cells. Any herbicide, whether synthetic or non-synthetic, has a degree of risk associated with its use, and products that are marketed as non-synthetic, natural, or organic may still have the potential to cause harm to the environment, people or animals. Caution should therefore be exercised during use and instructions on the label for storage, handling, application and disposal should be strictly adhered to.

Timing

The best time to treat weeds with herbicides is when they are small, actively growing and have not yet set seed. Weeds are easier to kill and require less herbicide when they are small. The most effective translocation of herbicide throughout the plant occurs if herbicide is applied when transpiration is greatest, usually during midday on a sunny clear day, provided there is no wind which (if spraying) could carry spray drift onto non-target species. Avoid treating weeds when rain is expected or when they are under stress (for example, during extremes in temperature, drought or if they are diseased) as they will be less likely to respond to treatment. The timing of application may also depend on the objective of weed control: for example, spraying weeds early in the growing season when they are small will give native plants more chance of surviving due to reduced competition. Bulbs, corms and tubers are ideally treated when the underground storage organs are depleted; woody weeds, when they are actively growing; and perennial grasses, when they are actively growing (before flowering). However, spraying later in the growing season may make it unnecessary to follow up with treatment for late germinants or weeds that germinate following initial spraying.

Selective: have been developed to kill a particular type of plant (e.g. grasses)

Non-selective: (or broad spectrum) herbicides kill a wide range of plants

Residual: remain active in the soil for some time and may kill germinating seeds and susceptible plants

Non-residual: (or knockdowns) kill existing weeds but have no effect on germinating seeds

Pre-emergent: kills germinating seedlings when applied to the soil before germination[8]

Non-synthetic: of natural origin; not derived artificially by chemical reaction, and free from chemical treatments or additives. Other terms commonly used to describe non-synthetic herbicides include natural or organic herbicides.

Techniques for herbicide application

There are many techniques for herbicide application. Selection of the most appropriate technique will depend on a range of factors including the weed species, extent and severity of infestation to be treated, nature of associated vegetation/habitat, available equipment and resources.

Herbicide wipe

This method is ideal for areas where spraying is not suitable: for example, where weeds are growing in environmentally sensitive areas that may be adversely affected by spray drift, such as within dense native vegetation or around inundated or waterlogged areas. Herbicide is wiped or brushed onto the leaves using equipment with materials soaked in herbicide such as a wick applicator, a modified hand sprayer or glove with foam attached. This method can be time consuming in areas where infestation is severe. Care needs to be taken to ensure that herbicide does not drip from weeds onto non-target species.

Foliar spraying

Foliar spraying is a good option for controlling wetland weeds where the risk of spray drift onto native vegetation (non-target species), inundated or waterlogged areas is minimal. Spraying should only be undertaken on fine, still days to minimise risk of run-off of chemical and/or spray drift. Foliar spraying techniques include spot spraying and blanket spraying, using equipment from hand sprayers, backpack sprayers to boom sprays operated from vehicles (see Figure 34). Whichever method is chosen, it is important that the operator knows the difference between weeds species and native species, particularly in areas where native grasses could be mistaken for weeds. The site should be inspected prior to spraying to ensure familiarity with target and non-target species. It is not recommended for saplings or mature trees with thick, waxy leaves (which limits absorption of herbicide) or where it is difficult to treat the canopy without off-target damage.

Figure 34. Spot spraying weeds using a backpack and hand held applicator minimises damage to non-target species. Photo - T Schwarten/Syrinx.

➤ For additional detail on herbicide application see section in this topic on 'Using contractors'.

Spot spraying

Using a handsprayer or backpack, this method allows selective targeting of weeds and is useful where weeds are growing in sensitive areas and more accuracy is required to avoid damage to non-target species.

Blanket spraying

Using a backpack or a boom spray operated from a vehicle is useful for treating large or dense infestations where potential for damage to off-target species is low.

case study

Challenges in wetland rehabilitation at Bibra Lake

By Denise Crosbie (Cockburn Wetlands Education Centre)
and Norm Godfrey (Wetlands Conservation Society)

Wetlands are dynamic in nature. Bibra Lake in Perth's southern suburbs experiences seasonal patterns of wetting and drying. Developing an understanding of these patterns has assisted in the development of a successful rehabilitation program at Bibra Lake.

Zoning in wetlands

Bibra Lake is a permanently inundated wetland approximately 135 hectares in size with a maximum depth of 2.5 metres. The area of the lake that is inundated fluctuates from season to season and year to year. Water levels are largely influenced by rainfall, groundwater flows and evaporation, peaking in October and falling to minimum levels during April. Different wetland plants and weeds are associated with different zones of the wetland and this has implications for rehabilitation activities (see Figure 35).

Getting started

Maps were prepared to gain a better understanding of site conditions including water levels, topography, type and extent of existing native vegetation and weeds.

Weed control

Moving from the seasonally inundated zone towards the waterlogged zone, Bibra Lake is ringed by water couch (*Paspalum distichum*), paspalum (*Paspalum dilatatum*) and kikuyu (*Pennisetum clandestinum*). Nutgrass (*Cyperus* spp.), spear thistle (*Cirsium vulgare*) and bushy starwort (*Symphotricum squamatum*) invade bare spaces amongst the grasses. Weed control has been a major task as the removal of these primary weeds creates a space for others (secondary weeds). A combination of manual and chemical control, combined with mulching and saturation planting, has been very effective (see Figure 36).

The weed control efforts at Bibra Lake provided the following learnings:

- Chemical treatment is best applied during summer when weeds are actively growing and water levels have receded.
- Roundup Biactive® has been effective for all primary and secondary weeds (no bulbous species were present).
- A staged approach has been essential because active growth of weeds is staggered as water levels recede.
- Commitment to monthly weed control has been required because weeds actively grow in waterlogged zones during periods of maximum water level, and grow in seasonally inundated zones at minimum water level.
- Weed biomass did not require slashing in the seasonally inundated zone because it decomposed during and after flooding events. It required mowing in the waterlogged zone in readiness for a planting event, as it took years to decompose.

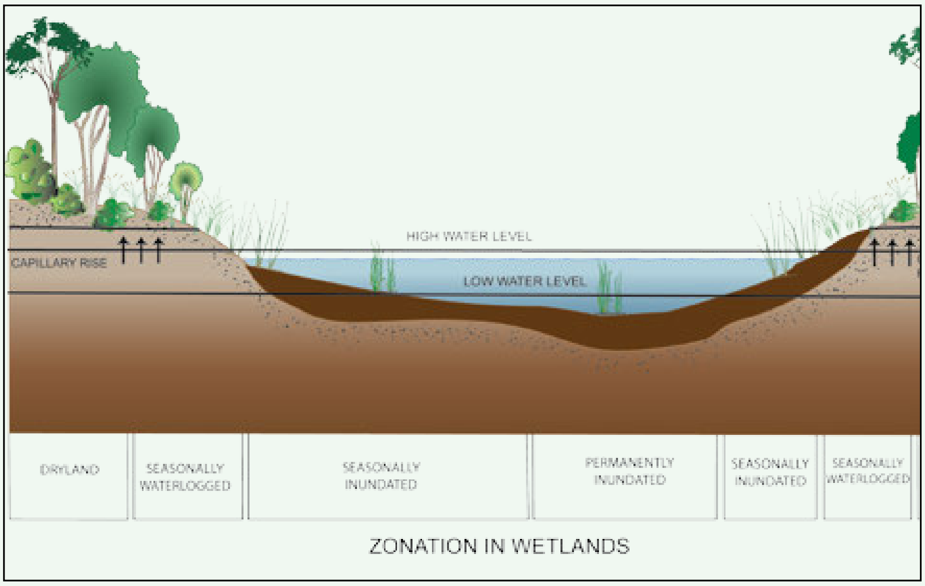


Figure 35. When controlling weeds, it is important to consider the different wetland zones and how they might influence where, when and how weed control should be undertaken. Adapted from - D Crosbie/Cockburn Wetlands Education Centre.

case study

- Mulching of the lower waterlogged to upper seasonally inundated zone with suitable mulch (the weediest zone) reduces the frequency of weed control (if using mulch, consideration should be given to dieback, weeds and nutrient input).
- Jute and paper weed matting barriers were ineffective where healthy populations of purple swamphens (*Porphyrio porphyrio*) exist.

Trials and tribulations

During the early days of rehabilitation at Bibra Lake the following problems were encountered:

- Timing of grants restricted the ability to order seedlings early and thus limited species availability.
- Chemically treated weeds did not mulch down in time for planting.
- Numerous seedlings needed replanting because they were established in the slashed weed biomass instead of the soil.
- Late plantings (September) required summer watering of the seasonally waterlogged zone.
- Secondary weed invasion was extensive.
- Planted sedges were predated by waterbirds.

Although wetland trees and tall shrubs were able to be established in weedy environments (though they grow more slowly), the object was to re-introduce understorey and attain a reasonably 'self-sustaining system' through dedicated weed control efforts.

Revegetation

Due to the dynamic nature of wetlands, many native plants may be growing outside of their optimal establishment zone. Be careful! Look at historical water data for the wetland, and at other wetland sites prior to planting. It is also difficult to predict future water levels, and during some years you may lose plants – this is part of the challenge.

Wetlands plants grow rapidly and are much quicker to reward you than their slower bushland counterparts. The planting efforts at Bibra Lake included:

- saturation planting to out-compete the weeds
- planting transitional, waterlogged and upper seasonally inundated zones during winter months
- staging planting of the lower seasonally inundated zones following a fall in water level (approximately November onwards)
- organising planting days after the maximum water levels
- removing tree guards the following winter to avoid summer predation by rabbits
- propagating locally sourced seed and establishing a wetland seed production area for future supplies.

So, can we really bring back the understorey?

Unfortunately there are no quick solutions when it comes to rehabilitation activities. The understorey is looking fantastic, bandicoot diggings are evident, and the frogs and birds are breeding. Bushy starwort, spear thistle, nutgrass and lotus invade bare areas where saturation planting has not been achieved. Our knowledge is growing and we need to continue long-term monitoring and evaluation to determine the true outcomes of our trials.

Established in 1993, the Cockburn Wetland Education Centre is an independent, not-for-profit community organisation dedicated to wetlands, restoration activities, environmental education, youth services and facility hire. Numerous volunteers implement the centre's activities along with the assistance of a small band of dedicated staff. The centre lies in the suburb of Bibra Lake, 15 kilometres south of Perth, Western Australia. It provides a gateway to Beeliar Regional Park, which contains 27 wetlands within two parallel wetland chains.

case study

Figure 36. (below) Weed control and revegetation at Bibra Lake. (a) pre-weed control, the three main grass weeds: kikuyu, paspalum and water couch; (b) the site post-spraying and preparation for revegetation; (c) post-mowing ready for planting; (d) seedlings were planted with tree guards and weed mats to help combat weed regrowth; (e) secondary weed growth – weed regrowth was less where mulch had been applied; (f) the site two years later following revegetation; (g) water couch (background) during the winter months when dormant and not actively growing. The inundated area in the foreground is where the water couch was treated the previous year and replanted with sedges; (h) water couch during the summer months when it is actively growing and the best time to spray. Photos – D Crosbie/Cockburn Wetlands Education Centre.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Stem injection

Stem injection is used to treat woody weeds such as trees and large shrubs which would be very difficult to physically remove, or those that produce suckers in response to damage to their roots or canopy. Physical removal of trees and large shrubs risks major disturbance and damage to non-target species. Stem injection involves drilling holes into the trunk or main stem, and injecting herbicide into the holes. The holes must penetrate the **sapwood tissue** to ensure that the herbicide will be transported throughout the plant. Ideally, holes should be drilled at 5–8 centimetre intervals and at a downward angle of 45 degrees to reduce the risk of spillage. Herbicide should be injected within 10 seconds of drilling to maximise uptake in the sapwood tissue (before the plant begins to 'seal' the wound and inhibit uptake).

This method allows selective treatment of individual plants with minimal risk to non-target species. Equipment used includes a cordless drill, drill bit and an injection gun or syringes for injecting the correct dose of herbicide. If a drill or injection equipment is not available, angled cuts can be made around the stem using a chisel or tomahawk (referred to as 'chipping' or 'frilling'). When using this second method, more care is required to avoid herbicide leaking from the cuts and dripping down onto the soil or other plants.

Cut and paint

This method is used for large trees or shrubs that re-sprout and involves cutting off the trunk or main stem horizontally, as close to ground level as possible. Herbicide is then painted or sprayed immediately onto the sapwood (not the **heartwood** which is inactive and will not circulate the herbicide around the plant). Equipment required to cut down woody weeds include secateurs, loppers, hand saws and chainsaws. Herbicide can be applied with a paint brush, squeeze or spray bottle, or wick wiper. If removing the cut plant material from the site, care should be taken to minimise damage to non-target species and prevent spreading seeds. This technique is not suitable for large infestations of mature trees as felling them may cause damage to surrounding native vegetation. In addition, painting the cut stems may not deliver enough herbicide to kill the rootstock.

Basal bark spraying

This method can be used to treat woody weeds such as larger trees with thin bark and small stems (less than 20 millimetres diameter): for example, saplings, regrowth and multi-stemmed shrubs and trees. Herbicides need to be oil soluble and mixed in an appropriate oil-based substance (such as diesel) and sprayed around the full circumference of the trunk or stem. Spraying should be from ground level up to 60 centimetres in height. Care should be exercised to ensure that the bark is dry and free from dirt and that the treatment solution does not drip or run off onto non-target vegetation, soils or into water bodies. This method is quicker than cut and painting or injection as it evenly distributes the herbicide throughout the sapwood.

Scrape and paint

This method is useful for vines or other creeping plants with a woody stem that cannot be injected or cut off at the stem and painted due to too small an area for herbicide uptake. It involves scraping off 20 millimetres to 1 metre of bark along the length of the stem and applying herbicide to the exposed sapwood. Stems smaller than 10 millimetres in diameter can be scraped on one side and those above 10 millimetres should be scraped on two sides. Care should be taken not to **ringbark** the stem as this will inhibit transport of herbicide throughout the plant.

If vines are tangled in amongst native vegetation, it may be best to leave them in place once they have been killed, as removing them may damage native plants.

Sapwood tissue: specialised plant tissue that transports water and minerals upwards from the roots to the stem, via capillary action

Heartwood: the central, woody core of a tree, no longer serving for the conduction of water and dissolved minerals, usually denser and darker in colour than the outer sapwood

Ringbark: to completely remove a strip of bark around the trunk or main stem of a tree or shrub, causing its death

Keeping records of herbicide use

It is important to keep records of herbicide use to monitor success of the weed control program. Details that should be recorded include:

- herbicides used
- rate of application
- weeds treated
- size of the area treated
- date and time of treatment
- method of application
- weather conditions.

This information will help determine which methods have been successful and which haven't, so that any follow-up weed treatment can be modified if required.

Integrated weed control

Integrated weed control involves the use of a combination of control methods to achieve the best results in the most cost effective and practical way. The aim of integrated weed control should be to achieve long-term weed control without damaging the environment. Integrated weed control methods should reinforce each other and, where appropriate, assist in reducing reliance on herbicides in the long term. Integrated weed control is particularly effective when used in combination with other land management methods (for example, fencing off wetlands from livestock, planting shelterbelts) that ultimately help to prevent and reduce the spread of weeds and improve the overall condition of the natural environment.

Good planning and understanding of the site conditions (for example, soil, topography, other vegetation, climate) and the life cycle and biology of weeds is essential to ensure that the various control techniques are applied in the correct manner, at the correct time(s) and reduce future effort and cost of weed control.

Summary of weed control methods

A summary of the weed control methods, their advantages and disadvantages and types of weeds they are best suited to is provided below in Table 5.

Table 5. Comparison of weed control methods (adapted from Cooperative Research Centre for Australian Weed Management, 2004)[7]

Treatment	Advantages	Disadvantages	Suitable for control of
Manual removal (hand pulling, digging etc)	• Selective • Minimises risk to surrounding plants • Supplements other techniques • Can prevent seeding and spread • Effective on small infestations • Enhances plant identification skills and familiarity with sites	• Can disturb soils if poorly done • Timing limitations, needs moist soils • Can spread weed propagules • Unsuited to large infestations • Inappropriate for some weed species and large plants • Labour intensive	• Annual grasses • Perennial grasses • Broadleaf herbs • Corms, bulbs, tubers • Aquatic weeds

Treatment	Advantages	Disadvantages	Suitable for control of
Soil cultivation and scalping	• Can eradicate weeds • Reduces nutrient loads • Removes soil-stored weed seed bank • Can aid site rehabilitation	• Non selective • Disturbs and potentially damages wetland soil values • Spreads propagules • Destroys local flora and fauna habitat • Removes soil stored local flora seed bank • Potential for erosion/run off • Expensive • Site rehabilitation required • Technical proficiency required	• Annual grasses • Broadleaf herbs
Slashing, mowing, cutting (brushcutters, mowers, slashers)	• Minimises soil disturbances • Mimimises risk to local flora • Can prevent seeding and spread • Removes excess foliage (or follow-up treatments) • Supplements other methods • Helps to weaken plants, making them susceptible to other forms of control • Inexpensive	• Usually doesn't eradicate weeds • Can prevent seeding by local flora • Can introduce/spread weed propagules • Can encourage weed growth • Can increase fuel loads (dried material)	• Annual grasses • Perennial grasses • Annual herbs
Competition strategies (direct seeding, plantings, natural recruitment)	• Suppresses weeds • Can alter light levels and nutrient-moisture availability • Restores vegetation structure • Restores floristic diversity • Enhances fauna habitat	• Altered conditions can favour weeds • Can undermine vegetation structure with inappropriate species selection • Often entails intensive management input during establishment phase • Can be labour intensive (costly) • Specialist knowledge required	• Annual grasses • Perennial grasses • Broadleaf herbs • Corms, bulbs, tubers (during flowering) • Aquatic weeds
Mulches and smothering treatments	• Inhibits/prevents weed seeding and spread • Can complement site rehabilitation • Erosion/run-off control • Aesthetics enhanced (mulches)	• Usually non-selective • Can encourage weed growth • Prevents local plant growth and spread • Can introduce weed propagules • Can alter soil chemistry • Affects soil conditions and soil microfauna • Ongoing maintenance required • Aesthetics undermined • Costly and labour intensive	• Annual grasses • Broadleaf herbs
Weed barriers	• Selective • Reduces reliance on herbicides • Supplements other methods • Can be incorporated into hard landscaping	• Constructed barriers can be expensive and labour intensive • Not suitable for large areas	• Annual grasses • Perennial grasses
Solarisation (clear or black UV plastic)	• Can be selective • Can control tenacious weeds • Inhibits/prevents seeding and spread • Supplements other methods • Appropriate on a small scale • Low costs (once installed)	• Usually non selective • Ineffectual on many weeds • Unsuitable for large infestations • Prevents local plant growth and spread • Affects soil conditions and soil micro-fauna • Ongoing maintenance require	• Annual grasses • Perennial grasses

Treatment	Advantages	Disadvantages	Suitable for control of
Fire (control burns, spot-burns)	• Removes dead and excessive foliage (for follow-up spray treatments) • Supplements other methods • Can encourage local flora regeneration • Encourages germination of soil stored weed seed bank (for follow-up treatments) • Relatively inexpensive • Can kill some weed seed banks	• Usually does not eradicate weeds • Inappropriate for non-fire adapted ecosystems • Damages native vegetation/fauna if used incorrectly • Seasonal and timing limitations • Encourages weed growth/ germination • Altered nutrient-moisture availability can favour weeds • Potential for run-off/erosion • Fauna, people, property risks • Can be costly if establishment of fire breaks and personnel to control fire are involved • Specialist knowledge required	• Not recommended in general
Flame and steam weeding	• Selective • Reduces reliance on herbicide in sensitive areas • Minimal soil disturbance • Minimal environmental impact	• Can be expensive to use • May require repeated applications • Labour intensive • Variable results • Risk of off-target damage • Risk of fire • Specialist knowledge required	• Annual grasses • Annual broadleaf
Biological controls	• Selective • Can suppress weed growth and spread • Supplements other methods • Long-term value for money • Minimal labour input (in the field) • Minimal direct environmental impacts	• Timing limitations • Variable results • Does not eliminate weeds • Other controls required • Expensive to develop • Limited range of weeds can be targeted	• Bridal creeper • Blackberry
Herbicides (foliar application)	• Selective (depending on choice of herbicide, timing, plant life cycles, operator skill) • Can prevent weeds seeding and spreading • Appropriate on small and large weed infestations • Minimises direct soil disturbances • Inexpensive	• Potential for non-selective damage/ may destroy local flora • Potential impacts on the broader environment • Technical proficiency required • Operator/public hazards	• Annual grasses • Perennial grasses • Broadleaf herbs • Corms, bulbs, tubers (at or during flowering) • Aquatic weeds
Woody weed treatments (cut and wipe, stem injection, scrape and paint etc.)	• Selective • Minimises risks to local flora • Prevents seeding and vegetative spread • Inexpensive (on small infestations)	• Site disturbances can be excessive, care is needed • Can spread weed propagules (by removal of plant material from the site) • Can destroy native fauna habitat • Can encourage weed growth/ germination • Operator/public hazards • Costly and labour intensive (on large infestations)	• Trees, large shrubs

Monitoring weed control

Monitoring is an important aspect of weed management. It helps to identify where weed control efforts have been successful (or otherwise) and where efforts may need to be continued or modified in the future. Regular monitoring (at least twice a year) will also indicate areas in which weeds are re-invading and therefore where prompt treatment is required while plants are still in the early stages of growth.

➤ For additional detail on wetland monitoring, refer to the topic 'Monitoring wetlands' in Chapter 4.

Long-term monitoring will help to finetune existing and future weed management programs and optimise the use of available resources. Weed surveys and mapping are useful ways of monitoring and recording the success of weed control measures. Taking photographs (photo points) is also a good way of recording weed mortality, regrowth and also any natural regeneration occurring after weed control.

Using contractors

When using contractors to undertake weed control, it is essential that they are trained and experienced in working in a wetland or bushland setting and will do everything necessary to ensure that weeds are not spread and environmental damage is avoided, particularly where herbicides are to be used. Spray contract businesses must be registered with the Pesticide Safety Section (PSS) of the Health Department of Western Australia.

Spray contractors must be able to tell the difference between weeds and native plants and be prepared to use equipment that minimises the risk of off-target damage (for example, use of backpacks or other hand-held sprayers or wiping devices). They should also be familiar with the risks of herbicide use near wetlands and understand the most appropriate chemicals and application rates for the target weed species.

It is helpful to provide contractors with a weed map and a guided site visit to ensure that they know the exact location of weeds to be controlled, their relationship with native vegetation and how to access those areas. They should also follow standard hygiene practices to avoid spreading seed and dieback to and from the site, e.g. by cleaning tools, equipment, machinery, vehicles (especially tyres) and boots appropriately.

Whether or not to manage weeds in a wetland

When deciding whether or not to manage weeds in wetlands, there are a number of factors that should be considered including: the biodiversity and other value(s) under threat; how practical and effective management will be; and the amount and availability of resources to undertake management (time, money and labour). As resources for weed control tend to be limited it is also important to consider the impact and invasiveness of various species and their current distribution. There may be a number of weed species present in or around a wetland and available resources may mean that not all of them can be dealt with. Therefore, priorities for control may be weeds with the greatest potential for rapid spread and environmental damage, for which effective control is achievable.

Some questions to help focus the decision-making process include:

- **Is the weed a declared plant species or a weed of national significance (WONS)?**

  Landholders are obliged to control these plants at their own expense. Declared plants and WONS can cause significant damage to ecosystems and agricultural productivity if not controlled. Early intervention provides the best chance of preventing long-term damage to wetlands.

- **Do the weeds pose a fire hazard?**

  Weeds that present a fire hazard should be controlled as a matter of priority. The impacts of a fire are far-reaching and can not only damage wetlands, they can also put human lives and infrastructure at risk.

- **Are the weeds inhibiting native plant growth and/or regeneration?**

  If weeds are preventing the growth or regeneration of native vegetation, it is likely that the vegetation structure of the wetland is becoming degraded and biodiversity values reduced. Over time, if weeds are allowed to dominate the understorey, the wetland will have reduced biodiversity value, and the scale of the weed problem may become unmanageable.

- **Are the weeds degrading native fauna habitat?**

  If habitat for native fauna is degraded by weeds, the decline in habitat diversity will reduce the biodiversity of the wetland. In cases where weeds provide some fauna habitat (for example, introduced bulrush can provide waterbird habitat), removal should be gradual to allow fauna time to adapt until natural regeneration (or revegetation) occurs.

- **Are any threatened fauna, declared rare flora (DRF) or threatened ecological communities (TECs) present?**

  Under the *Wildlife Conservation Act 1950*, individual species of plants and animals are protected, with the level of protection varying depending on whether the species is rare or endangered. Weeds can pose a threat to these values by altering vegetation structure and diversity and degrading fauna habitat. Landholders with identified threatened fauna, DRF or TECs on their land should contact the Department of Environment and Conservation before undertaking weed control or any other activity that has to potential to negatively impact on protected species.

  ➤ For additional detail on DRF and TECs see the topic ‘Wetland vegetation and flora’ in Chapter 2.

- **Are the weeds a potential threat to other values?**

  The potential for weeds to threaten other values both within and outside the wetland or property boundaries should be considered. For example, aesthetic and/or real estate values may be compromised, health problems may occur (for example, pollen or grass seeds causing allergies in humans, pets or livestock), or there may be the potential for weeds to spread into adjacent properties or wetlands.

Topic summary

- Weeds can be defined as ‘plants that become established in natural ecosystems, altering natural processes and leading to the decline of the communities they invade.’[3,1]
- Weeds threaten primary production, and the biodiversity and conservation values of Western Australian ecosystems. They affect severely on agriculture and biodiversity by competing with crops and out-competing native plants and degrading habitat.
- Weeds respond rapidly to disturbance, out-competing native plants for available light, water, space and nutrients. They also have fewer natural predators, pests or diseases than native plants, which assists them to grow and spread virtually unchecked.
- Weeds tend to invade areas where disturbance of soil or natural vegetation has occurred or where the natural fire regimes have changed. Activities that disturb natural areas such as clearing native vegetation for agriculture, settlement and transport, logging, rubbish dumping and livestock and vehicle movement contribute to the introduction and spread of weeds.
- Wetlands are particularly vulnerable to weed invasion where moist productive soils are present in association with disturbance factors, Phytophthora dieback and altered fire regimes.

- Understanding the life cycle and biology of weeds is essential for successful management.
- Weed management does not necessarily imply complete and permanent removal of every single weed in a given area. In many cases, complete removal of weeds is not desirable or feasible for many reasons – for example limited resources, increased potential for erosion or other adverse environmental impacts.
- Guiding principles for successful weed control include preventing weeds from becoming established in the first instance, accurately identifying weed species, mapping weeds and native vegetation, controlling weeds while in the early stages of growth (and before seed set), working from the least affected areas towards the worst affected areas using a combination of methods if possible, and hygiene management to avoid spreading weeds.
- Integrated weed management combines a number of weed control strategies to ensure the best possible result and most cost effective use of resources.
- Natural regeneration or revegetation should occur following weed control to minimise new weed invasions.
- Monitoring and recording the progress of weed control is essential to determine what has worked, what hasn't worked and how future weed control is best undertaken.
- When deciding whether or not to manage weeds in wetlands, a number of factors should be considered such as: impacts, invasiveness and current/potential distribution; the biodiversity and other value(s) under threat from both the weeds themselves and proposed control strategies; how practical and effective management will be; and the amount and availability of resources to undertake management over the timeframe necessary to achieve desired outcomes.

Sources of more information on managing weeds in wetlands

The following list of references is adapted from Hussey BMJ, Keighery GJ, Dodd J, Lloyd SG and Cousens RD (2007). *Western Weeds: a guide to the weeds of Western Australia, second edition*. The Weeds Society of WA (Inc).[9]

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Useful websites

Australian Pesticides and Veterinary Medicines Authority (APVMA)
www.apvma.gov.au
Herbicide registration information

Commonwealth Department of Sustainability, Environment, Water, Population and Communities
www.weeds.gov.au

Council of Australasian Weed Societies (CAWS)
www.caws.org.au

CSIRO Entomology (weed ecology and biological control)
www.csiro.au/science/InvasivePlants.html

Department of Agriculture and Food
www.agric.wa.gov.au
Declared Plants and their control, State Weed Plan for WA, Permitted and Prohibited species lists

Department of Environment and Conservation
www.dec.wa.gov.au/content/category/31/936/2275/
FloraBase, Urban Nature

Department of Water
http://portal.water.wa.gov.au/portal/page/portal/WaterQuality/Publications/WaterNotes?pAP=WaterManagement&pAS=Waterways
Water notes: advisory notes on river and wetland restoration

Environmental Weeds Action Network of WA (Inc.)
www.environmentalweedsactionnetwork.org.au

Global Compendium of Weeds
www.hear.org/gcw

HerbiGuide
www.herbiguide.com.au
Herbicide, weed and control information

Northern Australian Quarantine Strategy (NAQS)
www.aqis.gov.au/naqs
Target list of weeds

RG & FJ Richardson
www.weedinfo.com.au
Publishers

Weedbuster Week
www.weedbusterweek.info.au

Weeds Australia
www.weeds.org.au

Weeds Society of WA (Inc.)
www.wswa.org.au

Glossary

Annual: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) within a single growing season

Aquatic plants: a plant that grows for some period of time in inundated conditions and depends on inundation to grow and, where applicable, flower

Biennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) within two years

Biological control: the control of an introduced plant or animal by the introduction of a natural predator or pathogen, usually bacteria, viruses or insects, or by biological products such as hormones

Bioregion: a territory defined by a combination of biological, social and geographic criteria rather than by geopolitical considerations; generally, a system of related, interconnected ecosystems[1]

Broadleaf: plants that possess relatively broad flat leaves rather than needle-like leaves

Corms, bulbs, tubers: specialised underground fleshy storage organs that allow plants to flourish in nutrient deficient soils or to die back and enter a state of dormancy when conditions are extreme, such as during fire or drought[8]

Crown: the region of compressed stem tissue from which new shoots are produced, generally found near the surface of the soil

Cultivation: methods of breaking up and turning the soil

Disturbance opportunists: responding positively and rapidly to habitat disturbance

Ecosystem services: the processes by which the environment produces resources that provide benefits to humans, for example, flood and disease control, clean air, waste recycling, plant pollination[2]

Emergent: a plant that is protruding above the surface of the water or, where a water column is not present, above the wetland soils (as distinct from floating or submerged plants)

Environmental weeds: plants that become established in natural ecosystems, altering natural processes and leading to the decline of the communities they invade[3,1]

Heartwood: the central, woody core of a tree, no longer serving for the conduction of water and dissolved minerals, usually denser and darker in colour than the outer sapwood

Indigenous: a species that occurs at a place within its historically known natural range and that forms part of the natural biodiversity of a place

Life form: the shape or appearance of a plant that mostly reflects inherited or genetic influences

Local provenance: indigenous plants propagated from collections from locations as close as geographically (in terms of habitat) practicable to the location where the propagated plants are to be planted, ensuring that genetic integrity is maintained

Naturalised: plants that spread and persist outside of their normal range of distribution

Non-residual herbicides: (or knockdowns) herbicides that kill existing weeds but have no effect on germinating seeds

Non-selective herbicide: (or broad spectrum) herbicides that kill a wide range of plants

Non-synthetic: of natural origin; not derived artificially by chemical reaction, and free from chemical treatments or additives. Other terms commonly used to describe non-synthetic herbicides include natural or organic herbicides

Non-woody weeds: weeds with a non-woody green stem

Perennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) in two or more growing seasons

Photosynthesis: the process in which plants, algae and some bacteria use the energy of sunlight to convert water and carbon dioxide into carbohydrates they need for growth and oxygen

Pre-emergent herbicides: herbicides that kill germinating seedlings when applied to the soil before germination[8]

Residual herbicides: herbicides that remain active in the soil for some time and may kill germinating seeds and susceptible plants

Rhizomes: stems that are buried underground

Ringbark: to completely remove a strip of bark around the trunk or main stem of a tree or shrub, causing its death

Sapwood tissue: specialised plant tissue that transports water and minerals upwards from the roots to the stem, via capillary action

Scalping: involves slicing off the top layer of soil which contains weeds and weed seeds, leaving the surface bare in preparation for revegetation

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath is generally not split, there is no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Seed dispersal mechanisms: the means by which plants distribute their seeds, for example via wind, water, birds and insects etc

Selective herbicide: refers to herbicides that have been developed to kill a particular type of plant (for example, grasses)

Shelterbelts: belts or rows of trees and shrubs planted to provide protection against prevailing winds

Stolons: stems that usually run horizontally along the soil surface

Succulent: plants which have specialised fleshy, soft and juicy tissues designed for the conservation of water, for example, cacti

Vegetative reproduction: a type of asexual reproduction found in plants. It is also called vegetative propagation or vegetative multiplication

Weed: a plant that requires some form of action to reduce its harmful effects on the economy, the environment, human health and amenity, and [the term weed] can include plants from other countries or other regions in Australia or Western Australia[2]

Wetting agent: a substance that helps water or other liquid to spread or penetrate (also known as a surfactant or penetrant)

Woody weeds: perennial weeds with woody stems including shrubs, trees and some vines

Personal communications

Name	Date	Position	Organisation
Kellie Agar	September 2009	Program Coordinator – Invasive Plants	Department of Environment and Conservation, Western Australia

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A guide to managing and restoring wetlands in Western Australia

Water quality

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Water quality' topic

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Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Introduction

The quality of water in a wetland has a significant influence on the natural characteristics and values of the wetland. The native plants, animals, fungi, algae and bacteria of wetlands are adapted to particular water quality conditions, which are critical to their ability to survive. If water quality is changed to the extent that it exceeds the **tolerance limits** of wetland **organisms**, loss of individual organisms, **species**, habitat and ultimately **biodiversity** can occur. The nature of wetlands and the functions they perform can alter when water quality declines. For these reasons, understanding, protecting and managing water quality is essential to wetland management and critical to conserving wetland biodiversity in the long term. Poor water quality can also reduce people's enjoyment and use of wetlands, with nuisance midge populations and odours among the problems it can cause.

This topic focuses upon the management of human-caused changes to water quality in order to protect and maintain the natural characteristics of wetlands of conservation value in Western Australia. It includes individual sections on excess nutrients, acidification, turbidity and pollution by pesticides, metals, hydrocarbons (oils), pathogens, heated water and litter. While other water quality problems are beyond the scope of this version of this topic, many of the general principles for managing water quality covered in this topic will apply to other problems.

Tolerance limits: the upper and lower limit to the range of particular environmental factors (e.g. light, temperature, salinity) within which an organism can survive. Organisms with a wide range of tolerance are usually distributed widely, while those with a narrow range have a more restricted distribution.

Organism: any living thing

Species: a group of organisms capable of interbreeding and producing fertile offspring, for example, humans (Homo sapiens)

Biodiversity: encompasses the whole variety of life forms—the different plants, animals, fungi and microorganisms—the genes they contain, and the ecosystems they form. A contraction of 'biological diversity'.

Important note

Natural wetland water conditions are covered in more detail in the topic 'Conditions in wetland waters' in Chapter 2.

This topic has been written with the assumption that the reader has a certain amount of knowledge about natural wetland water conditions. This topic builds on the 'Conditions in wetland waters' topic by outlining the causes and effects of reduced water quality and strategies for preventing and managing impacts to water quality.

What is water quality?

Water quality is a term used to describe the condition of water relative to meeting certain standards for its intended purpose, such as drinking water or irrigation. Importantly, in this topic, the term **water quality** is used specifically to refer to the quality of water in the environment, such as a wetland, relative to its natural, undisturbed state. The closer it is to its natural state, the 'better' it is said to be.

However, wetlands each have their own individual natural water chemistry. This is the challenge in managing water quality - there is no simple water quality target that applies to all wetlands in WA. So what determines a wetland's natural water chemistry? The incoming surface water and groundwater are an important influence upon the water quality of a wetland, and the incoming water in turn is heavily influenced by the characteristics of the surrounding geology (rocks and soils) that the water flows through to reach the wetland. For example, the water picks up various salts and other materials in various concentrations depending upon the local geology. This influences the salinity (concentration of salts) and water softness/hardness (concentration of calcium, magnesium and bicarbonate) of water. Wetlands in WA range from fresh to hypersaline (that is, many times more saline than seawater), and from soft to extremely hard. How fresh or saline water is, and how hard or soft it is, can influence the organisms that occur in a wetland and also influence how a wetland is affected by nutrients, acid and pollutants.

Importantly, wetland water chemistry is not constant. It changes in response to environmental variables. In addition to the geology of an area and the quality of the incoming water, the **water regime** and **sediment** of the wetland also has a strong influence on its water chemistry. Wetting and drying, for example, dilute and concentrate salts, and drying exposes sediment to oxygen, triggering chemical changes in the sediment, which is typically where most of a wetland's nutrients are stored. Nutrients can be bound to the sediment or liberated from sediment depending on the composition of the sediment and the prevailing conditions. Permanently inundated wetlands tend to have less pronounced changes in water chemistry compared to those that wet and dry. Because decomposition processes are less vigorous in these wetlands, they also usually have a greater store of organic matter in their sediments. In turn, the composition of the sediment has a strong influence on water chemistry, with the mineral and organic particles present having differing affinities for binding with nutrients, metals and pollutants and for buffering acidity. These factors are described in more detail in this topic.

Water quality is often measured against a range of **physical, chemical** and **biological** characteristics or parameters such as turbidity, salinity and algal concentration. These parameters often influence each other (that is, they interact) and may vary seasonally, depending on a variety of factors.

Water quality: the quality of water relative to its natural, undisturbed state

Water regime: the specific pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.

Sediment: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology.

Physical parameters: physical characteristics of water such as temperature, turbidity, colour

Chemical parameters: chemicals found in water such as dissolved oxygen, pH, nutrients and pollutants

Biological parameters: organisms that inhabit wetlands such as algae, macroinvertebrates, fish

What are the most common water quality problems in WA wetlands?

Detrimental changes to wetland water quality have occurred in many wetlands in WA, particularly those in heavily populated, farmed, grazed and mined areas. In the past, the value of wetlands as unique ecosystems worthy of conservation and protection in their natural condition has been secondary to their usefulness to humans. Wetlands have been cleared, filled, drained and modified as a result of urban, agricultural, mining and industrial development. A number have been dug out to look more like the deep lakes of the northern hemisphere and to contain large volumes of stormwater and pollutants. Table 1 summarises the most common water quality problems in WA wetlands.

Table 1. A summary of common water quality problems applicable to WA wetlands.

Water quality problem	Potential impacts to plants, animals and humans	Indicators	Causes	Refer to
Excess nutrients (eutrophication)	Less nutrient-sensitive species and potentially more nutrient-tolerant species Algal and cyanobacterial blooms Odours Bird illness and death (avian botulism) Fish deaths Weeds Nuisance midge populations Reduced biodiversity of plants and animals	High nutrient levels in water High chlorophyll *a* levels Low dissolved oxygen levels/high biological oxygen demand High levels of ammonia Low light levels	Nutrient pollution of surface water and groundwater in the catchment Artificial permanent inundation of seasonally drying wetlands Landfill within the wetland (uncommon) Under some circumstances, wetland acidification	Page 36
Acidification	Impaired health of plants and animals Death of plants and animals Less acid-sensitive species and more acid-tolerant species Altered composition of plant and animal species Reduced biodiversity of plants and animals Increase in acid-tolerant mosquitoes	Marked reduction in pH of water or sediment Increased net acidity Jarosite in sediment Sediment scalds Water that is crystal clear, yellow/orange/brown or milky-white Reduction in oxygen levels Release of metals from sediment to water	Mobilisation of acidic groundwater via rising groundwater and deep drainage Generation of acids by exposing sulfides in soil to air, through drying and/or soil disturbance	Page 82
Secondary salinity	Impaired health of plants and animals Death of plants and animals Less salt-sensitive species and more salt-tolerant species Altered composition of plant and animal species Reduced biodiversity of plants and animals	Salinity of water (various measurements possible) Disappearance of salt-sensitive species Appearance of salt-tolerant species Death of trees and shrubs Salt scalds Deposits of solid salt	Rising saline groundwater Seawater intrusion Reduction in freshwater entering wetland due to various causes	'Secondary salinity' topic in Chapter 3
Pesticides	Impaired health of plants and animals Reduced ability of plants, algae and cyanobacteria to photosynthesise Disrupted fertility, reproduction and growth in plants and animals Death of plants and animals Less pesticide-sensitive species and more pesticide-tolerant species Altered composition of plant and animal species Reduced biodiversity of plants and animals	Pesticide levels in sediment and water Pesticide levels in incoming water (e.g. following heavy rain) Pesticide levels in affected organisms	Pollution	Page 111

Water quality problem	Potential impacts to plants, animals and humans	Indicators	Causes	Refer to
Excess metals	Impaired health of plants and animals Reduced reproductive success of plants and animals Birth defects Death of plants and animals Less metal-sensitive species and more metal-tolerant species Altered composition of plant and animal species	Metal levels in sediment and water Water appearance (in the case of aluminium and iron pollution) Metal levels in affected organisms	Pollution Acidification	Page 117
Hydrocarbons	Impaired health of plants and animals Death of plants and animals Altered habitat Altered composition of plant and animal species	Slicks on water Hydrocarbons in sediment and water Coatings on animals	Pollution	Page 124
Excess pathogens	Unusual behaviour and/or distress in animals Disease in plants and animals Death of plants and animals Changes in abundance and diversity of sensitive species	Pathogen levels in water	Pollution	Page 127
Unnatural turbidity	Reduced ability of plants, algae and cyanobacteria to photosynthesise Impaired health of plants and animals Death of plants and animals Less turbidity-sensitive species and more turbidity-tolerant species Altered composition of plant and animal species	Increased cloudiness or muddiness of water Smothering of benthic organisms	Vegetation clearing, grazing in catchment Loss of wetland vegetation Other including waterskiing, fires, inappropriate stormwater management practices and introduced animals.	Page 130
Thermal pollution	Reduced ability of plants, algae and cyanobacteria to photosynthesise Death of animals Altered composition of plant and animal species	Fish 'gasping' for oxygen at the water surface Temperature measurements	Pollution	Page 137
Litter and debris	Variable	Foreign material in/around wetlands	Pollution	Page 139
Loss of 'colour' (reduction in concentration of dissolved substances, commonly organic materials but may also include iron, manganese and copper). Colour affects the total incidence of light, and the wavelengths of light, that can penetrate the water column.	Increased susceptibility to algal and cyanobacterial blooms Increased susceptibility to nuisance populations of midge Altered composition of plant and animal species	Reduction in colour (measured in gilvin or true colour units).	Clearing in wetland and/or catchment reducing incoming dissolved organic matter Acidification (oxidation of organic matter, and flocculation and precipitation of tannins under low pH conditions)	For more information on colour, see the topic 'Conditions in wetland waters' in Chapter 2.

What are the causes of poor water quality?

Wherever land is used for urbanisation, agriculture, mining or industry, water quality of associated wetlands will be at risk from becoming degraded as a result of these activities. Poor water quality is not just about pollution. There are in fact three main causes of poor water quality in WA wetlands:

1. poor quality of incoming surface water or groundwater
2. poor quality of wetland water due to alterations to a wetland's water regime (for example, wet or dry longer than natural)
3. poor quality of wetland water due to other wetland disturbances (for example, clearing, grazing and soil disturbance)

Many wetlands in WA experience poor water quality because of one or more of these factors.

There is now a far greater appreciation that land uses and activities occurring kilometres away from wetlands can affect their water quality. The quality of the water a wetland receives from its surface water **catchment** and **groundwater capture zone** is critical. For example, one of the most common water quality problems in all types of aquatic ecosystems is an excess of nutrients, which can cause imbalances in their chemistry and ecology. A visible outcome of this is nuisance and toxic **algal** and **cyanobacterial** blooms. These are not uncommon in wetlands in highly developed areas of Perth, Peel, the south-west and south coast, and have also been reported from the Pilbara and Kimberley. Excess nutrients discharged from agricultural, urban and industrial land uses within the catchment of a wetland can enter wetlands from surface waters, such as overland flow, drains and waterways—that is, **stormwater**. They can also be washed into the soil, reaching the groundwater and then entering down-gradient wetlands via the groundwater.

Links to more information on catchments and capture zones

Identifying surface water catchments and groundwater capture zones are covered in more detail in the topic 'Wetland hydrology' in Chapter 2. A quick guide to identifying a wetland's surface water catchment is provided in the text box at the end of this section.

But pollution is only part of the problem. Poor water quality is also linked to alterations to surface water and groundwater flows. Urban areas are a good example. Before they are developed for urban land use, catchments are covered in native vegetation, and a high proportion of rainfall is **transpired** by vegetation or infiltrates into the ground to become groundwater. These two processes slow down the water, and as it travels over and through vegetation, soil and groundwater aquifers, it picks up materials in dissolved and **particulate** forms. For example, if the water flows through limestone on its way to a wetland, it may naturally pick up bicarbonates that buffer it against acidic water. Or, if it flows over granite, it may cause the water to naturally become more acidic. As it flows through vegetation, water can pick up soil particles, dissolved plant matter such as tannins, which have an influence on water chemistry, and other organic matter that provides energy that travels through wetland food webs. The process of flowing through soil and aquifer materials often also attenuates (removes) some materials in the water, such as nutrients.

Catchment: an area of land which is bounded by natural features such as hills or mountains from which surface water flows downslope to a particular low point or 'sink' (a place in the landscape where water collects)

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater capture zones: the area within which any recharge (infiltrating water) eventually flows into the wetland

Algae: a general term referring to the mostly photosynthetic, unicellular or simply constructed, non-vascular, plant-like organisms that are usually aquatic and reproduce without antheridia and oogonia, that are jacketed by sterile cells derived from the reproductive cell primordium; includes a number of divisions, many of which are only remotely related to each other

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Stormwater: water flowing over ground surfaces, in natural streams and drains as a direct result of rainfall over a catchment. It consists of rainfall runoff and any material (soluble or insoluble) mobilised in its path of flow.

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour

Particulate: in the form of particles (small objects)

Impermeable: does not allow water to move through it

In comparison, traditionally designed urban land uses in WA generate significantly more stormwater compared to undeveloped catchments. This is because the vegetation is cleared to make way for roads, houses and other buildings. These **impermeable** surfaces in urban areas don't use water and they don't allow the same volume of water to infiltrate into the soil, meaning that natural water loss is minimised, and that water flow paths and their associated filtration and accumulation processes are bypassed. As Perth and other urban areas around WA have grown, the easiest way to deal with this excess water has been to direct it into the most convenient receiving environment by pipe—be it a wetland, waterway or the ocean—or to create a depression to store the water. As a result, some wetlands are now much wetter for much longer, changing their water regime and altering the types of physical, chemical and biological changes that occur in the sediment. Because the water in these wetlands has not flowed through soil, vegetation and aquifers before reaching them, it hasn't accumulated natural dissolved and particulate materials, but it has picked up pollutants from roads and other built surfaces. These pollutants compound the problems caused by alterations to their water regime.

Changes to the natural stormwater and groundwater patterns, and their impacts on wetlands, are a legacy of historical urban and rural development. Without drains, many wetland areas of Perth and Peel, as well as other areas of WA, would not have been able to be used or converted to dryland for use as farming and residential land, and later for commercial and industrial land. Extensive networks of drains were installed to remove water from wetlands, and these remain today. As well as being a means of destroying or significantly altering many wetlands, the environmental impact of these drains was compounded, because the water from these drained wetlands were often directed into many of the remaining wetlands. In Perth, for example, large chains of wetlands are influenced by 'main drains'. The excess of water has changed the character of many of these wetlands. Importantly, unlike the urban drainage of other Australian cities, Perth's main drains are designed to intercept and convey shallow groundwater in addition to surface overland flow.[1]

Stormwater has been a significant source of pollutants for many WA wetlands. In addition to rainfall runoff, stormwater consists of material (soluble or insoluble) mobilised in its path of flow. Stormwater may discharge nutrients, acidic waters, suspended particulates, pesticides, metals, hydrocarbons, pathogens and litter into wetlands. Some stormwater reaches wetlands by overland flow, while some is captured by stormwater infrastructure such as drains, pipes and basins (particularly in urban areas) which then discharges into wetlands, waterways or the ocean (Figure 1). For example, stormwater

Figure 1. Pipes discharge stormwater into Lake Monger, Perth.
Photo – L Mazzella/Department of Water.

pollutants discharged into Herdsman Lake have been described in the thesis *Land use changes and the properties of stormwater entering a wetland on the sandy coastal plain in Western Australia.*[2]

Groundwater plume: body of polluted water within an aquifer

Wetlands are also receiving environments for discharge water from mining operations, which in addition to altering natural water regime, can be laden with acids, salts and pollutants.

Groundwater pollution is associated with a range of land uses. **Groundwater plumes** from a range of contaminants are evident in a number of locations in WA. For example, in the Perth metropolitan area, groundwater plumes are documented in association with landfill sites, residential development, waste recycling and treatment facilities, underground hydrocarbon storage tanks, liquid waste disposal sites, fertiliser manufacturing sites, railway workshops and mixed urban land uses.[3]

In a number of areas of WA, human alterations to groundwater are also a source of water quality problems in wetlands. Over-use of groundwater can cause groundwater dependent wetlands to become drier than natural, which is one of the causes of wetland acidification—via acid sulfate soils—that is especially prevalent in the south west of WA. In contrast, extensive clearing in the Wheatbelt has caused the groundwater table to rise significantly, making wetlands far wetter than natural, and far saltier than natural due to the mobilisation of salts present in the soil, and in some circumstances, far more acidic than natural.

➤ Secondary salinity is a complex water quality issue, covered in more detail in the topic 'Secondary salinity' in Chapter 3.

extra information

Determining the surface water catchment of a wetland

Topographic contours—lines showing the height of the land—and knowledge of the area are key to determining the surface water catchment of a wetland. Topographic contours can be obtained from sources such as Landgate's WA Atlas (www2.landgate.wa.gov.au/web/guest/wa-atlas). Of most use is a map (hard copy or digital) that shows aerial photography and is overlain with topographic contours.

First, mark the location of your wetland on the map. In most cases the wetland will be at a low elevation and the height of the surrounding land will rise; the numbers showing the height in metres on the lines of the topographic map will increase. Start at the north end of your wetland and, moving northerly, follow the rising topography lines until you reach the spot where the land elevation starts to decrease. The highest elevation point marks the edge of the wetland's catchment at that point. The water that falls on land north of this spot will flow away from your wetland; that which falls south of it will flow toward your wetland. Use this same exercise to mark the southern, eastern, and western boundaries of the watershed. Then connect the dots by a line between them that follows the land's topography. This is the boundary of your natural catchment. If you have trouble drawing in the line, imagine dropping a ball in the area and think again about which direction it would roll. If it would roll toward your wetland, then the area is within your wetland's watershed. However, sometimes the topography is not uniform, and the boundary can be complex, including water initially flowing away from the wetland before being directed back to it. So you may need to follow the route the water takes where a clear catchment boundary is not evident. Urban drainage can also change the rules, where water is artificially moved between natural catchments. Planners in the relevant local government authority (council or shire) may be able to tell you when this is the case.

Once you have determined what land drains to your wetland, it will be easier for you to recognise what or who else may be affecting your wetland. You may want to continue working with your map, labelling or marking where different activities are occurring and thinking about the likely effects on your wetland. For example, is there a new subdivision or a plan for one in the catchment? How about shopping malls? What fields are irrigated nearby? Where are animals pastured? Where are manure, fertilisers, or pesticides being spread or sprayed?

Acknowledgement: adapted from *At home with wetlands: a landowner's guide.*[4]

Who is responsible for managing wetland water quality?

Responsibility for managing wetland water quality generally lies with the landowner or land manager. The three main groups with responsibility are landowners, local governments, and pastoral lessees; with DEC another major wetland manager in many areas the state.

Of course, landowners often have little direct control over the quality of the water reaching their property from surrounding properties. There are many groups with a role or responsibility in ensuring that water that enters a wetland from the broader catchment is of an appropriate quality (as outlined in the next section). Landowners with concerns about the quality of water entering their property can liaise with these groups. There are also a range of government and non-government programs to assist private landowners with on-ground wetland water quality activities. For example, DEC's *Healthy Wetland Habitats* program: eligible landowners on the Swan Coastal Plain (from Moore River to Dunsborough) can receive management advice and funding to manage water quality. For more information telephone the *Healthy Wetland Habitats* program coordinator on (08) 9334 0333.

➤ For more information on various programs that provide landowners with assistance, see the topic 'Funding, training and resources' in Chapter 1.

Land developers have a specific role in wetland water quality management during the course of, and in the years following, the subdivision and development of an area of land. If a wetland is located within the parcel of land, it may be required to be ceded to the Crown as 'public open space' (often abbreviated to POS) through the subdivision or development approval process. For wetlands retained in areas of public open space within a residential development, for example, it is common for developers to be assigned responsibility for the management of the wetland for a period (usually three years) following the completion of a development. They are generally required to manage the wetland and associated buffer in accordance with a wetland management plan that has been prepared in liaison with, and approved by, relevant authorities (for example, DEC and/or the local government). DEC's *Guidelines checklist for preparing a wetland management plan*[5] forms DEC's key reference for this process, and includes a requirement to address wetland water quality. After the designated management period, if the developer has satisfied the requirements and implemented all management actions outlined in the approved wetland management plan, transfer of the open space and therefore responsibility for the management of the wetland passes to the nominated vesting body, typically the local government. The community can have an important role in the scoping, drafting and implementation of the wetland management plan and should be consulted by the land developer during the development of the plan.

DEC is the state government agency with the lead role in the protection and management of wetlands. DEC contributes to the management of wetland water quality through various statutory and non-statutory processes. DEC also provides an online map and data for WA's wetlands called *WetlandBase*. As well as showing the location of wetlands, it can display the survey data for individual wetlands. Survey data include water chemistry data, as well as survey records for waterbirds, aquatic invertebrates and vegetation, where available. The survey data is collated from a number of survey sources, including a range of government and university survey programs. It is available via http://spatial.agric.wa.gov.au/wetlands. DEC is preparing an alternative to *WetlandBase,* scheduled for release in 2014, that will continue to make this data publicly available.

There is no dedicated program for surveying or monitoring the water quality of WA's wetlands. Much of the surveying that occurs is a result of specific programs that may apply to certain geographic areas for particular time periods, in response to particular concerns and as funding opportunities allow. Other monitoring is carried out by landowners or their consultants in accordance with government requirements (for example, by a developer's environmental consultant in order to fulfil a condition of subdivision approval of a parcel of land containing the wetland).

Who is responsible for managing catchment water quality?

Wetland water quality is generally a product of actions in the broader catchment. In WA, there are many groups and organisations that have either a responsibility or role in ensuring that water in the catchment is of an appropriate quality. Effective management of water quality involves cooperation between member of the public, landholders, community groups, regional management authorities and local and state governments.

Individual responsibilities

All individuals are responsible for ensuring that their actions do not harm the environment. Releasing chemicals or carrying out activities that have an effect on the environment may constitute 'environmental harm' under the *Environmental Protection Act 1986*.

➤ For more information on environmental harm provisions, see the topic 'Legislation and policy' in Chapter 5.

There are many local, state and Australian government initiatives and community-based initiatives to assist individuals to use, store and dispose of chemicals such as nutrients, paints, oils, batteries and pesticides correctly and to manage other potentially harmful activities. A number of these are outlined in this topic.

There has been an overwhelmingly positive response amongst residential gardeners to reduce their fertiliser applications in order to reduce the impacts of nutrients on WA's wetlands and waterways. Significant reductions in nutrient levels in some areas demonstrate what can be achieved by individuals collectively working to improve water quality of wetlands.

Community-based initiatives

The community is at the forefront of a range of on-ground catchment water quality management initiatives in WA. Individuals, organisations and community groups such as 'Friends of' groups can play an important role in pollution prevention and control in the community. Grass-roots education activities and passive surveillance can be important drivers of behavioural change, improving compliance by industry and the uptake of best practice by businesses and the community in general.

Regional natural resource management (NRM) organisations can also play an integral role. The Light Industry Audit Project is an example of one such program. The project was delivered by Perth Region NRM between 2007 and 2012. The aim of the project was to minimise the discharge of nutrients and contaminant sources from small and medium sized enterprises by auditing the use, storage and disposal of all types of solid and liquid materials with the requirements of relevant environmental legislation. Typical activities of small and medium sized enterprises include mechanical repair, vehicle smash repair, engineering and metal fabrication, metal finishing, machinery hire, chemical manufacture and blending, transport depots, concrete products, landscape supplies and printing. In WA these industrial premises have been identified as representing a significant cumulative risk to the health of water resources.[6] Perth Region NRM completed a light industry audit and education program at the end of the project. The report identified that the main areas where businesses failed to minimise or mitigate the risk of pollution were:

- inappropriate liquid storage and spill management infrastructure
- inappropriate disposal of wastewater
- wastewater containing detergents, degreasers or sediments not properly treated and/or being discharged to open ground, septic tank system or stormwater drainage
- no emergency spill kit
- no emergency spill management plan and/or staff training for managing spills
- Material Safety Data Sheets not held on site for all chemicals used.

➤ Information on the Light Industry Audit Project is available on the Swan River Trust website: www.swanrivertrust.wa.gov.au/the-river-system/tackling-the-issues/addressing-contaminants/light-industry-program

The extensive range of catchment water quality improvement initiatives being undertaken by the Peel-Harvey Catchment Council is another example of the pivotal role regional NRM groups can play. These include nutrient filtering projects, broader stormwater quality improvement projects, drainage reform projects and delivery of the *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management*.[7] The Peel-Harvey Catchment Council has been recognised for this work, receiving the 'Rivers, estuaries and wetlands' award in the 2012 Western Australian Environment Awards.

The Phosphorus Action Project, hosted by the South East Regional Centre for Urban Landcare Inc. (SERCUL) and supported by the Swan River Trust, is another example of a water-quality focused community-based initiative. The Phosphorus Action Project has spearheaded a community education campaign to achieve greater awareness of how to minimise nutrient pollution. Its initiatives include an annual nutrient survey for local governments in the Perth metropolitan area, to identify the extent to which best management practices are being achieved and how improvements can be made.

➤ More information on the role that community and regional NRM organisations can play in wetland management protection is provided in the topic 'Roles and responsibilities' in Chapter 5.

Government programs

Various Western Australian government agencies coordinate and participate in the regulation, research and monitoring of water quality.

Industry regulation

Preventing the discharge of pollutants into the environment is the most effective and efficient way to protect wetlands from pollution. This may be achieved by preventing or minimising the generation of pollutants and their export from the source. Pollutants are generated by both industry and domestic sectors. DEC is responsible for regulating the emissions or discharge of a range of commercial and industrial activities that would otherwise pose a significant environmental risk. It has powers to investigate, enforce and to order pollution to be abated and remediated. DEC carries out these responsibilities in accordance with Part V of the *Environmental Protection Act 1986*. In particular, DEC manages 'prescribed premises' through works approvals and licences. Licensing of prescribed premises allows DEC to regulate emissions and discharges from these premises, through conditions contained within licences that relate to the prevention, reduction or control of particular emissions and discharges, and to the monitoring and reporting of them.

➤ DEC publishes details of granted and refused licences for prescribed premises. These are available to view at the 'Licensing and regulation' webpage of the DEC website www.dec.wa.gov.au/pollution-prevention/licensing-and-regulation.html.

Relevant regulations under the Act include:

- Environmental Protection (Abattoirs) Regulations 2001
- Environmental Protection (Abrasive Blasting) Regulations 1998
- Environmental Protection (Concrete Batching and Cement Product Manufacturing) Regulations 1998
- Environmental Protection (Controlled Waste) Regulations 2004
- Environmental Protection (Fibre Reinforced Plastics) Regulations 1998
- Environmental Protection (Metal Coating) Regulations 2001
- Environmental Protection (NEPM-NPI) Regulations 1998
- Environmental Protection (Packaged Fertiliser) Regulations 2010
- Environmental Protection (Petrol) Regulations 1999
- Environmental Protection (Rural Landfill) Regulations 2002
- Environmental Protection (Unauthorised Discharges) Regulations 2004

Figure 2. A DEC Compliance Officer inspecting tyre and battery storage during an industry regulation compliance inspection. Photo – DEC.

A range of industry activities are regulated by local governments. Local government approval is required for a range of activities through land use planning, extractive industry and offensive trades approvals and local government by-laws.

Department of Mines and Petroleum approvals apply to mine sites, petroleum industries and dangerous goods storage facilities.

Hazardous household waste

There are eight metropolitan and six regional centre permanent hazardous household waste facilities in WA, which are complemented by collection days in other areas of the state. These services provide householders with the opportunity to dispose of flammable, toxic, explosive and corrosive materials including substances such as batteries, paints and pool chemicals, at no charge.

➤ For more information on hazardous waste facilities, see the Western Australian Local Government Association website: www.walga.asn.au and Wastenet: www.wastenet.net.au/programs/hhwprog

Management of pollution incidents, contaminated sites and acid sulfate soils

DEC is responsible for investigating environmental harm caused by pollution. Wetlands are protected by environmental harm provisions under the *Environmental Protection Act 1986* (EP Act). Under the EP Act, an 'alteration of the environment to its detriment or degradation or potential detriment or degradation' or an 'alteration of the environment to the detriment or potential detriment of an environmental value' is considered environmental harm.

➤ To report pollution, call the Pollution Watch Hotline, 1300 784 782 (24 hours) or email pollutionwatch@dec.wa.gov.au.

➤ In the event of a hazardous materials release or life-threatening incident, call 000 and ask for Fire and Rescue.

➤ In the event of pollution, DEC may issue an environmental field notice to the responsible person or organisation requiring site remediation under the Environmental Protection (Unauthorised Discharges) Regulations 2004.

Figure 3. Officers of DEC's Pollution Response Unit. Photo – P Nicholas/DEC.

DEC is also responsible for administering WA's contaminated sites legislation, the *Contaminated Sites Act 2003*. This Act aims to protect people's health and the environment from harm. Under the Act, contaminated sites must be reported to DEC, investigated and, if necessary, cleaned up.

DEC is also the lead agency for the management of acid sulfate soils in WA.

➤ Contaminated wetlands and groundwater are identified in the *Contaminated Sites Database*, available from https://secure.dec.wa.gov.au/idelve/css/. This database also provides reports outlining the status of contamination for individual sites.

➤ For more information on DEC's role in pollution incidents, contaminated sites and acid sulfate soils, see www.dec.wa.gov.au/pollution-prevention.html.

Management of pesticides

Before a pesticide can be used in Australia, it must be registered by the Australian Pesticide and Veterinary Medicines Authority, an Australian Government body. The WA Department of Health and the Department of Agriculture and Food, as well as other state government agencies, play an important role in managing the use of registered pesticides to ensure they do not have untoward effects on humans, animals, agriculture or the environment. These agencies are represented on the Pesticide Advisory Committee. Local governments also play an important role in investigating pesticide misuse and minimising the approval of incompatible land uses in proximity to each other.

➤ More information on the roles and responsibilities of organisations and individuals is outlined in the document *Quick contacts for the use of pesticides in WA.*[8]

Agricultural best practice

The Department of Agriculture and Food provides advice to agricultural producers regarding best practice farming methods, including the efficient use of water, pesticides and fertilisers and the minimisation of erosion and other off-site impacts.

The Department provides a range of resources, tools and services, such as the Small Landholder Information Service.

➤ More information for small landholders on the management of pesticides, fertilisers and other agricultural chemicals is available via www.agric.wa.gov.au/PC_92609.html

Sewage and wastewater management

The Water Corporation removes about 432 million litres of wastewater a day and operates 106 wastewater treatment plants across the state. It also administers the Infill Sewerage Program, a WA Government initiative. It aims to provide sewerage connections to properties where the use of septic tanks poses a risk to public health and the environment. Infill sewerage is a system of buried pipes that takes wastewater away from residential properties for safe and healthy treatment and disposal.

A number of priority areas have been agreed with the State Government, based primarily on public health and environmental considerations. Current priorities are Bridgetown, Bunbury, Busselton, City Beach, Dawesville, Esperance, Falcon, Geraldton, Greenough, Kwinana, Mandurah, Port Hedland, Quinns Rocks, Ravenswood and Rockingham.

There are also controls on the use of on-site sewerage systems near sensitive receiving environments. The WA Government is currently reviewing its draft policies for the use and siting of on-site sewerage systems such as septic tanks.

Catchment water quality management and monitoring

The Department of Water is responsible for overseeing surface water and groundwater management policy in WA. It also has lead responsibility for policy regarding waterway management, while DEC has lead responsibility for policy regarding wetland management. The Department of Water provides advice on the quality of groundwater to support state development and the provision of drinking water. It carries out research and environmental investigations into salinity and conducts specific groundwater, river and estuary investigations into contamination. It provides a range of guidance material to assist people in understanding water quality issues and practical measures to protect water resources from harm (see www.water.wa.gov.au/Managing+water/Water+quality/Overview/default.aspx for publications). The Department also monitors flows and water quality in a number of the state's rivers.

Stormwater management in urban catchments

In liaison with the Department of Planning, the Department of Water provides guidance on appropriate stormwater management through guidelines including:

- *Stormwater management manual for Western Australia*[9]
- *Better Urban Water Management*[10]
- *Decision process for stormwater management in Western Australia*[11]

In collaboration with partners it also provides WA resources and training through the 'New WAter ways' program (www.newwaterways.org.au), which was formed in 2006 to build the water sensitive urban design capacity of government and industry to improve the delivery of urban water management and water sensitive cities. Project partners are the Department of Planning, Department of Water, the Western Australian Local Government Association, Urban Development Institute of Australia (WA) and Swan River Trust.

Over the past decade, significant reform in urban water management has been achieved in WA through the introduction and implementation of the above policies and associated initiatives. As a result, stormwater is much better managed to protect the environment in new urban developments in WA. However, there is much that can be done to improve stormwater management in older urbanised areas of the state as well as in rural areas, in collaboration with the relevant organisations. Table 2 outlines the roles of key water management organisations.

Figure 4. A main drain in Baldivis, south of Perth. Photo – J Higbid/DEC.

Most urban drains are managed by local governments. In the Perth region, these are typically smaller drains. Many of these feed into a network of 'main drains' managed by the Water Corporation (Figure 4). The Main Roads Department and the Public Transport Authority also manage drainage associated with their infrastructure.

While the Water Corporation is responsible for providing and managing part of the urban and rural drainage networks, the Economic Regulatory Authority operating licence does not require the Water Corporation to control water quality within the main drains. The Water Corporation's stated responsibilities lie in design, construction, operation and maintenance of the drainage networks that convey drainage water to meet the flood protection requirements of the Economic Regulatory Authority operating licence.[1] However the Water Corporation has recently stated that it recognises a holistic and integrated catchment scale approach is required for the adequate management of water quality.[1] It has recently funded research into the water quality of its main drains[1] and undertaken a revegetation trial for a section of a branch drain with the objective of developing a more environmentally sustainable approach to urban drainage management and reducing maintenance by installing long term native vegetation that, once established, would significantly reduce maintenance cost.

Where resources allow, local governments are well placed to make significant improvements to the water quality of the estimated 3,000 kilometres of drains within their networks. In WA, there has been a significant uptake of water quality management initiatives by local governments. For example, more than forty local governments are participants of the Water Campaign™ run by the International Council for Local Environmental Initiatives. As participants, these councils have identified the changes that they will make to the management of water within the local government area.

➤ Individuals and community groups can find out if their local government is a participant, and what changes they have committed to, at the ICLEI website: http://iclei.org/index.php?id=2389te.

Water management in rural catchments

Outside of the Perth metropolitan area the Water Corporation is responsible for maintaining rural drainage in six gazetted drainage districts: Mundijong, Waroona, Harvey, Roelands, Busselton and Albany. The rural drainage service was initially provided only to make land viable for agriculture. It provides a limited flood protection service, allowing adjacent land to be inundated following major storms.

Rural drainage is also governed by the Soil and Land Conservation Regulations 1992 under the *Soil and Land Conservation Act 1945*. The Act prescribes the assessment of proposals to construct drains or pump groundwater in agricultural regions by the Soil and Land Commissioner. The principles for assessing drainage proposals are outlined in the 2012 Department of Water document, *Policy framework for inland drainage*.[12]

➤ More information on the assessment of new drainage proposals is available from:

- the Department of Agriculture and Food website www.agric.wa.gov.au/PC_93235.html
- the topic 'Legislation and policy' in Chapter 5.

Landscape-scale salinity management in WA is primarily addressed by the Department of Water, Department of Agriculture and Food and Department of Environment and Conservation. One of the major programs that focus upon wetlands is the 'Natural Diversity Recovery Catchments' program. It is aimed at protecting areas of WA with high natural diversity that are threatened by rising water tables, salinity and associated poor water quality problems. A number of very significant wetlands are located within the six natural diversity recovery catchments: Buntine-Marchagee, Drummond, Lake Bryde complex, Lake Muir-Unicup, Lake Warden and Toolibin Lake.

➤ Information on the natural diversity recovery catchments program can be found at DEC's website and in the topic 'Salinity' in Chapter 3.

Water use

The Department of Water is the state government agency with the lead protection for the management of water resources in WA. It regulates the use of groundwater, which is a very important factor affecting the water levels and water quality of wetlands that are fed by groundwater. It licenses the taking of water and through this process it can apply conditions in licences that outline a licensee's responsibilities for managing the water resource.

➤ The allocation of groundwater and the regulation of its use is detailed in the topic 'Managing hydrology' also in Chapter 3.

➤ More information is also available from the licensing pages of the Department of Water website: www.water.wa.gov.au/Business+with+water/Water+licensing/default.aspx#1

Collaborations: non-government and government working together

A number of collaborations exist between non-government and government to achieve outcomes that could not be achieved by either party acting in isolation.

The Fertiliser Partnership

An important collaboration aiming to improve water quality in WA is the Fertiliser Partnership 2012–2016. This partnership between the State Government, the fertiliser industry, fertiliser user groups, and peak non-government organisations aims to foster a cooperative working relationship to reduce fertiliser nutrient loss to aquatic environments. The government also recognises that this can only be achieved through collaborative effort with, and involvement of, the broad community. The Fertiliser Partnership 2012–2016 supersedes the *Fertiliser Action Plan* (2007).

The objectives of the Fertiliser Partnership 2012–2016 are to:

1. contribute to a goal of 50 per cent reduction in nutrient loss to waterways and wetlands on the Swan and Scott Coastal Plains
2. optimise the content of fertiliser and nutrient binding soil amendment products to better suit conditions on the Swan and Scott Coastal Plains
3. improve fertiliser and water use efficiency in both commercial and residential settings whilst maintaining productivity of agriculture and related commercial operations
4. educate the community on the environmental and social values of aquatic ecosystems, including waterways and wetlands
5. educate the community on fertiliser efficiency, water use efficiency and the benefits of managing soil acidity

Strategies to achieve the objectives of the Fertiliser Partnership 2012–2016 are the:

- development and promotion of low phosphorus fertiliser products
- development and promotion of 'best practice' fertiliser use and management in broadscale agriculture, horticulture and other related commercial activities and urban land use applications
- development and promotion of 'best practice' based on relevant accredited programs and advisors
- research, development and trials of nutrient binding soil amendment products to improve nutrient use efficiency and reduce nutrient loss to waterways
- development and promotion of educational material on fertiliser use efficiency.

➤ The webpage for the Fertiliser Partnership 2012–2016 is www.fertiliserpartnership.agric.wa.gov.au

Table 2. The role of organisations in water management in Western Australia

Responsibility		Water Corporation	Department of Water	Swan River Trust	Department of Environment & Conservation	Local Government	Harvey Water	Ord Irrigation
POLICY	Develops policy for water resource management in WA		✔					
	Provides input into policy and regulation that affects wetlands		✔		✔	✔		
LICENCES	Licences groundwater and surface water abstraction		✔					
SERVICE DELIVERY	Delivers clean drinking water	✔						
	Removes wastewater	✔						
	Maintains drinking water, drainage network and sewage pipelines from residential and commercial properties to main network	✔						
	Maintains local government drains					✔		
	Pipes irrigation water from local dams to shareholders in Collie, Harvey and Waroona for agricultural use						✔	
	Pipes irrigation water to shareholders from Lake Argyle to the Ord irrigation area in Kununurra for agricultural use							✔
DEVELOPMENT / LAND USE PLANNING	Ensures future development and land use planning enhances ecological health and amenity of the Swan- Canning Rivers			✔				
	Provides advice on development and land use planning that has the potential to affect waterways, groundwater and catchments		✔					
	Provides advice on development and land use planning that has the potential to affect wetlands		✔		✔			
	Decision-making authority for development proposals					✔		
PROTECTION / RESTORATION	Protects waterways and catchments in WA		✔					
	Protects wetlands in WA		✔		✔			
	Manages wetlands and waterways within reserves				✔	✔		
	Protects and enhances the ecological health and community benefit of the Swan-Canning rivers			✔				
	Catchment management programs and activities e.g. conversion of stormwater drains to 'living streams'		✔	✔	✔	✔		
MONITORING	Monitors surface and groundwater (quality and water levels)		✔				✔	✔
	Monitors drinking water quality	✔						
	Monitors water quality and water level of Swan-Canning rivers			✔				
	Monitors water quality, quantity and treatment in dams, storage facilities and Perth desalination plant	✔						

What water quality survey data exists in WA?

As outlined in the previous section, responsibility for water quality management lies with many agencies and individuals in WA. Table 3 outlines some of the larger sources of water quality data in WA but is by no means a comprehensive listing. The Australian Government has announced the National Plan for Environmental Information initiative (www.bom.gov.au/environment/NPEI_info_sheet.pdf; www.bom.gov.au/jsp/eiexplorer/), which in years to come may provide wetland water quality data access options.

Table 3. A guide to sources of wetland water quality data in WA

Group, database or program	Data type	Available from
WetlandBase	Compilation of various water quality studies including: DEC's Inland aquatic integrity resource condition monitoring (RCM), 45 significant WA wetlands 40 Wetlands Study, Murdoch University South West Wetlands Monitoring Program, Department of Environment and Conservation (DEC) Aquatic Projects Database (Salinity Action Plan Survey), DEC South Coast Regional Wetland Monitoring Program, Department of Water Jandakot Mound Monitoring Program, Murdoch University Gnangara Mound Monitoring Program, Edith Cowan University	http://spatial.agric.wa.gov.au/wetlands Note: DEC is preparing an alternative to *WetlandBase*, scheduled for release in 2014, that will continue to make this data publicly available.
Local government authorities	Data for wetlands under their management	Relevant local government authority
Regional natural resource management organisation	Data for wetlands that fall within regional NRM organisation projects	Relevant regional NRM organisation
Department of Water	Waterway water levels, flows and quality, drinking water and groundwater levels and quality; some wetland water quality and level data	http://wir.water.wa.gov.au/SitePages/SiteExplorer.aspx www.water.wa.gov.au/Tools/Monitoring+and+data/default.aspx
Natural diversity recovery catchment program monitoring	Data for wetlands in natural diversity recovery catchments program: Buntine-Marchagee Drummond Lake Bryde complex Lake Muir-Unicup Lake Warden Toolibin Lake	DEC's Natural Resources Branch
Ramsar wetland data	Data for WA Ramsar wetlands	DEC's Wetlands Section

How is wetland water quality measured?

A number of physical, chemical and biological parameters and **indicators** are used when characterising or assessing water quality. Common indicators of wetland water quality include dissolved oxygen, acidity, salinity and nutrients. Table 4 outlines why these indicators are useful.

Where concerns warrant further investigation, diagnostic tests can confirm the presence of metals, pathogens, pesticides and hydrocarbons (referred to as 'pollutants' where they are introduced into, or liberated in, wetlands as a result of human activities).

Biological parameters that may be used as indicators of water quality condition include plants, animals, algae and cyanobacteria. Assessment of biota (living things) may involve studies of abundance, reproduction and health of individual organisms or populations. Biological indicators can provide a more direct measure of ecosystem health than episodic sampling of physical and chemical parameters.[13] However, living things respond to a wide range of factors besides water quality, and it can be difficult to conclusively identify cause and effect, especially with limited data. For example, diversity of macroinvertebrates can be linked to the seasonal weather trends and amount of water in a wetland.

Many wetlands have a water column for periods of time—wetlands that are inundated either permanently, seasonally or intermittently. However many wetlands do not support a water column; these wetlands are waterlogged such that their sediment is saturated for a period of time, but standing water is not typically present above the soil surface except after heavy rainfall. Regardless of whether wetlands are waterlogged or inundated, the **sediment pore waters** (or interstitial waters) are extremely influential to water quality. The sediment, especially near the interface with overlying water, plays a very important role in the removal of many chemicals (natural or otherwise) from water and their release to water. Despite this, the characteristics of pore waters and sediment tend to be sampled less often than the water column. This is partly because the conservation and science of waterlogged wetland types lags behind that of inundated wetland types, and also because sediment pore waters can sometimes be more difficult to sample, particularly when there is an overlying water column. Managing the water quality of waterlogged wetlands is important and will improve as more stakeholders take an interest in their management and protection.

In inundated wetlands, when the concentration of contaminants in sediment pore waters exceeds that of the overlying water column, diffusion to the water column will occur. Where required, the measurement of the fluxes of contaminants can be obtained using dialysis samplers (pore water peepers), benthic chambers or corer reactors.[14]

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site.

Sediment pore waters: water which is present in the spaces between sediment grains at or just below the land surface. Also called interstitial waters.

Table 4. Common water chemistry parameters, their roles, measurement and effects of change on wetland ecosystems. For more detail, see the topic 'Conditions in wetland waters' in Chapter 2.

Physical parameter	**Indicator:** Light
	What this indicator measures: Light penetration in the water column
	Role in wetland ecosystems: Light enables primary producers (plants, algae, photosynthetic bacteria) to produce their own energy needed for growth and survival, via photosynthesis. In wetlands with a water column, the amount of light entering the water directly affects the growth and survival of primary producers, which in turn affects the animals that rely on them for food and shelter. Light is also the major source of heat, which affects water temperature, which influences which species can occur in a wetland. Water temperature also influences other water quality parameters such as dissolved oxygen and pH.
	What is measured: Colour: a measure of how much light is absorbed or scattered by dissolved substances such as tannins and humic acids. Clarity and penetration: a measure of how much light is absorbed or scattered by suspended particulate matter.
	Effects of changes on wetland ecosystems: Increasing colour and turbidity reduce light penetration, decreasing photosynthetic capability and productivity of wetlands. Increased light penetration (e.g. as a result of removal of native overstorey wetland vegetation, changes in water depth, loss of colour) can lead to algal and cyanobacterial blooms and UV damage to wetland organisms.

Physical parameter	**Indicator:** Turbidity
	What this indicator measures: Concentration and mass of suspended particulate matter in the water column. Turbid conditions (cloudy-looking water) are caused by the presence of particulate matter such as silt and clay, organic and inorganic matter, and living or dead microscopic organisms, suspended in water.
	Role in wetland ecosystems: Turbidity affects the light and temperature in wetland waters. Increasing turbidity reduces light and increases temperature. Turbidity also affects predator-prey relationships. Some wetland species are adapted to naturally turbid conditions e.g. in claypans.
	What is measured: Turbidity is a measure of light passing through the water—the extent to which light is scattered, absorbed and reflected by particles suspended in the water column—and is usually measured with a turbidity tube or meter, or secchi disk.
	Effects of changes on wetland ecosystems: Increases in particulate matter can reduce light penetration and photosynthesis. Beyond normal variations it can smother or clog respiratory or feeding apparatus of aquatic fauna. It can contain metals and nutrients.

Physical parameter	**Indicator:** Temperature
	What this indicator measures: Temperature variations and/or stratification
	Role in wetland ecosystems: Temperature varies naturally both over time (temporally) and over the area (spatially) in wetlands. It affects the growth and survival of plants and animals via their metabolic processes as well as via oxygen levels in water and the chemical form (dissolved or precipitated) that toxicants and other substances take.
	What is measured: Water temperature
	Effects of changes on wetland ecosystems: Biota can be affected when temperature fluctuations exceed their thermal tolerance range e.g. affecting growth, spawning and reproduction.

Chemical parameter

Indicator: Dissolved oxygen (DO)

What this indicator measures: The equilibrium between oxygen-consuming processes, such as respiration, and oxygen-releasing processes, such as photosynthesis and transfer of oxygen from the atmosphere to the wetland.

Role in wetland ecosystems: Most aquatic organisms depend on oxygen for respiration. Via redox reactions, dissolved oxygen levels also affect the solubility of a range of chemicals, including nutrients and metals, and so the levels at the top of the sediment pore water is particularly important. The amount of dissolved oxygen in the water is influenced by the amount of respiration and photosynthesis occurring, as well as atmospheric pressure, temperature and concentration of other dissolved substances in the water (e.g. salts).

What is measured: Dissolved oxygen level

Effects of changes on wetland ecosystems: Reduced dissolved oxygen concentrations can have direct and indirect adverse effects on wetland organisms. An extreme reduction can result in the death of oxygen-dependent organisms (for example, fish, other vertebrates, invertebrates) and their replacement by a small suite of organisms that can tolerate very low oxygen levels. The toxicity of certain compounds such as many metals can increase at reduced DO concentrations, which can also have a detrimental effect on wetland organisms.

Chemical parameter

Indicator: Acidity and alkalinity

What this indicator measures: The acidity and alkalinity of water

Role in wetland ecosystems: Aquatic organisms are adapted to particular ranges of acidity or alkalinity in order to maintain normal physiological processes. Acidity also affects the solubility of compounds in water, including compounds that are required by or toxic to wetland organisms. The natural acidity or alkalinity of wetlands depends on factors such as the acidity of incoming water, sediment type, rate of photosynthesis and respiration occurring in the water and presence of humus. There are significant differences between wetlands that are naturally acidic and those that have become acidic due to human-induced changes, as explained in the 'Managing acidification' section later in this topic.

What is measured:

pH: concentration of hydrogen ions (water becomes more acidic with increasing concentration of hydrogen ions)

Acidity, as total titratable acidity: the weight of calcium carbonate (pure limestone, $CaCO_3$) or the equivalent such as sodium hydroxide (NaOH), needed to neutralise all of the acidity in a litre of water to pH 8.3.

Alkalinity: in waters with a pH greater than 4.5 is the amount of hydrochloric acid (HCl) needed to lower pH of a litre of the solution to pH 4.5.

Effects of changes on wetland ecosystems: Changes beyond normal variations can have serious effects on wetland organisms. Very acidic or alkaline waters may be directly toxic to biota. Very acidic waters can liberate toxic compounds such as metals. Very alkaline waters can lead to increased ammonia levels which can have toxic effects on biota.

Chemical parameter

Indicator: Water hardness

What this indicator measures: The concentration of calcium (Ca) and magnesium (Mg) ions in water, frequently expressed as milligrams per litre calcium carbonate equivalent.

Role in wetland ecosystems: Hardness affects the toxicity of some metals, such as aluminium, cadmium and copper, and the bioavailability of some nutrients, such as phosphorus, in water. In general, soft waters with low alkalinities have a low buffering capacity to resist pH fluctuations, and are more susceptible to acidification. Hard waters usually have high alkalinities, a high buffering capacity, and are less sensitive to acidification.

What is measured: Typically calcium carbonate concentration

Water hardness category[15]	Calcium carbonate milligrams per litre ($CaCO_3$ mg/L)
Soft	0–59
Moderate	60–119
Hard	120–179
Very hard	180–240
Extremely hard	400

Effects of changes on wetland ecosystems: Increasing hardness, particularly magnesium, can have adverse impacts on species adapted to soft water. Groundwater is usually harder than surface water. Changes in water sources may affect hardness and therefore acidity and nutrient and metal solubility.

Chemical parameter

Indicator: Salinity

What this indicator measures: Total concentration of salts in the water. Salts are compounds of cations (such as sodium Na^+, potassium K^+, calcium Ca^{2+}, magnesium Mg^{2+}) with anions (such as chloride Cl^-, sulfate SO_4^{2-} and bicarbonate HCO_3^-).

Role in wetland ecosystems: Salinity is an expression of the concentration of ions and determines the difference between 'freshwater' and 'saline' water. An excess of common salt, sodium chloride, is the main cause of water salinity problems and it can affect both freshwater and saline wetlands, although a sudden freshening of saline waters can also be detrimental. Wetland organisms are adapted to particular salt tolerance regimes in order to maintain normal physiological processes.

What is measured: There are several units of measurement used to express salinity including total dissolved salts and electrical conductivity.

- TDS: total dissolved salts (concentration of salts) – see table below
- EC: electrical conductivity (ability of water to conduct an electric current)
- Ionic composition (the types of salts present; the sum total provides total dissolved salts)

Salinity ranges commonly used in WA	Salt lake category (after Hammer[16])	Minimum total dissolved salts (TDS) (milligrams per litre, mg/L)	Maximum total dissolved salts (TDS) (milligrams per litre, mg/L)
Fresh	Fresh	0	500
Fresh	Subsaline	500	3,000
Saline	Hyposaline	3,000	20,000
Saline	Mesosaline	20,000	50,000
Hypersaline	Hypersaline	50,000	NaCl saturation (about 360,000)

Effects of changes on wetland ecosystems: Changes in salinity beyond normal variations can have direct toxic affects on aquatic biota by affecting physiological processes such as osmoregulation. Salts interact with other ions and compounds in water, so they influence other water chemistry processes.

Chemical parameter

Indicator: Nutrients

What this indicator measures: Nutrient levels and susceptibility to excessive plant, algal and cyanobacterial growth e.g. algal blooms

Role in wetland ecosystems: Nutrients such as nitrogen and phosphorus are essential for all wetland organisms. They flow through the food web, from the algae and plants through to animals and other organisms. Dissolved phosphate is the fraction of total phosphorus that is free in the water. High levels of phosphorus in wetlands can fuel algae growth to the extent that algal and cyanobacterial blooms occur.

What is measured: A range of chemical forms of nitrogen and phosphorus such as total nitrogen (TN), dissolved inorganic nitrogen, ammonium, total phosphorus (TP) and filterable reactive phosphorus (FRP).

Effects of changes on wetland ecosystems: Growth of plants, algae and cyanobacteria rely on nutrients. If nutrient levels are too low, growth of plants and algae is limited, which in turn affects productivity of organisms that feed on them. If too high, algal and cyanobacterial blooms and weeds may flourish and other related impacts can occur, leading to loss of wetland organisms.

Biological parameter	
	Indicator: Chlorophyll a
	What this indicator measures: Primary productivity and nutrient levels
	Role in wetland ecosystems: Chlorophyll *a* is the main light-capturing substance enabling photosynthesis in plant, algal and cyanobacterial cells. It is present in all green alga, diatoms and in some bacteria.
	What is measured: Chlorophyll *a* levels
	Effects of changes on wetland ecosystems: High levels of chlorophyll *a* can be indicative of nutrient enrichment and potential for algal and cyanobacterial blooms and related impacts.

Biological parameter	
	Indicator: Biological oxygen demand (BOD)
	What this indicator measures: The amount of oxygen being used by microorganisms to decompose detritus (the source of which may be pollution).
	Role in wetland ecosystems: Microorganisms such as bacteria are responsible for decomposing detritus such as dead plants and animals and their faeces, as well as leaves, grass clippings, faeces and sewage washed into wetlands. Bacteria break down this material in order to extract energy from it. If oxygen is available, they will use it during this process, depleting the dissolved oxygen, and reducing the amount available to larger wetland organisms.
	What is measured: Consumption of dissolved oxygen by microorganisms
	Effects of changes on wetland ecosystems: A high level of biological oxygen demand is likely to reduce oxygen levels, reducing the amount of oxygen available for respiration by water-dwelling wetland organisms and affecting the toxicity of a range of compounds such as metals (see dissolved oxygen parameter above for more information). If BOD is high enough, it may reduce oxygen levels enough to trigger phosphorus release from the sediment into the wetland water column (due to iron reduction).

Measuring water quality

A common experience amongst wetland managers is spending time, effort and money measuring water quality with the expectation that it will provide the answers needed, and being disappointed when this doesn't eventuate. The decision to measure a water quality indicator should be based on a sound analysis that really hones in on the reasons for investigating water quality. Is the purpose to:

- develop a baseline of the existing conditions via a survey?
- investigate a particular concern by starting with a single measurement or set or measurements?
- conduct an ongoing monitoring program that detects trends that indicate whether management is having the expected outcome?
- or something else?

The topic 'Monitoring wetlands' in Chapter 4 provides some guidelines on wetland monitoring. For more detailed guidelines, a range of resources are available, including:

- *Field sampling guidelines: A guideline for field sampling for surface water quality monitoring programs*[17]
- *Surface water sampling methods and analysis-technical appendices*[18]
- *Water quality protection note no. 30: Groundwater monitoring bores*[19]

For detailed guidelines on water quality sampling and monitoring for more complex or stringent purposes, see:

- *Australian guidelines for water quality monitoring and reporting*[20]
- *Water quality – Sampling. Part 1: Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples*[21]
- *Water quality – Sampling. Part 11: Guidance on sampling of groundwater.*[22]

New technologies are helping to refine sampling results and reduce costs. For example, passive samplers remain in situ, sample herbicides, pesticides and polyaromatic hydrocarbons and can detect contaminants at trace levels. For an example of how they are being employed locally, see the report *A baseline study of organic contaminants in the Swan and Canning catchment drainage system using passive sampling devices.*[23]

Figure 5. A passive sampler. Photo – courtesy of Department of Water.

extra information

Whether to monitor or survey?

The term 'monitoring' is often used in a casual sense to mean the act of measuring or observing something. However, in scientific terms, monitoring more accurately refers to the systematic collection of data, over time, in order to test a hypothesis. For example, a wetland manager may monitor the water quality of a wetland over a length of time, before and after carrying out a range of management activities, to determine the effect of those activities upon the water quality.

A survey is an exercise in which a set of observations are made about some components of an ecosystem. For example, surveying might involve measuring the water quality at a wetland on a single occasion or on an ad-hoc basis over time. This is not monitoring; as monitoring entails measurements being repeated over time, and designed in such a way as to test a theory about the effect of an action upon the water quality.

A 'baseline' survey refers to an initial measurement that may be used as a basis for future comparison.

The topic 'Monitoring wetlands' in Chapter 4 outlines how to design a wetland monitoring program, but also provides information relevant to wetland surveying.

What should a wetland's water quality be?

There is no set of numerical criteria, limits or concentrations that define the ideal water quality of a wetland in WA. The following information outlines how managers can make use of published water quality *guidelines* and/or develop their own water quality *objectives* for a wetland.

Water quality guidelines

Water quality guidelines are used to help manage the quality of a water resource in relation to its intended purpose. At a national level, the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14], or ANZECC guidelines as they are often called, provide guidelines regarding acceptable water quality, to ensure there are no significant impacts for the purposes that water resources are intended to support. The guidelines include acceptable quality for human drinking water, maintenance of aquatic ecosystems, primary industries (food production and industrial use) or recreational and aesthetic purposes. As the purpose of this guide is to provide guidance on the management and protection of the ecological values of wetlands, the section of the ANZECC guidelines referred to here are those that were developed for the maintenance of aquatic ecosystems.

In effectively unmodified wetlands, with high conservation/ecological value, the most appropriate guidance is that there should be no detectable change beyond natural variability. For **slightly disturbed** freshwater wetlands of south-west and north-west Australia, the ANZECC guideline default **trigger values** for physical and chemical parameters apply. These are summarised in Table 5, and are the concentrations or loads of a water quality parameter measured in an ecosystem, below which, or within which (in the case of those with a range), there exists a low risk that adverse biological (ecological) effects will occur. They indicate a risk if exceeded and should trigger some action; either investigation or management/remediation.[14]

Slightly disturbed: ecosystems that have undergone some changes but are not considered so degraded as to be highly disturbed. Aquatic biological diversity may have been affected to some degree but the natural communities are still largely intact and functioning. An increased level of change in physical, chemical and biological aspects of these ecosystems is to be expected.[13]

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response e.g. further investigation

ANZECC guidelines under review

The Council of Australian Governments has announced that the ANZECC guidelines are under review. This review includes the revision of sediment water quality guidelines, nitrate trigger values and toxicant trigger values. For more information, see www.environment.gov.au/water/policy-programs/nwqms/index.html#revision.

Table 5. Default trigger values for physical and chemical parameters for unmodified and slightly disturbed freshwater wetlands in Western Australia, from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*.[14]

	Effectively unmodified wetlands, with high conservation/ecological value	**Slightly to moderately disturbed freshwater wetlands**	
Water quality parameter		Trigger value, south-west Australia	Trigger value, north-west Australia
Chlorophyll *a* (micrograms per litre, μgL^{-1})	No detectable change beyond natural variability	30[a]	10
Total phosphorous (micrograms per litre, μgL^{-1})		60[a]	10–50[b]
Filterable reactive phosphate (micrograms per litre, μgL^{-1})		30[a]	5–25[b]
Total nitrogen (micrograms per litre, μgL^{-1})		1500[a]	350–1200[b]
Oxides of nitrogen (NO_x micrograms per litre, μgL^{-1})		100[a]	10
Ammonium (NH_4^+ micrograms per litre, μgL^{-1})		40[a]	10
Dissolved oxygen (% saturation)		Less than 90 and more than 110	Less than 90 and more than 120
pH		Less than 7.0 and more than 8.5[c]	Less than 6.0 and more than 8.0
Salinity (microSiemens per centimetre, μScm^{-1})		300–1500[d]	90–900[e]
Turbidity (nephelometric turbidity units, NTU)		10–100[f]	2–200[f]
Toxicants, such as types of metals, pesticides, hydrocarbons etcetera.		Refer to Table 3.4.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*	

Explanatory notes

a: elevated nutrient concentrations in highly coloured wetlands (gilvin >52 $g_{440}m^{-1}$) do not appear to stimulate algal growth

b: higher values are indicative of tropical WA river pools.

c: in highly coloured wetlands (gilvin >52 $g_{440}m^{-1}$), pH typically ranges from 4.5-6.5.

d: values at the lower end of the range are observed during seasonal rainfall events. Values higher than 1500 μScm^{-1} are often found in saltwater lakes and marshes. Wetlands typically have conductivity values in the range 500-1500 1500 μScm^{-1} over winter. Higher values (>3000 μScm^{-1}) are often measured in wetlands in summer due to evaporative water loss.

e: higher conductivity values will occur during summer when water levels are reduced due to evaporation. WA wetlands can have values higher than 900 μScm^{-1}.

f: most deep lakes and reservoirs have low turbidity. However, shallow lakes and reservoirs may have higher turbidity naturally due to wind-induced re-suspension of sediments. Lakes and reservoirs in catchments with highly dispersible soils will have high turbidity. Wetlands vary greatly in turbidity depending on the general condition of the catchment or river system draining into the wetland and the water level in the wetland.

Wetland managers in WA are fortunate to have these guidelines, with very few other Australian jurisdictions nominating trigger values for wetlands. These trigger values are an extremely useful guide if used with a proper understanding of their purpose. They are designed to be used in conjunction with professional judgement, to provide an initial assessment of the state of a wetland.[15] The difficulty with setting trigger values is that there is natural variation amongst wetlands, with the natural conditions in many wetlands being above or below these trigger values. For example, some wetlands have naturally high levels of salinity, turbidity, or naturally high or low pH. The topic 'Conditions in wetland waters' in Chapter 2 describes the reasons and patterns for natural variations in wetland water quality in WA.

Benchmark: a standard or point of reference; a predetermined state (based on the values that are sought to be protected) to be achieved or maintained

Reference range: a quantitative and transparent benchmark appropriate for the type of wetland

The trigger values for the south-west of WA have been derived from a limited set of data (two years) collected at forty-one wetlands within and near Perth (Davis et al 1993[24]) and are representative of basin wetlands of this region that are permanently or seasonally inundated. Care should be used when extrapolating to other wetland types (such as seasonally waterlogged wetlands) and other areas of the south-west of the state. The exception is the toxicant trigger levels, which were developed through a different process. The trigger values from the north-west of the state are derived from an even more restricted study (less than one year) in the Pilbara region.[14] Furthermore, the trigger values have not been designed specifically for application to naturally saline (primary saline) or secondary saline sites.

As the default trigger values do not fully reflect the potential range of natural wetland conditions in WA, the guidelines are not mandatory and have no formal legal status, nor do they signify threshold limits of pollution.[14]

Before using the trigger values in Table 2 to make decisions about a particular wetland or group of wetlands, it is a good idea to consider whether it is appropriate to apply the trigger values to them. Where possible, the aim of management should be to maintain the natural conditions of a wetland. In many landscapes it is often difficult to determine the natural conditions (and in many areas the extent of changes to the broader environment means that a return to natural conditions is unlikely to be achievable). Long-term monitoring data of a wetland aid this decision, but it is quite uncommon to have access to long-tem data. In its absence, the best approach is usually to combine an analysis of available data, and local and professional knowledge to reach a decision about suitable targets, **benchmarks**, **reference ranges** or trigger values, taking into consideration the natural factors affecting the water quality in wetlands, as outlined in the topic 'Conditions in wetland waters' in Chapter 2. Monitoring is a good way to build up a long-term picture of the water quality of a wetland, and can enable wetland managers to establish trends and refine targets along the way.

➤ For information on how to design a monitoring program, see the topic 'Monitoring wetlands' in Chapter 4.

As stated above, these guidelines are for the maintenance of aquatic ecosystems. Different guidelines exist for the assessment levels used by accredited contaminated sites auditors and DEC to determine whether a site is potentially contaminated and whether further investigation is required, as outlined in the document *Assessment levels for soil, sediment and water*.[25]

Water quality objectives

As outlined above, water quality guidelines are often, but not always, suitable for guiding the management of water quality in a wetland. Water quality objectives, on the other hand, tend to be targets based on knowledge of site-specific conditions. These are often identified by analysing available data, and taking into account local and professional knowledge and the natural factors affecting the water quality in wetlands.

Sometimes the use of a reference wetland may be a useful benchmark. For example, the trigger value may be set at a percentile of the reference wetland's distribution. The ANZECC guidelines provide guidance on refining trigger values for a particular wetland. See Sections 8.2 'Physical and chemical stressors' in Volume 2 and 3.3.2.3 'Defining low-risk guideline trigger values' in Volume 1) at www.environment.gov.au/water/policy-programs/nwqms/index.html#revision.

There may be enough research and expert knowledge to refine water quality targets for a particular region, sub-region or local area. For example, researchers have established references ranges for pH of inundated wetlands of the central Wheatbelt region.[26] These reference ranges have been developed by analysing existing pH data from the region, which is relatively data-rich due to the surveying conducted with funding under the Salinity Action Plan and State Salinity Strategy. Firstly, permanently or seasonally inundated wetlands that had been sampled in the region were identified as either saline basins, freshwater basins or turbid claypans. Following this, the least disturbed wetlands of each group were identified using expert opinion, and then the data of the least disturbed wetlands were analysed in order to establish a range in pH that may approximate the natural range.

There are some naturally extremely acidic wetlands in the region, particularly in the eastern area. Naturally acidic wetlands identified using a set of decision rules were excluded from this process. Excluding naturally acidic wetlands, the reference ranges for pH are as follows:

- naturally saline basins: 7.8–8.7
- freshwater basin wetlands: 6.8–8.1
- turbid claypans: 8.6–8.9.[26]

As per the ANZECC trigger values, these reference ranges should be used as a guide only and should be supported by site-specific studies if needed, due to the natural variability in acidity between wetlands.

Target setting requires research and data collection. The WA government endeavours to provide guidance for priority issues; for example, acidity/pH target values for aquatic ecosystems are the focus of ongoing work by the Department of Water and Department of Environment and Conservation.

Key techniques for managing wetland water quality

The techniques for managing water quality outlined in the following sections are focused on protecting and maintaining wetland biodiversity and conservation values.

Three 'scales of approach' for managing wetland water quality are presented here:

1. preventing the causes of poor water quality
2. intervening at the scale of the surface water catchment or groundwater capture zone
3. intervening at the wetland scale.

The most effective long-term strategy for managing water quality is preventing the causes: reducing pollution and preventing acidification. Intervention techniques, whether at the catchment or wetland scale, can be expensive, inefficient and require long term management.

It is not unusual to find that a combination of techniques from all three scales is needed. Both short and medium to long-term management strategies are outlined in the following sections. Short term strategies tend to alleviate the problem for a short time only, and focus on addressing symptoms rather than causes. Medium to long-term management strategies are typically required to address water quality problems.

Preventing the causes of poor water quality

Pollution prevention is critical to the management of wetland water quality because once many types of pollutants enter wetland water and sediments they can be extremely difficult to remove or remediate without significant effects to the wetland. Similarly, the process of wetland acidification can be difficult to treat.

As outlined in the previous section entitled 'Who is responsible for managing catchment water quality?', state and local government agencies play an important role in preventing and policing pollution in WA through regulation. However, awareness raising and incentives are important methods of achieving behavioural change and through these measures, individuals and groups can play an important role in further reducing the generation, use and release of pollutants, particularly nutrients, pesticides, litter and debris; and the process of acidification. Each section below (nutrients, acidification, pesticides, metals etcetera) lists relevant pollution prevention guidelines and techniques.

Awareness raising and incentives are often called 'non-structural controls' because they don't rely on changes to infrastructure. They include public education programs that can encourage the adoption of wetland-friendly practices in households (Figure 6), and local councils improving management of public open spaces (such as using less water, fertiliser and pesticides on lawns and gardens). A number of community education programs have been trialled and assessed in WA. For example, the South East Regional Centre for Urban Landcare (SERCUL) undertook a trial of a 'fertilise wise' community education program in new suburbs south of Perth for the City of Armadale.[27] In the long term, non-structural control options are more efficient and cost effective in reducing pollutants from entering wetlands than installation of structural control options as the sole means of reducing pollutants.

Figure 6. The green frog drain stenciling project by the Friends of Yellagonga Regional Park, the City of Joondalup and local schools is part of campaign to improve stormwater quality of wetlands in the Yellagonga catchment by changing people's behaviour. Photo – courtesy of Keep Australia Beautiful WA.

Reducing the potential for pollution: the importance of appropriate land use planning, setbacks and wetland buffers

Despite best efforts to manage pollutants appropriately, pollution events can and do occur. This is why sound decisions are needed about what land uses are appropriate near wetlands, and about what wetland buffers and setbacks are needed.

These decisions are made via the system widely referred to as the 'land use planning process'. In WA, the statutory basis for this process is the *Planning and Development Act 2005,* which is primarily administered by the Western Australian Planning Commission and the Department of Planning, and overseen by the State Government Minister for Planning. Under the *Environmental Protection Act 1986* the Environmental Protection Authority is empowered to assess land use proposals that have the potential to have a significant effect on the environment, and to make recommendations to the State Government Minister for Environment. The process enables the community to participate in land use planning, providing an opportunity to provide input. More information on how community can participate in the land use planning process is outlined in the topic 'Roles and responsibilities' in Chapter 5.

The EPA states that, where high value wetlands are located in areas to be developed:

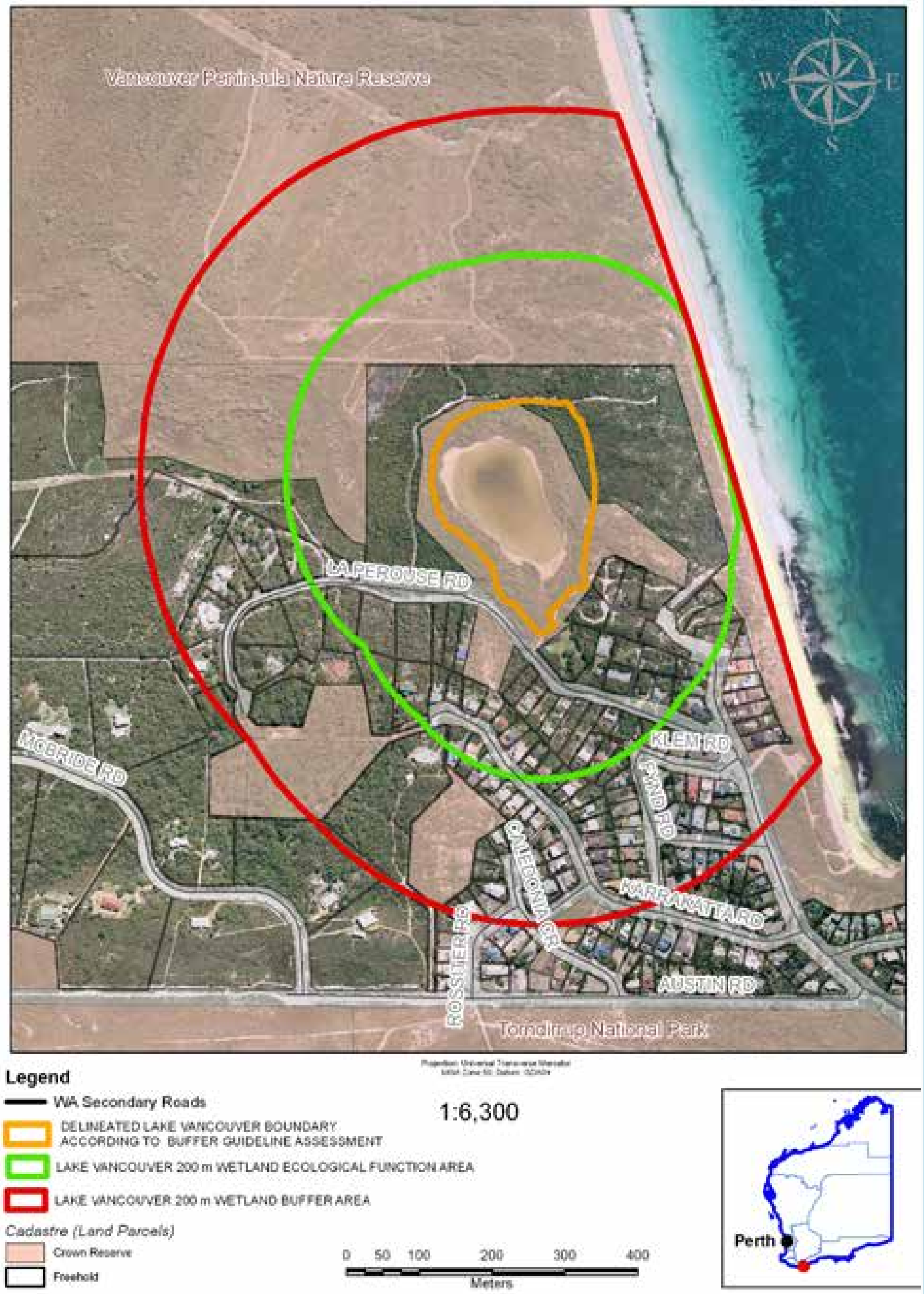
- when considering planning options for the study area, take into account the potential for adverse impacts (direct, indirect and cumulative) on wetlands given the site specific conditions. Avoid locating development where a high level of management is required to protect significant wetlands. For example, general industrial development is not an optimal land use over transmissive soils near significant wetlands.
- determine, protect and manage a buffer between a wetland and existing or proposed land uses. This is crucial to maintain or improve wetland values. A wetland buffer is the designated area adjoining a wetland that is managed to protect the wetland's ecosystem health. The buffer adjoining a wetland helps to maintain the ecological processes and functions associated with the wetland, and aims to protect the wetland from potential adverse impacts. A buffer can also help to protect the community from potential nuisance insects, for example, midges.
- setbacks for land uses with a relatively high potential for site contamination or nutrient export: the setback should take into account the potential of the development to adversely impact on the wetland, the proposed management of environmental impacts, and the extent to which enforceable conditions on the development will be imposed by decision-making authorities. Land uses associated with a relatively high potential for site contamination or nutrient export (for example, some forms of intensive agriculture, industry and some effluent treatment facilities) may need to be located farther away from the wetland than the determined wetland buffer.

- excerpts from Chapter B4 of the EPA *Environmental guidance for planning and development*.[28]

Reducing the potential for pollution: the importance of appropriate land use planning, setbacks and wetland buffers (cont'd)

A wetland buffers guideline has been prepared for the purpose of providing guidance to development proponents on how to determine the wetland buffer needed to protect a wetland from a proposed land use. Following its finalisation, the *Guideline for the determination of wetland buffer requirements* will be available from the 'Wetlands' webpage of the DEC website. Figure 7 shows an example of a wetland buffer requirement between Lake Vancouver in Albany and residential development.

Figure 7. The wetland buffer requirement (delineated in red) for Lake Vancouver in Albany, based upon residential land use. Image – A Shanahan/DEC.



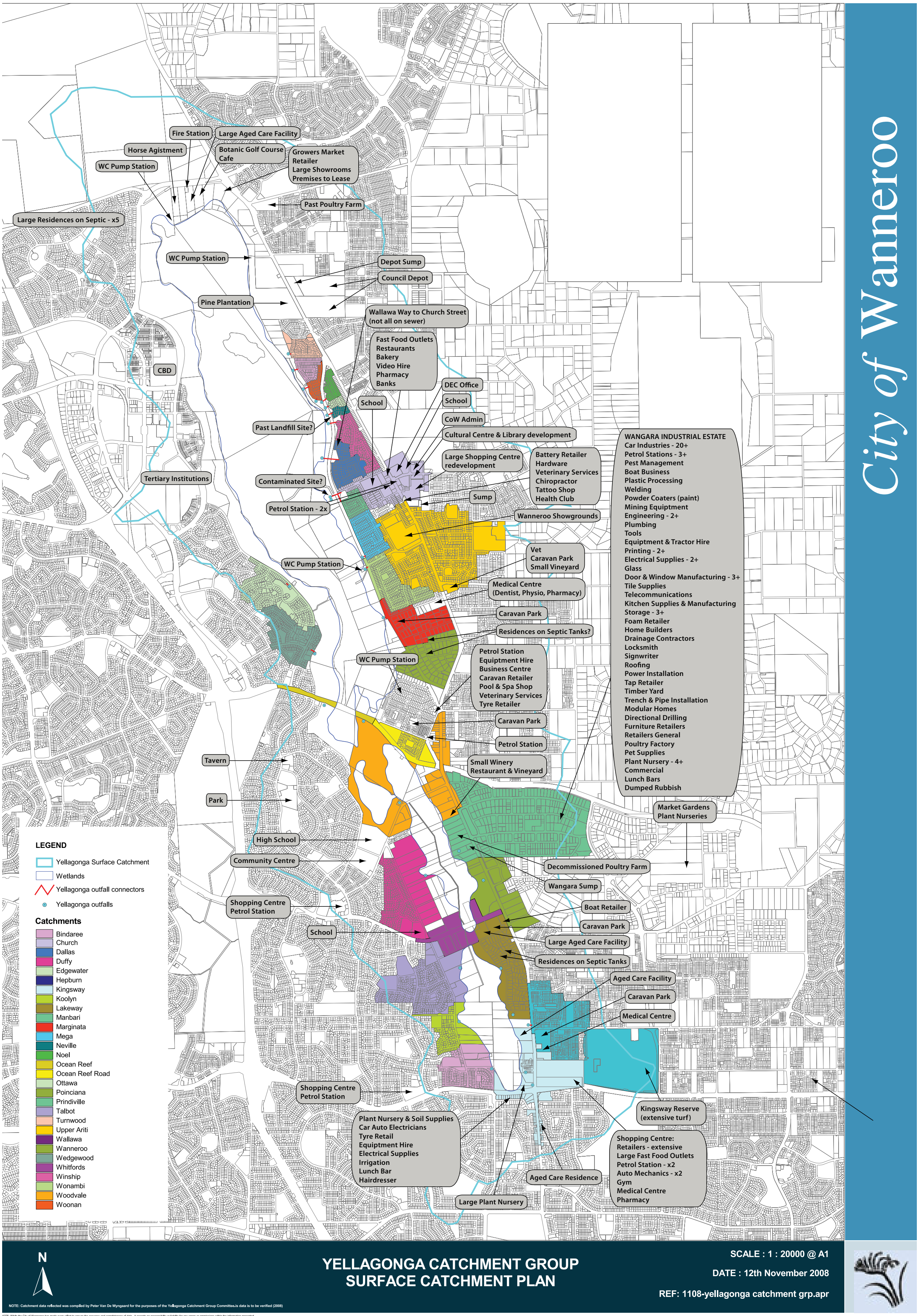
Intervening at the scale of the surface water catchment or groundwater capture zone

Improving water quality before it reaches a wetland is mostly achieved via catchment management. Catchment management activities that maintain or improve water quality include:

- matching land use with land capability so that highly degrading or polluting land uses are not sited in sensitive or transmissive environments
- using land and water appropriately to minimise changes in ground and surface water in the catchment, through appropriate agricultural and urban land uses, agricultural and urban land use design/retrofitting, water allocation and stormwater management
- protecting existing native vegetation through fencing, strategic revegetation/ regeneration of native vegetation
- employing agricultural and urban practices that minimise erosion (such as perennial pastures, no-till farming, suitable stocking rates accounting for total grazing pressure, contour farming, best practice construction methods)

Catchment management plans are an effective tool for identifying the causes of poor water quality and prioritising intervention measures at a catchment scale. For example, the *Yellagonga Integrated Catchment Management Plan 2009–2014*[29] highlights the potential sources of pollutants to the wetlands within the catchment (Figure 8).

Figure 8. A spatial summary of land uses can be an effective way to informally identify and rate potential pollutant sources within a catchment. Image – *Yellagonga Integrated Catchment Management Plan 2009–2014*.[29]



Stormwater management is commonly targeted when seeking to improve wetland water quality. Aspects of stormwater management include overland flows, waterways, water conveyed in drains and pipes and stormwater percolation to groundwater. In both urban and rural catchments, well-managed stormwater (sometimes referred to as 'runoff' or 'drainage') is important in contributing water to wetlands (other sources are groundwater and rainfall). Stormwater in well-managed catchments mimics the natural quantity and quality of water that would have reached a wetland prior to changes to a catchment, as well as the patterns of timing and frequency of flow. Groundwater intervention (treatment) is a much more difficult and expensive proposition, and is rarely used as a method to improve the water quality of individual wetlands.

Where stormwater is a significant cause of poor water quality in a wetland, improving the quality of stormwater in the catchment is typically much more effective and efficient than working at the wetland scale to improve the water quality of the receiving wetland. In such cases, the wetland manager should identify the relevant stormwater manager/s (in urban areas, usually local government) and work with them to identify the most appropriate techniques, both structural and non-structural, to improve water quality. Any modifications to stormwater systems or infrastructure, or their management, require the approval of the managing authority. Key concerns of managing authorities will include whether changes to waterways, pipes, drains or overland flows will increase the risk of flooding, or reduce the ease of management or public safety. Any proposed changes to the banks, cross-sectional area and levels of drains will require a professional hydrological assessment.

In urban environments, both structural and non-structural controls are needed to manage stormwater to protect wetlands and other natural areas. Structural control options minimise pollution through engineering solutions such as:

- gross pollutant traps
- oil-water separators
- constructed wetlands
- biofilters
- trash screens
- grass swales
- sediment detention basins.

In agricultural environments, land use changes such as strategic vegetation with deep-rooted perennials, contour farming, plantations and stocking and cropping modifications can be complemented by stormwater structural controls such as:

- fencing, stabilisation and rehabilitation of waterways that flow into wetlands
- creation of living streams
- creation of constructed wetlands
- creation of sediment detention basins.

These controls can help to reduce flow velocity, retain sediments, attenuate pollutants, increase shading, reduce water temperature, increase colour, increase biodiversity and increase water percolation to groundwater.

Factors that should be considered when designing structural controls include the type of pollutants to be removed, effectiveness in removing pollutants, maintenance requirements and cost, site constraints and ease of installation.

Stormwater management options

There are many structural and non-structural control options that can be used to improve water quality in wetland catchments.

The *Stormwater management manual for Western Australia*[30] has been developed to provide local government, industry, developers, state agencies, service providers and community groups with information on policy and planning principles and best stormwater management practices. For further information, see www.water.wa.gov.au.

For general information on managing stormwater quality in WA, see the 'Stormwater' webpage of the Department of Water's website: www.water.wa.gov.au/Managing+water/Urban+water/Stormwater/default.aspx#

Resilience: capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks

Intervening at the wetland scale

Intervening at the wetland scale may be an option if poor water quality, particularly as a result of excess nutrients, acidification, or unnatural levels of turbidity. It is often less effective in addressing pesticides, metals, hydrocarbons, hot/cold water, pathogens and litter.

In ideal situations, the link between poor water quality cause, effect and solution is clear. However, a common occurrence is one change in water chemistry that creates a domino effect of cascading changes. More than one water quality issue due to one or more causes may be at play in a wetland. It is important to consider the potential for complicating factors and anticipate the potential for unintended ecological impacts before initiating an activity, particularly when considering intervening at the wetland scale, especially when it involves altering the amount of water or disturbing the sediment. Wherever possible, interventions at the wetland scale should be reversible in nature, so that unintended consequences can be mitigated. It is safest to seek expert advice to identify the most appropriate strategies.

Managing wetland water quantity is an important aspect of managing wetland water quality. The physical, chemical and biological processes in a wetland are driven by the natural patterns of water presence and absence, in terms of timing, duration, frequency, extent and depth, and variability. When these natural patterns, known as wetland water regime, are altered, the conditions in the soil and water are also altered, and the wetland's **resilience** to other impacts is reduced.

Although effects vary depending on the wetland, in general, a drier water regime (for example, from dewatering, over-extraction of groundwater and declining rainfall) can lead to:

- loss of plants and animals that need wetter conditions
- acidification via actual acid sulfate soils
- increased susceptibility to fire
- the terrestrialisation of wetland areas (that is, wetlands slowly becoming dryland)
- changes in the mobility and availability of nutrients and metals

A wetter water regime (for example, from discharge of mine water or drains, or digging out of wetlands) can lead to:

- loss of plants and animals that need drier conditions

- increasing pollutant loads, including nutrients, salts and acid
- changes in the mobility and availability of nutrients and metals
- increasing frequency and severity of algal blooms
- nuisance midge and mosquito populations
- odour issues.

The management of wetland water regime is so critical that a whole topic is dedicated to it. General guidance is also provided in the following sections.

➤ For information on the natural water regime of WA wetlands, see the topic 'Wetland hydrology' in Chapter 2.

➤ The causes, effects and management of altered water regimes are covered in the topic 'Managing hydrology' in Chapter 3.

Bioavailable: in a chemical form that can be used by organisms

Eutrophic: nutrient rich waters or soil with high primary productivity (plant/algal/cyanobacterial growth). From the Greek term meaning 'well nourished'.

Midges: biting and non-biting species of a number of families within the true flies (Diptera) including the Chironomidae and Ceratopogonidae

Managing excess nutrients (eutrophication)

The nutrients nitrogen and phosphorus (commonly referred to as 'N' and 'P') are essential for living things due to their importance in the construction of living tissue and in metabolic processes. As well as being present in living things, nutrients can be dissolved in water or occur as part of coarse or fine particulate matter, and in wetlands phosphorus is often bound to sediment particles, for example. Plants, algae and some bacteria can make use of certain chemical forms of nutrients that are present in wetlands, or that washes into wetlands; these are known as **bioavailable** forms, as described in more detail in the topic 'Conditions in wetland waters' in Chapter 2. In turn, the nitrogen and phosphorus that animals, fungi and (other) bacteria consume originates from plants, algae or bacteria.

When phosphorus and/or nitrogen are in short supply, or not in a form that can be readily used, plant and algal growth is limited.[31] The soils of south-west Western Australia are old and weathered, and consequently have low natural levels of nitrogen and phosphorus (and many other nutrients). The native vegetation is adapted to low nutrients, and many plants have evolved mechanisms to increase their nutrient uptake. The most common problem associated with nitrogen and phosphorus in wetlands is when they are in excess amounts, that is, above the natural levels. Under the right conditions, for example, high light intensity and water temperatures, highly nutrient-enriched wetlands produce high rates of plant, algal and cyanobacterial growth and ultimately, the development of 'blooms'. These wetlands are said to be **eutrophic** and they often have low diversity of native species, which may be out-competed or suffer from nutrient toxicity; however they may have high abundances of algae, cyanobacteria, plants and animals tolerant of eutrophic conditions, including pest species of **midge**. Most permanently inundated wetlands in urban areas of metropolitan Perth and Peel are nutrient enriched.

Nutrient problems in wetlands: a summary

Causes: nutrient pollution, artificial maintenance of permanent inundation

Impacts: impaired health of native species, algal and cyanobacterial blooms, nuisance midge populations, reduced biodiversity of plants and animals, botulism, weeds

Indicators: high nutrient levels, high chlorophyll a levels, low dissolved oxygen levels, low light levels

Management options: a range of options for nutrient pollution prevention, catchment-scale stormwater intervention and wetland-scale intervention

Causes of excess nutrients

While the addition of nutrients from outside the wetland drives eutrophication, it can be exacerbated by the loss of wetting and drying patterns, or the influx of sulfur, both of which can trigger the release of nutrients from the sediment. Each of these is described below.

Nutrient pollution

Human settlement is always associated with excess nutrients from fertilisers and wastes, particularly phosphorus, building up in the local environment.[32] Surface and groundwater contain nutrients originating from a range of sources. Nitrogen and phosphorus can be present in the water column dissolved in solution, or they can be attached to sediments, in solid form as particulates. In areas where rainfall results in most of the water infiltrating into the ground, nutrients can leach into wetlands through the groundwater. When more water travels across the land surface as stormwater, nutrients dissolved in the stormwater, or attached to eroded soil particles, can be washed into wetlands. The transport of large amounts of nutrients into wetlands often occurs during the **first flush.**[33] In the south-west, this is often the first large rainfall of autumn, while in the north, this is often the first large rainfall of the wet season. Unseasonal rainfall events may also result in high pollutant loads in stormwater.

In urban residential areas, nutrient inputs are most commonly from diffuse sources, such as fertiliser applied to lawns, gardens and recreation areas such as parks and sports fields, and from sewage from septic tanks and other types of on-site sewage disposal systems. This is especially an issue on the **Swan Coastal Plain** where the soils have low nutrient-holding capacity, and nutrients are readily leached into the groundwater. Rates of input of nutrients in residential areas are generally greater than in broad acre farming, but less than inputs from horticulture.[32] Rubbish tips, industrial sites and sewage treatment works can also discharge large amounts of nutrients. Commercial areas contain a variety of potential sources of nutrients, including nurseries and garden centres. Industrial areas, particularly where fossil fuels are combusted, discharge gases and particulates that can end up in wetlands via atmospheric deposition; reducing this form of nutrient source is rarely considered a feasible or effective strategy for reducing wetland nutrient levels.

Wetlands that are within designated areas of public open space, especially with grassed areas, tend to receive large amounts of nutrients due to over-fertilisation, over-watering and feeding of waterbirds. Simple activities such as regular feeding of bread to birds can add significant amounts of nutrients. Researchers estimated that, in the early 1990s, up to 50 loaves of bread were fed to birds at Lake Monger each day.[34] Put into context, a loaf of bread contains between 1 and 2 grams of phosphorous, enough to turn a wetland with 50 cubic metres of water (equivalent to the size of a backyard swimming pool) eutrophic.[32] In addition, animals visiting wetlands, such as large flocks of native birds and introduced feral animals such as pigs, can import considerable amounts of nutrients in faeces.

In peri-urban and rural areas additional diffuse sources include horticulture, such as market gardens, turf farms, viticulture, hobby farms; broad-acre agriculture and animal-keeping businesses such as dog kennels and horse stables. Intensive animal farming, such as poultry farms, dairies and piggeries can be significant point sources of nutrient pollution. Wetlands are often favoured for some forms of agricultural production, such as horticulture and grazing, which can add large amounts of nutrients. At Benger Swamp in Benger, for example, it is estimated that 12,000 tonnes of superphosphate have been applied directly to the dry bed over the last forty years.[35] Horses, cows and other livestock can also add very significant amounts to wetlands.

First flush: the first rainfall for a period of time, resulting in stormwater dislodging and entraining relatively high loads of sediments, particulates and pollutants that have built up in the intervening period between rainfall events, and typically carrying a higher pollutant load than subsequent events

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

extra information

Horses, cows and nutrient pollution

Horses and cattle produce large amounts of faeces and urine. A standard light horse (450 kilograms) produces approximately 5.5 tonnes of wet faeces and 5.5 kilolitres of urine each year. This volume of waste contains 62 kilograms of nitrogen and 5.5 kilograms of phosphorus.[36] Cattle in feedlots produce an estimated 20–30 kilograms per year of nitrogen and more than 6 kilograms per year of phosphorus.[37]

Figure 9. Cows, such as this one grazing in a seasonally waterlogged wetland, can cause significant nutrient enrichment when allowed in and near wetlands. Photo – M Bastow/DEC.

High water soluble phosphorus fertilisers: products containing greater than 2 per cent total phosphorus and greater than 40 per cent of the total phosphorus as water soluble phosphorus

Phasing out the widespread use of **highly water soluble** forms of phosphorus fertilisers have been the focus of multiple campaigns in WA. Studies of the Peel-Harvey estuary and its hinterlands found that a high proportion (up to 80 per cent) of phosphorus in 'superphosphate', which is commonly used for agriculture, leaches through soil and is lost to production with winter rain.[7] Phosphorus has been the focus of campaigns because the loss pathways from the catchment source to the receiving wetlands, waterways and estuaries are better understood than nitrogen, and because effective change management options are available.[39]

There are also rural industrial sources of nutrient pollution. For example, it has been suggested that anecdotal evidence indicates that blast chemicals used in mining pits may be a source of nitrogen in dewatering discharge water in Goldfields salt lakes.[40]

Finally, chemicals applied to wetlands can contain nutrients. For example, organophosphate insecticides applied to wetlands in order to control midges have been implicated as a source of phosphorus in WA wetlands, while some fire retardants have been shown to increase the soluble nutrient load.[41]

The *Survey of urban nutrient inputs on the Swan Coastal Plain*[38] provides nutrient inputs rates of various land uses. Data compiled in the survey are shown in Figure 10 and Figure 11 for nitrogen and phosphorus respectively.

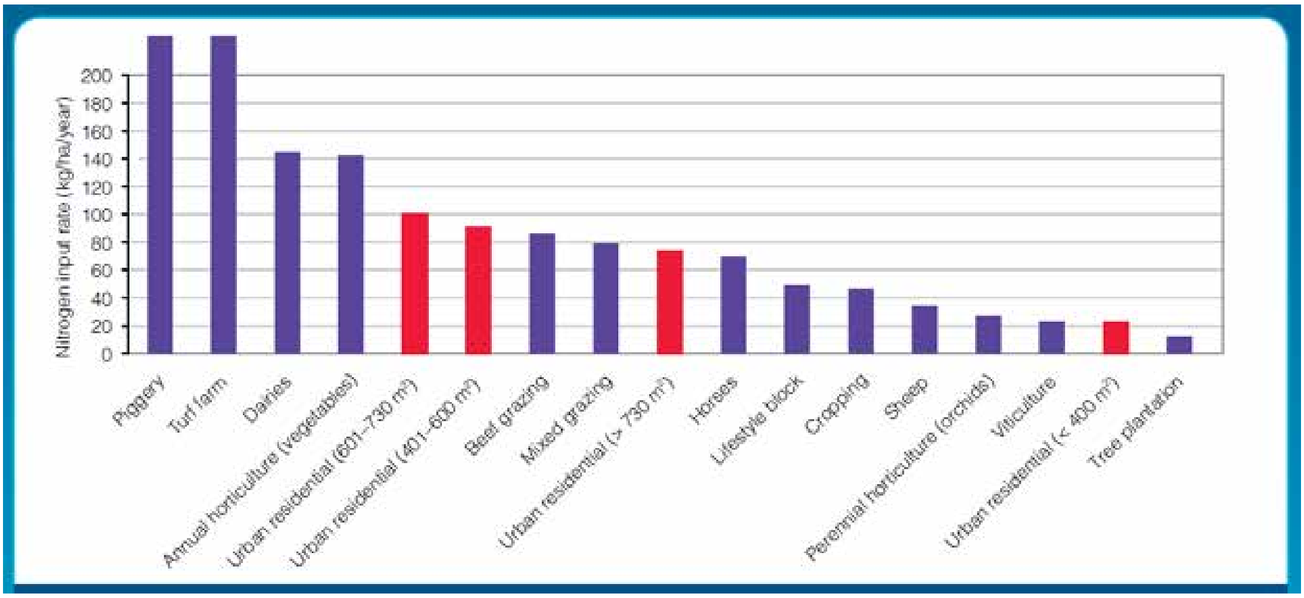


Figure 10. Total nitrogen input rates for rural and urban residential land uses ('piggery' inputs of 630 kg/ha/year and 'turf farm' of 433 kg/ha/year not fully displayed). Figure – Kelsey et al 2010.[38]

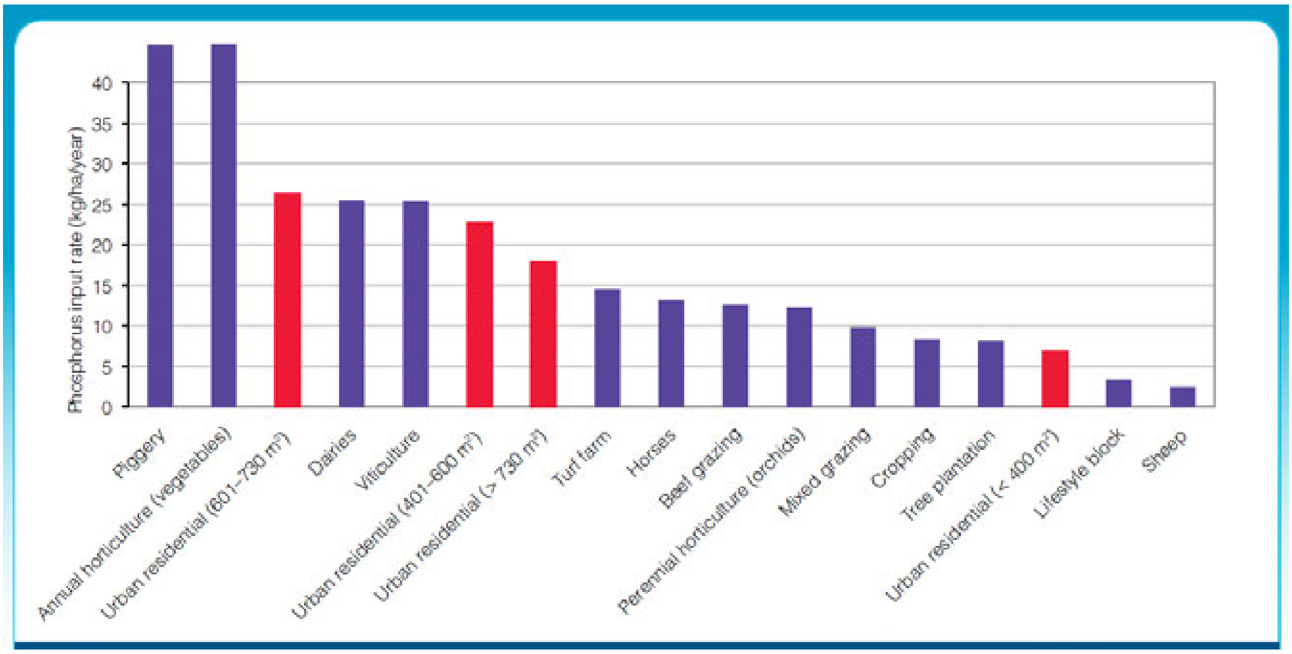


Figure 11. Total phosphorus input rates for rural and urban residential land uses ('piggery' inputs of 145 kg/ha/year and 'annual horticulture (vegetables)' of 130 kg/ha/year not fully displayed). Figure – Kelsey et al 2010.[38]

Loss of natural wetting and drying pattern

Wetting and drying on a seasonal or intermittent basis is a feature common to the majority of WA wetlands. However, human-induced changes means that many such wetlands are now permanently inundated, particularly those in urban environments in the south-west of the state. It can require investigations to determine whether this has occurred at a given wetland, especially when multiple changes occur in catchments, such as rising groundwater due to clearing, following by dropping groundwater levels due to water abstraction, as well as increased drainage inputs and drying due to climate change. Information on determining a wetland's natural hydrology is provided in the topics 'Wetland hydrology' in Chapter 2 and 'Managing hydrology' in Chapter 3.

Wetlands that naturally wet and dry do not tend to have severe problems associated with excess nutrients. The reasons for this vary, and include:

- In the south of the state, many seasonally inundated wetlands are dry during the hottest months of the year. Not having standing water during hot weather means that they are less susceptible to algal and cyanobacterial blooms, and blooms that do occur are likely to be for shorter periods of time (for example, as the water level drops and nutrients become concentrated prior to drying out).
- When sediments dry they are usually exposed to air. **Decomposition** is far more efficient in **aerobic** (oxygenated) conditions, meaning that decomposition processes are stimulated. This can result in more organic matter being removed as a potential energy store from the sediment and keeping the accumulation of organic matter in check.
- When wetland sediments are oxygenated, phosphorus tends to bond with iron and aluminium in the sediment, meaning there is less phosphorus available for plants, algae and bacteria. Similarly, when wetland sediments are oxygenated, nitrogen can be exported from wetlands as a gas, meaning there is less nitrogen available for plants, algae and bacteria. This point is explained further in the following paragraphs.

Sediments typically contain the largest proportion of nutrients in a wetland[15], compared to the proportions of nutrients present in the water column and in living things. However, sediments cannot indefinitely go on storing sediments, and at saturation will release nutrients into the water column. Alternatively, wetland sediments may release nutrients into the water column if conditions in the sediment pore water are suitable. This form of water column nutrient loading is known as 'internal loading' and can cause '**internal eutrophication**', and explains why high nutrient levels can persist in wetlands long after nutrient pollution has been minimised.

Human-induced changes to wetlands can promote the conditions that trigger nutrient release from the sediment. In particular, the conversion of naturally wetting and drying wetlands to permanently inundated wetlands has been linked with internal eutrophication. Many wetlands, particularly those in urban areas and the Wheatbelt, no longer have a 'dry' phase that was naturally part of their water regime. If sediments become permanently inundated, lower oxygen levels in the sediment pore waters and at the interface between the water column and the sediment pore waters may be sustained (Figure 12) and **anoxic** conditions may even occur. In contrast, wetlands that naturally have either a natural low water/partial drying phase that exposes more of the wetland soils or shallow water to air, or a dry phase with complete drying down, undergo changes to the chemical makeup of their sediment and water. These natural changes are largely driven by the greater amount of oxygen in the sediment pore water and/or the interface between the sediment and the water column, which drives changes in the redox potential.

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its physical breakdown. Also known as mineralisation.

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Internal eutrophication: eutrophication of wetland surface waters as a result of changes in water quality without additional external supply of nutrients[42]

Anoxic: deficiency or absence of oxygen

These changes typically result in more of the phosphorus being bound to iron in the sediment and therefore less available in the water column for algal and cyanobacterial overgrowth and blooms (particularly in wetlands that don't have much calcium present). The changes stimulated by drying also affect the nitrogen levels, with shallow water often promoting the loss of nitrogen in gaseous forms from wetlands.

When the naturally drying phase no longer occurs, less nitrogen may be exported from the wetland, and more of the nitrogen and phosphorus is likely to be present in the sediment pore waters and water column in a chemical form that is available to plants, algae and bacteria, stimulating increased growth and productivity. Beyond a certain point, this increased productivity may be in the form of blooms and weeds, which tends to reduce biodiversity and if sustained may result in a shift in the ecological character of the wetland.

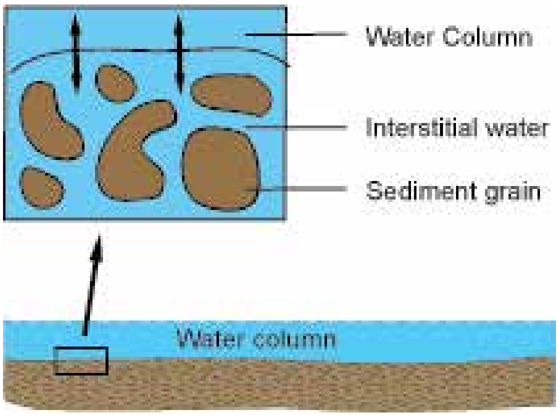


Figure 12. The very top of the sediment pore water, and the interface between the water column and the sediment pore water, is where a lot of chemical transformations take place. The dissolved oxygen levels in this zone are very influential. Oxygen is generally limited to the upper 10 millimetres.[42] Image – J Higbid/DEC.

extra information

The effect of wetting and drying on nutrients: a closer look

Phosphorus

Phosphorus has an affinity for calcium, iron and aluminium, and will bind with these elements when they are available, taking phosphorus out of the water column. Wetting and drying influences the extent to which iron and aluminium will bind with phosphorus.

In wetlands that experience inundation, when their water levels fall enough that there is shallow water and/or exposed sediments, much greater amounts of oxygen can reach the wetland sediment. The increase in oxygen creates more oxidising conditions, which promotes changes in the chemical form of iron present in the sediment. In these conditions, the chemical form that iron takes (ferric iron) significantly increases the ability of phosphorus to bind with it, via the processes of **adsorption** and **precipitation**. Through these processes, sediments can become a phosphorus sink. This is particularly relevant in wetlands with circumneutral or acidic conditions. In alkaline wetlands, the calcium concentration influences the precipitation of phosphorus, but this process isn't linked to wetting and drying.

In contrast, when wetlands are permanently inundated, the sediments are likely to have lower amounts of oxygen (plants are an important source of oxygen in these sediments, as they leak oxygen from their roots into an area of soil around the roots called the rhizosphere). As oxygen levels falls, conditions become more reducing and phosphorus desorption occurs: the chemical form iron takes (ferrous iron) does not bind with phosphorus and the formerly adsorbed phosphorus is released into sediment pore waters. Unless there is an oxidised soil layer above this, the phosphorus can diffuse into the water column.

extra information

The effect of wetting and drying on nutrients: a closer look (cont'd)

The solubility of oxygen declines as salt content increases, so secondary salinity (that is, human-induced salinity) can compound nutrient problems in affected wetlands. In saline wetlands, where there are greater concentrations of sulfur, another process is also significant: iron preferentially binds with sulfide over phosphorus.

Nitrogen

The changes stimulated by drying also affect the nitrogen levels, with oxygen availability associated with shallow water and exposed sediments often promoting the loss of nitrogen in gaseous form from freshwater wetlands through coupled **nitrification** (ammonium is converted to nitrate) and **denitrification** (nitrate is converted to nitrogen gas or nitrous oxide that can then leave the wetland) as well as ammonia volatilisation (ammonia is produced).

When the wetting-drying pattern is changed to permanent inundation and oxygen levels are low, levels of a form of nitrogen known as ammonia may build up to toxic levels. Ammonia is made up of nitrogen and hydrogen. Its chemical symbol is NH_3 (not to be confused with ammonium, NH_4^+). Its concentration increases with increasing pH. In high concentrations, ammonia is acutely toxic to invertebrates, frogs and fish.

Influencing factors

A range of factors heavily influence these processes. The extent to which they will occur in a particular wetland depends upon the interplay of many physico-chemical and biological factors in a wetland. These include the frequency with which wetting and drying occurs, the duration of each phase, the redox potential, iron, sulfur, aluminium, calcium, magnesium, salinity, pH, acid neutralising capacity and microbial processes, covered in detail in the topic 'Conditions in wetland waters' in Chapter 2.

Nitrification: the conversion of ammonia (NH_3) or ammonium (NH_4^+) to nitrate (NO_3^-) in freshwater wetlands under oxygenated conditions, facilitated by specialised bacteria, if conditions (pH, temperature, organic carbon availability) are suitable

Denitrification: the conversion of nitrate (NO_3^-) to elemental nitrogen (N_2) under deoxygenated conditions, facilitated by specialised bacteria

Sulfate-mediated eutrophication: eutrophication of wetland surface waters as a result of changes in water quality associated with sulfate rather than additional external supply of nutrients

Reinstating the natural wetting and drying cycle would seem the logical solution to this problem. However, drying of sediments that have long been inundated poses significant risks. Long-term inundation not only leads to the build up of nutrients; it can also lead to the build up of sulfides, which if exposed to air, can react to form harmful acids (actual acid sulfate soils)—an impact that can be much harder to mitigate than eutrophication. Any attempt to reinstate drying should be carried out carefully and with expert advice. More advice is provided below.

Release of sediment nutrients due to sulfate pollution

Sulfur is an important element in the environment, and is present in the atmosphere, soil and water as well as being present in organisms. Sulfur is naturally occurring in wetlands, with greater amounts present in saline wetlands; sulfur is one of the salts that contribute to salinity (for more information, see the 'Salinity' section in the topic 'Conditions in wetland waters' in Chapter 2).

Sulfur has a strong influence on phosphorus in wetlands. Phosphorus in the sediment is often bound to iron or aluminium in the sediment. If sulfur is added to a wetland, under the right conditions the sulfur, in the form of sulfate, can preferentially bind with the iron, releasing the phosphorus and making it available for cyanobacterial and algal use. This modification to the iron-phosphorous cycle is one form of '**sulfate-mediated eutrophication**'.

Sulfate pollution can greatly increase the release of phosphorus from the sediment, causing eutrophication. Human activities can significantly increase the amount of sulfur entering wetlands from the surrounding landscape and atmosphere. Sulfates are applied to catchments in fertilisers, causes include sulfate air pollution from the burning of fossil fuels; sulfates from industrial land uses entering via stormwater; acid mine drainage; rising saline groundwater and seawater intrusion. Under the right conditions, sulfate in the wetland can also be mobilised by other compounds.[42]

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between the layers

extra information

Other effects of sulfur in wetlands

Under the right conditions, sulfur in the form of sulfates can be converted to sulfides, which can also pose problems in wetlands. This process can result in increased anoxia (depletion of oxygen) in the wetland. The conversion to sulfides also enhances the methylation of mercury (commonly referred to as MeHg), which increases the toxicity and bioavailability of mercury in wetlands.[43] This is not well studied in WA but potentially has significant ecological implications. Research suggests that sulfate needs to be kept below 1 milligram per litre to manage this problem.

If sustained, concentrations of free sulfide may also accumulate in the sediment pore water to levels toxic to rooted submerged plants.[42] Elevated sulfides can change species composition and favour weeds. In Florida, *Typha domingensis* (native to areas of WA) has been found to have a higher tolerance to sulfide toxicity than many wetland plants, and in Florida it tends to invade wetlands where sulfate pollution is occurring.[44] It is possible that the introduced species of bulrush, *Typha orientalis*, is also tolerant due to similar physiological traits (hollow stems that efficiently transport oxygen to roots to detoxify the root zone). Internationally, some jurisdictions have established interim trigger values, such as Minnesota Department of Environment's interim value of 10 milligrams of sulfate per litre to protect an endangered wetland plant. In the absence of trigger values, it may be possible to determine locally appropriate levels using mesocosm experiments (for an example, see the journal article by Geurts et al 2009[45]).

Impacts

Impacts of excess nutrients include:

- algal and cyanobacterial blooms
- botulism
- poor health/death of native fauna
- smelly gases
- nuisance midge levels
- reduced biodiversity of native species
- increased weeds

These are described below.

Importantly, wetlands receiving the same amount of nutrients may not show the same impacts. The impact depends on a number of factors including the wetland's water hardness, salinity, colour, pH, and the extent to which resuspension, **stratification**, flushing and mixing occur. For this reason, characterising a wetland's water chemistry is recommended prior to identifying management strategies, as their effectiveness will vary.

For example, phosphorus has an affinity for calcium, and will often bind with it to form a precipitate, removing it from the water column. This process may reduce the eutrophication of calcareous wetlands (that is, wetlands with a lot of calcium, often in the form of calcium carbonate).

Algal and cyanobacterial blooms, smelly gases and nuisance midge levels

Algae and cyanobacteria are a natural part of wetland ecosystems and play an important role in food webs. The types that occur in WA and their natural ecological roles are described in the topic 'Wetland ecology' in Chapter 2. Algae and cyanobacteria obtain dissolved nutrients from the surrounding water. When they reach a certain density in the water column, algae and cyanobacteria are said to be in '**bloom**'. In many wetlands they will never form blooms, while in other wetlands they may bloom for a few days or weeks at times of the year as part of the normal wetland cycle without causing a problem. Although nutrients are necessary for the development of algal and cyanobacterial blooms, other factors such as their concentration, bioavailability, light availability, pH, degree of detention and stratification, salinity and temperature also influence the composition of the bloom[46] and competition and predation are also important. Data for Perth and surrounds indicates that high water temperatures (20–30 degrees celsius), high pH (8–10), calm water and low light intensity favour the development of cyanobacteria.[46]

Bloom: rapid, excessive growth, generally caused by high nutrient levels and favourable conditions

Benthic: the lowermost region of a wetland water column; the organisms inhabiting it are known as benthos

Some algae and cyanobacteria, such as species of green algae *Cladophora* and *Enteromorpha*, can significantly alter wetland ecosystems when in bloom proportions, forming extensive mats that cover the water surface, shading out and restricting growth of submerged aquatic plants and other algae below (Figure 13). Algae attached to the leaves of submerged aquatic plants can have a similar effect when in bloom proportions, by blocking out available light and preventing photosynthesis. If algal blooms are prolonged, submerged aquatic plants can die. **Benthic** blooms may also occur, covering large areas of sediments. Large scale detachment and drift of benthic cyanobacteria can occur, with masses of floating clumps potentially appearing similar to a surface bloom.

(a) (b)

Figure 13. Blooms can cover the entire water surface of wetlands, blocking light from reaching plants and animals below the water's surface; (a) constructed lake, Perth (b) Herdsman Lake, Herdsman. Photos – J Lawn.

Algal and cyanobacterial blooms eventually collapse. This may be due to the exhaustion of nutrient or oxygen supply, changes in water chemistry, or damage due to prolonged UV exposure of the individuals at the top of the water column. The spike of available algal or cyanobacterial material represents a massive food source for bacteria and animals that can cope with the bloom conditions, such as midge larvae. In consuming and decomposing the dead algae or cyanobacteria, these organisms use oxygen, to the extent that the decomposition of large blooms results in the depletion of oxygen from the water. The impacts of the anoxic conditions are two-fold: firstly, other life in wetlands are deprived of oxygen they need to survive, and secondly, they promote the release of nitrogen and phosphorus from the sediments, further 'feeding' algae and cyanobacteria populations.[47] The death of fish *en masse,* known as 'fish kills' is often due to oxygen falling below levels needed by fish; although other causes, such as diseases or toxins, may be to blame. It is thought that fish cannot survive less than 30 per cent oxygen saturation.[48] Anoxic conditions can lead to noxious odours due to the release of hydrogen sulfide and other compounds associated with changing chemical conditions. There may be discolouration of the water, such as white areas. Outbreaks of large populations of nuisance insects such as midges are also common, because midge larvae feed on live and dead algae and they are adapted to anoxic conditions.

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

➤ For additional details on midges see the topic 'Nuisance midges and mosquitoes' in Chapter 3.

These conditions can also be suitable for the build up of ammonia to toxic levels. Ammonia is made up of nitrogen and hydrogen. Its chemical symbol is NH_3 (not to be confused with ammonium, NH_4^+). Ammonia can be produced via the decomposition of **detritus** (specifically, via 'ammonification') and by dissimilatory ammonia production in sediments with low levels of oxygen. In high concentrations, ammonia is acutely toxic to invertebrates, frogs and fish. It is taken up by tadpoles and fish via their gills. Acute exposure may be lethal or sub-lethal, while chronic exposure can be sub-lethal. Several factors are known to affect the development and toxicity of ammonia, including pH, dissolved oxygen concentration, temperature, salinity and carbon dioxide concentrations. A pH of more than 9 can cause a shift from ammonium to ammonia.

➤ As a potential toxicant, trigger values for ammonia in wetlands is provided in Table 3.4.1 in Volume 1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* which needs to be cross-referenced with Table 8.3.6 in Volume 2 of the guidelines.[15,14]

Some cyanobacteria species produce toxins that can harm or kill plants, animals and algae. Cyanobacteria that produce these toxins include *Anabaena*, *Microcystis*, *Nodularia* and *Oscillatoria*. Toxins produced by cyanobacteria include neurotoxins (affecting the nervous system), hepatotoxins (affecting tissues and liver) and lipopolysaccharides (causing gastroenteritis).[46] Toxins can persist for more than three months before being degraded by sunlight and microbial activity.[49] In Australia, toxins have been implicated in the poisoning of native animals including kangaroos, rodents, amphibians, fish, bats, waterbirds and zooplankton, and reductions in dragonflies and aquatic beetles has also been attributed partially to toxins and partially to low oxygen levels.[50] Cows, sheep and goats are susceptible to toxins, and consuming as little as one cup of toxic water can cause death. They usually develop muscle tremors and start staggering within 30 minutes of drinking toxic water, and lie down and die with convulsions within 24 hours. Animals that survive develop liver damage, jaundice and photosensitisation.[49]

Exposure to cyanobacteria is linked to increased incidence of several neurodegenerative diseases. Recent research suggests that these toxins could be a contributing factor triggering a motor neuron disease, amyotrophic lateral sclerosis, in humans.[51] While it is likely that it is a multifactorial condition requiring several factors to come together to trigger disease, an analysis of New Hampshire in the United States tracked patients of the motor neurone disease to having lived by lakes or other bodies of water that were subject to frequent algal blooms.

➤ A summary of cyanobacterial toxins can be found in the document *Cyanobacteria: management and implications for water quality*.[52]

Figure 14. Black swans in Lake Monger, in the suburb of Leederville, with their undersides covered in unidentified algae/cyanobacteria. Photo – M Blythman/DEC.

Protecting humans and animals from toxic algae and cyanobacteria

If poisoning from algal or cyanobacterial blooms is suspected, the wetland should be closed off immediately from people, livestock and pets, and no water, fish, shellfish or other foods from the wetland should be consumed. If livestock or pets have been exposed, seek veterinary advice. People should seek medical advice without delay. Sick native birds or other native animals should be reported to the Wildcare Helpline on 08 9474 9055, which operates 24 hours a day. It may be appropriate to employ noise or visual disturbance to discourage birds from the wetland as a short-term option.

In the case of public lands, the responsible authority should be notified, for example, the local government authority, the land manager or relevant state government department. When an algal bloom of human health concern is detected at potentially harmful levels on public lands the Department of Health is advised and a public warning may be issued. Warning signs will be located in affected areas and messages may be broadcast on television, radio, in local or regional newspapers and on the Department's website (www.health.wa.gov.au/press/index.cfm). The Department of Health's Environmental Health Directorate can be contacted on 08 9388 4999 or by email: algalblooms@health.wa.gov.au.

Botulism

Outbreaks of the bacteria *Clostridium botulinum* are almost always associated with decomposing blooms and anoxic conditions in nutrient enriched wetlands. Inhabiting soil and sediments, spores of *C. botulinum* germinate in warm, anoxic conditions, producing a potent nerve toxin. If the toxin is ingested or wounds are exposed to it, birds, fish, frogs and mammals including humans can become very sick, and die. This form of bacterial poisoning is known as botulism, and more specifically avian botulism in bird populations (Figure 15). A cycle of infection can occur if birds ingest fly larvae that have absorbed the toxin from feeding on dead infected birds.[46] One outbreak at Toolibin Lake in 1993 caused the death of 450 birds[53], while an outbreak at Mary Carroll Park wetlands in Gosnells was reported to affect over 2000 birds.[54] Symptoms of botulism in birds are similar to symptoms of cyanobacterial poisoning and include inability to stand, fluffed out feathers and wings not crossed above the tail. Onset of paralysis renders birds unable to fly, instead propelling themselves across the water using their wings. In advanced cases, total paralysis and respiratory distress (gasping) may occur, followed by death.[46]

Although outbreaks of *C. botulinum* can occur at any time, temperature, oxygen and a suitable energy source are thought to be the factors that determine whether an outbreak of *C. botulinum* will occur. Outbreaks tend to be more severe in warm conditions, often between November and April. In wetlands, warm weather and anoxic conditions are optimal conditions for an outbreak, and this is why avian botulism is commonly associated with algal or cyanobacterial blooms. The spores of *C. botulinum* can lie dormant for many years, germinating and multiplying when conditions are right.[55]

Botulism in humans is generally food-borne rather than due to exposure from a wetland, and no cases have been reported in WA since it became a statutory notifiable infectious disease in 2001.[56]

Figure 15. Botulism is a serious consequence of algal blooms and can cause death of wetland fauna. Photo – D Mort/City of Rockingham.

Endemic: naturally occurring only in a restricted geographic area

Invertebrate: animal without a backbone

Protecting humans and animals from botulism

If botulism is suspected, the wetland should be closed off immediately from people, livestock and pets, and no water, fish, shellfish or other foods from the wetland should be consumed. If livestock or pets have been exposed, seek veterinary advice. People should seek medical advice without delay. Sick native birds or other native animals should be reported to the Wildcare Helpline on 08 9474 9055, which operates 24 hours a day. It may be appropriate to employ noise or visual disturbance to discourage birds from the wetland as a short-term option.

In the case of public lands, the responsible authority should be notified, for example, the local government authority, the land manager or relevant state government department. When botulism is detected at potentially harmful levels on public lands the Department of Health is advised and a public warning may be issued. Warning signs will be located in affected areas and messages may be broadcast on television, radio, in local or regional newspapers and on the Department's website (www.health.wa.gov.au/press/index.cfm). The Department of Health's Environmental Health Directorate can be contacted on 08 9388 4999 or by email: algalblooms@health.wa.gov.au.

Reduced biodiversity of native species, increased weeds

Plants, algae and cyanobacteria respond to nutrient enrichment in varying ways. In general terms, nutrient enrichment can increase the total biomass (growth and abundance) and change the species composition of plants, algae and cyanobacteria in a wetland, with winners and losers. Many important **endemic** wetland plants of a region that are adapted to low nutrient levels are likely to be losers. The highest diversity of wetland plant species is often found at intermediate dissolved nutrient levels. Significant nutrient enrichment of permanently inundated wetlands (lakes) typically results in the loss of submerged aquatic vegetation and substantial increases in algae and cyanobacteria.

Changes to plants and other primary producers can have profound effects on wetland animals, because primary producers can have such an influence on animal habitat, in terms of both its physical and chemical characteristics. **Invertebrates**, which play a key role in many wetland ecosystems, demonstrate the profound effects that nutrient enrichment can have on biodiversity. Moderately nutrient enriched wetlands in WA generally support the richest invertebrate fauna and the greatest number of rare species.[24,57] The increased productivity of plants and algae often fuels an increase in grazing and predatory invertebrates. In very nutrient enriched wetlands, there is an abundance of a few tolerant species. There tends to be a progressive disappearance of invertebrate species, leading to a decrease in species richness and ultimately the wetland is inhabited by very large numbers of the few tolerant invertebrate species.[24,57] These changes tend to have effects up the food chain, affecting larger animals.

Weeds that flourish in wetlands often have broad tolerance limits to nutrients, pH, salinity and hydrological regimes and many are 'disturbance opportunists', responding positively and rapidly to habitat disturbance. Elevated nutrient levels can favour weeds over native plant species. For example, a study carried out at four wetlands in Perth found that elevated sediment nutrient concentrations favoured the growth and reproduction of the introduced bulrush *Typha orientalis* over that of *Baumea articulata*[58], a sedge common to many wetlands of the south-west of the state. It has been suggested that the nutrient stripping ability of introduced bulrush is generally inferior to local species that grow in the same environment and are less seasonal in the growth cycle.[59] Weeds are able to respond to nutrient enrichment in all types of wetlands, including those with waterlogged soils. Elevated sulfides can also change species composition, and favour weeds. In Florida, *Typha domingensis* (native to areas of WA) has been found to have a higher tolerance to sulfide toxicity than many wetland plants, and in Florida it tends to invade wetlands where sulfate pollution is occurring. It is possible that the introduced species of bulrush, *T. orientalis*, is also tolerant due to similar physiological traits.

Macroalgae: algae large enough to be seen with the unaided eye

Microalgae: microscopic algae

Indicators

Indicators of excess nutrients include:

- algal and cyanobacterial blooms
- high nutrient levels in water
- high chlorophyll *a* levels

Algal and cyanobacterial blooms

It is important to distinguish between wetlands with normal levels of nutrients and algal growth and those that are eutrophic that have developed, or are at risk of developing serious algal blooms. As discussed previously, algae form an important component of wetland ecosystems and may become abundant at various times of the year as part of the normal wetland cycle. In contrast, rapid algal growth may occur in eutrophic conditions, more frequently and last longer than natural bloom cycles during warm weather (from late spring through to summer).

The most easily recognisable type of algal bloom in wetlands are filamentous green algae (a form of **macroalgae**), which looks like green slime comprised of individual strands or filaments. In the late stages of a bloom, it forms extensive mats covering the water surface, which may accumulate in shallow areas and on wetland banks where it can start to rot and produce noxious odours (Figure 16). Other types of blooms involving **microalgae** may appear as a coloured 'scum' on the water surface (Figure 17) or throughout the water column. Depending on the type of microalgae present, scums can appear green, blue-green, reddish, yellowish, orange or brown in colour.

extra information

Natural blooms and scums

Not all blooms and scums in wetlands are harmful and they may be a natural, seasonal feature such as naturally occurring oils and foams produced by harmless bacteria and algae or from breakdown of organic matter. Pollen that has accumulated in wetlands is often mistaken for an algal bloom. The *Scum book*[60] is an excellent, WA-produced resource providing a local guide to oils, foams and scums.

As a precaution, if any type of bloom or scum is present in wetlands, contact by both humans, pets and stock should be avoided. In the case of public lands, the responsible authority should be notified (for example, local government, the land manager or relevant State Government department). Where warranted, the Health Department may also be involved.

Figure 16. Filamentous green algal bloom. Photo - D Mort/City of Rockingham.

Figure 17. Some algal blooms appear as a 'scum' on the water surface. Photo – W Van Lieven/City of Gosnells.

extra information

When is a bloom officially a bloom?

Microalgal cell counts also provide a direct indicator of the presence and severity of algal blooms. When algal cells of a moderate to large size (greater than 15 to 20 microns (µm) in diameter) exceed 15,000 cells per millilitre of water, it is referred to as a bloom.[61] Smaller sized microscopic algae (less than 1 to 5 microns in diameter) are considered to be in bloom proportions at around 100,000 cells per millilitres[61]; they discolour the water at much higher densities. Cyanobacterial densities in excess of 15,000 cells per millilitre make the water unsafe for people to drink, and even densities of 500 to 2,000 cells per millilitre require action by water managers. These levels are a guideline only; detrimental impacts on wetlands, humans or animals may result from much lower densities, particularly if toxic species are present, in which densities as low as 5 cells per millilitre may pose a threat.[61]

The concentration of algal cells on the surface can vary during the day, and can be 20–50 times the 'integrated' density in calm conditions (an integrated sample is the combined sample from a range of depths in a water column). Measurement of microalgal counts in water samples taken from wetlands should be undertaken by a laboratory.

- Source: Water facts 6: *Algal blooms,* originally published by the Water and Rivers Commission in 1998, and available from the Department of Water website: www.water.wa.gov.au/PublicationStore/first/10085.pdf.

- Identification and cell count services are carried out by specialised laboratories, such as the Phytoplankton Ecology Unit of the Department of Water, various private industry and university specialists, for example, the algae and seagrass research group at Murdoch University. Identification is reliant upon the appropriate collection, storage and preservation of algae prior to its identification. The WA Herbarium and associated regional herbaria do not specialise in the identification of wetland algae and do not maintain wetland algae collections (marine algae collections are maintained).

Water nutrient levels

The absence of obvious symptoms of eutrophication, such as algal blooms, does not mean that a wetland is not eutrophic and therefore not at risk of developing blooms in the future. Water quality often declines over many years before catastrophic symptoms such as algal blooms appear.[61] Measuring nitrogen and phosphorus over time can provide insight into seasonal fluctuations and longer-term trends. Levels can be compared with those in Table 6.

Trophic: from the Greek word for 'feeding', it relates to food and nutrition

Trophic classification: the classification of an ecosystem on the basis of its productivity or nutrient enrichment. The three main trophic classes are oligotrophic, mesotrophic and eutrophic.

Limiting nutrient: the nutrient in an ecosystem which limits further growth because it is available at proportionately lower levels with respect to other nutrients needed for primary producers to increase their abundance

Table 6. Default trigger values relating to nutrient enrichment for slightly disturbed wetlands in WA, from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14]

Water Quality Parameter	Trigger Value Southwest Australia	Trigger Value Northwest Australia	Notes
Unit of measurement	Micrograms per litre, µg/L		d: higher values are indicative of tropical WA river pools
Total phosphorous	60	10-50 [d]	
Filterable reactive phosphate	30	5-25 [d]	
Total nitrogen	1500	350-1200 [d]	
Oxides of nitrogen (NO_x)	100	10	
Ammonium (NH_4^+)	40	10	

Measuring the total concentration of a nutrient (for example, total nitrogen or total phosphorus) can over-estimate the proportion of nutrients that are actually available for plant, algae or cyanobacterial growth at a point in time.[14] For example, total phosphorus is a measure of the dissolved and particulate forms of inorganic and organic forms of phosphorus in the water, including the bioavailable (soluble reactive phosphorus/ filterable reactive phosphorus/orthophosphate) and unavailable (or potentially available) forms. However, it can provide an understanding of the total 'pool' of these nutrients in the water that may become available under the right conditions, to guide long term management actions. Measuring the inorganic fraction of a nutrient, such as phosphate, nitrogen oxides (nitrate, nitrite) and ammonium provides an idea of what proportion of the total is available to plants, algae and cyanobacteria, although it too is a snapshot of a point in time. Measuring nutrients in the water column does not take into account nutrients stored in the sediments which can become available for plant and algal growth.

Determining the **trophic** status of wetlands can be useful in assessing nutrient levels and potential of algal blooms developing in the future. **Trophic classifications** are used to describe the amount of productivity (usually algal) or nutrient richness occurring within wetlands[62,63] and result in a wetland being identified as eutrophic, oligotrophic or mesotrophic. Of the many methods for determining the trophic classification of wetlands, the Pan American Center for Sanitary Engineering and Environmental Sciences criteria[64], known as CEPIS criteria, developed for warm-water tropical lakes are most often used for WA wetlands.[65] This system uses total phosphorus as the basis for classification. This is because phosphorus tends to be the main **limiting nutrient** in freshwater wetlands, so it is often what determines the presence and extent of algal blooms.[31] The mean and range (within two standard deviations) of annual mean total phosphorus concentrations are used to define trophic categories under the CEPIS scheme, shown in Table 7.

Table 7. CEPIS trophic state classification system based on total phosphorus[64]

	Oligotrophic	Mesotrophic	Eutrophic
Unit of measurement	Micrograms per litre, µg/L		
Mean (average) annual total phosphorus	21.3	39.6	118.7
Range ± 2 standard deviations	10–45	21–74	28–508

The term 'hypertrophic' is sometimes applied to those that are grossly enriched[46] while wetlands that have dark-coloured water from naturally occurring tannins and low pH are referred to as **dystrophic**.[46]

Dystrophic: a wetland that suppresses increased algal, cyanobacterial and plant growth even at high nutrient levels due to light inhibition

➤ For additional detail on nutrients in wetlands see the 'Nutrients' section of the topic 'Conditions in wetland waters' in Chapter 2.

➤ For information on taking wetland water quality samples, see the topic 'Monitoring wetlands' in Chapter 4.

Research conducted by the Cooperative Research Centre for Water Quality and Treatment resulted in the below findings about the nutrient concentrations required to sustain cyanobacterial growth.

Table 8. Nutrient concentrations limiting cyanobacterial growth as defined by the CRC for Water Quality and Treatment.[66]

Water Quality Parameter	Concentration	Application
Unit of measurement	Micrograms per litre, µg/L	
Filterable reactive phosphorus	Less than 10	Concentrations less than this are considered to be growth limiting
Soluble inorganic nitrogen	100	This concentration is considered to be the minimum required to maintain growth during the growing season

Chlorophyll *a*

Nutrient levels can also be indirectly assessed by measuring the concentration of chlorophyll present in the water column. Chlorophyll *a* is one of the pigments required for photosynthesis in plants, algae and cyanobacteria. Its concentration in a water sample is the best indicator of the growth response of the existing algal biomass in the water column. Very high chlorophyll *a* levels may indicate an algal or cyanobacterial bloom due to nutrient enrichment of the wetland. Concentration of chlorophyll *a* in samples taken from wetlands can be assessed against the trigger value for chlorophyll *a* for wetlands in the south-western or north-western Australia specified in the ANZECC guidelines. Measurement of chlorophyll *a* in water samples taken from wetlands should be undertaken by a laboratory.

Table 9. Default trigger values for chlorophyll ***a*** for slightly disturbed wetlands in WA, from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14]

Water Quality Parameter	Trigger Value Southwest Australia	Trigger Value Northwest Australia
Units of measurement	micrograms per litre, µg/L	
Chlorophyll *a*	30	10

➤ For information on sampling chlorophyll *a* in wetlands, see the topic 'Monitoring wetlands' in Chapter 4.

Managing nutrients, algal and cyanobacterial blooms

Table 10 provides a summary of the potential strategies for managing excess nutrients and associated blooms. They focus at one or more of three scales:

1. preventing the causes of poor water quality
2. intervention at the catchment scale
3. intervention at the wetland scale.

As outlined earlier, some strategies that may be considered suitable for artificial wetlands are not covered here. Similarly, strategies that may be viable in other countries but which have limited application in WA, such as lake flushing, are not covered.

Table 10. A summary of the main strategies that have been considered by wetland managers for managing excess nutrients in WA wetlands

Potential strategies
Preventing the causes of poor water quality
• reducing the amount of nutrients in the catchment
• reducing sulfate pollution
Intervention at the catchment scale
• stormwater treatment to reduce the amount of nutrients reaching the wetland
Intervention at the wetland scale
• not feeding waterbirds
• no-fertilising zones
• fencing out livestock and feral animals
• revegetating the wetland
• revegetating the dryland
• converting drains to overland flows
• aerating water
• eradicating introduced fish
• stopping/managing waterskiing, boating
• harvesting algae
• adding nutrient consuming bacteria
• adding bacteria-boosting enzymes
• remediating groundwater
• harvesting wetland plants
• reinstating the wetting and drying cycle
• diverting nutrient-laden inflows
• nutrient binding and sediment capping
• sealing the sediment
• removing sediments

Preventing nutrient enrichment: reducing the amount of nutrients in the catchment

Reducing the volume of nutrients entering wetlands is the most effective long-term strategy for preventing and managing nutrient enrichment and eutrophication. Intervention techniques, whether at the catchment or wetland scale, can be expensive, inefficient and require long term management.

Identifying the source of the nutrients is the first step to reducing nutrient inputs. This process may be relatively informal, based on a general understanding of the surrounding land uses. Figure 8, reproduced from the *Yellagonga Integrated Catchment Management*

Government action on fertilisers

The WA government has recognised the importance of preventing the causes of eutrophication in WA's wetlands, waterways and estuaries. In response, it has developed and enacted regulations that reduce the solubility of phosphorus in fertilisers: the Environmental Protection (Packaged Fertiliser) Regulations 2010 of the *Environmental Protection Act 1986*. The regulations are two-phased, with 2010 and 2013 cut-off dates for phasing out fertilisers with excess phosphorus.

It has also established the Fertiliser Partnership 2012–2016. This partnership between the State Government, the fertiliser industry, fertiliser user groups, and peak non-government organisations aims to foster a cooperative working relationship to reduce fertiliser nutrient loss to aquatic environments. This is described in more detail in the earlier section of this topic entitled 'Who is responsible for managing catchment water quality?'. The webpage for the Fertiliser Partnership 2012–2016 is www.fertiliserpartnership.agric.wa.gov.au

Plan 2009-2014, is an example of a concise spatial summary of land uses that can help identify and rate potential nutrient sources in a catchment. Alternatively more detailed studies of nutrient loadings and budget based on sampling and modelling of drains, groundwater and sediments in the catchment can be produced.

There are two potential sources of nutrients: the catchment and the wetland sediment (see the text box 'Determining the surface water catchment of your wetland' earlier in this topic for more guidance of the catchment extent). Gaining an understanding of the amount of nutrients coming into the wetland, and the amount of nutrients stored in the sediment, enables good decision making. If the nutrients are being internally recycled in the wetland, controlling catchment inputs alone will not always result in changes in condition. Sampling of sediment and sediment pore-water will indicate whether this is likely to be the case.

In terms of catchment sources of nutrients, an assessment of land use both immediately surrounding the wetland and within the wider catchment will assist in identifying existing and potential sources of nutrients. Sometimes it is historic, rather than current, land uses such as old landfill sites that are a large source of nutrients (often referred to as 'leachates'; in particular, nitrogen in the form of nitrate is very mobile and can leach from a site into the groundwater). This is the case in Bibra Lake, south of Perth, for instance, for which a 1998 study estimated that the nearby landfill contributed up 507 kilograms per year of phosphorus and 15,065 kilograms per year of nitrogen.[67] Where nutrients have been discharged into a wetland for a very long time or at very intense rates, the nutrient 'pool' in the sediment can form the main source of nutrients.

Depending on the severity of the problem, the complexity of nutrient sources and the values being threatened, the development of a nutrient balance or budget may be warranted. A nutrient balance quantifies the sources of nutrient inputs and outputs of a wetland. It typically accounts for the nutrients within the water column and the sediment, as well as incoming groundwater and surface water sources. Any areas of contamination, such as landfill within or adjacent to the wetland, are also accounted for. It is of most help in catchments with many current or historic land uses (such as landfill) which make identifying the relative contribution of different sources of nutrients a complex task. A nutrient balance should account for seasonal and longer-term fluctuations. The information in a nutrient balance can help wetland managers determine which management actions will have the most effect on nutrient levels.

The nutrient loading and dynamics of some riverine catchments are already well-studied and this information can be informative when developing a nutrient balance for wetlands in those catchments. For example:

- Avon River Basin: *Nutrient management for the Avon River Basin: A toolkit for managing nutrient loss to the environment from a range of land uses*[37]
- Peel Inlet and Harvey Estuary water quality improvement plan: www.fertiliserpartnership.agric.wa.gov.au/water-quality-improvement-plans; www.environment.gov.au/water/policy-programs/nwqms/wqip/wa/peel-harvey.html
- Swan Canning Estuary water quality improvement plan: www.fertiliserpartnership.agric.wa.gov.au/water-quality-improvement-plans; www.environment.gov.au/water/policy-programs/nwqms/wqip/wa/swan-canning.html
- Vasse Wonnerup and Geographe Bay water quality improvement plan: www.fertiliserpartnership.agric.wa.gov.au/water-quality-improvement-plans; www.environment.gov.au/water/policy-programs/nwqms/wqip/wa/swan-canning.html
- Leschenault water quality improvement plan: www.fertiliserpartnership.agric.wa.gov.au/water-quality-improvement-plans
- Hardy Inlet water quality improvement plan: www.fertiliserpartnership.agric.wa.gov.au/water-quality-improvement-plans

Once a better understanding of sources of nutrient input is gained, the best combination of preventative and intervention measures can be determined.

➤ For information on how to sample water for nutrients, see the ‘Monitoring wetlands’ topic in Chapter 4.

There are many ways to reduce the amount of nutrients being released into wetland catchments. The following strategies list some of the most pertinent methods, guidelines and contacts for assistance. The strategies are listed by type of catchment: urban or agricultural. Many peri-urban catchments will be able to use strategies from both groups.

Ways to reduce nutrient enrichment in urban catchments

Urban catchment **Strategy number 1: use fertilisers more efficiently and effectively in home gardens and lawns**	
Management actions	**How to**
Use low water solubility, slow release fertilisers instead of highly water soluble fertilisers.	A list of Fertilise Wise endorsed fertilisers is available from www.fertilisewise.com.au
Apply when plants are growing (in the south-west spring and early autumn (September–November; March–April).	
Water only as needed, to minimise leaching below plant roots.	See Water Corporation's water wise gardening tips: www.watercorporation.com.au
Use native plants, as they need less nutrients.	
Who to go to for assistance	
Great Gardens program.	http://greatgardens.info/
Associated benefits: reduced fertiliser use can significantly reduce costs.	

Urban catchment **Strategy number 2: use fertilisers more efficiently and effectively in parks and other maintained recreational areas**	
Management actions	**How to**
Develop a nutrient management plan or nutrient and irrigation management plan	*Nutrient and irrigation management plans* WQPN[68]
Use low water solubility, slow release fertilisers instead of highly water soluble fertilisers.	A list of Fertilise Wise endorsed fertilisers is available from www.fertilisewise.com.au
Use native plants, as they need less nutrients.	
Who to go to for assistance	
Industry training program Fertcare (Fertilizer Industry Federation of Australia and the Australian Fertiliser Services Association)	www.fertilizer.org.au
Turf managers: Fertilise Wise fertiliser training program.	www.fertilisewise.com.au www.fertilisewise.com.au/docs/ TurfTrainingAdvertGeneral.pdf
Associated benefits: reduced fertiliser use can significantly reduce costs.	

Urban catchment **Strategy number 3: contain point source nutrients on-site**	
Maintain best practice industry standards, including:	**How to**
Urban development industry water sensitive urban design develop using reticulated sewerage in sewerage-sensitive areas	New WAterways www.newwaterways.org.au
Nursery and garden centre industry	*Nurseries and garden centres* WQPN[69]
Light, general and heavy industry	*Industrial wastewater management and disposal* WQPN[70] *Light industry near sensitive waters* WQPN[71] *General and heavy industry near sensitive waters* WQPN[72] *Stormwater management at industrial sites* WQPN[73]
Building industry	'Construction practices' guidelines in Chapter 7, Section 2.1 of the *Stormwater Management Manual for Western Australia*[30]
Associated benefits: better on-site management can reduce costs, significantly improve compliance with regulations and lead to the recovery of resources.	

Ways to reduce nutrient enrichment in rural catchments

Rural catchment Strategy number 1: improve nutrient management in agricultural industries	
Management actions	**How to**
Develop a nutrient and irrigation management plan	*Nutrient and irrigation management plans* WQPN[68]
Develop a property plan	*Property planning manual for Western Australia*[74]
Maintain best practice industry standards, including:	
Irrigate and amend soil appropriately	*Irrigation with nutrient rich wastewater* WQPN[75] *Soil amendment using industrial by-products to improve land fertility* WQPN[76]
Dryland crop industry	*Agriculture - dry land crops near sensitive water resources* WQPN[77]
Floriculture industry	*Floriculture activities near sensitive water resources* WQPN[78]
Horticulture industry	*Best environmental management practices for environmentally sustainable vegetable and potato production in Western Australia: a reference manual*[79] *Code of practice for environmentally sustainable vegetable and potato production in Western Australia*[80]
Orchard industry	*Orchards near sensitive water resources* WQPN[81]
Turf industry	*Environmental guidelines for the establishment and maintenance of turf and grassed areas*[82]
Viticulture industry	*Environmental management guidelines for vineyards*[83] *Wineries and distilleries* WQPN[84]
Aquaculture industry	*Aquaculture* WQPN[85]
Animal industries	*Stockyards* WQPN[86]
Abattoir industry	*Rural abattoirs* WQPN[87]
Beef industry	*Guidelines for the environmental management of beef cattle feedlots in Western Australia*[88]
Dairy industry	*Dairy processing plants* WQPN[89] *Effluent management guidelines for dairy sheds*[90] *Effluent management guidelines for dairy processing plants*[91]
Horse industry	Environmental guidelines for horse facilities and activities[36]
Pastoral rangeland industry	*Pastoral activities within rangelands* WQPN[92]
Pig industry	*Environmental guidelines for new and existing piggeries*[93] *National Environmental Management Guidelines for Piggeries*[94]
Poultry industry	*Environmental code of practice for poultry farms in Western Australia*[95]
Associated benefits: cost effectiveness, compliance with environmental regulations, corporate citizenship.	
Who to go to for assistance	
Department of Agriculture www.agric.wa.gov.au Department of Water www.water.wa.gov.au Department of Environment and Conservation www.dec.wa.gov.au	
Relevant regulation	
Approval may be required to establish and operate an intensive animal industry. This may include a works approval, license or registration under the *Environmental Protection Act 1986.*	Department of Environment and Conservation

Rural catchment Strategy number 2: improve livestock management near wetlands and waterways	
Management actions	**How to**
Fence wetlands to significantly improve control of livestock in and near wetlands, and where possible, exclude livestock	'Livestock' topic, Chapter 3
Construct livestock crossings to improve control of livestock use of wetlands as water sources	'Livestock' topic, Chapter 3
Provide shade and livestock watering points away from wetlands and waterways	'Livestock' topic, Chapter 3
Associated benefits: Water quality is maintained for livestock use.	
Who to go to for assistance	
See the 'Livestock' topic, Chapter 3	

Preventing nutrient enrichment: reducing sulfate pollution

Sulfate pollution can be reduced by managing the sulfates being applied to catchments in fertilisers, in air pollution due to the burning of fossil fuels, sulfates from industrial land uses entering via stormwater, acid mine drainage, rising saline groundwater and seawater intrusion. Studies of the northern Everglades in Florida demonstrate that canals are a significant source of sulfate pollution for these wetlands.

Controlling fertiliser use has been identified as an important management measure internationally. There are no trigger values for sulfate; an appropriate trigger value will depend upon the wetland type. For example, inputs of less than 10 milligrams per litre of sulfate is estimated to be a suitable provisional target for managing the concentrations in Bassendean Dune wetlands on the Swan Coastal Plain. In the absence of trigger values, it may be possible to determine locally appropriate levels using mesocosm experiments (for an example, see the journal article by Geurts et al 2009[45]).

Catchment–scale intervention: stormwater treatment

Treating nutrients following their release in the catchment is a less effective and often much more expensive approach to managing nutrient levels than preventing them from being released in the first place. However they do play a role in managing nutrients, particularly combined with preventative measures. They are still far more effective long term measures than some forms of wetland-scale interventions.

Catchment-scale intervention measures include retrofitting or installing:

- conveyance systems (swales and buffer strips, bioretention systems, living streams)
- detention systems (detention areas and constructed wetlands)
- infiltration systems (soakwells, pervious pavement, infiltration trenches and basins)
- pollutant controls (sediment, litter and hydrocarbon controls)
- groundwater remediation downstream of significant nutrient sources, such as landfill (that is, redirection of groundwater to a stripping area for treatment).

➤ These intervention measures have been trialed and implemented in WA. Many can be viewed in person and there are a number of studies into their effectiveness at specific sites.

➤ Brochures with useful summaries of different intervention measures are available from the Department of Water's website: www.water.wa.gov.au/Managing+water/Urban+water/Water+Sensitive+Urban+Design+brochures/default.aspx#1

➤ Examples and detailed guidance on choosing and installing appropriate catchment intervention measures is provided in the Department of Water's *Stormwater Management Manual for Western Australia*[30], particularly 'Chapter 9: Structural controls'.

➤ Additional design guidance and information on trials on the effectiveness of bioretention systems and constructed wetlands is provided by the Swan River Trust:

- *Manley Street bio-retention system assessment*[96]
- *Constructed ephemeral wetlands on the Swan Coastal Plain: the design process*[97]

Catchment-scale intervention measures in urban areas need to be developed in liaison with relevant authorities, including the local government and the Department of Water. In the coming years, local investigations are likely to generate greater understanding of the efficiency of many of these intervention measures, which will aid developers and catchment management stakeholders in determining the most useful measures for a particular site.

Wetland scale intervention: managing nutrients

Wetland-scale management measures may vary between wetlands depending on a range of factors such as source(s) of nutrients, mode of entry into wetlands (for example, via surface or groundwater flows or other means), wetland shape and hydrology, climate and other factors that may influence how and when nutrients enter the wetland. Often, a combination of strategies may be required to achieve a reduction in nutrient levels, leading to improved water quality in the long term.

Reducing nutrient inputs into wetlands at the catchment scale, through prevention and intervention measures, is the most effective long-term strategy for preventing and managing the impacts of eutrophication, such as algal blooms. At the wetland scale, the most effective strategy is to increase the proportion of nutrients that are 'sequestered' (retained) within plants and the sediment in the long term, in order to reduce the proportion that is available for cyanobacteria, algae and weeds. Localised, short term measures, such as physical removal of excess algae or dredging nutrient-laden sediments from wetlands, may potentially reduce symptoms but fail to address the cause and thus prevent algal blooms from occurring in the future. The consequence of managing symptoms in isolation is that management actions will need to continue indefinitely as long as nutrient inputs remain the same or increase.

The techniques below do not include interventions that may potentially be applied to wetlands of low conservation value or to constructed wetlands, such as bioretention systems requiring earthworks and using materials such as cracked pea gravel, sand-sawdust mixes and zeolites (aluminosilicate minerals). These may be suitable for use upgradient of the wetland in order to improve water quality reaching the wetland, and are addressed under the previous section 'Catchment-scale intervention: stormwater treatment'.

Table 11 lists the wetland-scale techniques for managing nutrients presented in this topic.

Table 11. Wetland-scale nutrient management techniques, grouped and colour-coded according to their potential risk of unintended ecological effects.

✓ Typically low risk	
No feeding of waterbirds	Converting drains to overland flows
No-fertilising zones	Aerating the water
Fencing out livestock, feral animals	Eradicating introduced fish
Increasing wetland vegetation	Reducing/managing waterskiing, boating
Increasing dryland vegetation	Harvesting algae/cyanobacteria scums
✓ to ✗ Low to high risk	
Harvesting wetland plants	Reinstating natural wetting and drying
Diverting nutrient-laden inflows	
? Unassessed risk	**✗ Potentially high risk**
Remediating groundwater	Removing sediments
Adding nutrient-consuming bacteria	Nutrient inactivation, binding and sediment capping
Adding bacteria-boosting enzymes	Sediment sealing

No feeding of waterbirds

✓ Low risk

Preventing people from feeding waterbirds is an easy and cost-effective measure for reducing nutrients in wetlands. It can be achieved through a combination of public awareness campaigns and, preferably as last resort, enforcement of legislation such as local government authority by-laws. As well as reducing nutrient sources, stopping of bird feeding can also improve waterbird health.

No-fertilising zones around wetlands

✓ Low risk

No-fertilising zones around wetlands are an easy and cost-effective measure. No-fertilising zones work well with another low-risk strategy, dryland revegetation. Many local governments have formally designated no-fertilising zones in many public areas.

Fencing out livestock and feral animals

✓ Low risk

Fencing out livestock and other introduced animals such as cattle, sheep, horses and feral pigs prevents them from defecating and urinating in wetlands, compacting and eroding soils by overgrazing and creating direct damage from pugging, rooting, digging, burrowing or wallowing.

➤ A wide variety of techniques to minimise the impacts of livestock on wetlands are provided in the topic ‘Livestock’ in Chapter 3.

➤ Techniques to control and eradicate feral animals from wetlands are outlined in the topic ‘Introduced and nuisance animals’ in Chapter 3.

Increasing the amount of native vegetation in the wetland

✓ Often low risk, but can be a risk if wetland acidification may be an issue

There are three constraints to cyanobacteria in the water column: light, nutrients and temperature. Plants can effectively alter the conditions in a wetland so as to favour plant growth and reduce the suitability of conditions for algae and cyanobacteria. To differing degrees, plants can:

- compete with algae and cyanobacteria for nutrients and light
- increase shading
- reduce water temperature
- reduce turbidity
- increase oxygen in the sediment, which leads to phosphorus binding to sediment
- increase coloured dissolved organic matter in the water
- provide habitat for zooplankton such as the microcrustacean *Daphnia* that consumes some species of algae and cyanobacteria.

Regeneration can be used to increase the amount of native vegetation in wetlands. Regeneration occurs when natural processes of regrowth and recruitment of plants take place. Wetland managers can aid this process by weeding and reducing disturbances. Where regeneration/assisted regeneration is not possible, revegetation may be appropriate (for example, planting).

➤ Wetland vegetation management, including assisted regeneration and revegetation, are described in the topic 'Managing wetland vegetation' in Chapter 3.

Considerations

- Plants in growth phase take up nutrients. Some plants such as rushes and sedges and some submerged plants can act as nutrient 'sponges'. When nutrient availability is high, they are capable of taking up more nutrients than they need for current growth and storing them for future growth. The name of this process is '**luxury uptake'** (or luxury consumption). They can also internally recycle nutrients by withdrawing them from senescing leaves and stems for use in new growth.[98] This recycling ability also allows them to survive in naturally low nutrient level conditions. Trees provide long-term storage of nutrients while herbs have shorter life cycles and their nutrients are returned to the system more rapidly.
- Plants that can supply oxygen from their roots to the surrounding sediment can help retain phosphorus in the sediment (it bonds with iron in these conditions). Some plants are better at this than others. Plants known to do this include *Typha domingensis*, *Eleocharis sphacelata*, *Schoenoplectus validus, Baumea articulata* and *Cyperus involucratus*.[99]
- Aerobic bacteria also take up nutrients. Plants such as rushes and sedges provide habitat for bacteria, fungi and algae that grow on them as **biofilms**. Plants also support aerobic bacteria living in the sediment by leaking oxygen into the sediment around their roots (the 'rhizosphere').
- In addition to taking up nutrients, many plants, and particularly woody plants such as species of *Melaleuca* and *Eucalyptus,* produce tannins, which are thought to help reduce the incidence of blooms in freshwater wetlands. Tannins (a high molecular weight **polyphenol**) are dissolved organic materials derived from plant material. They impart a dark colour that are said to 'stain' or 'colour' the water. Water that is a yellow or tea colour is usually a product of tannins. These dissolved organic materials are thought to suppress algae and cyanobacterial growth. For more information see the topic 'Conditions in wetland waters' in Chapter 2.
- Because of the wide range of ecological roles wetland plants fulfill, wetland revegetation can improve many facets of water quality, not just nutrient reduction, as well as improve habitat and overall wetland condition.

Luxury uptake: the process by which some organisms take up more nutrients than they need for current growth, instead storing them for future growth

Biofilm: bacteria, microalgae, fungi and unicellular microorganisms enmeshed in a hydrated mucopolysaccharide secretion that sequesters ions and isolates microorganisms from the water column.[101] May be present on living and non-living surfaces and substrates.

Phenol: complex organic compounds derived from plant materials

- Very reductive sediments may prevent germination of seeds present in seed beds[42] (for more information on reductive soils, see the section on 'redox' in the topic 'Conditions in wetland waters' in Chapter 2). Similarly, the levels of phosphorus in extremely nutrient-enriched soils are toxic to some dryland species (for example, *Banksias*), and this may also be the case for some wetland species.
- In highly turbid conditions that algal and cyanobacterial blooms can create, submerged wetland plants may struggle to establish because the turbidity can stop light from reaching them, prevent them from photosynthesising (for more information, see the section 'Light availability' in the topic 'Conditions in wetland waters' in Chapter 2). It may be necessary to initially plant species that grow in the waterlogged zone, or emergent species such as rushes and sedges that won't be outcompeted by the algae and cyanobacteria.
- Trees and to a lesser extent shrubs can require considerable amounts of water for transpiration. A high density of trees may result in the use of a large amount of wetland water. Unless water levels are unnaturally high, this may pose a threat to the life within the wetland, arising from a reduction of water needed by organisms, and from the possible exposure of acid sulfate soils in the wetland due to lowered water levels. If this is a possibility, the use of wetland vegetation with a lower water use should be considered, for example, sedges and rushes. See the 'Managing acidification' section for more information on these soils, and the topic 'Managing hydrology' in Chapter 3 for more information on water use of trees in wetlands.
- Increasing salinity may affect a plant's ability to take up nutrients. For example, sodium may inhibit a plant's ability to take up ammonium.[100]

Increasing the amount of vegetation in dryland areas adjacent to wetlands

✓ Often low risk, but can be a risk if wetland acidification may be an issue

Regeneration can be used to increase the amount of native vegetation on lands surrounding wetlands. Native vegetation helps to maintain wetland water regimes and removes surface and groundwater nutrients. These vegetated zones may be included as part of the wetland buffer that assist in maintaining the natural character of a wetland. Where regeneration/assisted regeneration is not possible, revegetation may be appropriate.

➤ The process for formally designating dryland buffers to wetlands (that is, through government planning and environmental processes) is outlined in the *Draft Guideline for the determination of wetland buffer requirements* (DoP and DEC 2010).[102] Once finalised, the guideline will be available from the 'Wetlands' webpage of DEC's website: www.dec.wa.gov.au/wetlands.

Considerations

- If revegetation is necessary, planting/seeding using native species of local provenance is recommended. Planting non-native species can create additional water quality problems and change the ecological character of the wetland. For example, some deciduous trees can drop all of their leaves in short time period, and these soft leaves can create a 'spike' in nutrient levels entering wetlands.
- In addition to helping to take up nutrients, areas of native vegetation around wetlands provide habitat for wetland species such as turtles, frogs and birds. The vegetation contributes carbon and tannins to the wetland. It also helps to

moderate the speed and volume of overland flows and wind turbulence, reducing scouring, erosion, sedimentation and turbidity.

- Adding non-native grassed areas is not recommended. Grass maintenance can contribute to excess nutrient problems due to the fertilisation and mowing regimes, especially when lawn clippings reach the wetland (ride on mowers do not have the ability to catch lawn clippings). Short grass is also a poor habitat for native species such as turtles, frogs and bandicoots, as it provides relatively little cover or food.
- Trees and to a lesser extent shrubs can require considerable amounts of water for transpiration. A high density of trees may result in the use of a large amount of water that would otherwise 'feed' the wetland. Unless wetland water levels are unnaturally high, this may pose a threat to the life within the wetland, arising from a reduction of water needed by organisms, and from the possible exposure of acid sulfate soils in the wetland due to lowered water levels. If this is a possibility, the use of lower-water use species should be considered. See the 'Managing acidification' section for more information on these soils, and the topic 'Managing hydrology' in Chapter 3 for more information on water use of trees in wetlands.

Converting drains into overland flows through adjacent dryland vegetation

✓ Low risk

Drains that flow directly into wetlands bypass most of nature's nutrient-stripping methods. Drains can deliver high loads of nutrients to wetlands in single rainfall events, creating a massive 'pulse' in nutrients that can outstrip or even unbalance a wetland's natural nutrient management processes such as plant uptake and sedimentation.

Converting drains to overland flows prior to entering wetlands can address this. Overland flows through vegetation essentially recreate natural flow paths to wetlands. This form of runoff is described as 'sheet flow' compared with the channelised flow in drains, and works by distributing water across the landscape to a shallow depth only. The vegetation slows flows, enabling greater infiltration; and traps sediment and takes up nutrients. Stormwater managers describe this technique as 'disconnecting' receiving environments such as wetlands from pollution sources.

Overland flow through adjacent dryland vegetation is generally considered to be appropriate for WA wetlands. In contrast, the construction of new pipes or constructed stormwater channels into wetlands, especially those of conservation significance, is not supported. This position has been published in the *Decision process for stormwater management in WA*.[30] A range of other government documents support this approach, and encourage the replacement of inappropriate drainage facilities, for example, *Guidance Statement No. 33: Environmental Guidance for Planning and Development.*[28]

Converting drains to overland flows requires sound engineering design and approvals from relevant decision making authorities.

Considerations

- Drains can protect infrastructure such as roads and buildings from water damage such as flooding and waterlogging. It is important to ensure that the upstream environment is not at risk when converting drains to overland flows. This can be achieved with sound design, construction, monitoring and possibly maintenance.
- Disconnecting drains from wetlands also has the added benefit of reducing the potential for other contaminants to be conveyed directly to the wetland. For example, illegal dumping of unwanted chemicals, or accidental spills from petrol

tankers, industry and so on.

- Drains can present a range of safety hazards, as well as ongoing maintenance costs, so a full cost/benefit analysis may demonstrate that their conversion can have multiple environmental, social and economic advantages to landholders and the community.
- Overland flow through the dryland buffers can improve the condition of the buffer vegetation by reinstating or more closely imitating the natural water regime.

Aerating water

✓ Low risk, but requires sound design

Water aeration is the addition of oxygen to the water column of a wetland. The addition of oxygen works to reduce the incidence and severity of algal and cyanobacterial blooms in a number of ways.

Oxygen stimulates efficient decomposition of organic matter by aerobic bacteria and fungi, which reduces the energy store. Oxygen also helps to either export or bind nutrients in unavailable forms. It promotes the conditions needed to export nitrogen from wetlands as either the mobile nitrate form which can leach to groundwater under the right conditions, or in gaseous form which can diffuse to the atmosphere. Similarly in non-calcareous wetlands it promotes the conditions needed for phosphorus to bind with the sediment and in doing so, becoming unavailable for uptake by algae or cyanobacteria. In more technical terms, reduced ferrous iron becomes oxidised to ferric iron, which causes phosphate to bind with it, reducing phosphorus availability. Ammonium, a form of nitrogen, gets converted to nitrate, which is lost more easily from wetlands through leaching of groundwater and conversion to nitrogen gas via the process of denitrification. Finally, volatilisation of ammonia to the atmosphere is promoted. These processes are explained in the topic 'Conditions in wetland waters' in Chapter 2.

Adding oxygen may also help to physically mix layers that have developed in the water column that can promote low-oxygen conditions in deeper layers.

Additionally, because still water favours the development of cyanobacterial blooms, the agitation of the water column can also help reduce the risk of cyanobacterial blooms.

Aeration can be achieved by installing commercially available mechanical devices known as aerators, such as specially designed paddles or rotors, curtains of bubbles rising from near the bottom of the water column (bubblers, bubble plumes), and jets of water spraying into the air using waterfalls, fountains etc (Figure 28). Subsurface aeration employing fine bubbles is often effective because it adds oxygen and creates a moderate amount of mixing throughout the water column. Aeration using curtains of bubbles is likely to generate the least disturbance to sediment and fauna while enabling aeration and mixing. Recirculation systems may also be employed, achieving aeration by pumping low oxygen water out of the wetland, adding oxygen to it, and then returning it to the bottom of the water column, without disturbing sediments. This approach has been used in the Swan and Canning Rivers, using oxygenation plants on the bank of the Canning River and a mobile barge unit on the Swan River.

Considerations

- Bigger is not automatically better – systems that create a lot of surface or sub-surface disturbance in wetlands do not mimic natural conditions and pose a number of problems to natural wetland ecosystems.
- The presence of sulfidic sediment should be investigated prior to undertaking an aeration or oxygenation project due to the potential acidification that can occur

when these sediments are exposed to oxygen.[30] For guidance, see the following section of this topic, entitled 'Managing acidification'.

- Care should be taken to avoid aeration that involves the disturbance of sediments. Sediments stirred up by aeration rapidly remove dissolved oxygen, because dissolved oxygen is consumed by processes in the sediments.[31] Oxygen should not be pumped into the sediment itself.
- Aeration systems must be appropriate for the purpose and maintained to specifications to ensure that they do not pose a safety hazard and continue to operate efficiently and effectively.
- The water columns of most inundated wetlands in WA is less than 5 metres. In general, when employing bubble plumes in these wetlands, the individual air flow rates of the plumes must be very small to maintain efficiency.[52]
- The destratification of naturally stratified wetlands is not desirable. The aeration of naturally stratified water columns should be designed to replenish dissolved oxygen to address the deficit, while preserving stratification. If destratification occurs, nutrient-rich waters may be brought closer to the surface and stimulate algal growth.
- Many sedges are natural sediment aeration units. Many use internal spaces and pressurised gas flow to transport oxygen to their roots, and in the process some of this oxygen leaks into the sediment. This is why revegetation can be a good technique to couple with aeration.
- It is possible that aeration systems may affect the behaviour of fauna, with the potential for some fauna to be attracted to the area and some to be deterred from the area. It is also possible for chemical changes to have adverse impacts, for example, supersaturation can cause gas bubble disease in fish, which can be fatal.[31] Disruption of the water surface may reduce habitat for those invertebrates that inhabit the water surface and rely on surface tension, such as many of the true bugs (of the Order Hemiptera). However, aeration is unlikely to affect the entire water surface of a wetland. These issues should be accounted for when choosing the aeration system and, particularly if the wetland is important habitat for a fauna species, it may be important to monitor fauna to determine any effects.
- Aeration typically involves both capital costs to design and install infrastructure and ongoing expenditure to operate and maintain infrastructure.

Removing introduced fish

✓ Low risk

Mosquito fish (*Gambusia holbrooki*) (Figure 18) prey on water fleas (*Daphnia carinata*), an aquatic invertebrate that in turn feeds primarily on algae. Some species of *Daphnia* will eat cyanobacteria, which are unpalatable to many predators. In this way, the predation of water fleas by mosquitofish can increase the potential for algal blooms in a wetland.

In addition, European carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*) vigorously stir up sediment while feeding, which can release phosphorus stored in the sediments.[103] Goldfish have also been found to stimulate the growth of some toxic cyanobacteria species that pass through their gut, such as *Microcystis aeruginosa*.[104] Under the right conditions species such as *Microcystis* can form blooms which can cause significant ecological impacts in wetlands. An increase in cyanobacteria can in turn provide goldfish with an abundant food source, creating the potential for an ongoing cycle of ecological impacts. Researchers found this to be an issue of significant concern for the Vasse River in the south-west of WA.[105]

➤ Introduced fish control and eradication techniques are outlined in the topic 'Introduced and nuisance animals' in Chapter 3. A case study of introduced fish control to improve water quality in a Perth wetland is included in this topic.

Figure 18. Eradicating the introduced mosquito fish, *Gambusia holbrooki,* can help to improve wetland water quality. Photo – C Lawrence/Department of Fisheries.

Reduce/manage boating, waterskiing

✓ Low risk

Engine-powered boating and water-skiing disturbs sediments and creates wash on the water's edge, which can reduce the suitability of conditions for plant establishment and growth. Furthermore by disturbing sediments, these activities can re-suspend nutrients in the water column. In addition, in order to access wetlands with water-skis and boats, vegetation clearing may occur, which further reduces the nutrient-stripping ability of the wetland. Access via unsealed entry points can also result in erosion and increased siltation of wetlands.

Harvesting surface scums of wetland algae, cyanobacteria

✓ Low risk

Some species of cyanobacteria form surface scums, for example, *Microcystis*, *Anabaena* and *Aphanizomenon*. They possess gas vacuoles that allow them to move up or down in the water column over the course of 24 hours to make the best use of sunlight to photosynthesise in the upper water column as well as to access nutrients present lower in the water column, and to avoid constant UV radiation. In suitable densities, it can be possible to harvest these scums, as well as dislodged, floating clumps of benthic cyanobacterial mats.

Manual harvesting may be carried out using rakes or skimmers. Oil-spill booms and skimmers have been used to remove surface cyanobacteria in wetlands and on the Swan River in Perth where in 2000, over 900 tonnes of *Microcystis aeruginosa* were removed and safely disposed using sewage treatment facilities.[106]

Considerations

- The personal safety of the people harvesting algae or cyanobacteria is a priority. A full risk assessment should be taken to avoid health issues arising from exposure to toxic algae, cyanobacteria or bacteria (for example, botulism from *Clostridium botulinum*).

- The disposal of the cyanobacteria should be to an appropriate waste disposal facility. This needs to be determined in advance of the harvesting.
- Optimal removal is likely to be in calm conditions in the early morning when cyanobacteria have migrated to the top of the water column.

Adding nutrient-consuming bacteria

? Unassessed risk

Nutrient-consuming bacteria can be added to a wetland in order to reduce nutrients available for algae and cyanobacteria. This technique has been used in highly degraded wetlands in the Perth metropolitan region.

Considerations

- Bacteria are ubiquitous and can naturally repopulate a wetland. This method seeks to rapidly repopulate a wetland. However, if the depletion of bacteria is due to unsuitable conditions in a wetland, and those conditions persist, this method will not be suitable.

Adding bacteria-boosting enzymes

? Unassessed risk

Enzymes are biological molecules (proteins) that catalyse (initiate and increase the rate of) biological chemical reactions. They can be specifically designed and manufactured for a wide range of purposes. The manufacture and addition of specifically designed enzymes to water may result in increased bacterial uptake of nutrients. Commercially available products are sold for this purpose in Western Australia. DEC has not assessed the effectiveness or ecological risk of these products, but notes the following considerations.

Considerations

- Bacteria use the enzymes, meaning that the treatment will need to be repeated over time to address nutrient levels.
- Some products marketed for the purpose of nutrient reduction in wetlands contain surfactants. Some surfactants are harmful to wetland organisms such as frogs.
- Wetlands with large volumes of water will require large doses of enzymes. This can be expensive in terms of cost and labour.
- Like all products, application must be in accordance with the instructions for use and the material safety data sheet (MSDS).
- Enzymes are reported to be more cost-effective than bacteria broadcasting.[30]

Groundwater remediation

? Unassessed risk

Intercepting and treating groundwater prior to it entering a wetland is a fairly new technique. Proposed methods include creating a trench up-gradient of a wetland along its groundwater capture zone and filling the trench with phosphorus-binding material. Suggested materials include crushed pea gravel or a soil-Phoslock®™ combination (for more information on Phoslock®™ see the 'sediment capping' section below).

Considerations

- There are relatively few examples of how this works in practice.
- It is a medium term option, as the material in the trench will eventually become saturated with phosphorus. After this time, the material will need to be replaced.

Harvesting wetland plants (natives and weeds)

✓ to 🎖 Risk ranges from low to high

Harvesting is the removal of some or all parts of a plant. Under the right circumstances, the harvesting of wetland plants may reduce the nutrient levels in wetlands by exporting the nitrogen and phosphorus stored in some plants. Some sedges, for example, employ 'luxury uptake', which is the ability to take up and store more nutrients than they need. Harvesting may be manual or mechanical, with manual forms generally having a much lower impact on wetlands.

In considering plant harvesting, it is important to ensure that natural vegetation will be maintained in the wetland and its surrounds so that natural ecological processes are maintained. Any harvesting program should be supported by a clear understanding of the role of the vegetation and its capacity to regenerate after harvest.

In wetlands where acidification may potentially occur, removing wetland plants removes a source of carbon that can help mitigate acidification. In these wetlands, weeds should not be removed; while they can still be controlled, for example, through crushing of *Typha orientalis*, they should be left in-situ rather than harvested. Although this does not address the nutrient load within these weeds, it is a more manageable issue than a highly acidic wetland. For more information, see the 'Managing acidification' section later in this topic.

Legal authorisation is required

The harvesting of native plants, whether dead or alive, is with few exceptions a form of clearing as defined by the *Environmental Protection Act 1986* and as such is subject to the Act and the Environmental Protection (Clearing of Native Vegetation) Regulations 2004. Native plants are also protected flora under the *Wildlife Conservation Act 1950*, and a licence is required to take such plants from Crown lands. For more information, see the topic 'Legislation and policy' in Chapter 5 or the native vegetation legislation and flora licensing webpages of DEC's website www.dec.wa.gov.au.

Native species

Considerations

- Because of the significant ecological roles of plants in wetlands, the harvesting of all plants should be planned and carried out with due care, but especially the harvesting of native plants.
- During the planning phase, it is important to ensure that the plant material does not provide important fauna breeding habitat.
- Methods involving the removal of below-ground parts can have a detrimental effect on the sediment and should be avoided if possible.
- Floating plants (such as duckweed, a species of *Lemna* in WA's south-west) may be logistically easier to harvest with little disturbance to sediment.
- Plants compete with algae for nutrients. When harvesting plants, it is important not to alter the conditions that favour plants over algae. For example, clear water favour plants while turbid water conditions favour algae. Plants promote

clear water by physically increasing sedimentation and reducing resuspension of sediments. If all the plants are removed, or the harvesting process overly disturbs the sediment, the sediments may become much more susceptible to suspension, providing a competitive advantage to algae (Figure 19).

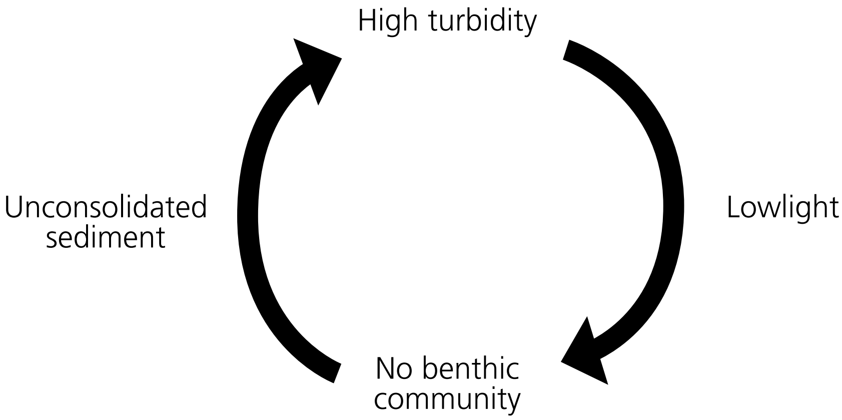


Figure 19. Feedback loop promoting turbid conditions in wetlands.

- Repeated removal of a portion of a plant's above-ground plant material over time is a relatively low-impact way of gradually removing nutrients from the wetland. For example, harvesting of sedges by removing a portion of their stem (but remaining above the waterline so as not to 'drown' them) enables them to continue to photosynthesise, thereby taking up more nutrients in order to fuel their growth.

Wetland weeds

Harvesting of wetland weeds can provide dual benefits of removing nutrients and reducing the current and future impact of those weeds on the wetland. This is particularly relevant for the control of extensive areas of wetland weeds where their control without removal may create ongoing problems in a wetland. For example, an extensive infestation of the floating weed water hyacinth *Eichhornia crassipes* (a weed of national significance) at Lake Monger in the 1950s was treated with herbicides. The dead plants then settled to the lake bed and provided an ongoing nutrient source for the lake.[34]

Considerations

- During the planning phase, it is important to ensure that the plant material does not provide important fauna breeding habitat.
- Matching the method with the weed is important; in some cases, fragmentation of plant parts during harvesting may contribute to their spread.
- If the harvesting of weeds is likely to result in plant death (or is planned as a weed removal option), regeneration of native species is the optimal outcome. If regeneration does not occur, a program of plant replacement with suitable native species should be carried out, to maintain vegetation function and natural ecosystem processes.
- The timing of harvesting should be appropriate for the weed in question. For example, the seed head of the introduced bulrush *Typha orientalis* can hold up to 300,000 seeds that are easily spread via disturbance and transport, so it should not be harvested when holding mature seed. In the south-west this is generally during January and February.

- Floating aquatic weeds can be harvested by hand, using long-handled rakes for instance.
- Methods involving the removal of below-ground parts can have a detrimental effect on the sediment and should be avoided if possible.
- Aquatic weed harvesters are sometimes used to remove large amounts of weeds. These machines can be purchased in Australia and have been used with varying degrees of success in WA. An aquatic weed harvester typically has large cutting blades that cut the weed above the sediment layer (Figure 20). Harvesters remove emergent weeds such as introduced bulrush (*Typha orientalis*) and floating weeds such as salvinia (*Salvinia molesta*). The disadvantage with aquatic weed harvesters is they are expensive to purchase and they can cause damage to native aquatic vegetation and disturb the sediment layer, causing increased turbidity and re-suspension of nutrients or other pollutants.
- It is important that weeds moved off-site are disposed of in a manner that prevents them from becoming weeds elsewhere. Collected plant material may be stored in bags for solarisation, composting or landfill disposal or used as stock feed if suitable. Use of bunds may be useful for larger areas to prevent aquatic weeds from entering 'weeded' out or uninfested areas.

Figure 20. Aquatic weed harvester. Photo – K Tripp/Shire of Wyndham East Kimberley.

case study

Case study - salvinia control in Lily Creek Lagoon, Kununurra

Approximately 135 hectares in area, Lily Creek Lagoon in Kununurra is part of the Ramsar wetland site that encompasses Lakes Kununurra and Argyle. It is directly connected to Lake Kununurra, the supply dam for the irrigation area and environmental flows to the Lower Ord River. The township of Kununurra wraps around Lily Creek Lagoon, which is an important habitat for migratory birds, freshwater crocodiles and numerous species of fish. It also provides an attractive backdrop and recreational area for the town.

A small infestation of salvinia (*Salvinia molesta)* was first discovered by a local resident in May 2000. It was immediately identified to be of major concern due to its potential to completely smother the water body and cause damage to the native aquatic ecosystem. The control and eradication process of salvinia has been a joint effort of the local and state government and non-government organisations.

Several different methods have been used over the past nine years to eradicate salvinia. Initial controls involved the containment of the weed through a boom fence and the manual removal of the bulk of the salvinia where possible. This was followed up by spraying with Roundup Biactive®, and installation of more boom fences (see Figure 21).

The floating boom fences, which are partly submerged beneath the surface to about 35 centimetres depth, are designed to trap salvinia and prevent it from spreading to uninfested areas. Initially one boom fence was used for containment, with more booms being installed later to create additional holding cells. The holding cells served two functions, to trap salvinia that was regenerating from small pieces missed hiding in the native typha (*Typha domingensis*) stands, and to trap any new plants entering the lagoon from the drain leading into it.

The major difficulty of salvinia being trapped within dense stands of native typha made access for control and removal very difficult. A clearing permit was obtained to remove a small area of native typha in order to allow greater access to the salvinia infestations. The most successful strategy for controlling native typha was mechanical removal with follow up spraying of regrowth. An excavator was used to remove approximately 600 square metres of native typha, which created an open water area which allowed access for eradication of salvinia. Removal of native typha was undertaken outside the breeding season of the swamp hen, which relies on the dense stands for nesting.

Figure 21. (a) Salvinia monitoring and collection (b) salvinia trapped within stands of native typha (c) salvinia containment area using boom fences. Photos – D Pasfield/Ord Land and Water.

(a)

(b)

(c)

Reinstating the natural wetting and drying pattern

✓ to ✗ Risk ranges from low to high

In permanently inundated wetlands, there may be an annual release of nutrients from wetland sediments that were previously subject to a natural wetting and drying cycle. Where this is found to be the case, it may be appropriate to reinstate the wetland's natural hydroperiod, which in southern WA is usually seasonal, that is, wet in winter/spring and dry in summer/autumn.

For example, in the Perth region, many areas that were seasonally inundated in the 1800s became permanently inundated in the 1914–1920 period. For example, Butler's Swamp became Lake Claremont and Perry Swamps became Perry Lakes.[107] Many such lakes are now reverting back to seasonally inundated basins (that is, sumplands) with lower rainfall and abstraction of groundwater.

Reinstating the natural pattern in lakes for the purpose of managing excess nutrients is often not appropriate. Important considerations include:

- whether the ecological community that is present is adapted to permanent water, and the ecological values of this ecological community
- whether the wetland has already built up sulfidic material to the extent that reinstating the regime would trigger wetland acidification via acid sulfate soils
- whether there are other permanently inundated areas that provide refuge in prolonged dry weather/drought.

If, on the other hand, a wetland is drying due to causes such as low rainfall (climate change), this indicates further need to consider managing the wetland through the transition to a seasonally drying wetland.

Reinstating the natural wetting and drying pattern may help to alleviate eutrophication in a number of ways. As with aeration, drying enhances the decomposition of organic matter and the diffusion of oxygen to the sediment, which promotes a range of chemical reactions due to the change in the redox potential. See the 'aeration' technique earlier in this topic for more information. Susceptibility to blooms is minimised in wetlands in the south of the state that dry on a seasonal basis, because of the lack of water in hot conditions. They may also receive a smaller soluble nutrient load because of reduced flows in dry weather.

There are substantial risks associated with drying wetlands, and for this reason wetland scientists should be consulted prior to attempting these changes. Despite good intentions, because of the potential to cause environmental harm, a proposal to alter the wetland water regime may trigger referral to the Environmental Protection Authority for assessment under Part IV of the *Environmental Protection Act 1986*.

Reinstating a natural wetting and drying cycle is discussed further in 'Managing hydrology' in Chapter 3.

➤ For information on managing wetland hydrology, please refer to the topic 'Managing hydrology' in Chapter 3.

➤ For information on legislation and policy protecting WA's wetlands, see the topic 'Legislation and policy' in Chapter 5.

Diverting nutrient laden inflows

✓ to ☠ Risk ranges from low to high

Diverting very high nutrient inflows can be very effective at reducing nutrients, but may deprive the wetland of water. It may also have downstream impacts. An example of where it has been used is in Jackadder Lake, in the Perth suburb of Woodlands. The water and nutrient balance conducted for Jackadder Lake informed the decision to reduce the volume of nutrient-rich water redirected into the wetland from the Osborne Park Main Drain in summer, which has been reported as reducing the susceptibility of the wetland to algal problems.[108] This water was previously directed into the wetland to maintain summer water levels.

Nutrient binding, nutrient inactivation and sediment capping

☠ High risk

Nutrient binding, nutrient inactivation and sediment capping products are types of algistat, which are chemicals or additives added to water that inhibit or retard the growth of algae or cyanobacteria, either directly, or by chemical modification of the water column.[109] These materials are typically applied in a liquid, slurry or powder form from a boat. The material reacts with phosphorus dissolved in the water column, coagulating or adsorbing with it and then settling on to the sediment. It is thought that they then form a thin active barrier on the surface of the sediments, reducing nutrient exchange between the nutrient-enriched sediment and the water column and absorbing further phosphate from the water column.[110] In this way these materials may alter the chemical composition and the physical properties of a wetland. Materials that have been proposed previously include specific formulations of clay and limestone, salts of aluminium and iron and minerals based upon zeolite. Commercially available products include Phoslock®™ (a modified clay nanomaterial with rare earth elements) and Algalblock (a modified calcium carbonate product).

Because of the potential for significant environmental impact, proponents considering the application of products of this nature to wetlands should consult with the Office of the EPA to determine whether the referral of their proposal to the Environmental Protection Authority is required under Part IV of the *Environmental Protection Act 1986*.

Considerations

- The addition of chemicals to wetlands can alter the chemical composition of wetlands. For example, alum, or aluminium sulfate, increases the amount of the highly toxic heavy metal aluminium in the wetland, and under some circumstances may lead to highly toxic shock events, particularly at lower pH levels. The addition of sulfate can trigger phosphorus release from sediments under certain conditions as well as forming salts. Similarly, some products may directly change the pH, or the buffer solutions that are required to be added prior to products may change the pH.
- Wetland sediment is an extremely important part of a wetland. It helps to form the ecological character of a wetland, being important as habitat for a range of species and the site of the most important chemical processes in most wetlands. It also affects the wetland hydrology. Activities that alter the wetland sediment may have short, medium and long-term effects on wetland ecology, including potentially irreversible changes to wetlands. Manufacturer claims that products have no effect on benthic organisms have not been assessed by DEC. However, alterations to the physico-chemical nature of the sediment may affect benthic fauna.

- Disturbing and changing the chemical composition of sediments has the potential to mobilise contaminants, such as arsenic and lead, in toxic concentrations if they are present in the sediment.
- The change in sediment properties may reduce its hydraulic permeability. If the wetland is connected to groundwater, there may be reduced flushing of the wetland with groundwater. This can (a) alter wetland water regimes and (b) either reduce or increase the amount of nutrients entering the wetland depending on whether the groundwater has less or more nutrients than the wetland.
- If there are a lot of algae in the wetland water column, this proportion of the wetland's existing phosphorus load will not be capped.
- Sediment capping materials will not address new inputs of phosphate. Similarly, if large amounts of sediment enter the wetland following the sediment capping materials, they may be subject to burial, and it may be necessary to apply further sediment capping material.
- Plants may short-circuit the barrier, by taking up nutrients buried below the sediment surface. When they senesce and decay, they can release nutrients above-ground.[42]
- Animals may alter the layer, by disturbing or turning over sediment. This is known as bioturbation, and may be carried out by many animals, for example, birds, fish, turtles, insects, midge, crustaceans and mussels.
- The efficacy of using a product in a particular wetland needs to be carefully considered. Factors such as pH, redox and hardness need to be considered. For example:
    - aluminium sulfate, known as alum, has been used with the view of it forming a flocculent precipitate of aluminium hydroxide that binds phosphate ions and organic materials, which settle to the wetland bed.[111] Use around the world suggests varying levels of success. Trialled at Jackadder Lake in Perth's northern suburbs, 20 tons of alum failed to stop phosphorus levels from reaching pre-treatment levels within a matter of weeks.[110,108] The phosphorus binding capacity of alum is pH sensitive. A constant supply of sulfate-enriched water will interfere with the iron-phosphate bond, with iron bonding with sulfate and releasing phosphate.
    - lime application is thought to be more effective in hard water wetlands where the water may become supersaturated with calcium ions.[42]
- At thousands of dollars per hectare[108], costs may be considerable. For example, estimates provided for the application of Phoslock®™ to a 65 hectare area of Yangebup Lake, assuming a phosphorus concentration of 0.12 milligrams per litre, was $850,000 in 1995. At Bibra Lake an unspecified material was costed at $30,000 for a 2500 square metre trial area in 1998. Repeat applications may also be required for longer term benefit.
- The environmental cost of sourcing materials also needs to be taken into consideration, with mining of dryland and wetland environments. For example, lime is quarried from limestone. In WA a major source of bentonite clay is from threatened wetlands. The 'Herbaceous plant assemblages on Bentonite Lakes' ecological community of the Avon Wheatbelt is listed by the WA Minister for Environment as a threatened ecological community.
- Some studies suggest that products may have the potential to alter the microbial processes of coupled nitrification and denitrification and also to induce active element leaking from agents.

extra information

Phoslock®™, a new product

Phoslock®™ is a relatively new product (sold commercially since 2004) that is used for water quality management in a number of countries. In WA, it has been used at sites including the Vasse and Canning rivers and Emu Lake, Ballajura. It is marketed as a phosphorus inactivation product for those situations where phosphorus release from sediments is a main driver of algal bloom formation. Below are some of the considerations regarding its use.

Phoslock®™ forms a reactive permeable layer typically 1 millimetre in thickness on bottom sediments. Phoslock®™ contains lanthanum and bentonite; bentonite is a clay that occurs in wetlands and is mined from wetlands in WA for various applications. While lanthanum is thought to be toxic in dissolved or free forms, the manufacturer states that the lanthanum ions are locked in the structure in the Phoslock®™ mineral, thereby dramatically reducing the toxicity and availability of its free form, with the concentration of dissolved lanthanum stated to remain very low in the water body.[112] Studies reporting lanthanum release to the water column during trials cite levels of around 2 milligrams per metre per day over a fortnight[113] (see also van Oosterhout and Lrling[114]). In a comparison of the ecotoxicity of alum and Phoslock®™ the manufacturer of Phoslock®™ concluded that "Al [aluminium] poses more threat to aquatic life than that of lanthanum".[112] The manufacturer states that lanthanum is more likely to pose a risk of being present in dissolved form in the water column if applied to low alkalinity water at the wrong dose.[112] The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[15] do not specify a trigger value for lanthanum as a toxicant, due to insufficient data to derive a reliable trigger value (although it does provide an indicative interim working trigger value; for more information see Table 3.4.1 and section 8.3.7 of the guidelines).

Phoslock®™ has been used by the Swan River Trust and DEC in the Canning and Vasse Rivers. Following a trial conducted on Canning River, the Swan River Trust reported that "A comprehensive suite of indicators of environmental impacts, including fish, waterbirds, macro-invertebrates and periphyton, was measured before and after application of Phoslock®™. Interpretation of the data collected was affected by a number of events including heavy rains, and a fuel spill upstream of the trial area soon after the application. However results showed that the application of Phoslock®™ did not adversely affect populations of macro-invertebrates, freshwater shrimps or periphyton".[115] Laboratory testing of acute and chronic toxicity was undertaken by the CSIRO Centre for Advanced Analytical Chemistry Analysis on a species of cladocera (a microcrustacean), green alga and fish, and no toxicity effects were observed in these test species.[115] It has been reported by the WA Midge Research Group that "There is potential for Phoslock™ to cause acute toxicity to fish (LC50 = 4350 mg Phoslock™ L-1) (Martin and Hickey 2004) if the correct application rate is exceeded or if an accidental spill occurred and this should be considered before use".

International studies indicate that the efficacy of the treatment can vary, and that variables include water characteristics such as water softness/hardness and the concentration of humic acid.[116] It is stated that the optimal pH range is 6–9 but it operates over a pH of 4–11.[112] Reports state that cost of treating around 50 hectares of water can range from $100,000 to $500,000 depending on the problem and the dose rate.[117] The life of the treatment depends on the condition of the water body and the levels of nutrient inflows. In Emu Swamp, in the suburb of Ballajura north-east of Perth, yearly doses are likely to be necessary (Emu Lake was a natural wetland that has been modified). Analysis based on the use of Phoslock®™ in constructed lakes in Perth and the south-west suggest that, used alone, repeated treatments over the long-term would be required in eutrophic wetlands.[108]

Sediment sealing

ꝏ High risk

As the name suggests, sealing of sediments aims to prevent nutrient exchange between the sediments and the water column by installing an impermeable barrier between them. Impervious materials such as plastic sheeting and linings are used. This effectively smothers, and cuts off, benthic organisms from the water column, including insects, mussels, snails, roundworms, leeches and rotifers and rooted vegetation. It also cuts off wetland organisms from the sediment (for example, waterbirds that feed from the sediment, and oblong and flat-shelled turtles, some crayfish and some fish that **aestivate** or otherwise burrow in the sediment during dry conditions). Organisms such as insects, beetles, flies, midge, algae, bacteria and plants may inhabit sediment during stages of their lifecycle, in life forms including larvae, eggs, spores, cysts and seeds; hence the loss of sediment habitat can reduce wetland biodiversity.

Aestivating: being in a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Considerations

- Wetland sediment is an extremely important part of a wetland. It helps to form the ecological character of a wetland, being important as habitat and the site of the most important chemical processes in wetlands. It also affects the wetland water regime. Sealing the wetland sediment can have short, medium and long-term effects on wetland ecology, including potentially irreversible changes to the ecological character of a wetland. Proposals of this nature can have significant ecological impacts and require referral to the Environmental Protection Authority under Part IV of the *Environmental Protection Act 1986.*
- Sealing does not remove the source of nutrients and is effective only up to the point where new sediments accumulate on the surface of the capping material.
- Materials such as plastic sheeting can be expensive, difficult to install and may be damaged, limiting its effectiveness.
- Sealing requires a uniformly cleared wetland floor that means the removal of any rooted vegetation from the area to be sealed. This can affect natural wetland ecology and functioning.
- Technical limitations such as the generation and release of gas from sediments below the seal need to be accounted for.
- The disturbance and mixing of sediments by sediment-dwelling organisms and waterbirds (known as bioturbation) could hasten the breakdown of capping.
- The breakdown of capping materials has the potential to affect wetland organisms.

Removing sediments

ꝏ High risk

Sediments can be a significant source of phosphorus, which can be released as the bioavailable form, phosphate, during periods of anoxia and bioturbation. Dredging, skimming and excavating sediment has been proposed at a number of Perth wetlands as a means of reducing the volume of phosphorus in the wetland.

Dredging has been carried out at some wetlands including Hyde Park Lakes and Mary Carroll Park Lake. Hyde Park Lake contained high levels of lead and sulfide. Consequently, an acid sulfate soil management plan was required to be prepared and implemented in order to remove the sediments, to limit the potential for lead mobilisation.

Because of the potential for significant environmental impact, proponents considering the removal of wetland sediments should consult with the Office of the EPA to determine whether the referral of their proposal to the Environmental Protection Authority is required under Part IV of the *Environmental Protection Act 1986*.

Considerations

- Wetland sediment is an extremely important part of a wetland. It helps to form the ecological character of a wetland, being important as habitat and the site of the most important chemical processes in wetlands. It also affects the wetland water regime. Removing wetland sediment can have short, medium and long-term effects on wetland ecology, including potentially irreversible changes to wetlands.
- Some wetland plants and animals rely on sediment for aestivation (such as turtles, some crayfish, some fish, many frogs, mussels, snails, roundworms, leeches and rotifers), or as habitat for vulnerable life stages such as larvae, eggs, spores, cysts and seeds (used by many insects, beetles, flies, midge, algae, bacteria and plants), hence the loss of natural sediment habitat can reduce wetland biodiversity.
- Disturbing the sediments can disturb acid sulfate soils and cause acidification of the wetland.
- Disturbing sediments has the potential to mobilise contaminants, such as arsenic and lead, in toxic concentrations if they are present in the sediment.
- Wetlands typically do not provide firm ground from which to operate conventional excavating machinery such as front-end loaders or scrapers. Geotechnical investigations need to confirm that the extent of consolidation of wetland sediments is sufficient to support machinery.
- Floating dredges using industrial strength suction pumps have been proposed in the past. These required the establishment of settling ponds to enable dredged sediment to settle, given an extraction ratio of 5 per cent sediment to 95 per cent water followed by the return of the water to the wetland. Previous proposals have also required a minimum water depth of 1 metre to enable the dredge to operate.
- Knowledge of the depth of the sediment that is phosphorus-enriched is needed to inform the proposal.
- Depending on the depth of sediment required to remove the phosphorus-enriched portion, considerable deepening may be a result. Deepening can alter the habitat and water regime, as well as potentially leading to stratification, which can have implications for nutrient management in the future.
- The disposal of the excavated sediment may be regulated. Sediments containing contaminants may be classified as contaminated waste, for which there are specific disposal requirements. For example, it may have high levels of heavy metals.
- Dredging can be expensive, particularly in larger wetlands. An undated estimate of the cost of sediment removal at Bibra Lake a number of years ago was reported to be approximately 30 million dollars.

case study

Case study – toxic algal bloom in Hawker Lake, Rockingham

Hawker Lake, in Rockingham, has had serious water quality problems for many years. These problems culminated in a toxic bloom in the summer of 2007 when water temperatures, sunlight and nutrient levels in the water lead to the development of a toxic bloom (Figure 22). The bloom and sick and dying birds at the wetland prompted an investigation by City of Rockingham staff into the causes of the poor water quality. Samples of water were collected from the wetland by the City's environmental staff for analysis.

Figure 22. Bloom in Hawker Lake, City of Rockingham. Photo – D Mort/City of Rockingham.

Analysis of water samples confirmed the presence of a toxic cyanobacteria as well as the bacterium *Clostridium botulinum*, which can cause the rare but dangerous disease botulism, which poses a serious health risk to humans, pets and wildlife. The wetland was immediately closed as a precaution to protect the surrounding community (Figure 23).

Figure 23. Sign erected at Hawker Lake warning of health risks associated with algal blooms. Photo - J Nichol/DEC.

How did the lake water become toxic?

Staff began their investigation into how the water had become so toxic by looking at the location of the wetland and influences from the surrounding catchment. The wetland lies at the lowest point of the catchment and receives stormwater from surrounding roads, drains and gardens (Figure 24). It was likely that the stormwater contained high loads of nutrients (from fertiliser and animal faeces) and possibly other pollutants such as herbicides, hydrocarbons and pathogens.

Figure 24. This stormwater drain transports nutrient rich water into the lake, contributing to the bloom pictured here. Photo - D Mort/City of Rockingham.

The council also recognised that wetland vegetation around the water's edge had been replaced with grass, which was regularly fertilised (Figure 25). These conditions were most certainly encouraging the development of blooms.

Figure 25. Replacing native vegetation with fertilised grassed areas around the lake contributed to blooms. Photo - D Mort/City of Rockingham.

case study

Case study – toxic algal bloom in Hawker Lake, Rockingham (cont'd)

Remediation of Hawker Lake

Since the bloom in 2007, the council has spent over $70,000 undertaking a number of projects to improve water quality in Hawker Lake. Engaging the community in the 'Yellow Fish' education program was a key strategy in reducing pollutants entering the wetland and improving water quality. The Yellow Fish program encouraged neighbours to consider the impacts of their activities at home, particularly those that result in pollution of stormwater entering the wetland, such as excessive use of fertilisers on lawns and gardens. The community was actively involved in revegetating the wetland and its surrounding area with local native plants (Figure 26). Newly established native vegetation has also provided benefits for local waterbirds, which have returned to the site (Figure 27).

Figure 26. Revegetation of the wetland with native species to reduce nutrients entering the lake.
Photo - D Mort/City of Rockingham.

Figure 27. Newly established native vegetation provides habitat suitable for many of the local birds which have returned to the site. Photo - J Nichol/DEC.

Large scale 'bubblers' and water fountains have been installed in the lake to aerate and circulate the water, reducing the release of nutrients stored in the sediments and subsequent growth of algae and toxic bacteria (Figure 28).

Figure 28. Bubbler (foreground) and fountains (rear) aerate the water and prevent anoxic conditions which can increase release of nutrients from the sediment and growth of algae and cyanobacteria.
Photo - J Nichol/DEC.

Staff at the council continue to work with the community to encourage improved catchment management by encouraging local residents to grow native plants and reduce the application of fertiliser, water and herbicide on lawns and gardens. The community are also helping by replacing introduced fish such as Koi, which stir up the sediments, resulting in the release of nutrients, with native fish.

The water quality in the lake has vastly improved since the remediation activities have been implemented. It is hoped these activities will reduce the possibility of future algal and cyanobacteria blooms and botulism outbreaks in Hawker Lake so the community and wildlife can enjoy a more natural wetland environment.

Wetland scale intervention: algae and cyanobacteria control methods

Algaecide: any chemical or biological agent intended to kill algae

Algae and cyanobacteria control methods are considered a short-term approach because they address the symptoms and not the causes of blooms. When scoping potential control methods it is important to be aware that a number of methods used in reservoirs and drinking water supply waterbodies are not suitable for use in wetlands of conservation value because of their effects on the physical, chemical and biological characteristics of wetlands.

Table 12. Wetland-scale algae and cyanobacteria control methods, grouped and colour-coded according to their potential risk of unintended ecological effects.

✓ Typically low risk
Harvesting algae and cyanobacteria
Potentially high risk
Applying algaecides
Adding organic material

Harvesting wetland algae, cyanobacteria

✓ Low risk

Some species of cyanobacteria form surface scums, for example, *Microcystis*, *Anabaena* and *Aphanizomenon*. They possess gas vacuoles that allow them to move up or down in the water column over the course of 24 hours to make the best use of sunlight to photosynthesise in the upper water column as well as to access nutrients present lower in the water column, and to avoid constant UV radiation. In suitable densities, it can be possible to harvest these scums, as well as dislodged, floating clumps of benthic cyanobacterial mats.

Manual harvesting may be carried out using rakes or skimmers. Oil-spill booms and skimmers have been used to remove surface cyanobacteria in wetlands and on the Swan River in Perth where in 2000, more than 900 tonnes of *Microcystis aeroginosa* was removed and safely disposed using sewage treatment facilities.[106]

Considerations

- The personal safety of the people harvesting algae or cyanobacteria is a priority. A full risk assessment should be taken to avoid health issues arising from exposure to toxic algae, cyanobacteria or bacteria (for example, botulism from *Clostridium botulinum*).
- The disposal of the cyanobacteria should be to an appropriate waste disposal facility. This needs to be determined in advance of the harvesting.
- Depending upon the species of cyanobacteria, optimal removal is likely to be in calm conditions in the early morning when cyanobacteria have migrated to the top of the water column.

Applying algaecides

Algaecides (also known as algicides) are a short-term measure (weeks to months) for the management of algal blooms in wetlands because they kill the algae but do not reduce the nutrient levels needed to prevent further algal blooms. Algaecides can be sprayed from a boat. Algaecides are a type of pesticide and their use is regulated by the Health (Pesticides) Regulations 1956.

Considerations

- Algaecides should not be used in natural wetlands, particularly those of conservation value, because they can be toxic to wetland plants and animals, including crustaceans, fish, birds and non-target algae and bacteria that are not in bloom proportions. Similar considerations apply to algistats (any substance or agent that inhibits the growth of algae). Copper, a metal, is the active constituent of many algaecides is a toxic heavy metal in aquatic environments. Copper can accumulate in sediments and be taken up by organisms in this form or released into the water under certain conditions. As outlined in the 'Metals' section later in this topic, aquatic plants are thought to be particularly sensitive to iron, copper and aluminium.[118]
- The death of large amounts of algae provides a food source for bacteria. In decomposing this large energy source, the bacteria consume oxygen, leading to the deoxygenation of the water column and anoxic conditions that can result in odours, fish kills and botulism, and potentially a boom population of midge.
- It is important to be aware that the use of algaecides can cause the mass release of toxins produced by cyanobacteria upon the dissolution of their cells (lysis), and that these toxins may persist long after the cyanobacteria die. This needs to be taken into consideration if native animals or livestock are at risk, for example, if the wetland is being used to water livestock. The toxins are generally very stable compounds that are resistant to chemical breakdown and may remain in natural waters for several months. Under natural conditions, sunlight and bacteria may cause the breakdown of some toxins. It is also a lot more difficult to detect algal toxins than whole algal cells. Once algal cells are killed, the only way to determine whether algal toxins are still present in the water is through toxin testing, which can take up to a week and is far more expensive than testing for algal cells.[109]
- Cyanobacteria resistant to algaecides may flourish following treatment and death of other species of cyanobacteria.[109]
- Algaecides may kill zooplankton that graze on algae, increasing the potential for future algal blooms.

Using algaecides

Any chemical or biological agent intended to kill a living thing, such as a poison, is a pesticide, and an algaecide is a type of pesticide. Extreme care must be taken to ensure that the use of pesticides does not constitute an offence or cause environmental harm. In WA, anyone who uses pesticides is bound by the Health (Pesticides) Regulations 1956. These regulations were developed to provide protection for the applicator, the public and the environment from misuse of pesticides. Pesticide labels are written in accordance with the regulations and therefore any pesticide user has a legal obligation to read and follow instructions on the label. By law and without exception, pesticides cannot be used in any manner contrary to that described on its label without the permission of the Australian Pesticides and Veterinary Medicines Authority. The label provides instructions for use, for the protection of the environment, information about storage and disposal and recommendations for personal protective equipment. Anyone proposing to apply a pesticide to a natural area of conservation value should have appropriate authorisation and should undertake training in the correct preparation, handling, application, transport and storage of pesticides.

Adding organic material

The addition of organic matter has been used with varying levels of success in wetlands in Australia and internationally as an algistat – that is, to prevent new growth. Theories for algistatic effects observed have been put forward including that the decomposition of straw cell walls releases phenolic compounds (such as tannins) that inhibit the cyanobacteria; that the absorption of UV light by the dissolved organic matter produced generates reactive oxygen species which may damage tissues and alter the bioavailability of limiting trace metals; and that the addition of this material stimulates the production of antibiotics by fungi. However, in a review of barley straw, Water Quality Research Australia Limited, a company funded by the Australian water industry, concluded that "The evidence on the efficacy of barley straw from Australia conflicts with overseas studies. Of the two published studies a lab investigation failed to find any inhibitory effects from extracts derived from rotting straw on isolates of *M. aeroginosa* [a cyanobacterium], and a comprehensive field-based trial also found no algicidal or algistatic effects from barley straw over a 6-month period. These contradictory findings and the unknown identity of the phytotoxic compounds in rotting barley straw would indicate that this technique is too poorly understand to recommend for widespread use as an algal control measure, particularly in drinking water supply situations".[66] The potential for the organic matter to increase the biological oxygen demand (BOD) of the wetland needs to be assessed before considering using this technique, as low oxygen levels or anoxia could create a range of problems.

Acidity: the amount of acidity associated with all dissolved ions in a solution, expressed as an amount of pure calcium carbonate needed to neutralise these. Dissolved ions include hydrogen ions and commonly free dissolved metals such as aluminium, iron and manganese.

Ion: an atom that has acquired an electrical charge by the loss or gain of one or more electrons

Alkalinity: a solution's capacity to neutralise an acid, expressed as the amount of hydrochloric acid needed to lower pH of a litre of solution to pH 4.5. The concentration of bicarbonate (HCO_3^-), or when pH is greater than 8.3, the concentration of carbonate (CO_3^{2-}). Sometimes due to dissolved silicate, phosphate or ammonia in relatively high concentrations (tens of milligrams per litre).

Latent: dormant, inactive

Managing acidification

Wetland acidity is a chemical characteristic that, like dissolved nutrients and pesticides in water, can't be seen. However, like nutrients and pesticides, acidity can have significant effects upon a wetland and, when a wetland is very acidic, these are very visible.

Acidification of wetlands: a summary

Causes: rising acidic groundwater, acid sulfate soils, acidification of shallow groundwater

Impacts: reduced biodiversity of plants and animals, oxygen deficiency, metal toxicity

Indicators: wide range of changes in vegetation, soil and water characteristics

Management options: a range of options for preventing acidification, a number of wetland-scale interventions and treatments

What is acidity?

In chemical terms, **acidity** is a high concentration of dissolved hydrogen in water. Hydrogen has the chemical symbol 'H', while the chemical shorthand for the dissolved, **ionic** form of hydrogen that produces acidity is 'H^+'. Waters with a low concentration of dissolved hydrogen are often referred to as alkaline waters, however, the term **alkalinity** specifically refers to a solution's capacity to neutralise an acid.

The presence of hydrogen ions reflects acidity at a point in time. However, it is also important to be aware that wetlands have a **latent,** or stored, form of acidity in the presence of dissolved iron and aluminium in the water. Latent acidity can account for more than 80 per cent of acidity in a wetland.[119,120] Latent acidity can become actual acidity when the wetland water is exposed to air, causing the dissolved metals iron and aluminium to progressively react with oxygen and water and to precipitate as oxyhydroxide minerals. In the process of doing this, more hydrogen ions are released into solution, generating actual acidity.

Why is acidity important?

Acidity and alkalinity are properties of water that directly affect the ability of organisms to function, breed and survive in water. Acidity and alkalinity also have a strong influence on many chemical reactions in water that affect organisms and which help to shape a wetland's ecological character.

There are wetlands in WA that are naturally extremely acidic or alkaline, though most are naturally within a relatively neutral range ('circumneutral'), or mildly to moderately acidic or alkaline. In WA, when human activities cause a change to a wetland's acidity, the effect is typically to increase acidity, and for this reason the focus of this section is upon managing human-induced acidity in WA wetlands. However, human-induced increases in alkalinity can also have serious effects on WA wetlands and where there is a risk of this occurring (for example, when applying chemicals to treat acidic wetlands), specialised monitoring and management is required.

Wetland animals, plants and microbes are adapted to particular ranges of acidity or alkalinity for survival, breeding and normal function.[14] Most WA wetland plants, animals and microbes are adapted to within the range of circumneutral to moderately acidic or alkaline conditions. Some wetlands are naturally acidic, and these wetlands support species that are tolerant of this acidity, and in some cases, may support acid-specialised species known as acidophiles. Organisms are directly affected by the level of acidity or alkalinity, with tolerance depending on the species and factors such as the stage of their life cycle. They can also be affected by secondary effects of acidity or alkalinity, including changes to oxygen levels, toxicity of dissolved metals and turbidity.

How is acidity measured?

Acidity levels can vary in a wetland over time and is influenced by a range of factors. One commonly used measure is the pH scale, which commonly ranges from pH 0 (strongly acidic) to pH 14 (strongly alkaline). pH is a very crude indicator of the acidity of a wetland, as this measurement only indicates the presence of hydrogen ions – in essence, the instantly available acid at a specific moment in time. Importantly, it doesn't measure the acidity present in a latent or stored form in the presence of dissolved iron and aluminium in the water. For this reason, samples of water from two wetlands may have the same pH, but quite different total acidity values, because of their different iron and aluminium concentrations. The pH scale is logarithmic, meaning that a fall of one pH unit represents a ten-fold increase in hydrogen ions.

The best way of assessing wetland acidity is to measure both pH and total titrateable acidity using a field test kit. Commercially produced test kits are available for purchase, or alternatively can be made using items from the supermarket and pharmacy; instructions for making these kits are described in the below text box 'Making simple field test kits to measure the total titratable acidity'.

The unit of measurement for acidity is the weight of calcium carbonate (pure limestone, $CaCO_3$) or the equivalent such as sodium hydroxide (NaOH), needed to neutralise all of the acidity in a litre of water to pH 8.3. In contrast, the unit of measurement for alkalinity in waters with a pH greater than 4.5 is the amount of hydrochloric acid (HCl) needed to lower pH of a litre of the solution to pH 4.5. When acidic waters are neutralised by alkaline materials, dissolved metals like iron and aluminium consume large quantities, while pH consumes comparatively small quantities.

Acidity in the pore waters of sediments has a wider range of reactivity than acidity of water columns. Acidity in sediments may be a combination of soluble (reacts over minutes to hours), exchangeable (minutes to days) and insoluble (hours to decades, sometimes centuries) forms. The acidity stored in soils and sediments can be more than 100 times that held in overlying water.[121]

extra information

Making simple field test kits to measure the total titratable acidity

-by Dr Steven Appleyard, Department of Environment and Conservation

The acidity of a water sample can be determined by a process known as an acid-base titration. This involves adding in a drop-wise fashion a solution of sodium hydroxide of known concentration to a measured volume of the water sample to which has been added a few drops of an acid-base indicator. The drop-wise addition of sodium hydroxide (with swirling of the sample) is continued until the colour of the solution just changes colour (the titration end-point). The volume of sodium hydroxide solution added to the water sample is then measured, and the acidity of the water sample can then be calculated, usually in units of the equivalent mass of calcium carbonate required to fully neutralise the acidity, or milligrams per litre as $CaCO_3$. The total titratable acidity of a water sample is generally measured by titrating the sample to a pH of 8.3, the pH at which the acid-base indicator phenolphthalein changes from colourless to a pink colour.

There are a number of commercially available acidity test kits that can be used to carry out this titration on water samples in the field. However, these kits are generally expensive (of the order of $100 each). It is possible to make kits of an equivalent accuracy to the commercial kits for a small fraction of the cost using only materials that can be readily purchased in a supermarket and a pharmacy and using recycled plastic or glass containers.

Components of the test kit

The components of a test kit include:

- a 50–100 millilitre plastic bottle containing the standard sodium hydroxide solution
- a small syringe or an eyedropper which is graduated in fractions of a millilitre
- a medicine glass or a small plastic container which has marks indicating volumes of 5 millilitre and 25 millilitre
- a small bottle (5–10 millilitre) with a drop dispenser (or use another eyedropper) containing turmeric-based acid-base indicator which changes colour at the same pH as phenolphthalein.
- a plastic lunch-box or a similar container to house components of the test kit.

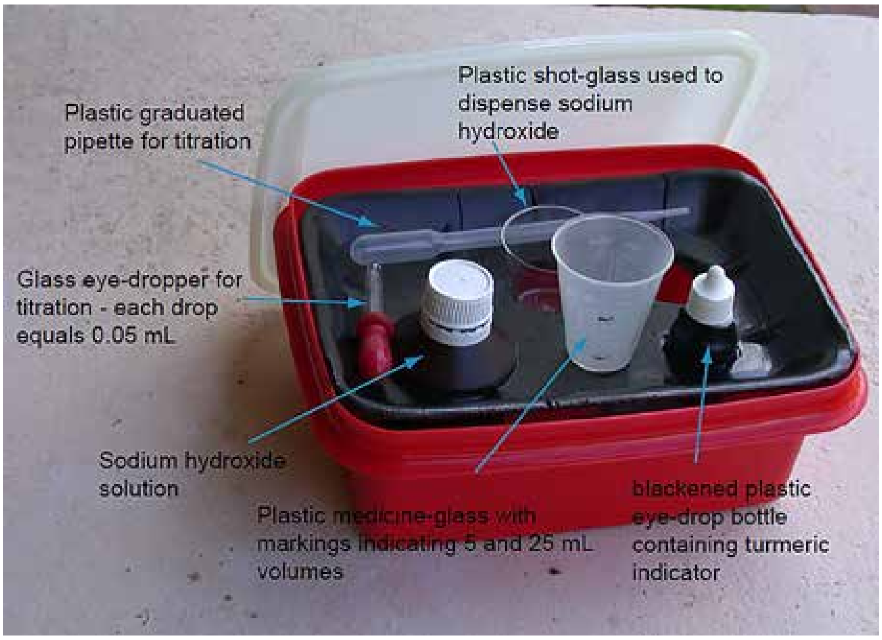


Figure 29. Components of a total acidity test kit housed in a plastic lunch box with an insert made with a foam meat tray to keep containers upright. Photo – courtesy of ASSAY newsletter.

Making the standard sodium hydroxide solution

The sodium hydroxide solution can be made using sodium hydroxide pellets and distilled water that can be obtained cheaply from a supermarket or hardware store (reagent grade materials are not needed). Weigh 8 grams of pellets of sodium hydroxide and add to 1 litre of deionised water (also available cheaply in supermarkets). This solution is further diluted by a factor of 10 with deionised water to make the standard solution (that is, a concentration of 0.02 molar NaOH). This solution can be made using kitchen scales and plastic measuring jugs, so it is not necessary to have access to laboratory equipment. It is recommended that the solution is discarded and replaced at 6-monthly intervals, as the sodium hydroxide progressively reacts with carbon dioxide absorbed from air to form sodium carbonate.

extra information

Making an acid-base indicator with turmeric

If phenolphthalein is not available, an alcoholic extract of powdered turmeric (the spice available in supermarkets) will provide a suitable acid-base indicator. This is made by placing a teaspoon of powdered turmeric in a small, dark-coloured glass or plastic container (turmeric extracts are light-sensitive) and covering the powder with methylated spirits. The active ingredient in the extract is the dye curcumin which changes colour from yellow to bright red at the same pH that phenolphthalein changes from colourless to a pink colour. This solution is used in the same way at phenolphthalein, and only 1–2 drops should be added to the water sample before carrying out a titration.

Using the acidity test kit

The sample to be tested should be collected using a standard method, such as the field sampling protocol published by the Massachusetts Water Watch Partnership: www.umass.edu/tei/mwwp/phalk.html.

A 5 millilitre volume of water is added to the medicine glass and 1–2 drops of the indicator solution is added to the sample. The standard sodium hydroxide solution is added drop-wise with the eyedropper or small syringe while swirling the water sample until the colour of the solution just permanently changes colour from yellow to red. The volume of sodium hydroxide added to the water sample is then determined, and the acidity (in units of milligrams per litre as $CaCO_3$) is determined by multiplying the volume in millilitre by 500. The volume added from an unmarked glass eye-dropper can be determined by counting the drops added as 1 drop is equivalent to a volume of 0.05 millilitre (20 drops are equivalent to a volume of 1 millilitre).

If the calculated total acidity value of the sample is less than 100 milligrams per litre as $CaCO_3$, the precision of the test can be improved by measuring a 25 millilitre volume of the water sample and then repeating the titration as before. The total acidity of this volume of water is determined by multiplying the volume of sodium hydroxide added by a factor of 100.

What determines the natural acidity of a wetland?

As indicated, the range in the natural acidity/alkalinity levels of WA wetlands is very broad. In fact, the area between Hyden and Norseman in the Great Southern/Esperance districts contains some of the most naturally acidic wetlands anywhere on the planet, with pH values as low as 1.5[122] (with the organisms that inhabit these salt lakes being the subject of NASA-sponsored research). The natural level of acidity or alkalinity in wetlands in WA is strongly influenced by natural acids produced, and the natural buffering capacity present. Key factors include:

- The chemical properties of the catchment (the rocks and the aquifer materials) that the surface water and groundwater flows through prior to reaching the wetland, as well as those of sediment.
- Rainwater tends to be naturally slightly acidic, and the chemical properties of the land surface and aquifers it flows through before reaching a wetland, and upon entering the wetland, determines whether it will be altered. Geological substrates and wetland sediments containing calcium carbonate (limestone, $CaCO_3$) tend to be naturally alkaline and are often 'buffered' (stabilised) against rapid changes in acidity.[123] Other sources of potential acid buffering also include clay minerals, aluminosilicate and organic matter.[124] On the other hand water flowing over granite is typically poorly buffered. Wetlands on sandy soils often have very little buffering capacity and are often acidic.
- Wetlands that receive surface water from naturally acidic or alkaline waterways or wetlands, or that have groundwater capture zones that receive water from upgradient acidic or alkaline wetlands, may reflect this acidicity or alkalinity.
- The level of acid produced by decaying plant matter.

- Wetlands can be naturally acidic if their sediments release organic (tannic, humic and fulvic) acids from decomposing vegetation. Wetlands with peat or lots of organic matter tend to be naturally acidic. The pH level attributable to natural organic acidification is generally thought to be as low as 4.5,[125,126,15] though levels as low as 4 have been attributed to this process.[127] Peats can also contain pyrites which, if exposed to air, can lead to acidification. Peats contain up to 15 per cent by weight of oxidiseable sulfur.[128]
- The use of carbon dioxide by primary producers, and the production of carbon dioxide by all organisms.
- Photosynthesising organisms (plants, algae and cyanobacteria) use carbon dioxide (and in the case of plants, also bicarbonate, HCO_3^-). If they use carbon dioxide from the water column or sediment pore waters, there will be a decline in carbon dioxide. This tends to increase the pH of the water. During an algal bloom, pH levels may increase as a result of increased photosynthesis. Because photosynthesis occurs during the day, pH is likely to be higher later in the day due to the cumulative effect of removing carbon dioxide from water. On the other hand, carbon dioxide produced by organisms via the processes of (cellular) respiration and bacterial decay decreases the pH of water. The lowest pH from carbon dioxide production in soil is around 4.6.[129] In very shallow granite rock pools, sometimes referred to as vernal pools, the very small volume of water relative to the high plant biomass and the poorly buffered nature of the water results in large day-night fluctuations in carbon dioxide and pH.[130]
- The degree to which oxidation of iron sulfides naturally occurs.
- Wetlands with iron sulfide minerals in sediment that undergo natural drying or burning events may release acid from the oxidation of iron sulfides. Naturally seasonally drying wetlands do not build up a significant store of iron sulfide minerals and therefore normal levels of drying do not generate significant amounts of acid.[131]

The level of acidity or alkalinity in wetland waters can change as a result of chemical reactions occurring in the water column and wetland sediment. They are affected by the chemical composition of substances in the wetland plus those substances entering and leaving the wetland. They can vary naturally over the course of the day (due to changes in carbon dioxide levels) and over the course of a season (due to multiple factors) as well as over longer timeframes.

➤ For more information on what influences the natural acidity or alkalinity of a wetland, see the topic ‘Conditions in wetland waters’ in Chapter 2.

What should a wetland’s acidity be?

Due to the existence of a wide range of natural levels of acidity in WA wetlands, there is no ‘normal’ range for wetland acidity or pH. A default trigger value for total acidity is not provided in the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC). As stated earlier, pH is only an imprecise measure, but trigger values are available; the ANZECC guidelines indicate that the pH in most natural, freshwater inundated wetlands in WA should not drop below pH 6.0 or exceed pH 8.5 if no negative impact to the ecosystem is to occur[15] (Table 13). There are a number of exceptions, including humic (coloured) wetlands which are often naturally acidic, as outlined in the section ‘What determines the natural acidity of a wetland?’). Note that because the pH scale is logarithmic, a fall of one pH unit represents a ten-fold increase in the effective concentration of hydrogen ions.

Information from other studies are presented in Tables 14–16 below, with Tables 15 and 16 relating specifically to Wheatbelt wetlands.

Buffering capacity: a measure of the soil's inherent ability to buffer acidity and resist the lowering of the soil pH

Acid neutralising capacity: a measure of the soil's inherent ability to buffer acidity and resist the lowering of the soil pH

Table 13. Default trigger values for pH for slightly disturbed freshwater wetlands in Western Australia, from the ***Australian and New Zealand Guidelines for Fresh and Marine Water Quality***[14]

Water Quality Parameter	Trigger Value Southwest Australia	Trigger Value Northwest Australia
pH	Greater than 7.0 and less than 8.5	Greater than 6.0 and less than 8.0
Notes	In highly coloured wetlands (gilvin >52 $g_{440}m^{-1}$) pH typically ranges from 4.5 to 6.5	NA

Table 14. Biological threshold for pH for saline aquatic ecosystems in the Wheatbelt (Jones, Francis, Halliday & Leung 2009[118])

Water Quality Parameter	Threshold for Wheatbelt saline aquatic ecosystems
pH	6

Table 15. Reference ranges for pH in various central Wheatbelt wetland types (Jones, Pinder, Sim & Halse 2009[26])

Wetland type	pH range	Notes
Naturally saline basin wetlands subject to inundation	7.8–8.7	Excludes naturally acidic wetlands
Freshwater inundated basin wetlands subject to inundation	6.8–8.1	
Turbid claypans subject to inundation	8.6–8.9	

How sensitive are wetlands to acid generating processes?

When acid is generated in a wetland, the change in acidity levels that occurs depends on the **buffering** or **acid neutralising capacity** of the wetland (or, in groundwater, the aquifer sediments). Materials and processes in the wetland can buffer against large changes in pH. These include the presence of carbonate minerals (shells and other calcareous matter) in the sediment, the process of anaerobic respiration and the presence of alkalinity (bicarbonate ions). Acidification occurs when the rate of acid input or generation exceeds the rate at which acid can be neutralised by these processes.

The United States Environmental Protection Agency (EPA) has classified the sensitivity of lakes and ponds to acidification, based upon their alkalinity, measured as the concentration of calcium carbonate ($CaCO_3$) as shown below.

Table 16. US EPA classification of sensitivity of lakes and ponds to acidity. Source: Massachusetts Acid Rain Monitoring Project[132]

US EPA category	Total alkalinity measured as concentration of $CaCO_3$ in milligrams per litre
Acidified	Less than 1 and pH of less than 5
Critical	Less than 2
Endangered	2–5
Highly sensitive	5–10
Sensitive	10–20
Not sensitive	More than 20

Causes of human-induced acidification

In WA, human-induced acidification of wetlands is primarily caused by:

- the discharge of iron-rich acidic groundwater, such as occurs in the Wheatbelt
- the disturbance or exposure of soils containing sulfidic materials to air, causing localised acidification, as occurs in many coastal areas of south-west WA
- the disturbance or exposure of soils containing sulfidic materials to air, causing acidification of shallow groundwater systems, as has occurred in the shallow groundwater of the Bassendean Dunes.

Additional factors are the deposition of aerial sulfidic material and acid rain due to industrial pollution, although these are more prevalent in the northern hemisphere, and acid mine drainage. Acid mine drainage is an important issue but in terms of impacts to wetlands it is currently not considered to have the widespread scope of other forms of acidification, and is not specifically addressed in this guide. Proposals to mine that may cause acid mine drainage are considered in mining and environmental approval processes.

Acidic waters are generally considered to be very similar regardless of whether they are generated via acidic groundwater, acid mine drainage or acid sulfate soils, with the exception that acidic waters in the Wheatbelt are generally also saline.

Rising naturally acidic groundwater (Wheatbelt)

Acidification associated with iron poses a significant threat to many Wheatbelt wetlands. It is associated with acidic groundwater; the groundwater of the eastern Wheatbelt is generally less than pH 5.5, and there are several areas of acidic groundwater in the Wheatbelt where the pH is between 3.0 and 4.5. It is thought that groundwater acidity was present in many areas prior to clearing and salinisation of the Wheatbelt landscape. While it is generally accepted that oxidation of sulfides is not the cause of this acidity[133] (unlike acid sulfate soils, below), researchers continue to investigate the cause for this groundwater acidity, with the most accepted explanation being that in wetter conditions in the past, waterlogged soils in affected areas were iron-rich and this water percolated to the groundwater over tens of thousands of years. This theory accounts for the fact that alkaline soils (calcareous or carbonate-rich) often overlie areas with acidic groundwater.[134] The iron-rich water is believed to have acidified soils below these carbonate layers, resulting in groundwater that is acidic but still contains some unreacted iron.

A range of human activities have mobilised this acidic groundwater, bringing it into contact with wetlands. Most importantly, the widespread clearing of deep-rooted native vegetation for agriculture has caused groundwater to rise extensively across the Wheatbelt, mobilising salts and bringing acidic and salt laden groundwater up the soil profile, affecting wetlands, waterways, valleys, farming land and infrastructure.[135, 136] The high concentrations of dissolved iron in this groundwater means that, as it rises and moves into more **oxidising** conditions in the formerly unsaturated zone and eventually seeps into wetlands, waterways and other low-lying areas, it has the potential to become even more acidic on exposure to oxygen through a chemical reaction known as iron oxidation/hydrolysis or **ferrolysis**, which can significantly lower pH.[134] While acidity in saline waters is rare on a worldwide scale[120], over a quarter of a million hectares of valley floors in the Wheatbelt are influenced by shallow saline groundwater that has pH of less than 4, to as low as pH 2.8.

The construction of deep (2–3 metres), open drains, or alternatively groundwater pumping, can intercept this saline, acidic groundwater. While acidic before discharge into a drain, the pH of drain waters can fall further due to the reaction of dissolved iron

Oxidation: the removal of electrons from a donor substance

Iron ferrolysis: a process by which anoxic groundwater containing dissolved ferrous ions is exposed to air and ferrous irons are oxidised to ferric ions, which reacts with water to form orange-brown precipitates, gels or crusts of ferric oxyhydroxides, releasing free hydrogen ions in the process with oxygen on exposure of the water to air. Deep drainage can also facilitate other acidifying processes, such as the exposure of sulfidic materials to oxygen (described in the next section). The water in these drains is transported downstream into receiving environments such as wetlands and waterways which can, in turn, be acidified.[137] Estimates in 2002 suggested that, of more than 90,000 kilometres of salinity earthworks constructed in the Wheatbelt, at least 4,000 kilometres are deep, open drains intercepting groundwater.[135] Approximately 1000 kilometres of deep drains are being constructed each year.[138] In the eastern Wheatbelt, more than half the drains sampled were strongly acidic, with an average pH of 3.0.

Wetland sediments can contain significantly more acidity than overlying water columns. For example, an analysis of samples found that some Wheatbelt wetlands contained up to several thousand times more acidity in sediments than in waters at the time of sampling, and shallow soils along wetland margins were found to have higher levels of acidity again.[135]

Given that naturally and human-induced acidic wetlands in the Wheatbelt appear to have similar geochemical properties[135], the extent of wetland acidification caused by human activities is difficult to determine (particularly that caused by groundwater rise and discharge). Studies indicate that acidic lakes may occur across a much larger area of the eastern WA Wheatbelt than previously recognised, with the extent and degree of acidification present unlikely to be attributable to natural causes (for example, Degens et al, 2008[135]). With groundwater rise and increased discharge likely to continue in many areas for coming decades, it is likely that more wetlands may become acidic, compounding the serious effects of secondary salinity; it has been found that acidic saline wetlands have less aquatic diversity than alkaline saline lakes.[139] Acidic groundwater is widespread across all agricultural regions of WA.[135]

Acid sulfate soils: includes all soils in which sulfuric acid is produced, may be produced or has been produced in quantities that can affect the soil properties. Also referred to as acid sulphate soils.

Potential acid sulfate soils: soils that can contain significant sulfidic material, which on oxidation can cause the pH of the soil to fall to very low levels

Active (or actual) acid sulfate soils: soils in which the sulfidic minerals have oxidised and the pH has fallen to very low levels

extra information

Technical information is available from the following reports:

- *Mapping acidic groundwater in Western Australia's Wheatbelt*[133]
- *Avon catchment acidic groundwater – geochemical risk assessment*[135]

Acid sulfate soils

Acidification in wetlands can also occur when naturally occurring sulfur compounds known as sulfides or pyrites present in rocks, soils or iron-rich groundwater are exposed to air.[137] When exposed to air, sulfides oxidise. They undergo a complex series of oxidation reactions that ultimately produces sulfuric acid. This can result in significant and sometimes persistent acidic conditions.

Sulfidic soils are known as **acid sulfate soils** or **ASS** for short. Left undisturbed and unexposed to air, they are harmless. In this state they are known as **potential acid sulfate soils** or **PASS** for short. When exposed to air, they are known as **active (or actual) acid sulfate soils** (**AASS**). The word 'sulfate' can also be spelt 'sulphate'.

The sulfides in PASS are commonly contained in waterlogged soil layers, often below the groundwater table and at a pH of between 6 and 8. The layers containing PASS materials can be clay, loam, sand, mud, peat or 'coffee rock' (cemented iron and/or organic rich sands), ranging in colour from pale grey to dark grey and black to red-brown and olive greens.[141,142] While they remain waterlogged, the sulfides in the soil are stable and the soil pH is usually circumneutral. Left undisturbed, PASS are harmless and can remain so indefinitely.

extra information

The formation of potential acid sulfate soils

Acknowledgement: some text sourced from Department of Sustainability, Environment, Water, Communities and Population.[140]

Potential acid sulfate soils are prevalent in wetlands because they form when there is a source of:

- sulfate, which in the Australian landscape comes mainly from ancient seawater brought inland with rain
- metal ions, some of which can be naturally prevalent
- organic matter, which builds up in many wetlands due to the presence of water/ lack of oxygen
- low or no available oxygen, due to the presence of water.

As shown in Figure 30, acid sulfate soils are formed by bacterial activity in waterlogged conditions when there is no or little available oxygen. Naturally occurring bacteria convert sulfate (dissolved salt) from seawater, groundwater or surface water into sulfide (another type of compound that contains sulfur). This sulfide reacts with metals especially iron in the soil sediments or water column, to produce metal sulfides (the main components of acid sulfate soils). In order to convert the sulfate into sulfide, the bacteria also need a source of energy provided by organic material such as decaying vegetation.

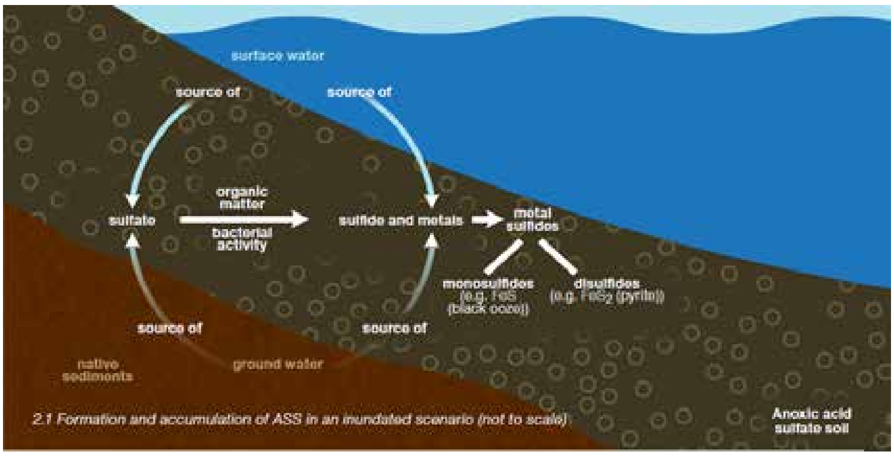


Figure 30. Formation and accumulation of ASS in an inundated scenario (not to scale). Source - *National Guidance for the Management of Acid Sulfate Soils in Inland Aquatic Ecosystems.*[131]

The issue of ASS has been recognised as being of national importance. In WA, acid sulfate soils are a critically important management issue, particularly for the groundwater dependent wetlands on the Swan Coastal Plain (Jurien–Dunsborough), the Scott Coastal Plain (Augusta–east of Donnelly River), the Albany–Torbay region, Geraldton, the Pilbara coastline and estuaries in the Kimberley. The extent of inland ASS is largely unknown at this time.[143]

Swan Coastal Plain wetlands that are undergoing ASS, have experienced ASS events or have permanently acidified, include Lake Gnangara (late 1970s), Lake Mariginiup (since at least 2005), Melaleuca Park, Lake Gwelup, Lake Wilgarup and Lake Jandabup (detected since 1997). Importantly, the **Bassendean Dunes** of the Swan Coastal Plain

Bassendean Sands: (also known as the Bassendean Dunes) a landform on the Swan Coastal Plain, comprised of heavily leached aeolian sands, located between the Spearwood Dunes to the west and the Pinjarra Plain to the east have also been identified as being of high to moderate risk; this area supports many seasonally waterlogged wetlands of high conservation significance, and in particular, many **damplands.** The Bassendean Dunes have been found to have the potential to become very acidic when soils are exposed to air, due to the very poor acid buffering capacity of their soils, which are typically dominated by quartz sands and which contain very little clays or carbonates.[144] The environment around wetlands that have acidified can also been severely affected; for example, acidic groundwater extends 5–10 metres below the watertable in Stirling.[128]

Damplands: seasonally waterlogged basin wetlands

Gnangara groundwater system: the groundwater system formed by the superficial, Leederville and Yarragadee aquifers located in northern Perth, east to Ellen Brook, south to the Swan River, west to the Indian Ocean and north to Gingin Brook

➤ Broad-scale risk maps have been compiled by DEC for several coastal regions of WA where a high or moderate probability of ASS occurrence has been identified. This risk mapping of acid sulfate soils is available via the DEC website: www.dec.wa.gov.au/management-and-protection/land/acid-sulfate-soils/ass-risk-maps.html

Triggers

Exposure of PASS to air occurs when the soils undergo drying or are disturbed.

Factors that can contribute to wetlands drying out include:

- less surface and/or groundwater entering the wetland, due to reduced rainfall, associated with climate change, such that the wetland has shorter periods of inundation and waterlogging and longer periods of drying out than normal, on a much more frequent basis
- lowering of the groundwater table due to over-extraction of groundwater (for example, bore water for irrigation)
- lowering of the groundwater table due to dewatering (for example, draining wetlands for urban development)
- lowering of the groundwater table as a result of deep drainage
- less surface water/lowering of the groundwater due to interception of rainfall by plantations
- compaction of soils, reducing their water-holding capacity.

Activities that disturb PASS include:

- earthworks such as excavating in or around wetlands
- digging drainage channels to manage waterlogging and salinity in agricultural areas
- fire, particularly the burning of peat, which may release significant amounts of stored acidity[126] and which can act as a source of acidification for extended periods of time because it can smoulder for months
- livestock and feral animals (for example, pigs and camels)
- vehicle access
- digging holes (for example, when planting)

Acidification of groundwater systems

The acidification of shallow groundwater that naturally interacts with wetlands has been identified in WA in recent years. An investigation found that groundwater acidification near the water table has occurred on a regional scale in Bassendean Sand in the **Gnangara groundwater system** due to oxidation of iron sulfide minerals.[124] This oxidation process has been triggered by a decline in the groundwater level, exposing iron sulfide minerals to oxygen. The investigation also identified associated impacts including elevated dissolved aluminium levels on a regional scale. This regional scale acidification affects the quality of groundwater for ecosystems and groundwater users. It presents a risk to the ecological value of wetlands on the Gnangara Mound.[102,119,120] For example, elevated levels of dissolved aluminium are flowing towards high conservation value wetlands including Lake Jandabup, Lake Mariginiup, Lake Gnangara, the Lexia wetlands and Egerton Seepage.[124]

A review indicated that acidification was also common on the crest of the Jandakot Mound[145] (located south of the Swan River). The risk to groundwater quality on the Gnangara and Jandakot mounds in Perth and surrounds due to iron sulfide minerals oxidation is predicted to increase, with researchers concluding that "As the depth to the water table increases due to water extraction, evapotranspiration by deep rooted vegetation (e.g. pine trees), development, dewatering and climate change we can anticipate drying of aquic soil profiles with a consequent release of acidity, consequently the above issues should represent priority areas for future research".[146] Wetland managers in areas of risk, such as the Bassendean Sand formation and similarly poorly buffered (non-calcareous) aquifers, can use well designed groundwater monitoring to inform management. Expert advice is typically needed to establish well designed monitoring programs in order to obtain consistent hydrogeochemical monitoring data from groundwater in the capture zones of wetlands.

Impacts of acidification

Acidic waters are generally considered to very similar regardless of whether they are generated via acidic groundwater, acid mine drainage or actual acid sulfate soils, with the exception that acidified waters in the Wheatbelt are also saline. Furthermore, naturally acidic wetlands and acid tolerant biota can suffer harm due to human-induced acidification.[147]

Wetland acidification affects wetland organisms both directly and indirectly. In addition to increased acidity, the key impacts of acidification are deoxygenation, the release of metals and metalloids and increased turbidity and smothering. Changes in bioavailability of nutrients can also occur. Each of these processes can have serious detrimental effects on organisms, and can be compounded when more than one occurs. The overall effect on wetlands is typically to alter their ecological characteristics and to reduce their biological diversity. Fish, crustaceans and molluscs are typically particularly sensitive to the direct and indirect effects of acidification. Changes in pH can also accelerate or retard the degradation of pesticides in wetlands.[14]

The rate and effects of acidification are dependent upon many factors, including the

- acidity generated
- amount of available buffering or acid neutralising capacity within the environment
- duration of acid generation/flows
- regularity of acid production/acid flows
- other factors, such as secondary salinity.

Cycles of decline and recovery in wetland macroinvertebrates have been documented. Sommer and Horwitz[148] documented cycles over 12 years of monitoring in three Gnangara Mound wetlands affected by drought-induced acidification. Acidification did not result in a reduction of the total number of macroinvertebrate families present, however, there were clearly identifiable groups of acid-sensitive taxa and acid-tolerant taxa. The effects of acidification were reversed in the wetland in the study that was artificially supplemented with water, with acid-sensitive taxa reappearing and acid-tolerant taxa decreasing in numbers.

extra information

Studies which consider the effects of acidification on wetland organisms in WA include:

- *The potential effects of groundwater disposal on the biota of wetlands in the Wheatbelt, Western Australia*[118]
- *Aquatic invertebrate assemblages of wetlands and rivers in the Wheatbelt region of Western Australia*[149]
- *Vulnerability of organic acid tolerant wetland biota to the effects of inorganic acidification*[147]
- *Macroinvertebrate cycles of decline and recovery in Swan Coastal Plain (Western Australia) wetlands affected by drought-induced acidification*[148]
- *Diatoms and invertebrates as indicators of pH in wetlands of the south-west of Western Australia.*[150]
- *Diatom and micro-invertebrate communities and environmental determinants in the Western Australian Wheatbelt: a response to salinization*.[151]

Impairment and death due to acidification

Although it can be difficult to separate out the effects of acidity from associated effects including deoxygenation, the release of metals and metalloids and increased turbidity and smothering, acidity of itself can have serious effects upon organisms. Acidity directly affects organisms by affecting the function of cells – specifically, the functions of enzymes and membranes.

Some wetlands are naturally acidic, and these wetlands support species that are tolerant of this acidity, and in some cases, may support acid-specialised species ('acidophiles' such as the brine shrimp *Parartemia contracta*, and the ostracods *Reticypris* sp. and *Diacypris* sp., which appear to be restricted to acidic conditions of pH lower than 5).[118] However the acidification of other wetlands can significantly alter the natural processes in their soils and waters, and affect wetland plants, animals, fungi, algae and bacteria; resulting in the loss of acid-sensitive species (commonly affected species include amphipods and isopods, ostracods, chydorid and daphnid cladocerans, mayflies, oligochaetes, clams and snails), favouring acid-tolerant species (for example, sandfly larvae, macrothricid cladocerans and water boatmen) and reducing biodiversity in wetlands.

Acidification can lead to impaired function, growth and reproduction, disease and death in some groups of wetland organisms. Some invertebrate groups are particularly sensitive to acidic conditions because appendages such as gills (filter-feeders) or calcareous shells tend to be acid-sensitive. Studies have found that crustacean abundance and richness are markedly reduced in acidic conditions due to their calcium needs and as acidic conditions can soften outer calcareous shells. Groups like mayflies and caddisflies, which have more porous bodies and larger membranous surfaces such as gills, also tend to be sensitive. Groups with a lower permeability to water and ions such as beetles are more resistant. Mosquitoes can actually become more prevalent in acidic waters[152] and may lead to an increasing prevalence of acid-tolerant mosquitoes which can carry diseases like Dengue fever and Ross River virus.[140]

Susceptibility of an organism can also depend on which stage of their life-cycle they are at when exposed. For example, acidification of sediments can affect the survival of organisms inhabiting sediment during resting stages.

At the wetland scale, impairment of wetland vegetation and algae can reduce the primary productivity of wetlands, with flow-on effects through trophic levels (herbivores, carnivores and decomposers). Low pH/low buffer capacity can provide poor environmental conditions for microbial growth[153] with most microbes growing within the pH range 4–9[154] and inhibit decomposition processes[42], resulting in less organic matter being cycled back into a form that can be used by plants and animals, ultimately limiting productivity. Death of wetland shrubs and trees can significantly reduce the shading of wetland waters, which can cause additional changes in the wetland, due to increased water/sediment temperature and greater amounts of light penetrating the water column.

Bioaccumulate: process in which tissues of an organism accumulate a chemical because uptake is greater than elimination and breakdown

Biomagnify: an increase in the concentration of a chemical along a food chain

Flocculation: the joining of particles (small objects) into loose masses (floc) in water

Impairment and death due to deoxygenation (loss of oxygen)

Individual wetlands differ in their capacity to buffer against natural changes in pH, particularly in their capacity to neutralise acid. This means that the severity of acidification will depend on the characteristics of each wetland. However, even in those wetlands in which the acid released during an acidification event is neutralised, the oxidation of these soils can consume oxygen, removing the oxygen from the water column. When this happens, organisms in the water column that rely on dissolved oxygen can perish if oxygen concentrations drop too much. Acidic drain waters in the Wheatbelt have also been found to often be poorly oxygenated, and these can lower the oxygen concentration in wetlands they discharge into.[121]

➤ For more information, see the information on oxygen in the topic 'Conditions in wetland waters' in Chapter 2.

Impairment and death due to the release of metals and metalloids

Acidification can trigger the release of toxic quantities of metals and metalloids from sediments, such as aluminium, iron, lead, copper, zinc, nickel, uranium, rare earth elements (lanthanum, cerium), cadmium, arsenic and selenium. For example, the solubility of aluminium is significantly increased when pH is less than 4.5. Iron from acid sulfate soils is known to stimulate harmful *Lyngbya* blooms. These metals are present naturally, but in many cases they may be present at elevated levels due to pollution.

These metals and metalloids are released from bound forms into dissolved forms, which are far more toxic to organisms. These metals can have toxic effects on plants, algae, animals, fungi and bacteria, leading to disease and death. Greatly reduced abundance and diversity of some types of organisms, such as macroinvertebrates, may occur. Metals such as cadmium and metalloids such as arsenic and selenium have the potential to be **bioaccumulated** in organisms and **biomagnified** in wetland food chains and cause effects such as genetic damage. Under these conditions, monitoring of organisms may detect declines in species richness, abundance and productivity. It is important to note that some metals and metalloids are as soluble in very alkaline conditions as under acidic conditions.[119] The community structure of wetlands can alter as a result, including the physical structure created by plant communities.

Acidified areas that have above background concentrations of contaminants in soils, sediments and/or waters, and which present or have the potential to present a risk to human health or the environment, may be classified as contaminated sites under the provisions of the *Contaminated Sites Act 2003*.[119]

➤ For more information, see the 'Managing metals' section in this topic.

Impairment and death due to turbidity associated with metal flocculation

Acidification can promote **flocculation** in the water column, and the resulting floc can coat the gills of fish, smother plants and benthic organisms and modify habitat, resulting in simplified ecosystems and a loss of biodiversity. For example, iron sludges and precipitates can smother organisms, and sludges are readily resuspended into the water column, repeatedly directly affecting organisms in the water column.

➤ For more information, see the 'Managing turbidity' section in this topic.

Changes in nutrient availability

In wetland soils, acidity can alter the availability of nutrients such as phosphorus, nitrogen, magnesium and calcium. For example:

- Calcium availability tends to be limited in acidic conditions.[155]
- Ammonium (NH_4^+), a form of nitrogen that is used by plants, algae and bacteria, may reach high levels under acidic conditions. Acidic conditions can inhibit nitrification, the process by which ammonium is converted to nitrate (NO_3^-). While both forms of nitrogen are available for plants, algae and bacteria, nitrate is much more easily lost from wetlands via groundwater flow and by the coupled process of denitrification, whereas ammonium is retained in wetlands. Nitrification rates are generally thought to drop steeply below a pH of 4.5.[154]
- Under acidic to neutral and oxygenated conditions, phosphate, a form of phosphorus that is used by plants, algae and bacteria, adsorbs or precipitates to iron and aluminium, particularly in freshwater wetlands. This reduces the availability of phosphorus for primary production. This is thought to be the case at Spoonbill Lake, an acidified wetland in the suburb of Stirling, which is reported to have become ultra-oligotrophic (that is, have very low nutrient levels), and as having a lack of wildlife.[156] However, under acid and anoxic conditions, phosphate can be released into the soil pore water if sulfur is present. This is because the sulfur facilitates the reduction of iron to form FeS.
- Very acidic conditions are not optimal for microbes, with most microbes growing within the pH range 4–9.[154] Decomposition processes are inhibited in poorly buffered waters[42], resulting in less organic matter being cycled back into a form that can be used by plants and animals, ultimately limiting productivity.

The alterations to nutrients compound the direct effects that wetland acidification causes.

➤ For more information on the relationships between nutrient availability and acidity, see the 'Conditions in wetland waters' topic in Chapter 2.

Increased salinity

Acidification typically increases the salinity of water, due to the release of sulfate salts. However, the increases may not be large in some freshwater wetlands.

Indicators of acidity

Indicators of PASS

There are often few visual indications of PASS being present. PASS are widespread in freshwater wetlands and coastal landscapes. They are common in wetlands with dark organic soils and muds, peaty sediments, pale grey sands and coffee rock (cemented iron and/or organic rich sands). DEC has mapped high risk areas for several coastal regions of WA. These provide a broad-scale indication of the area where PASS are most likely to exist in shallow soils (within 3 metres of the ground surface). No distinction is made in the risk maps between whether actual and potential ASS might occur.

➤ Maps showing areas that are at high risk of potential acid sulfate soils are available from the ASS webpages of the DEC website: www.der.wa.gov.au/your-environment/acid-sulfate-soils.

Net acidity: the degree of acidity in water, accounting for dissolved alkalinity (that is, acidity minus alkalinity, measured in units of CaCO3 equivalent per litre)

Identifying the presence of PASS

Confirming that PASS or AASS are present in a wetland can cost thousands of dollars. The Australian Government has adapted a two-stage approach for determining their presence or absence, described in the document, *National guidance for the management of acid sulfate soils in inland aquatic ecosystems*.[131] It entails a rapid assessment, and where this indicates a high likelihood of ASS, it is confirmed by carrying out a detailed assessment.

The rapid assessment uses data sourced from the desktop and a site visit. Desktop data includes:

- water and sediment quality data
- flooding history
- source of water

The site visit requires the collection of data quantifying:

- pH, and where practicable, field measurements of acidity and alkalinity
- conductivity
- sulfate

The purpose of the detailed assessment is to determine the wetland's **net acidity**. In simple terms net acidity can be summarised as acidity minus alkalinity. The below equation is used to calculate net acidity:

> Net acidity = potential sulfidic acidity + actual acidity + retained acidity – acid neutralising capacity

Net acidity accounts for the fact that some water has acidity (due to dissolved metals) and alkalinity (mostly as bicarbonate) at the same time (for reasons, see section 3.2 of Degens, 2009[121]).

Obviously, these investigations are highly technical and it is advisable that they are designed by an appropriately qualified practitioner with ASS experience. For more information, refer to the *National guidance for the management of acid sulfate soils in inland aquatic ecosystems*.[131]

Indicators of acidity (including AASS)

Soil and water characteristics can indicate that acidic conditions are having an effect upon the environment. A brief outline is provided below. Field tests and laboratory analysis provide diagnostic tools. For more information see:

- *Identification and investigation of acid sulfate soils and acidic landscapes*[143]
- Known sites of AASS recorded in the *Contaminated Sites Database*, available from https://secure.dec.wa.gov.au/idelve/css/.

Biological indicators

Visual indicators that a wetland may be acidifying include:

- plants in poor health, stunted or that are dead/dying
- the disappearance of wetland vegetation and the appearance of clear 'beaches' around the water's edge

- decreasing diversity of macroinvertebrates and increasing abundance of acid-tolerant fauna such as water boatmen (*Notonecta glauca*) and mosquito larvae
- an increasing abundance of filamentous algae (algae with long strands visible)

Soil indicators

Soil indicators of acidity including the presence of jarosite, iron staining, iron monosulfides, salt crusts and scalds.

- Jarosite is a good indicator of actual acid sulfate soils as it only forms under acid conditions. AASS are often recognised by the presence of 'flecks' of jarosite in soil profiles, which appears as either a butter-coloured (Figure 31) or mottled orange coloured mineral.

Figure 31. Jarosite is a butter or mottled orange coloured mineral that is a good indicator of actual acid sulfate soils as it only forms under acidic conditions.

- Increased iron staining can form around the water margins in summer months in response to acidification.
- Iron monosulfides are gooey black sediments formed in low oxygen environments. They can form in wetlands and drains. Beneath the water surface, they remain black and gooey. However, if the water is removed, the soil surface turns a bright orangey-red colour as the iron monosulfides are exposed to the air. Iron monosulfides should not be confused with iron floc (particles).
- Salt crusts on the soil surface can be a by-product of AASS and may indicate the need for further investigation. In inland areas, salt crusts are often found where groundwater tables are close to the surface (Figure 32).

Figure 32. White, fluffy salts accumulating on soil surfaces during summer may indicate acid salts: a combination of iron, aluminium, calcium and magnesium based salts. Photo B Degens/Department of Water.

- Spongy sediments, when excavated. They often resemble lava flow.
- Bare areas of land within or around wetlands may be either an acidic or saline 'scald'. Scalds occur when plants die and only bare soil remains (Figure 33). Once bare, the soil water evaporation is accelerated, drawing water containing toxic oxidation products from soil layers beneath the surface. The bare surface layers of the scald accumulate acidity and salinity during dry periods, due to increased soil water evaporation. During wet conditions, the concentrated pollutants can be washed into adjacent areas. Once bare, conditions that produce the scald can quickly develop further and revegetation can be difficult. Scalds can vary in size and are not always permanent features. During wet years, additional water in the soil may encourage salt and acid tolerant vegetation (including some weed species) to grow and the scald may disappear for a short time.

Figure 33. AASS scalding with salt crusting in a seasonally inundated wetland, Ravenswood. Photo – B Degens/Department of Water.

Surface water indicators

Indicators that groundwater is acidifying due to the oxidation of sulfides include:

- a sulfate/chloride (in milligrams per litre) ratio greater than 0.5 in estuarine environments
- an alkalinity/chloride (in milligrams per litre) ratio of less than 5 in freshwater environments
- a pH of less than 5
- a soluble aluminium concentration greater than 1 milligram per litre.[129]

Indicators that a wetland it is acidifying due to the oxidation of sulfides include:

- sudden decreases in pH, generally during summer months (in the south-west). During the early stages of acidification, pH values may moderate during winter[119]
- large diurnal (that is, between day and night) fluctuations in pH, with changes of up to 2 pH units occurring within a 24 hour period[119]
- decreasing alkalinity values[119]
- increasing values of the sulfate/chloride ratio[119]
- increasing concentrations of soluble iron and aluminium[119]

Visually, clear water, and water stained yellow, brown, orange, milky-white or blue-green can be a sign that acidification has occurred. Oily-looking bacterial scums may also be present.

- Milky-white water at pH of 5 to 6 can indicate aluminium particles due to reactions associated with AASS.
- Blue-green water with a pH of 4 to 5 is caused by aluminium floc (fine colloidal particles).
- Clear water isn't necessarily good water. Crystal clear water can indicate a pH level of 3 to 4. High levels of aluminium can cause the soil and sediment particles to drop to the bottom of the wetland, leaving the water clear (Figure 34).

Figure 34. Crystal clear acidic water (pH 3.5) with iron bacteria in a wetland near Mandurah. Photo – B Degens/Department of Water.

- Iron flocs (particles) can appear in the water at pH levels below 4. These flocs are usually coloured a red-brown or brown-yellow and will be present throughout the water (Figure 35). If water recedes, this floc is deposited on the vegetation and soil.

Figure 35. Iron floc in a seasonally inundated wetland, Jarrahwood. Photo – B Degens/Department of Water.

- Water affected by AASS can have high levels of dissolved iron, which colours the water yellow, brown or orange (Figure 36). Iron is soluble (dissolved) at pH levels below 3.8.

Figure 36. Yellow-brown water can be an indicator of iron, which is released from sediments under acidic conditions. Photo - A Lillicrap/Department of Food and Agriculture WA.

Other indicators

Acid can corrode concrete and steel (Figure 37). Noxious odours such as rotten egg smells (hydrogen sulfide) and metallic, burnt gunpowder odours (sulfur dioxide) indicate that acidification may possibly be occurring.

Figure 37. Road culverts that have corroded as a result of acidic drainage. Photo – B Degens/ Department of Water.

Preventing acidification

Preventing acidification associated with iron

Reduce the rate of rising acidic groundwater

Arresting the rise of groundwater in the Wheatbelt is a large scale, long-term endeavour. Effective management of rising groundwater relies on coordinated effort and investment across regions and areas of expertise and can be very costly to implement, with long-term time scales for change. Agronomic change, revegetation and protection of remnant vegetation are all part of the solution. As with secondary salinity, it will not be possible to stop the acidification of all wetlands in the Wheatbelt, and prioritisation processes will be important in determining which wetlands are identified for preventative measures.

➤ More information on approaches to arresting the rise of groundwater in the Wheatbelt are outlined in the topic 'Secondary salinity' in Chapter 3.

Design and management of drainage channels

Proposing new drainage

When proposing drainage into a wetland, an important consideration is the ecological and other values of the wetland. The wetlands receiving drainage water can be so adversely affected that they are often called 'sacrificial' wetlands, because their values have been sacrificed in order to save other values in the landscape.

Because of their potential to create serious environmental impacts, proposals to construct drains or pump groundwater in agricultural regions require assessment via the Soil and Land Conservation Regulations 1992 under the *Soil and Land Conservation Act 1945*. The principles for assessing drainage proposals are outlined in the 2012 Department of Water document, *Policy framework for inland drainage*.[12]

➤ More information on the assessment of new drainage proposals is available from:

- the Department of Agriculture and Food website www.agric.wa.gov.au/PC_93235.html
- the topic 'Legislation and policy' in Chapter 5.

A broadscale assessment of the value of many of the Wheatbelt's wetlands has been conducted by DEC. A methodology for assessing individual wetlands at a finer scale, as is needed to help determine its suitability as a sacrificial wetland, has been developed and published by DEC, for proponents to use in preparing an application to decision making authorities.

➤ For more information on the existing evaluation of Wheatbelt wetlands, and the detailed evaluation methodology for the region's wetlands, see the Wheatbelt wetland mapping page on the DEC website: www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-mapping/wetlands-of-the-wheatbelt-mapping.html.

Treating existing drainage

Treating acidic water of drainage channels prior to discharge into wetlands is an important intervention measure. The Department of Water has developed guidelines for treating acidic drain waters for the Avon catchment, based on trials.[157] These guidelines outline in-drain treatment options, including lime-sand beds, subsoil carbonate beds, in-drain composting beds and diversion wells. The guidelines also discuss end-of-drain treatment options including lime-sand basins, composting 'wetlands' (that is, purpose-built structures), lime-sand reactors and hydrated lime dosing.

The Department of Water has also published a discussion paper[120] on draft proposed interim acidity levels for discharge into Wheatbelt ecosystems, as outlined in Table 17.

Table 17. Draft proposed interim net acidity guideline for discharges into primary and secondary saline ecosystems in the Wheatbelt (DOW 2013[120])

Water quality parameter	Discharge to slightly disturbed ecosystems	Discharge to highly disturbed ecosystems
Net acidity	10 milligrams of calcium carbonate ($CaCo_3$) per litre, provided that the water has had time to react with air, to allow any metals to precipitate and settle as sludge prior to discharge	20 milligrams of calcium carbonate ($CaCo_3$) per litre

Preventing actual acid sulfate soils

Prevent oxidation of potential acid sulfate soils

PASS are benign when left in a waterlogged, undisturbed environment. Where PASS are present, disturbance and drying of the soil should be avoided. To minimise disturbance and drying, the Government of WA has put in place controls on the development of land, drainage alterations and water abstraction, as outlined below.

Controls on the development of land

Land development is subject to many controls to minimise the development of actual acid sulfate soils. These controls are outlined in the following documents:

- *Planning Bulletin 64/2009: Acid sulfate soils*[158], which provides advice and guidance on matters that should be taken into account in the rezoning, subdivision and development of land that contains acid sulfate soils. This planning bulletin introduces a set of revised acid sulfate soils planning guidelines.
- *Acid sulfate soils planning guidelines*[159], which outline the range of matters that need to be addressed at various stages of the planning process to ensure that the subdivision and development of land containing acid sulfate soils is planned and

managed to avoid potential adverse impacts on the natural and built environment.

Drainage associated with urban development needs to be approved via the appropriate land use planning legislation, and typically needs to be consistent with approved water management plans for the area. For more information, see the policy *Better Urban Water Management*.[160]

Controls on dewatering

Dewatering is regulated via groundwater abstraction licences from the Department of Water, except if an exemption applies. If a hydrological impact assessment shows that impacts are likely, dewatering management plans may be required as a condition of licence. The Department of Water must inform the Environmental Protection Authority if a water licence being sought under the *Rights in Water and Irrigation Act 1914* would have a significant effect on the environment. As outlined in the Department of Water's *Western Australian water in mining guideline*[161] and the *Strategic policy 2.09: Use of mine water surplus*[162], water generated by mining dewatering operations must first be used for the mitigation of environmental impacts. This involves ensuring that water is returned to the environment, through injection back into the aquifer or augmenting reduced environmental flows of groundwater-dependent wetlands. This is usually enforced via conditions of the licence.

➤ *Dewatering of soils at construction sites*[163] outlines how the Department of Water assesses impacts of dewatering associated with construction.

DEC also has requirements for proposed dewatering in proximity to wetlands. The document *Treatment and management of soils and water in acid sulfate soil landscapes*[119] (section 5.3.9) states that dewatering must not alter the wetland water level or water quality of valuable wetlands (such as conservation and resource enhancement management category wetlands). Proposals to dewater within 500 metres of a valuable wetland must implement a range of management measures to protect the wetland. These include:

- baseline laboratory analysis of wetland water quality data, capturing seasonal variation
- baseline water level monitoring
- water level and water quality monitoring during dewatering
- a range of monitoring, mitigation and remediation measures in the event of changes in water quality or water level.

There are alternatives to dewatering near wetlands. Driven pile construction, sheet piling and slurry walls can avert the need for dewatering associated with various types of construction. Trenchless technologies for installing or repairing underground cables and pipelines, such as microtunnelling, avoid the need for open trenching or dewatering.

➤ The Australasian Society for Trenchless Technology website (www.astt.com.au) is a source of information on potential alternatives to trenching and dewatering.

Dewatering techniques differ in their potential to affect nearby wetlands. For example, an array of dewatering well-points or spears connected to a common suction pump or vacuum extraction system is a technique that can have a larger radius of influence than sumps with submersible pumps at their base.[119]

Carrying out works when the watertable is lowest in summer can reduce the depth and/or size of the dewatering footprint and rates. Using groundwater recharge trenches to constrain the lateral extent of the cone of depression by creating a hydraulic barrier between the wetland and the cone of depression is another important technique. Examples of this can be found in the Pilbara.[164]

Controls on rural and semi-rural drainage alterations

To minimise the development of acid sulfate soils, rural and semi-rural drainage alterations are governed by the following controls:

- Proposals to construct drain or pump groundwater in agricultural regions require assessment via the Soil and Land Conservation Regulations 1992 under the *Soil and Land Conservation Act 1945*. The principles for assessing drainage proposals are outlined in the 2012 Department of Water document, *Policy framework for inland drainage*.[12]

Controls on water abstraction

Under the *Rights in Water and Irrigation Act 1914* the Department of Water requires applications for a licence to take groundwater to state whether acid sulfate soils been identified at the site, and when present, require an acid sulfate soils management plan to be submitted to the Department of Environment and Conservation.

Controls on activities that disturb wetland sediments

Activities that disturb wetlands are subject to approval under the *Planning and Development Act 2005* and the *Environmental Protection Act 1986*. These include activities such as:

- installing infrastructure, for example, boardwalks, drainage swales and so on
- burning of wetlands
- clearing of wetland vegetation and wetland buffer vegetation, including forms of clearing such as cattle grazing

Reduce the risk and extent of secondary salinity

The discharge of salts, including sulfate, to wetlands increases the potential for the formation of PASS. Therefore reducing the mobilisation of salts in the landscape is key. In agricultural areas, this can be achieved by preventing regional groundwater tables from rising above normal levels, and avoiding discharge of deep drainage into wetlands. Both of these management options tend to require regional-scale works and involve many land managers in the broader community. Arresting the rise of groundwater in the Wheatbelt and other agricultural areas is typically a large scale, long-term endeavour. Effective management of rising groundwater relies on coordinated effort and investment across regions and areas of expertise and can be very costly to implement, with long-term time scales for change. Agronomic change, revegetation and protection of remnant vegetation are all part of the solution. As with secondary salinity, it will not be possible to stop the acidification of all wetlands in the Wheatbelt, and prioritisation processes will be important in determining which wetlands are identified for preventative measures.

➤ For information on the management of secondary salinity, please refer to the topic ‘Secondary salinity’ in Chapter 3.

Maintain natural seasonal drying regime

Wetlands that are naturally wet on a seasonal basis and dry out in the intervening period limit the excessive accumulation of sulfide in sediments. This is because oxygen is used in preference to sulfate by bacteria, minimising the reduction of sulfate to sulfides. Maintaining this natural wetting and drying regime is therefore a cost-effective preventative measure.

extra information

Proactive monitoring by wetland managers

A number of the measures for preventing wetland acidification require decision-making authorities to control land or water use. However, some acidification triggers are not within the scope of these frameworks, for example, drying of wetlands caused by climate change. Wetland managers can play an essential role by identifying valuable wetlands that are at risk of acidification, monitoring them and providing an early warning of possible changes.

Wetland managers should advise DEC if there are signs of acidification or if triggers of acidification are likely (for example, a wetland is progressively holding less water each summer).

Where it is not possible for land managers with numerous wetlands under their management to continually monitor all the wetlands under their management, a prioritisation process for monitoring at-risk wetlands is a strategic way to manage the risk. Such a prioritisation process should take into account risk of acidification and the conservation value of wetlands (for guidance on the conservation value of wetlands, the wetland management category can be used, if available, or if not, guidance can be provided by DEC). To identify a wetland's risk of acidification, two factors should be determined: present and/or future triggers for acidification, as outlined in this topic, and the sensitivity of the wetland to acid generating processes. Table 18 shows a possible prioritisation matrix.

Table 18. Framework for prioritising wetland monitoring

Matrix 1: wetland acidification risk assessment framework

Acidification sensitivity (as per Table 16)	**Potential for drying, disturbance or receiving acid drainage (acidification triggers)**		
	Low potential	**Medium potential**	**High potential**
Not sensitive	Low risk	Low risk	Medium risk
Sensitive	Low risk	Medium-high risk	High risk
Acidified, critical, endangered or highly sensitive	Medium-high risk	High risk	High risk

Matrix 2: wetland monitoring priority framework

Wetland conservation significance	**Risk of acidification determined using matrix 1**		
	Low risk	**Medium risk**	**High risk**
Low (e.g. multiple use management category)	Lowest priority	Lowest priority	High priority
High (e.g. resource enhancement management category)	Lowest priority	High priority	Very high priority
Very high (e.g. conservation management category)	High priority	Very high priority	Very high priority

Treating acidification

Involve experts when dealing with acidification

Managing acidification can be a serious and complex issue. Inappropriate management actions can result in serious environmental harm, with economic and legal implications. Specialists should always be consulted.

Acidification often involves a complex series of chemical reactions which are influenced by the local geochemical conditions. Management of AASS requires a site-specific strategy developed using the findings of a detailed investigation that should only be conducted by practitioners experienced in this field. Once field investigation and testing has been completed, appropriate management actions can be developed. Options that can be considered as part of this planning process are described below.

➤ Key resources include:

- The acid sulfate soils webpage of DEC's website: www.dec.wa.gov.au/pollution-prevention/contaminated-sites/acid-sulfate-soils.html
- *Treatment and management of soils and water in acid sulphate soil landscapes*[119]
- *National guidance for the management of acid sulfate soils in inland aquatic ecosystems*[131]

Despite good intentions, because of the potential to cause environmental harm, a proposal to implement some of the options listed below may trigger referral to the Environmental Protection Authority for assessment under Part IV of the *Environmental Protection Act 1986*.

➤ For information on legislation and policy protecting WA's wetlands, see the topic 'Legislation and policy' in Chapter 5.

The management techniques described below may help to address the chemical, physical and biological changes that have occurred due to acidification, but success is not guaranteed. Trial and error is still common in this area, as highlighted in the below case study. Further trials at sites as well as laboratory studies are likely to provide more insight in future.

case study

Case study – treating the acidification of Spoonbill Lakes, Stirling

Spoonbill Lakes, two seasonally inundated basins in the Perth suburb of Stirling, have undergone acidification due to acid sulfide soils, and widespread acidification of the surrounding groundwater table has occurred. A number of factors contributed to the acidification of groundwater in the area, including a decline in the groundwater table due to low rainfall, the disturbance of sulfidic peat soils through dewatering and excavation for two new residential developments, and excavation of Spoonbill Lakes, with spoil used to create central islands. Groundwater pH measurements as low as 1.9 have been recorded, while the pH of the Spoonbill Lakes has been as low as 2.4.[128] A distinct plume of acidic groundwater stretches many hundreds of metres to the south, affecting domestic bores, and generally extends 5–10 metres below the watertable.[128]

A treatment trial has been carried out at Spoonbill Lakes by researchers at Edith Cowan University in partnership with the City of Stirling. The wetlands have low conservation value, having been seriously degraded by clearing, earthworks, alterations to their water regime and water quality. As a result, they have been identified as a 'multiple use' management category wetland by DEC (in the *Geomorphic Wetlands Swan Coastal Plain* dataset). For this reason, an *in situ* treatment trial was carried out by researchers.

The trial employed a number of techniques in a 'treatment train' sequence. These included neutralisation with sodium hydroxide, followed by settling and removal of iron and aluminium hydroxide sludge. This was followed by treatment using organic matter in two bioreactor tanks, using 10 tons of potatoes and *Eucalyptus* mulch. Following aeration down a concrete riffle, the water was directed through 1 ton of potatoes and mulch on the wetland bank, and 2500 rushes (*Schoenoplectus validus* and *Baumea articulata)* for aerobic polishing. The assessment of the treatment indicates that so far, some aspects of the water quality have improved, but that there have been a number of problematic outcomes that were not anticipated, and that to date the treatment has not improved water quality or increased biodiversity. Some aspects of the treatment are expected to become more important over time, while redesign of other parts of the treatment process have been identified in order to optimise the treatment processes.[165,156]

Neutralisation using chemical additives

Neutralising the acid produced may be a potential option at some wetlands. Some waterways in eastern Australia have been treated with chemicals with a high neutralising capacity. These chemicals are either applied to the water or the sediment to increase the pH buffering capacity. A range of chemicals have been tested, including calcium carbonate, calcium oxide, calcium hydroxide, lime kiln dust, magnesium oxide, sodium carbonate, seawater neutralised red mud, fly ash and biochar. These chemical ameliorants, and their advantages and disadvantages, are discussed in the *National guidance for the management of acid sulfate soils in inland aquatic ecosystems*[131] and *Treatment and management of soils and water in acid sulfate soil landscapes*.[119] Before investing is neutralisation programs, consideration needs to be given to the potential for future acid generation to occur and whether these causes can be addressed, and if not, whether neutralisation can be maintained.

Neutralisation may be a temporary treatment rather than a long-term solution. For example, despite being treated with 5 tonnes of calcium hydroxide, the pH of Spoonbill Lakes had returned to the pre-treatment level after not more than 1 month.[119] At this site, groundwater flow is continuing to transport acidity into the wetlands. Groundwater flow may continue to transport acidity into wetlands for many decades.[119]

It is necessary to consider the potential unanticipated effects of additives. For example, some neutralising agents can increase salinity, particularly those containing sodium (chemical symbol 'Na'). It is also necessary to consider aspects of water quality that can be modified during treatment. These include changes in nutrient concentrations, increases in salinity and changes in ionic composition. Contact of acidified water with a neutralising agent will cause precipitation of metals from solution, and consideration needs to be given to how issues such as flocculation will be managed. The potential to use materials to remove metals and attenuate acidity is likely to continue developing as research continues (for example, Wendling et al 2010[166]).

Neutralisation using chemical additives needs to be carefully planned. Proposals to apply neutralising agents need to be approved by the land owner and relevant authorities, including the relevant state government agencies. In the case of wetlands, this includes DEC. Technical expertise is needed to quantify the acidity in a wetland and determine the appropriate neutralisation agent, effective neutralisation value, application method, rate, volume and purity/contaminants in additives. It is possible to 'overshoot' and create highly alkaline conditions, which can also be extremely harmful to wetland organisms. Similarly, in severely acidified waters, elevation of pH to the acidity at which aluminium is most toxic—between 4.4 and 5.4—should be avoided.

The origin and potential other inadvertent effects of neutralisation materials also warrants attention. Reliance on natural materials that result in degradation of other natural environments is not sustainable (for example, quarrying of limestone from intact ecosystems). Additionally proposals to use alkaline waste materials need to rigorously demonstrate that they do not pose a risk to human health or the environment.

Neutralisation using organic matter (via microbially-driven increases in alkalinity)

Neutralising the acid produced in a wetland by generating alkalinity in a wetland is a potential option, although there are a number of issues to consider before proceeding. In essence, the addition of carbon sources in the form of plant material enables microbial respiration. This in turn reduces the oxygen levels in the wetland, leading to microbially-mediated sulfate and iron reduction, which initially creates a drop in pH, but ultimately produces alkalinity (that is, sulfate reducing bacteria use sulfate instead of oxygen for respiration, producing bicarbonate as a by-product). Carbon is typically added in the form of wetland plants or mulch of plant material. One of the risks posed by this option is that sulfate reduction produces sulfide – the material that caused the problem in the first place! This option needs to be carefully considered and is generally perceived as a stop-gap measure while longer term measures are being investigated. Microbially-driven neutralisation was employed as part of the treatment of Lake Mealup, as described in the case study below. The *National guidance for the management of acid sulfate soils in inland aquatic ecosystems*[131] outlines the principles of this treatment option, while section 7.3.1 of the *Treatment and management of soils and water in acid sulfate soil landscapes*[119] describes passive treatment systems that employ these principles. Locations where this form of treatment, driven by biological reactions, occurs are sometimes referred to 'bioreactors'.

case study

Case study – treating the acidification of Lake Mealup, West Pinjarra

Declining water levels in Lake Mealup culminated in the annual drying of the wetland each year from 1994 until 2012. This is thought to be due to a combination of reduced rainfall and a reduction in surface water flowing into the wetland, due to the closure of a shallow channel that had previously connected the wetland to the Water Corporation's Mealup Main Drain. Signs of drying and acidification were abundant: the pH dropped from 7 to below 3, algal blooms were common, waterbirds were less common and the invasive introduced bulrush *Typha orientalis* expanded to cover 80 per cent of the wetland. The Lake Mealup Preservation Society worked to secure the involvement and collaboration of many people and organisations in order to halt Lake Mealup's ecological decline. Studies confirmed the presence of actual acid sulfate soils. Approvals and funding were sought and provided to divert drainage flows from the Mealup Main Drain into Lake Mealup by way of a variable height weir on the drain. 43 hectares of *Typha orientalis* was flattened and left in situ to provide a carbon source to promote microbially-driven neutralisation of acid, and control of regrowth was carried out using herbicides. The first diversion of drain water was carried out in June 2012. The pH has stabilised at 7 and the signs of life are reappearing, with frogs and waterbirds evident. A close eye is kept on the wetland's water chemistry, with fortnightly monitoring of pH, oxygen reduction potential and dissolved oxygen. More information on this project is available from the topic 'Roles and responsibilities' in Chapter 5.

Figure 38. The dry sediment in an area of Lake Mealup, showing signs of acidification prior to the diversion of drainage flows into the wetland.
Photo – H Bucktin/DEC.

Figure 39. The crushed introduced bulrush ***Typha orientalis***, left in place to provide a carbon source following inundation. Photo – H Bucktin/DEC.

Figure 40. The adjustable height weir, receiving flows diverted from the Mealup Main Drain.
Photo – H Bucktin/DEC.

Figure 41. Lake Mealup, full in August 2012.
Photo – R Rose.

Reinstatement or artificial replenishment of permanent inundation

Where wetlands have dried out and the exposed acid sulfate soils have oxidised, causing acidification, reinstating permanent inundation or artificial maintenance (replenishment) of water levels can slow down or halt further acidification. By keeping wetland sediments covered with water, acid production can be more effectively managed. This technique has been employed to address acidification of Lake Jandabup, as outlined in the case study below. This technique can however present problems. Maintaining static water levels may alter the ecological integrity of wetland species that are adapted to changing water levels. Furthermore, sourcing the water from groundwater may cause further drawdown of the water table, and exacerbate the problem that led to the wetland drying out in the first place. Groundwater pumping is expensive and may not be suitable for every situation. It also does not address some of the major causes of acidification such as over-use of groundwater supplies and reduced rainfall. It is not a practical or sustainable solution for the vast majority of wetlands in the long term. Diverting surface water may provide a suitable water source for artificial maintenance. It is important that the diversion is not detrimental to receiving environments downstream if they are of equal or higher ecological value than the wetland being treated.

case study

Case study – treating the acidification of Lake Jandabup, Wanneroo

Lake Jandabup, a seasonally inundated wetland 22 kilometres north of Perth, became acidic as a result of increasing extent and duration of summer drawdown of water levels between 1997 and1999. This became apparent from routine monitoring of the water quality conducted by scientists from Edith Cowan University, who noticed that pH readings in surface waters declined from ~6 to 8 to ~4 to 5 over a four year period. Monitoring also indicated that changes in the aquatic macroinvertebrate community structure of the wetland had occurred in this period. Macroinvertebrate species such as small crustaceans, water snails and some types of worms disappeared or declined in number. Increases in acid tolerant species such as sandfly larvae, water boatmen and macrothricid water fleas was also indicated were also observed.

Researchers from Edith Cowan University carried out further research to find out why the wetland had become acidic. It was discovered that due to the prolonged drought conditions over a four year period, wetland sediments had become dry and cracked for longer than they normally would (over summer and autumn periods), leading to oxidation of exposed acid sulfate soils. When the sediments became wet again following subsequent autumn rains, a decline in pH occurred due to the acid released into the water column as a result of oxidation of the sediments.

To reduce the risk of further acidification occurring as a result of excessive drying and oxidation of acid sulfate soils, groundwater has been pumped into the wetland to maintain saturation of wetland sediments. The challenge in artificial maintenance of water levels in Lake Jandabup is that the wetland naturally wets and dries and wetland plants, animals, fungi, algae and bacteria are adapted to seasonal cycles in wetting and drying. As a result, artificial maintenance needed to find a balance between maintaining normal wetland ecological processes as much as possible whilst preventing further oxidation of acid sulfate soils. It was also necessary to consider the amount of groundwater pumped into the wetland, as this action could contribute to excessive drawdown of the water table impacting on other natural areas.

As a result of these management actions, artificial maintenance of water levels in Lake Jandabup has been successful. pH levels have returned to normal and macroinvertebrate species that had disappeared have returned to the lake. However, without other actions being taken, the wetland will revert back to severe drying and acidification if pumping ceases.

Revegetating acidified areas

Revegetation of persistent ASS scalds has several benefits. Plants increase the organic matter in the soil; reduce surface evaporation, minimising upward soil-water movement; intercept groundwater, leaving acidic products at depth; and bind up large amounts of soluble iron and aluminium.[167] Revegetating acidified soils involves some approaches not required in standard revegetation. Where ASS scalds persist, digging holes in the soil should be avoided, with planting in windrows consisting of wood mulch or other organic-rich organic material considered to be a suitable alternative. Mulch is considered to be the single most effective treatment[167] as it prevents evaporation, slowing the accumulation of acidity in the root zone; though for optimal results a combination of practices such as fencing, windrows, mulching and neutralisation with a chemical additive may be required. Sedges or other low-water use plants are often more appropriate than trees or shrubs that transpire large volumes of water and in doing so reduce the soil moisture level. These areas should be fenced to exclude cattle and feral animals that may disturb the soil and reduce plant germination, growth and survival.

Pesticide: any chemical or biological agent intended to kill animals or plants

Managing pesticides

Pesticides include all groups of chemicals used to control undesirable plants and animals, such as insecticides, herbicides and fungicides. They come in various physical forms including liquids/sprays, powders, pellets and baits.

Causes

Pesticides are, at times, deliberately applied directly to wetland areas, for example, for controlling weeds, insects such as midges and mosquitoes, and introduced animals such as exotic fish. Pesticides can also be unintentionally transported into wetlands in a number of ways including:

- careless use or spillage near wetlands, or discarding used containers and drums
- drainage of irrigation water or stormwater following rainfall after pesticide application
- leaching through soil profiles to the water table
- drift of spray to wetlands during application
- accidental application over wetlands during aerial spraying
- erosion and transport of contaminated soil particles and organic matter into wetlands.[168]

Sampling of drains in the Swan and Canning catchments in Perth found that "high concentrations of herbicides in drains that feed the Swan and Canning Rivers commonly appear to be linked to rainfall patterns, as heavy rainfall or overhead irrigation soon after irrigation can wash herbicides from foliage, causing loss with runoff".[23] The sampling also found that occurrences of insecticides in surface waters may be linked closely with heavy rainfall events causing insecticide runoff.

Pesticides are also present in wetlands as a legacy of their historical use. For example, in the 1950s and 60s organochlorines were applied to wetlands to kill midge larvae.[169] With far less regulation in the past, pesticides were often used in very large amounts, with very little management with regard to the natural environment, and a number of the pesticides used are still present wetlands of WA.

Impacts

Pesticide impacts are often considered in terms of toxicity and exposure (concentration and duration of contact). Pesticides can be taken up by wetland organisms through contact with body and respiratory surfaces, by ingestion of water, suspended particles and organic matter or by inhalation of aerosols. Once absorbed into body tissue, they can disrupt function at the cellular level, impair metabolism and result in damage to, or death of the affected organism. Effects of pesticides on wetland organisms and ecosystems as a whole are not well understood, particularly where several pesticides and/or other contaminants may be interacting in combination to produce a chemical 'cocktail'. Furthermore, some chemicals may persist in the soil and water longer than others, which may increase the likelihood of toxic effects in exposed organisms over a longer period. Persistence in the environment depends on the susceptibility of the pesticide to degrading processes such as photodecomposition (due to sunlight), microbial decomposition and chemical degradation.[170]

Some highly toxic pesticides causing **lethal effects** may have low persistence in the environment and conversely, some pesticides with lower toxicity may have a higher persistence in the environment. For example, the group of insecticides known as 'organochlorines' including DDT, dieldrin, aldrin and chlordane are known to persist in the environment for many years and may become 'liberated' from sediments under the right conditions.[168] Although they don't dissolve in water, they dissolve easily in fat, so they can accumulate in fatty tissues in the brain and reproductive organs, for example.[171] DDT was de-registered for agricultural use in Australia in 1987, while the use of chlordane and dieldrin was ceased in Australia in 1994. The importation, manufacture and use of all organochlorine pesticides has been completely banned in Australia since 2004. However, these compounds are still identified in sampling of aquatic ecosystems in WA today. Dieldrin, for example, is known to be particularly persistent in groundwater. **Endocrine** disruption, immune system damage, **carcinogenic**, **mutagenic**[14] and **teratogenic** effects are potential ecological impacts. The degradation products of many of these chemicals are even more toxic than the parent compound. Changes in pH can retard or accelerate the degradation of the chemical. The breakdown rate of the organochlorine pesticide endosulfan, for instance, increases rapidly in acidic waters, and the organophosphorus pesticide profenofos is many orders of magnitude more stable at pH 9 than pH 5.[14] Organophosphates, on the other hand, are thought to be less persistent than organochlorines, but they are water soluble and are far more toxic than organochlorines.[171] All of these factors play a role in the severity and duration of toxic effects on wetland ecosystems.

Known impacts on aquatic organisms from pesticides may range from **acute** to **chronic toxicity**, depending on the concentration of the chemical(s), duration of exposure and individual tolerance limits of exposed organisms. It is likely that the most serious impacts occur as a result of sublethal effects from chronic toxicity, where organisms become less able to tolerate other environmental stresses such as changes in salinity.[31] **Sublethal effects** involving cellular damage can result in impacts ranging from reduced ability of plants and algae to photosynthesise to disruption to fertility, reproduction and growth in animals such as birds, fish and macroinvertebrates. For example, atrazine, which has been found in many of the drains feeding the Swan River[23] is an endocrine disruptor which amongst other effects has been found to induce hermaphroditism in genetically male frogs at levels as low as 0.1 micrograms per litre (as cited by Foulsham et al 2009[23]).

It should be noted that toxicity testing of herbicides often only tests the active compound. Herbicide formulations often contain additional substances such as fillers, wetting agents, solvents or stabilisers. Some of the additives in commercial formulations may have a harmful effect on aquatic life or may modify the toxicity of the herbicide.[172] Glyphosate is an important point in case. It is a broad spectrum, non-selective herbicide. It is the most extensively used herbicide in Australia today. Only some formulations of

Lethal effect: where exposure to an agent such as a toxin results in death

Endocrine system: a complex network of glands and hormones that regulates many of the body's functions, including growth, development and maturation, as well as the way various organs operate

Endocrine disruptor: a synthetic chemical that when absorbed into the body either mimics or blocks hormones and disrupts the body's normal functions

Carcinogenic: cancer-causing

Mutagenic: mutation-causing

Teratogenic: causing malformations of an embryo or foetus

Acute toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent in a short time (usually less than 24 hours)

Chronic toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent over a longer time period (months or years)

Sublethal effect: where exposure to an agent such as a toxin is insufficient to cause death, but may result in other adverse impacts glyphosate are currently approved for use on environmental weeds in or near aquatic ecosystems in WA, in accordance with the off-label permit. This off-label permit, PER13333, has been obtained by the Department of Agriculture and Food from the Australian Pesticides and Veterinary Medicines Authority and is in force until March 2017. The reason why only some glyphosate formulations are permitted for use in or near aquatic ecosystems is that non-target organisms may be harmed. In particular, tadpoles and mature frogs have been found to be extremely sensitive to the **surfactants** (surface active agents, a type of **adjuvant**) used in many glyphosate formulations. They can cause damage to tadpole gills and frog skin, and result in death (e.g. Mann 2000[173]; NRA 1996[174]; DEP 1995[175]). Newer formulations of glyphosate are now available, for example, Roundup Biactive®, which is reported to be one hundred times safer for frogs than the original Roundup® formulation.[176] However people may mistakenly assume that it is safe to combine any adjuvant with a safe formulation. Extreme care needs to be taken to ensure that adjuvants used are permitted for use in or near wetlands.

Surfactant: a substance that helps water or other liquid to spread or penetrate. Also known as a wetting agent or penetrant.

Adjuvant: includes substances such as surfactants, oils, penetrants and wetting agents

Bioaccumulation of pesticides, where pesticides accumulate in organisms over time, may occur in wetlands. This applies to persistent pesticides such as organochlorines, for example, DDT, dieldrin and chlordane. Accumulation can result in consumers that are high in the food chain, such as birds and mammals, suffering toxic effects as a result of eating contaminated fish or crustaceans that have accumulated high levels of chemicals in their tissues.

It is important to remember that wetland organisms can be exposed to pesticides outside of water. For example, reptiles including turtles, frogs, lizards and snakes, and mammals such as quenda can be exposed to pesticides sprayed on wetland vegetation in seasonally waterlogged areas and adjacent dryland areas; and mobile species such as birds can be exposed to pesticides further afield.

Indicators

Visual indicators of pesticide contamination may range from decline in health of individual organisms sensitive to particular toxicants (for example, plant deaths from exposure to herbicides) to mass mortality events (for example, death of fish, frogs, birds etc). Indicators may provide some insight as to whether the contamination is mainly in the form of pesticides that are adsorbed to particles, for example, if filter feeders and detrital feeders are the predominant groups affected (through the ingestion of particles). The time taken for organisms to display visual symptoms of toxic poisoning after initial exposure will vary depending on a range of factors including the nature and concentration of the toxicant(s), sensitivity of individual organism/species and frequency, duration and nature of exposure. External symptoms of toxicity may not be evident and impacts may go unnoticed until longer term effects such as decline in species abundance and diversity becomes apparent due to effects such as decreased fertility and reproduction and increased birth defects.

The presence of pesticides can be more accurately determined through testing of water and sediment or alternatively, testing organisms via tissue samples from affected organisms such as fish, crustaceans and molluscs. Herbicides tend to be more concentrated in surface water, whereas the less soluble insecticides are more likely to be concentrated in sediment (as cited by Foulsham et al 2009[23]). Where contamination is suspected, samples of water and/or sediment should be analysed by chemical laboratories to determine the presence of specific pesticides. The results of testing should then be compared against trigger values for pesticides in Chapter 3.4 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.*[14] There are two important notes about the guideline trigger values: they are for freshwater ecosystems, they have not been developed for application to saline wetlands; and concentrations do not account for the potential of pesticides to bioaccumulate.

Table 19. Default trigger values for pesticides in freshwater wetlands in WA, from the ***Australian and New Zealand Guidelines for Fresh and Marine Water Quality***.[14]

Parameter	Effectively unmodified wetlands, with high conservation/ecological value	Slightly to moderately disturbed freshwater wetlands
Pesticides in water	Chemicals originating from human activities should be undetectable. Naturally occurring toxicants should not exceed background concentrations	Refer to Table 3.4.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*
Pesticides in sediment		Refer to Table 3.5.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*

Managing pesticides

Management of pesticides should focus on preventing their entry into wetlands through reducing level of usage at the point source and controlling levels in inflowing groundwater and surface water runoff.

➤ The use of pesticides to control midges and mosquitoes in wetlands can contribute significant amounts of pesticides. The management of pesticides used for this purpose is discussed in the topic 'Nuisance midges and mosquitoes' in Chapter 3 of this guide.

In an emergency

In the event of an accidental spill of pesticides, or adverse effects to wildlife or wetlands occurring, call the Pollution Watch Hotline: 1300 784 782 (24 hours). In the event of a hazardous materials release or life-threatening incident, call 000 and ask for Fire and Rescue).

Research into the treatment of contaminated water is progressing, for example, CSIRO researchers have developed a nanomaterial that can filter herbicides such as paraquat in water. However the widespread application of such technologies for wetland protection is likely to be limited due to their diffuse pollutant sources and cost. Activated carbon and carbonaceous material is identified as a potential amendment material for pesticide-polluted sediments.[177] However, once pesticides enter a wetland, treatment options are very limited at most wetlands. Pesticides decompose in soil and water, but the total decomposition time can range from days to years. Removal of soils contaminated with pesticides requires special permits and involves a highly regulated disposal process. Seek advice from DEC if this is being considered. If pesticides are present in a wetland, minimising their harmful effects is a key strategy. Disturbance of sediments with high levels of pesticides bound to them should be avoided, in order to reduce the potential for resuspension and remobilisation of pesticides into the water column.

All pesticide users are bound by legal requirements, as outlined in the text box below, but the levels of pesticides detected in aquatic systems in WA indicate the need for awareness and behaviour change across the cross-section of pesticide users. All parts of our community, from individuals, non-government organisations, for-profit sector and local and state government, can take actions that will contribute to reduced pesticide pollution of WA's wetlands.

Specific strategies and techniques for preventing and managing pesticide pollution in wetlands include:

- Better managing wetlands so that the need for pesticide application is reduced. Chemical-free methods for preventing and controlling the invasion of weeds, introduced pest animals, and nuisance populations of midge and mosquitoes are outlined in this guide – see the topics 'Introduced and nuisance animals' and 'Wetland weeds' for information. In the future a topic 'Nuisance midges and mosquitoes' may also be available.
- Reducing the use of pesticides in surrounding urban, peri-urban and agricultural areas and replacing chemical control options with chemical-free forms of pest and weed control where feasible.
- Reading and following the guidance in the Materials Safety Data Sheet (MSDS) for each product, available from various websites such as www.msds.com.
- Observing best management practices. Many industry bodies have developed specific codes of practice or guidelines to assist industry practitioners with this. Key resources are presented in Table 20 below.
- Training of pesticide users. Almost all pesticide training carried out in WA is provided by ChemCert WA, an independent, not for profit organisation that provides a range of pesticide training courses delivered either by independent consultant trainers, or through the TAFE colleges. For more information on training, see *A guide to the use of pesticides in Western Australia*.[178]
- Careful timing of pesticide application is important; for example, contamination of wetlands from groundwater leaching and surface runoff is less during dry periods than in wet conditions, and during still periods the risk of spray drift is less than in windy periods.
- Best practice management of stormwater in the catchment. For example, converting piped discharge into wetlands to overland flows through vegetated buffers can help attenuate pesticide levels. Management of sediment entrained in runoff and erosion can reduce the transportation of contaminated sediments and organic matter into wetlands. This may involve use of vegetated buffer strips or swales, creation of artificial wetlands and other structures such as sediment traps and infiltration basins to assist in settling out and removing sediments and suspended particulate matter from water flowing into wetlands. For more information, see the *Stormwater Management Manual for Western Australia.*[30]
- Appropriate storage and disposal of pesticide chemicals and containers. ChemClear® and DrumMuster provide these services.

  ChemClear® (www.chemclear.com.au) provides a reliable and responsible recovery, collection and disposal service is a hazardous waste recovery, collection and disposal service for currently registered obsolete rural chemicals manufactured by association members of Crop Life Australia Limited, Veterinary Manufacturers Association (VMDA) and other participants. This service is offered to users of agricultural and veterinary chemicals.

  DrumMuster (www.drummuster.com.au) is a chemical industry organisation that, in conjunction with cooperating local governments, provides a pesticide container disposal service for empty, clean agvet chemical containers. It collects millions of drums each year totalling thousands of tonnes of waste.

➤ For information on minimising unintended impacts of herbicides in wetlands, see the topic 'Managing weeds' in Chapter 3.

Legal requirements of pesticide users

In Western Australia, anyone who uses pesticides is bound by the Health (Pesticides) Regulations 1956 of the *Health Act 1911*. These regulations were developed to provide protection for the applicator, the public and the environment from misuse of pesticides. Pesticide labels are written in accordance with the regulations and therefore any pesticide user has a legal obligation to read and follow instructions on the label. The label provides instructions for use, for the protection of the environment, information about storage and disposal and recommendations for personal protective equipment. By law and without exception, pesticides cannot be used in any manner contrary to that described on its label without the permission of the Australian Pesticides and Veterinary Medicines Authority. For more information refer to www.apvma.gov.au/publications/fact_sheets/docs/permits.pdf, and to view the minor use and emergency use permits that have been issued, see www.apvma.gov.au/permits/search.php. Anyone proposing to apply a pesticide to a natural area of conservation value should have appropriate authorisation and should undertake training in the correct preparation, handling, application, transport and storage of pesticides. Extreme care must be taken to ensure that the use of pesticides does not constitute an offence or cause environmental harm. Legislation regarding the use of chemicals is under review and in future this may become a legal requirement. *A guide to the use of pesticides in Western Australia*[178] from www.health.wa.gov.au/publications/documents/11627_Pesticides.pdf is recommended reading for pesticide users. Reports of illegal pesticide use within natural wetlands should be reported to DEC.

Table 20. Guidelines on managing pesticides

Application	**Guideline**
General	*A guide to the use of pesticides in Western Australia*[178]
Local governments	*A guide to the management of pesticides in local government pest control programs in Western Australia*[179]
General	*Contaminant spills – emergency response* WQPN[180]
General	*Toxic and hazardous substances – storage and use* WQPN[181]
General	*Pest control depots* WQPN[181]
General	*Nutrient and irrigation management plans* WQPN[68]
Industry-specific	
Dryland crop industry	*Aerial spraying of crops with pesticides* WQPN[182] *Agriculture - dry land crops near sensitive water resources* WQPN[77]
Floriculture industry	*Floriculture activities near sensitive water resources* WQPN[78]
Horticulture industry	*Best environmental management practices for environmentally sustainable vegetable and potato production in Western Australia: a reference manual*[79] *Code of practice for environmentally sustainable vegetable and potato production in Western Australia*[80]
Orchard industry	*Orchards near sensitive water resources* WQPN[81]
Turf industry	*Environmental guidelines for the establishment and maintenance of turf and grassed areas*[82]
Viticulture industry	*Environmental management guidelines for vineyards*[83] *Wineries and distilleries* WQPN[84]
Aquaculture industry	*Aquaculture* WQPN *85*
Animal industries	*Stockyards* WQPN[86]
Abattoir industry	*Rural abattoirs* WQPN[87]

Application	Guideline	
Beef industry	*Guidelines for the environmental management of beef cattle feedlots in Western Australia*[88]	
Dairy industry	*Dairy processing plants* WQPN[89]	
Horse industry	*Environmental guidelines for horse facilities and activities*[36]	
Pastoral rangeland industry	*Pastoral activities within rangelands* WQPN[92]	
Pig industry	*Environmental guidelines for new and existing piggeries*[93] *National Environmental Management Guidelines for Piggeries*[94]	
Poultry industry	*Environmental code of practice for poultry farms in Western Australia*[95]	
Associated benefits		
Cost effectiveness, compliance with environmental regulations, corporate citizenship.		
Who to go to for assistance		
Department of Agriculture www.agric.wa.gov.au Department of Water www.water.wa.gov.au Department of Environment and Conservation www.dec.wa.gov.au		
Relevant regulation		
Health (Pesticides) Regulations 1956 of the *Health Act 1911*	Department of Health	
Environmental Protection (Unauthorised Discharges) Regulations 2004 of the *Environmental Protection Act 1986*	Department of Environment and Conservation	
Approval may be required to establish and operate an intensive animal industry. This may include a works approval, license or registration under the *Environmental Protection Act 1986.*	Department of Environment and Conservation	

➤ The following are sources of more information on pesticides:

- The Department of Health's pesticides webpage: www.public.health.wa.gov.au/3/1139/2/pesticide_use.pm
- Section 8.3.7.15 through to section 8.3.7.21 of the *Australian and New Zealand guidelines for fresh and marine water quality. Volume 2. Aquatic ecosystems - Rationale and background information (Chapter 8)*[14]
- The Australian Pesticides and Veterinary Medicines Authority: www.apvma.gov.au
- National Pollutant Inventory: www.npi.gov.au

Managing metals

A number of metals and metalloids (semi-metals) that have been associated with contamination and potential toxicity in aquatic ecosystems include aluminium, lead, cadmium, mercury, arsenic, chromium, copper, iron and zinc. Metals and metalloids are collectively referred to as 'metals' in this topic and can occur in many forms in water, including dissolved or attached to particulates and sediments.

Causes

Metal pollution

Metals can occur naturally in wetlands in low concentrations, sometimes referred to as natural 'background' levels. There is natural variation among wetlands, due to factors such as geological substrate of groundwater. For example, it has been proposed that concentrations of most metals are naturally high in surface waters of salt lakes in the Goldfields, based on evidence of the concentrations of cadmium, cobalt, chromium, copper, lead, nickel and zinc.[40]

Human activities can increase levels of metals in wetlands significantly, beyond the tolerance of wetland organisms. Metal contamination tends to be highest in areas situated in close proximity to mine sites (both active and abandoned), industrial installations and heavily populated areas such as cities. The document *Potentially contaminating activities, industries and landuses*[183] indicates that metals are a very common potential contaminant type, used in such a wide range of industries and land uses. Examples of activities that generate metals as a product or by-product of their operations include pulp mills, coal fired power stations, tanneries, foundries, and plants producing petrochemicals, chlor-alkali, fertilisers, metal plating, glass, cement, textiles, paints and pesticides.

Metals can enter wetlands from diffuse sources such as atmospheric deposition, urban and agricultural stormwater, groundwater discharge and leaching; and point sources such as accidental spillages and discharge of metals, products containing metals, and contaminated wastewater from urban, mining, industrial and agricultural land uses. Metals are transported attached to sediments or dissolved in water. As such, most metals in wetlands are found in suspended particles in the water column and within the sediment.[46] Metals in sediment are generally orders of magnitude more than levels in water (in fact, the US Environmental Protection Agency states that sediment solids can hold up to a million times more metal than an equivalent volume of water[184]). Input into wetlands generally occurs as short, intense pulses during flow events, but can also occur as slow, gradual inputs via contaminated groundwater.

Examples of metal pollution in WA wetlands include:

- lead detected in Lake Monger in Perth's northern suburb is thought to originate from landfill, road runoff and aerosols. In 1991 it was estimated that 138 kilograms of lead were entering the lake per year, primarily via stormwater drains.[34] High levels of arsenic, zinc and copper have also been detected.
- the application of superphosphate fertilisers in WA since 1982 has resulted in more than 273 tonnes of cadmium being added to ecosystems.[185] Fifty percent of this is water soluble and therefore eventually leaches into waterbodies and accumulates in the sediments.
- metals in mine dewatering discharge. In salt lakes of the Murchison and Coolgardie bioregions, dewatering discharge has been implicated as a source of arsenic, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel and zinc.[40,186] Salt lakes with high concentrations of metals have been linked to lower **diatom** species richness and often abundance, with strong correlation between the discharge footprint and the effect upon diatoms in larger salt lakes.[40]
- metals including copper sulfate, arsenic and mercury have also been applied directly to wetlands in an effort to control algae.[111] Copper chrome arsenate (CCA) treated wood may have been used in wetland areas.[187]

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, freely moving in the open water and forming fossil deposits

Metal dissolution, precipitation and suspension in-situ

The chemical form a metal takes in wetland soils or water influences how mobile and available a metal is to organisms – in short, its bioavailability. Understanding bioavailability is essential in assessing the potential toxicity of metals and their compounds. Human-induced changes in water chemistry can alter the mobility and bioavailability of metals and is a major cause of metal toxicity in some wetlands.

The bioavailability of chemical contaminants in the environment depends on the nature of the medium in which they are found (for example: soil, water or organic matter). Soil chemical and microbial processes affecting metal mobility and toxicity are very different in wetland soils compared to dryland soils. A number of metals present in wetlands may be more or less toxic, depending upon the water chemistry, and in particular, the acidity. Water-soluble metals are the most mobile and plant-available form, and together with exchangeable metals (those weakly bound to soil surfaces by cation-exchange processes), are considered to pose the most risk to organisms[188] (see the text box below for more information on different chemical forms metals may take). Where sediments are highly contaminated with metals, bioavailability will be low if the metals are bound very strongly to sediment particles, such as when sediments have a high clay/humic fraction. If conditions change, for example the water becomes more acidic, the bonds between metals and sediments may be broken and metals will be released into the water where they can be taken up by organisms. Dissolved organic matter derived from the partial decomposition of organic materials is also a powerful agent for the binding of metals and therefore also plays an important role in regulating metal toxicity and mobility.[189] This includes fulvic and humic acids, products of the degradation of lignin and cellulose, which can stain the water the colour of tea. Decomposition of dissolved organic matter can release metals.

extra information

Chemical forms metals may take in wetlands

Metals can exist in a range of chemical forms including:

- water-soluble metals
- metals soluble as free ions
- metals soluble as inorganic or organic complexes
- exchangeable metals
- metals precipitated as inorganic compounds including metal oxides, hydroxides and carbonates (strongly controlled by pH)
- metals complexed with large molecular weight humic materials
- metals adsorbed or occluded to hydrous oxides
- metals precipitated as insoluble sulfide
- metals bound within the crystalline lattice structure of primary minerals

Source: Wright and Keddy[188] (undated)

The pH and water hardness are particularly influential; pH is probably the single most important variable that influences the behaviour of metals in the environment; and in sediments, redox potential is also considered to be a controlling factor.[184] If pH becomes moderately to strongly alkaline or acidic, metals may be converted to mobile forms. For example, dissolved aluminium is most toxic to aquatic organisms in freshwater at pH values of 5 to 6.[119] Studies have found fish, amphibians and phytoplankton to be susceptible.[14] Acidification processes, such as acid sulfate soils, and acid mine drainage can result in metal toxicity in wetlands. Acid mine drainage can be a significant source of metals through seepage and stormwater containing acidic water from tailings or spoil heaps into groundwater, natural or artificial waterways and wetlands. Acid wastewater from mining operations may not only contain toxic metals, its acidity can trigger the release of metals stored in sediment of receiving wetlands, rendering them bioavailable. Not all metals are more soluble or toxic with increasing acidity; zinc toxicity, for example, generally decreases with decreasing pH below a pH of 8.[14] Redox potential is also important, with sediment oxygen deficiency altering the chemistry of metals such as iron and manganese, which in turn will affect the behaviour of other heavy metals that were previously bound to oxides of iron and manganese.[14]

The toxicity of many metals decreases with increasing water hardness. This is the case for aluminium, cadmium, copper, lead and zinc for instance.[14]

As more permanently inundated wetlands undergo drying due to climate change and other factors, they are at risk of metal mobilisation. Permanently inundated wetlands tend to accumulate humic materials, which metals have a strong association with. In aerated soils that occur due to drying, decomposition of organic matter is enhanced and metals bound to organic matter are released, leading to enhanced bioavailability of metals. Drying of these wetlands can also result in the dissolution of metal sulfides, mobilising metals and releasing acid.

Impacts

All organisms require certain trace metals (such as manganese, zinc, cobalt and selenium) for normal growth and functioning at low concentrations. These elements occur naturally in soil and water as a result of physical and chemical weathering of rocks over millions of years. Some metals are relatively abundant and have naturally high concentrations, such as aluminium and iron, while others are rare and have naturally low concentrations, such as mercury, cadmium, silver and selenium, which are collectively referred to as 'trace elements'. At low concentrations, many of these metals are referred to as 'micronutrients' that are essential for life (though lead, cadmium and nickel have no known botanical function[188]).

Metals can become toxic when concentrations exceed natural levels and are in a bioavailable form, but it is important to note that the toxicity of metals is species-specific. In addition, the concentration at which any given metal becomes toxic depends on the metal itself and factors such as temperature, pH, water hardness, phosphate concentrations, salinity and interactions with other metals.[46] In general, low pH and high water temperatures increase the bioavailability and toxicity of metals, whilst high salinity and increasing water hardness decrease the toxicity and uptake of trace metals.[14,190,190]

The toxic effects of metals can result in changes in the abundance and diversity of wetland species and the composition of wetland communities. In immediate areas of high concentrations, in certain forms, metals can be highly reactive with algae, plants and animals. Metals enter wetland organisms through body and respiratory surfaces, and by ingestion of water, suspended particles and organic matter. Once absorbed into tissue, they can disrupt function at the cellular level, impair metabolism and result in damage to, or death of the organism. While sediments are the major accumulator of metals in wetlands, wetland plants and macroinvertebrates can also accumulate metals, but generally to a lesser extent.

Plants can absorb and accumulate metals from the sediment, water or air, depending on the degree of inundation and/or emergence out of the water.[191] For example, a study by the Bannister Creek Catchment Group in Perth's south-eastern suburbs found that watercress (*Rorippa nasturtium-aquaticum*) in Bannister Creek contained zinc, manganese, lead, copper, chromium and arsenic. In response to reports of locals harvesting watercress from the creek, the Water Corporation and Department of Health warned people that the continued consumption could be detrimental to people's health and should not be fed to farmed animals like chickens. While local research on the effects of metals on local wetland plants is limited, aquatic plants are thought to be particularly sensitive to iron, copper and aluminium.[118] It has been suggested that sedges have higher tolerances to heavy metals than shrub and tree species (for example, Regeneration Technology 1995[34]).

As reported by Jones et al (2009)[118], an increase in trace metal concentrations in wetland water may result in the loss of sensitive plant species and a reduction in productivity and growth. The specific metal sensitivities of WA wetland plant species are not known.

Wetland plants display a wide range of tolerances to iron. A study of iron toxicity in forty-four British wetland plant species found that iron concentrations greater than 10 milligrams per litre influenced the growth and distribution of wetland plant taxa.[192] Monocotyledonous species tended to have higher tolerance to iron compared to dicotyledonous species. Symptoms of iron toxicity include growth retardation, reduction in leaf size, abnormalities in root growth and discolouration of leaves.

In excess, copper inhibits vegetative growth, induces senescence, reduces photosynthesis and disrupts membrane integrity. Toxicity thresholds vary considerably between plant species. Some species of algae are particularly sensitive to copper.[14]

The tolerance of plants to excessive aluminium varies widely between species and no thresholds are available for WA species. Aluminium toxicity limits growth in acidic conditions. This is generally applicable at a soil pH of less than 5.0, but can occur at around 5.5. Aluminium toxicity in acidic soils has been shown to reduce plant rooting depth by interfering with cell division in plant roots, increase susceptibility to drought by interfering with the uptake, transport and use of water and several elements (calcium, magnesium, phosphorus, potassium) and decrease the use of subsoil nutrients by fixing phosphorus in a less available form in the soil or plant roots. Algae are generally the most sensitive to aluminium.[14]

A range of animals, including fish, birds, frogs, mussels and mammals, can accumulate metals such as lead, cadmium and selenium through direct exposure or by consuming plants and other animals that contain them. Limited information exists on the toxicity of trace metals to Australian invertebrates, but in general terms zinc and lead are thought to be of particular concern.[118] Metals can be taken up by plants or animals over a period of time and passed on through the food chain without immediate noticeable effects. As the level of toxins increase within affected organisms, when symptoms do present, they may occur as skin lesions due to fungal infections in fish, thinning of bird's egg shells and birth deformities. International studies suggest that lead exposure in frogs can result in physical deformities and defects, behavioural changes, reduced reproductive success and death.[193]

Researchers found that cadmium in superphosphate fertiliser easily leaches into stormwater and groundwater, then travelling into wetlands and waterways. Cadmium can then enter the food web through algae and benthic animals and may ultimately be passed to humans. The cadmium levels of the priority 4 species Carter's freshwater mussel (*Westralunio carteri*), endemic to the south-west of WA, have been found to exceed statutory Australia New Zealand Food Authority (ANZFA) guidelines for maximum permissible concentrations (MPCs) with respect to human consumption (these MPCs have now been removed). The cadmium levels bioaccumulate in freshwater mussels elevated with increasing catchment clearing, being highest in degraded catchments.[185]

Some species more tolerant of metal contamination thrive as a result of the decline of species that are sensitive to metals. For example, abundance of cyanobacteria and green algae have been known to increase significantly in wetlands following the loss of algae-grazing organisms as a result of metal poisoning.[46]

Metals may progressively accumulate in sediments or in biological tissues to levels that are much higher than water column concentrations (bioaccumulation). Chronic effects of bioaccumulated toxicants in organisms include deformities, alterations in growth, and reduced reproductive success and competitive abilities. Elevated toxicant concentrations in organisms such as fish and shellfish may also pose health risks to consumers of those organisms, including humans.

Indicators

Visual indicators of dissolved metal contamination may range from decline in health of individual organisms sensitive to particular toxicants, for example, lesions in fish, to mass mortality events such as fish kills. The time taken for organisms to display visual symptoms of toxic poisoning after initial exposure will vary depending on a range of factors including the nature and concentration of the toxicant(s), sensitivity of individual organism/species and frequency, duration and nature of exposure.

Some dissolved metals such as aluminium or iron may be identified through changes in the appearance of the water or sediments. For example, wetlands affected by high levels of acidity containing aluminium may have 'crystal clear' water ranging through to blue green or milky white colour with increasing water pH. Similarly, contamination from iron may result in water appearing a yellow-brown colour, particularly evident in slow flowing water, when there has been no recent rainfall. There may be iron flocs (particles) present which can be a red-brown or brown-yellow colour, again depending on the pH.

The presence of metals can be more accurately determined by testing the water, sediment and organisms (from tissue samples from affected organisms such as fish, crustaceans and molluscs). Where heavy metal contamination is suspected, samples of water, sediment and biota should be analysed by chemical laboratories to determine the presence of specific metals. The results of testing can then be compared against standard guidelines for water quality criteria, for example the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*.[14]

Table 21. Default trigger values for metals in freshwater wetlands in WA, from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*.[14]

Parameter	Effectively unmodified wetlands, with high conservation/ecological value	Slightly to moderately disturbed freshwater wetlands
Metals in water	Chemicals originating from human activities should be undetectable. Naturally occurring toxicants should not exceed background concentrations	Refer to Table 3.4.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*
Metals in sediment		Refer to Table 3.5.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*

Managing metals

Management of metals should focus on preventing their entry into wetlands and/or reducing their impacts once they have entered wetlands. No pollutant trap is successful in removing the majority of heavy metals encountered in stormwater.[194] Strategies and techniques for preventing and managing nutrients are applicable to metals and include:

- regulation of mining, industrial and other activities to reduce generation of metals and acid effluent
- effluent control from point and diffuse sources of pollution (such as reducing water flow through contaminated areas and sealing tailings ponds with impervious materials)
- catchment management practices to reduce erosion and runoff
- construction of settling ponds, sediment traps and artificial wetlands to trap and strip metals

Many of these techniques are discussed in more detail under the heading 'Managing nutrient enrichment'. Specific guidelines for managing metals are outlined in Table 22.

Where metals are present in wetlands, optimising those conditions which promote their immobilisation may be considered. Plants and some charophytes (complex algae described in the 'Wetland ecology' topic in Chapter 2) such as *Nitella congesta* have been found to hyper-accumulate metals[195], but there is the potential to affect animals that consume it. Promoting conditions needed for metal adsorption (binding to soil particles) and precipitation (forming solid compounds) include:

- avoiding disturbing wetland sediments, resulting in re-suspension of metals, rendering them bioavailable
- avoiding disturbing or exposing potential acid sulfate soils to air
- where serious metal contamination is known, monitoring pH levels with the aim of, where appropriate, maintaining neutral pH to limit metal toxicity
- avoiding drying of permanently inundated wetlands.

Table 22. Guidelines on managing metals

Application	**Guideline**
General	*Toxic and hazardous substances – storage and use* WQPN[181]
General	*Contaminant spills – emergency response* WQPN[180]
Light, general and heavy industry best practice	*Managing waste in the metal manufacturing industry*[196] *Industrial wastewater management and disposal* WQPN[70] *Light industry near sensitive waters* WQPN[71] *General and heavy industry near sensitive waters* WQPN[72] *Stormwater management at industrial sites* WQPN[197] *Mechanical servicing and workshops* WQPN[198] *Mechanical equipment washdown* WQPN[199]
Associated benefits	
Cost effectiveness, compliance with environmental regulations, corporate citizenship.	
Who to go to for assistance	
Department of Environment and Conservation www.dec.wa.gov.au	
Relevant regulation	
Environmental Protection (Metal Coating) Regulations 2001 of the *Environmental Protection Act 1986* Environmental Protection (Unauthorised Discharges) Regulations 2004 of the *Environmental Protection Act 1986*	Department of Environment and Conservation

➤ The following are sources of more information on metals:

- Section 8.3.7.1 of the *Australian and New Zealand guidelines for fresh and marine water quality. Volume 2. Aquatic ecosystems - Rationale and background information (Chapter 8)*[14]
- National Pollutant Inventory: www.npi.gov.au

Managing hydrocarbons

Hydrocarbons—including oil, grease and petroleum products—refer to several hundred chemical compounds that originate from crude oil, polycyclic aromatic hydrocarbons (PAHs) and benzene, toluene, ethylbenzene and xylene (these four compounds are sometimes collectively referred to by the acronym BTEX).

Causes

Hydrocarbons generally enter wetlands via stormwater and groundwater that has received hydrocarbons from urban roads, contaminated runoff from light industrial areas and service stations and deliberate or accidental spillage of chemicals. A wide range of industries, land uses and activities use and emit hydrocarbons, as outlined in the handy reference document *Potentially contaminating activities, industries and landuses*.[183] Under the Environmental Protection (Unauthorised Discharges) Regulations 2004 it is illegal to discharge hydrocarbons to wetlands, groundwater or stormwater.

These manufactured hydrocarbons should not be confused with natural oils produced from the decomposition of plants in the Myrtaceae and other families. Although these can reduce oxygen transmission to the water column, natural oils are a natural part of wetland ecosystems and are not associated with significant detrimental effects in wetlands.

The extent of hydrocarbon pollution in WA's wetlands is not known, due to a lack of survey data. However, in large urban centres of WA, hydrocarbon pollution is considered likely to be a problem. Studies of the Swan and Canning catchments, for example, show that high concentrations of polycyclic aromatic hydrocarbons are entering waterways and will have both chronic and acute effects.[23] They are commonly found in road runoff.[14]

Impacts

Hydrocarbon pollution can have a range of serious environmental impacts. Hydrocarbons can coat animals and plants and other surfaces including sediment and the water surface. Slicks upon the water surface reduce the diffusion of gases between the atmosphere and the water, causing a number of problems. In particular, hydrocarbons can reduce the amount of oxygen that dissolves in water by preventing gas exchange across the air-water interface. As oxygen exists in much lower proportions in water (about 1 per cent) than in air (about 21 per cent), this exchange is critical for aquatic life in wetland waters, as well as driving many chemical processes in the water column and sediments. Hydrocarbons and surfactants also alter the surface tension of the water, which many insects and other invertebrate aquatic animals rely upon in order to survive, because they primarily inhabit the water surface. Oil and surfactants such as household detergents decrease the surface tension, reducing the ability of these 'surface dwellers' such as water striders (Gerridae, Veliidae) to repel water with the hydrophobic hairs on their legs, causing them to sink.[200] Oils can cause damage to the water proofing on birds feathers, and prove toxic to birds which ingest it during preening. The decomposition of oils by bacteria can also consume oxygen, further reducing oxygen levels in the water column and sediments.

Many polycyclic aromatic hydrocarbons are acutely toxic and several are described as endocrine disrupting, mutagenic, carcinogenic and teratogenic (defined in the glossary). Their toxicity has been shown to increase with increased molecular weight, while degradation time has been shown to decrease with increased molecular weight. They have the potential to be bioaccumulated. It is reported that concentrations of PAHs in aquatic ecosystems are generally highest in sediments, intermediate in aquatic biota and lowest in the water column and that a mixed microbial population in sediment water systems may degrade some PAHs, with degradation progressively decreasing with increasing molecular weight.[14]

Indicators

A film on the water or sediment surface is the main visual indicator of hydrocarbon contamination in wetlands. Oily films are sometimes confused with scums. For more guidance on natural oils, from plants and in some cases algal blooms (for example, from *Botryococcus*), see the *Scum book*[60], produced specifically for south-western Australia. Oily-looking bacterial scums may also be present when acidification is occurring, as outlined earlier (see 'Managing acidification').

Bioremediation: the use of microorganisms to break down environmental pollutants

Detecting hydrocarbons and tracing their source is becoming easier with the use of hydrocarbon capture pads in stormwater systems. These are being employed in various areas of Perth, for example, the South East Regional Centre for Urban Landcare (SERCUL) in partnership with the Swan River Trust and the City of Gosnells, has carried out Hydrocarbon Track and Trace project in the Maddington industrial area.

The presence of hydrocarbons can be accurately determined through testing of water and sediment analysed by chemical laboratories to determine the presence of specific hydrocarbons. The results of testing can then be compared against trigger values for hydrocarbons in Chapter 3.4 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14] (Table 23).

Table 23. Default trigger values for hydrocarbons in freshwater wetlands in WA, from the ***Australian and New Zealand Guidelines for Fresh and Marine Water Quality***.[14]

Parameter	Effectively unmodified wetlands, with high conservation/ecological value	Slightly to moderately disturbed freshwater wetlands
Hydrocarbons in water	Chemicals originating from human activities should be undetectable. Naturally occurring toxicants should not exceed background concentrations	Refer to Table 3.4.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*
Hydrocarbons in sediment		Refer to Table 3.5.1 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*

Managing hydrocarbons

In the event of a spill, rapid and effective containment and removal of the hydrocarbon is critical. The DEC responds to serious pollution incidents, taking action to stop the discharge, minimise environmental harm and direct clean-up works. It maintains a Pollution Response (HAZMAT) Unit (PRU) in Perth that can be deployed quickly around the state in the event of major pollution incidents. DEC Regional Offices also have ability to respond to pollution incidents and can obtain support from PRU as required. Equipment such as oil spill booms and skimmers may be used to contain and remove hydrocarbons effectively.

In an emergency

In the event of an accidental spill of hydrocarbons, call the Pollution Watch Hotline: 1300 784 782 (24 hours). In the event of a hazardous materials release or life-threatening incident, call 000 and ask for Fire and Rescue).

Preventing hydrocarbons from entering wetlands, and water that enters wetlands from drains, should always be the focus of management. The management of runoff and discharges from roads, industrial areas and service stations is particularly important. Table 24 lists guidelines on hydrocarbon management. In some circumstances, **bioremediation** may help to reduce the impacts of hydrocarbon pollution.

Figure 42. DEC's Pollution Response Unit found this site to have a number of environmental hazards including overflowing wash down bays, oil discharges that were leading into a constructed wetland and more than 500 drums of unknown liquid waste stored near stormwater drains. This site has since been cleared of the liquid waste and mineral oil drums, empty drums, packaging, pallets, used tyres and chemical containers. Oil spills and stains have been cleaned up and systems put in place to prevent recurrences. Photo – DEC.

Table 24. Guidelines on managing hydrocarbons

Application	**Guideline**
General	Pollutant control section, Chapter 9, S*tormwater management manual for Western Australia*[30] *Toxic and hazardous substances – storage and use* WQPN[181] *Contaminant spills – emergency response* WQPN[180]
Light, general and heavy industry best practice	*Service stations* WQPN[201] *Mechanical servicing and workshops* WQPN[198] *Mechanical equipment washdown* WQPN[199] *Motor sport facilities near sensitive waters* WQPN[202] *Industrial wastewater management and disposal* WQPN[70] *Light industry near sensitive waters* WQPN[71] *General and heavy industry near sensitive waters* WQPN[72] *Stormwater management at industrial sites* WQPN203
Relevant regulation	
Environmental Protection (Petrol) Regulations 1999 of the *Environmental Protection Act 1986* Environmental Protection (Unauthorised Discharges) Regulations 2004 of the *Environmental Protection Act 1986*	Department of Environment and Conservation

➤ The following are sources of more information on hydrocarbons:

- Section 8.3.7 of the *Australian and New Zealand guidelines for fresh and marine water quality. Volume 2. Aquatic ecosystems - Rationale and background information (Chapter 8)*[14]
- National Pollutant Inventory: www.npi.gov.au

case study

Mitigating the impact of hydrocarbon spills in the catchment

The City of Stirling has installed a hydrocarbon interception system to protect Herdsman Lake from hydrocarbon contamination carried in with stormwater from the surrounding light industrial area. Booms made of specialised toxicant capture material have been installed across stormwater drains. These booms are marketed as being able to capture up to 30 kilograms of oil contaminants; and as still capturing oil contaminants up to 12 months after initial deployment, and are marketed to float even when fully saturated with oil up to one year. Underflow weirs prevent surface flow oil and emulsified oil and water from flowing under the boom, which is reported as causing poor performance in some types of boom systems. The second line of containment employs high floating mats that capture any oils that breach the first line of containment during high flow events. The capture material is marketed as capturing organics from BTEX to oil and greases and heavy metals (as suspended organo-metals) commonly from internal combustion engine wear.

Figure 43. The hydrocarbon interception system installed by the City of Stirling to protect Herdsman Lake from hydrocarbon contamination carried in with stormwater from the surrounding light industrial area. Photo – Oleology.

Managing pathogens

Pathogen: any organism or factor causing disease within a host

Infectious microorganisms such as bacteria, viruses, protozoans, fungi and parasites that can cause disease or illness in humans, animals and plants are **pathogens**. Water can play a significant role in transmitting a wide variety of diseases and illnesses if contaminated with pathogens (for example, amoebic meningitis).

One introduced pathogen, *Phytophthora cinnamomi*, is so pervasive and destructive in wetlands as well as dryland communities in WA, a whole topic is dedicated to it.

➤ The topic ‘Phytophthora dieback’ is also in Chapter 3 of the guide.

Another, *Clostridium botulinum*, causes botulism, and is linked with nutrient enrichment, and is covered in the ‘Nutrients’ section of this topic.

Causes

There is a strong link between the presence of many pathogens and contamination of water by human and/or animal faecal material.[168] Humans can be exposed to pathogens in wetlands from immersion of head and face, wading or swimming and swallowing water Pathogens can enter organisms through the mouth, eyes, ears, nasal cavity, skin (particularly cuts and abrasions) and upper respiratory tract. Infection can also ensue when organisms (such as fish or crustaceans) that are already contaminated with a pathogen are consumed.

Some pathogens occur naturally in wetlands, without causing a problem. Under natural conditions, pathogens can be destroyed by exposure to ultra violet light in open waters, adsorption and predation. However pollution can significantly alter the number or type of pathogens present. The main sources of pathogens in wetland waters include:

- Groundwater leaching and stormwater from urban areas containing animal and human faecal material. Human faecal material carries the pathogenic bacteria *Escherichia coli* and animal faeces can carry the pathogenic protozoans *Cryptosporidium* and *Giardia*, all of which can cause serious illness in humans. Risks to humans from pathogenic organisms are greater in highly populated urban areas with septic tanks and on-site sewage disposal systems or leaking sewage connections.
- Groundwater leaching and stormwater from rural and/or agricultural areas containing animal faeces, including dog kennels and horse keeping areas, and intensive animal industries such as poultry farms, dairies and piggeries.

Concentrations of pathogens in wetlands are likely to be highest during high rainfall events when groundwater leaching and stormwater into wetlands is greatest.

Some pathogens occur naturally in the water column or sediments of wetlands, without causing a problem until conditions change that favour an outbreak, such as changes in water temperature, pH, salinity, light or dissolved oxygen. For example, the bacterium *Clostridium botulinum* (which causes botulism in fauna such as fish and birds) can be present in the sediment without causing a problem. When conditions are favourable, such as during algal blooms and anoxic (low oxygen) conditions, an outbreak can be triggered.

Low pH conditions resulting from acidification of wetlands can cause damage to fish skin and gills and increase their susceptibility to fungal infections, which may have lethal consequences. Activities that disturb sediments, causing re-suspension of pathogens, may also lead to outbreaks of disease or illness in vulnerable organisms.

Impacts

Disease and death of sensitive species from pathogens can result in changes in the abundance and diversity of wetland species and the composition of wetland communities.

For example, bandicoots in urban areas have been found to be infected with strains of the parasite toxoplasma and cases of neurological disease have also been detected. Murdoch University researchers are investigating the effect of closer contact of humans due to urbanisation and clearing, with causes such as people giving them food scraps or exposure via septic systems being considered.

Indicators

The presence of pathogens in wetlands should be suspected if there are signs of illness or disease, or death, in organisms that have been exposed to potentially contaminated water. Symptoms of infection from pathogens in humans range depending on the pathogen involved. For example, symptoms of infection by the amoeba *Naegleria fowleri*, which causes amoebic meningitis in humans, include a severe and persistent headache, sore throat, nausea, vomiting, high fever and sleepiness. Fish exposed to pathogens may display unusual behaviour such as swimming on their sides, or develop skin lesions or ulcers. Birds and other native fauna, pets and livestock may show signs of confusion, respiratory distress and paralysis.

Detecting the presence and type of bacterial and viral pathogens in water can be difficult and where there is potential risk to human health, sampling should only be undertaken by professionals trained in handling biohazardous substances, such as public/environmental health officers from the local shire or the Department of Health. Analysis of water samples should be undertaken by specialist pathology laboratories. Where faecal bacterial densities are being measured, these should be assessed according to the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14].

Managing pathogens

Management of pathogens in wetlands will depend on the type of pathogen(s) present and the level of existing (or potential) risks posed to humans or other organisms that may be exposed. Where pathogens are entering wetlands from diffuse or point sources of pollution, management strategies will be similar to those already discussed for managing nutrients (see heading 'Managing nutrients' in this topic), as the sources of pathogens are also potential sources of nutrients. Management strategies include:

- Reducing pathogen contamination at the source. For guidelines on source reduction, see the guidelines listed in Table 25.
- If leaking or overflowing septic tanks are the cause, these should be replaced, fixed or removed. Connection to mains sewage may be the best long term solution, if this is a viable option.
- Where pathogens originate from faecal matter from livestock or other animals defecating in or around wetlands, exclusion of these animals may be necessary. For additional information on managing pathogens from livestock in wetlands, see the topic 'Managing livestock' in Chapter 3.
- Where pathogens are naturally present in wetlands, preventing the onset of conditions that can trigger problematic outbreaks (for example, eutrophication and algal blooms, anoxic conditions, disturbing wetland sediments, acidification).

Turbid: the cloudy appearance of water due to suspended material

Table 25. Guidelines on managing pathogens

Maintain best practice industry standards, including:	Guideline
General	*Contaminant spills – emergency response* WQPN[180]
On-site domestic wastewater and sewage disposal	*Wastewater treatment – onsite domestic systems* WQPN[204]
Bridle trails	*Bridle trails near sensitive water resources*[205]
Aquaculture industry	*Aquaculture* WQPN[85]
Animal industries	*Stockyards* WQPN[86]
Abattoir industry	*Rural abattoirs* WQPN[87]
Beef industry	*Guidelines for the environmental management of beef cattle feedlots in Western Australia*[88]
Dairy industry	*Dairy processing plants* WQPN[89] *Effluent management guidelines for dairy sheds*[90] *Effluent management guidelines for dairy processing plants*[91]
Horse industry	*Environmental guidelines for horse facilities and activities*[36]
Pastoral rangeland industry	*Pastoral activities within rangelands* WQPN[92]
Pig industry	*Environmental guidelines for new and existing piggeries*[93] *National Environmental Management Guidelines for Piggeries*[94]
Poultry industry	*Environmental code of practice for poultry farms in Western Australia*[95]

Managing turbidity

The presence of fine, suspended matter in the water column, referred to as particulates and colloidal matter, can significantly influence wetland functions. These particulates may be clay, silt, phytoplankton or detritus and they affect the availability of light in the water by scattering and reflecting it. Wetlands with high levels of these particulates suspended in the water column are said to be **turbid**, and the measure of the extent to which light is scattered and reflected by these particles is the **turbidity**. Although having a similar appearance, highly coloured waters are not considered to be turbid because the effect is due to dissolved substances rather than suspended particles, and they play a different role in wetland ecology.

Causes

Naturally turbid wetlands

Natural levels of turbidity in WA wetlands can vary significantly between wetlands and within individual wetlands on a daily or seasonal basis (Figure 44). Turbidity is generally highest during peak surface inflows, such as during wet season rainfall and after intense rainfall events such as cyclonic rain. Upon reaching wetlands, suspended particulates may settle to the bottom, however they may be re-suspended in the water column if sediments are disturbed by natural phenomena include strong wind and wave action and native fauna movement. Many claypans support naturally high levels of turbidity almost all of the time. These claypans can support fauna that use the turbid conditions to their advantage. For example, turbidity can shelter animals from predators or protect them from harmful ultraviolet radiation. Most wetlands with a deep water column have low turbidity, while those with a shallow water column may have a naturally higher turbidity due to wind-induced re-suspension of sediments. The characteristics of the catchment also plays a key role in natural turbidity levels. Wetlands in catchments with highly erosive clay soils and low vegetation cover may have naturally high turbidity.

Figure 44. A wetland with high natural turbidity. Suspended silt particles give the water a milky appearance. Photo – DEC.

Vegetation clearing and grazing in the catchment

Turbidity is influenced by the general condition of the catchment draining into the wetland. Wetlands in heavily cleared and grazed catchments can be very turbid due to erosion of soils in the catchment.

Mining and industrial processes

Runoff from mining and industrial sites can contain suspended solids if not managed appropriately. The processes being carried out can generate significant levels of suspended solids. Some have a high level of genotoxicity (that is, can cause DNA damage in aquatic organisms). For example, iron-ore mine effluent has been found to affect fish in receiving lakes in Canada.[206]

Sediment re-suspension activities

Many human-induced activities can also cause re-suspension of particles, including waterskiing, increase volumes and intensity of stormwater flows, and clearing and fires that cause erosion in the catchment. In addition, a range of introduced and nuisance species are known to disturb sediments, including midge larvae, introduced fish such as carp, and pigs, horses and cattle.

Impacts

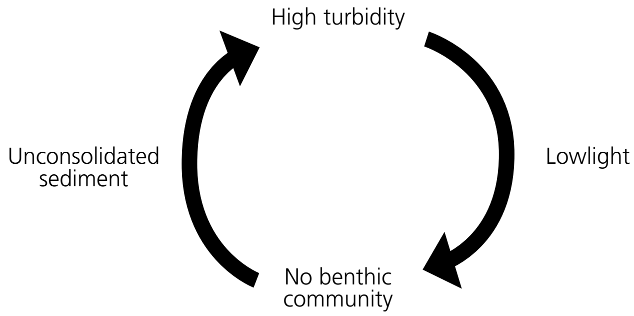
Suspended particulate matter can cause problems in wetlands both when in suspension in the water column and when it settles out in the bottom sediments. While in suspension, particulate matter can reduce light penetration, reducing photosynthesis in algae and submerged plants. It cause damage to fish and other aquatic organisms by clogging, coating or abrading respiratory structures such as gills, and by smothering benthic organisms and altering their habitats.[14] Suspended solids in runoff from some mining and industrial processes can cause cell damage in aquatic organisms. Suspended particulate matter is also important in that if these originate from inflows from the surrounding catchment, the particles can transport contaminants into wetlands such as nutrients, pesticides, bacteria and metals. The latter commonly bind to soil particles in catchments and can be transported via these to wetlands. The introduction of nutrients, pesticides and metals with particulate matter can also have adverse impacts on aquatic organisms (these are discussed under the headings 'Nutrients' and 'Metals' in this topic).

Impacts of increased turbidity on wetland ecosystems can be dramatic, in particular due to the effects on plants and algae, which are primary producers that form the basis of wetland food webs. Secondary effects as a result of increased turbidity, such as eutrophication (due to introduction of nutrients attached to particulate matter) and algal blooms, further exacerbate the problem. These impacts can lead to loss of species, altered communities and ultimately a reduction in wetland biodiversity.

Turbidity affects the amount and quality of light available for photosynthesis. Due to the different photosynthetic adaptations to light and shade of different plant and algal species, high levels of turbidity or shade can change species dominance, especially in phytoplankton. For example, cyanobacteria are quite often moderately shade-tolerant, and are also problem species in algal blooms due to the toxins produced by many species.[31] On the other hand, aquatic plants that grow close to the sediment can be severely disadvantaged by turbid conditions.

The low light conditions caused by high turbidities may prevent the establishment of bottom-dwelling (benthic) communities (for example, submerged wetland vegetation, benthic microbes), or lead to the loss of previously-established communities. This can often lead to 'positive feedback loops' in which sediments are not consolidated by benthic communities, leading to further turbidity and so on (Figure 45). This continual resuspension of inorganic sediments can also lead to elevated water column nutrient levels, since nutrients in the sediments are constantly resuspended, and sequestration (taking up) by rooted plant material does not occur. This feedback process forms part of the mechanism for maintaining a 'turbid, phytoplankton-dominated state'.

Figure 45. Feedback loop promoting turbid conditions in wetlands.



Indicators

Turbidity can be determined in a number of ways including:

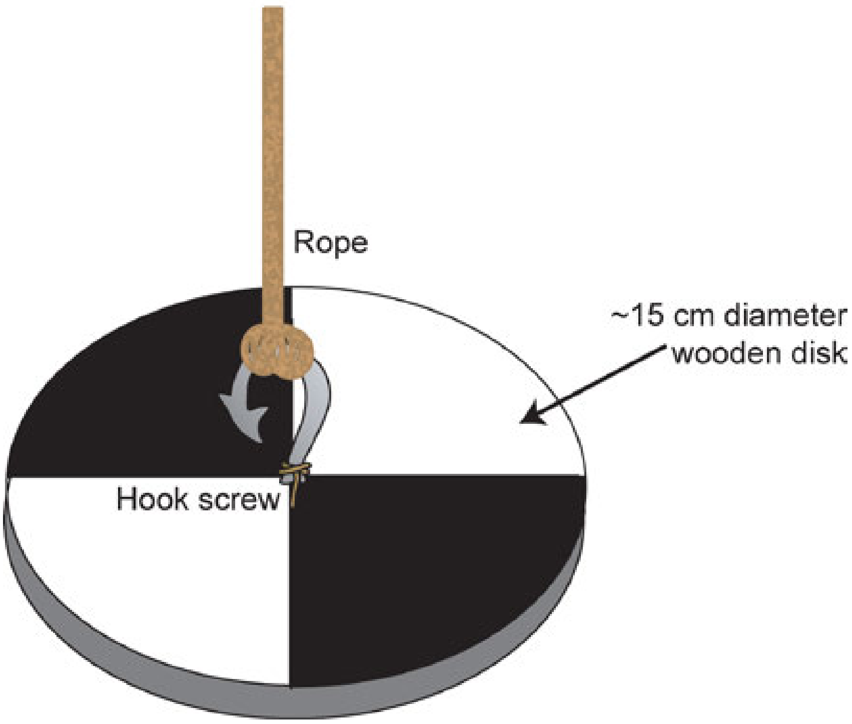
- visual observation
- measurement in the field
- measurement in the laboratory using a water sample taken in the field.

The simplest, but potentially least accurate method of determining increased turbidity, is visual inspection of the water body. If the water looks more 'cloudy' or 'muddy' than normal, increased turbidity is likely. It is more likely to be evident following rainfall when an increase in inflow of water into wetlands via stormwater occurs. Turbidity due to soil erosion from surrounding land may look brownish in colour, depending on the colour of the soil being washed into the wetland. Turbidity from stormwater may not be an obvious colour and the water may just look more 'cloudy' than normal.

Turbidity can be more accurately determined using several different methods:

- Measuring the 'cloudiness' of water using a 'turbidity tube', which is filled with water and small quantities are poured out until a black cross at the bottom of the tube becomes visible (from looking down through the water sample from the top of the tube). The turbidity value (measured in units called NTU, nephelometric turbidity units) is then determined by the measurement on the tube scale that corresponds with the water level.
- Measuring the transparency of the water using a secchi disk (pronounced 'sekki'). A secchi disc is used for measuring water transparency (Figure 46). The secchi depth of a water body is found by lowering the disc into the water until the black and white quadrants are no longer discernable. The depth at which this occurs is the secchi depth and the transparency of the water column is double the secchi depth.

Figure 46. Recommended width, colouration and weighting of a secchi disc.
Image - www.globe.gov.[207]



- Measuring the concentration (by mass) of suspended particulate matter per volume of water (often measured as milligrams per litre (mg/L)). This is undertaken under laboratory conditions.
- Measuring the fraction of light scattered at right angles as it enters the water (the more suspended particulate matter present, the more light is scattered). This is undertaken using a nephelometer under laboratory conditions.

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*[14] trigger values for turbidity in northwest and southwest Australian freshwater ecosystems are between 2–200 and 10–100 **NTUs** respectively (Table 26).

NTU: nephelometric turbidity unit is a measure of the clarity of water. Turbidity in excess of 5 NTUs is just noticeable to most people.

ANZECC guidelines under review

The Council of Australian Governments has announced that the ANZECC guidelines are under review. This review includes the revision of sediment water quality guidelines, nitrate trigger values and toxicant trigger values. For more information, see www.environment.gov.au/water/policy-programs/nwqms/index.html#revision.

Table 26. Default trigger values for turbidity for slightly disturbed wetlands in WA, from the ***Australian and New Zealand Guidelines for Fresh and Marine Water Quality.***[14]

Water quality parameter	Trigger value Southwest Australia	Trigger value Northwest Australia
Units of measurement	Nephelometric turbidity units (NTU)	
Turbidity	10-100 [c]	2-200 [c]

Notes
c: most deep lakes and reservoirs have low turbidity. However, shallow lakes and reservoirs may have higher turbidity naturally due to wind-induced resuspension of sediments. Lakes and reservoirs in catchments with highly dispersible soils will have high turbidity. Wetlands vary greatly in turbidity depending on the general condition of the catchment or river system draining into the wetland and the water level in the wetland.

➤ For additional information on monitoring turbidity, see the topic 'Monitoring wetlands' in Chapter 4.

Managing turbidity

In those wetlands where the material in the water causing turbid conditions is either algae or cyanobacteria, managers should determine whether eutrophication is the primary cause. If it is, the previous section on managing eutrophication should be referred to.

In wetlands where the material in the water is primarily abiotic (that is, not living) and the turbid conditions are due to human causes rather than being the wetland's natural state, there are three key measures for managing it:

1. reduce the influx of suspended solids
2. reduce high velocity flows into the wetland
3. reduce re-suspension of solids.

Reducing the influx of suspended solids and high velocity flows

The most effective measure is to determine where sediments are coming from and to implement measures to prevent or reduce sediment loads entering wetlands.

Reducing erosion

Erosion can be considerable on pastoral lands due to grazing and soil disturbance by livestock. Managing stocking rates, and total grazing pressure accounting for feral animals, weather and land conditions, is important.

Erosion rates vary significantly across the state, with the Kimberley and the west Pilbara having the highest average rates of soil loss. Declines in soil stability have been noted in the Gascoyne, Murchison, Pilbara and Kimberley.

➤ The Department of Agriculture and Food has detailed information about local conditions across the state and can calculate the relevant permissible stocking rates on request. The department's Small Landholder Information Service provides advice tailored for small landholders. For more information, see the topic 'Livestock' in Chapter 3.

➤ The *State of the Environment Report 2007*[137] provides information about soil erosion; see www.soe.wa.gov.au.

If the source of sediments is sheet or gully erosion, measures to reduce stormwater flow rates, improve infiltration and stabilise soil surfaces can be very effective.

This can be achieved in a number of ways, for example:

- strategic revegetation of the dryland area around wetlands, to stabilise sediment and intercept sediment in stormwater, and regeneration of wetland vegetation
- constructing sediment traps/settling ponds
- retrofitting stormwater systems to reduce direct discharge of stormwater into wetlands via drains and increase diffuse overland flow of stormwater through vegetated dryland buffers.
- installation of erosion control banks to channel runoff to other areas.

Reducing suspended solid transport from building sites

Tips for building sites include:

- prepare a site management plan that includes evaluation of the site conditions and risks and outlines measures to manage wastes, control erosion and reduce the risk of stormwater pollution
- secure all litter and waste on site before disposing of it thoughtfully
- keep the verge, footpath and gutter free of building materials and wastes
- install an erosion/sediment barrier to catch sand and coarse sediment
- place sand, mulch and gravel stockpiles behind sediment barriers
- contain wash water and wastes from concrete, plaster, paint or brickwork in one area on site
- ensure rainfall runoff from downpipes does not leave the site
- use a shovel and broom to clean up sediments tracked onto roads by vehicles.

➤ For detailed information on how to manage sediments in the catchment, see the *Stormwater management manual for Western Australia.*[30] Managing construction practices are outlined in Chapter 7, Section 2.1.

Reducing suspended solid transport from mining and industrial sites

Guidelines for reducing suspended solid transports generated by mining and industrial sites are listed in Table 27.

Table 27. Guidelines on managing suspended solids in mining and industry

Application	Guideline
General	*Ponds for stabilising organic matter* WQPN[208]
Extractive industries	*Extractive industries near sensitive water resources* WQPN[209]
Mining and mineral processing	*Mining and mineral processing: tailings facilities water quality protection guideline*[210]
Mining and mineral processing	*Mining and mineral processing: liners for waste containment*[211]
Industrial sites	*Stormwater management at industrial sites* WQPN[212]
General and heavy industry	*General and heavy industry near sensitive waters* WQPN[72]
Light industry	*Light industry near sensitive waters* WQPN[71]

Reducing re-suspension of solids in wetlands

Erosion and re-suspension by animals within wetlands is readily addressed, and is described in other topics of this guide.

➤ Controlling introduced animals in wetlands is described in 'Introduced and nuisance animals' in Chapter 3.

➤ Horses, cattle and sheep are covered in 'Livestock' in Chapter 3.

➤ Nuisance midge populations may be covered in a future topic 'Nuisance midge and mosquitoes' in Chapter 3.

Closing wetlands to waterskiing and powerboats is also an effective measure. For example, in May 2012, DEC in co-operation with the Department of Transport closed Lake Jasper in D'Entrecasteaux National Park to powerboats. Approved waterskiing sites are listed at www.transport.wa.gov.au/marine.

Turbidity is generally manageable using catchment prevention and intervention techniques. Where human-induced turbidity presents a serious problem in wetlands of conservation value, removing sediments is not considered a viable solution. This is because:

- Wetland sediment is an extremely important part of a wetland. It helps to form the ecological character of a wetland, being important as habitat and the site of the most important chemical processes in wetlands. It also affects the wetland water regime. Removing wetland sediment can have short, medium and long-term effects on wetland ecology, including potentially irreversible changes to wetlands. Proposals of this nature can have significant ecological impacts and require referral to the Environmental Protection Authority under Part IV of the *Environmental Protection Act 1986*.
- Disturbing the sediments can expose acid sulfate soils and cause acidification of the wetland.
- Disturbing sediments has the potential to mobilise contaminants, such as arsenic and lead, in toxic concentrations if they are present in the sediment.

Considerations

- Wetlands typically do not provide firm ground from which to operate conventional excavating machinery such as front-end loaders or scrapers. Geotechnical investigations need to confirm that the extent of consolidation of wetland sediments is sufficient to support machinery.

- Floating dredges using industrial strength suction pumps have been proposed in the past. These required the establishment of settling ponds to enable dredged sediment to settle, given an extraction ratio of 5 per cent sediment to 95 per cent water followed by the return of the water to the wetland. Previous proposals have also required a minimum water depth of 1 metre to enable the dredge to operate.
- Considerable deepening may be a result. Deepening can alter the habitat and water regime, as well as potentially leading to stratification, which can have implications for nutrient management in the future.
- The disposal of the excavated sediment may be regulated. Sediments containing contaminants may be classified as contaminated waste, for which there are specific disposal requirements. For example, it may have high levels of heavy metals.

Thermal water pollution: the excessive raising or lowering of water temperatures above or below normal seasonal ranges in streams, lakes, estuaries, or oceans as a result of the discharge of hot or cold effluents into such waters

Managing thermal pollution

Thermal pollution of wetlands can occur when wastewater discharged into wetlands is significantly warmer or cooler than the ambient water temperature of the receiving water.

Causes

Heated wastewater may be a by-product of industries such as power generation plants, which use water to cool machinery (cooling water), before being discharged. Urban stormwater (from roads and car parks) and clearing fringing vegetation around wetlands (reducing shading) may also lead to increased water temperature in wetlands.

Another form of thermal pollution, 'coldwater pollution', can occur when very cold irrigation water is released from dams or other storage bodies (for example, for flood irrigation) and enters waterways and wetlands.[31] Both forms of thermal pollution can have serious impacts on aquatic ecosystems, in particular, aquatic fauna such as fish, amphibians and macroinvertebrates.

Impacts

Temperature plays an important role in regulating photosynthesis in plants and algae, and aerobic respiration, metabolism, growth and reproduction in aquatic organisms. Temperature changes of 1 or 2 degrees Celsius may be enough to cause significant damage in sensitive organisms, affecting reproduction and mortality. For example, some species of fish are dependent on specific temperature regimes to trigger development of reproductive organs and spawning.[31] Variations in temperature outside of the tolerance limits of aquatic organisms can result in loss of species and changes in community structure to favour species that are more tolerant of temperature fluctuations.

Water temperature strongly influences physical and chemical parameters that play a role in maintaining healthy functioning of aquatic organisms, such as dissolved oxygen level, pH and conductivity. For example, water is more likely to become anoxic due to decreasing availability of dissolved oxygen as temperature increases and increased bacterial respiration. Temperature also affects arsenic toxicity and aluminium speciation and solubility.[14]

The degree to which aquatic organisms and wetland ecosystems as a whole may be affected by thermal pollution includes:

- Tolerance range (and duration of exposure) of aquatic organisms during different stages of their lifecycle. Aquatic organisms may be more or less sensitive to temperature changes during the various life stages. Juveniles and adults at reproductive stage may be more sensitive than adults generally.

- How growth of primary producers (plants, algae, cyanobacteria) is affected by temperature change. If growth is stimulated by increased temperature, this may lead to nuisance growths such as algal or cyanobacterial blooms.
- Whether or not temperature changes lead to increased abundance of introduced or pest species and decreases in the diversity and abundance of native species.

Indicators

Visual indicators of thermal pollution may not be immediately obvious where temperature changes are not so sudden or great as to produce immediate lethal effects. In instances where temperature changes are localised within a wetland (such as around a drain outlet), fish and other organisms may avoid these areas and congregate in areas where temperatures are within their tolerance range. If a temperature rise results in deoxygenation of water, fish may be seen at the water surface 'gasping' for air. Lethal effects may be noticeable where an abrupt and significant increase or decrease in water temperature occurs and fish and other organisms are killed shortly after exposure (thermal shock).

Thermal pollution can be determined by measuring water temperature and comparing this against known 'ambient' temperatures, or if these have not been previously determined, compared against the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*.[14] It should be noted that water temperature may fluctuate naturally during the course of a day due to changes in air temperature, sunlight, shading and local water movement. For example, temperature of surface water varies during the day and tends to be highest in the later afternoon as the sun is setting, and the interpretation of temperature measurements needs to consider these natural variations. Further, some wetlands may be naturally stratified, in which large temperature differences occur between surface and bottom waters. This can occur in deeper wetland bodies such as lakes and in shallow coloured lakes due to heat absorption.

Temperature measurements are usually made with digital instruments or mercury thermometers (with 0.1 degrees Celsius increments). Temperature loggers can also be used to measure and record temperatures at different depths and over specified periods of time.

Long-term monitoring of water temperature provides an indication of natural variations in temperature cycles, as well as temperature anomalies caused by human activities (for example, large changes in temperature).

➤ For additional information on monitoring temperature in wetland waters, see the topic 'Monitoring wetlands' in Chapter 4.

Managing thermal pollution

The most effective strategy for managing thermal pollution is to prevent heated/cooled water from being discharged into wetlands. If this is not possible, a range of techniques may be used to manipulate temperature of inflow water to temperatures that are within normal ranges of receiving wetlands. Temperature manipulation techniques would normally be undertaken at the point source of wastewater generation (for example, industrial operations) and include:

- Cooling ponds – heated wastewater is passed through specially constructed cooling ponds, where water temperatures are reduced by mixing (dilution), evaporation, convection and radiation.
- Cooling towers – heat from wastewater is transferred to the atmosphere by evaporation or heat transfer.

- Aeration – aerators can be used in cooling ponds before wastewater reaches wetland, or within the wetland itself. A well mixed water column prevents stratification from developing (i.e. a layer of warm water developing within the wetland water column), thus buffering the effect of thermal pollution.
- In urban areas, heated stormwater runoff can be diverted to groundwater through infiltration basins or artificial wetlands.

Managing litter and debris

Apart from being unsightly, litter and debris can cause significant problems in wetlands, particularly where these materials contribute to nutrient loads from breakdown of organic matter or the release of toxic materials. Examples of litter and debris that can be introduced into wetlands, affecting water quality include:

- household rubbish such as paper, cardboard, plastic, fishing line, food waste, aluminium cans, animal excreta, bricks, rubble, furniture, mattresses, white goods, clothing, batteries and containers holding toxic substances such as herbicides, insecticides, paint, petrol, oil etc
- garden waste such as street sweepings, prunings, lawn clippings, weeds, leaves, soil and mulch
- larger items such as timber, car bodies, and metal objects (Figure 47).

Figure 47. Dumped car bodies in wetlands are not only unsightly, they can also leak toxic substances into wetlands. This car was dumped in a wetland in Kemerton. Photo – DEC/ Wetlands Section.

Causes

Litter and debris can enter wetlands from stormwater (for example, as overland flow or from urban stormwater and agricultural drains), or they may blown into wetlands or deliberately disposed of by humans.

Impacts

Litter and debris can directly or indirectly affect water quality by introducing weeds, pathogens, nutrients, sediment and suspended particulate matter, metals, pesticides, acids and a range of other chemicals and toxicants. The effects on wetland ecosystems will depend on the type of litter or debris that is introduced, for example, garden waste can introduce pathogens such as *Phytophthora cinnamomi* responsible for phytophthora dieback, weeds and cause nutrients to build up as a result of waste decomposition upon reaching the wetland. Dumping of building materials such as sand and rubble can increase turbidity due to erosion and stormwater mobilising particulates from stockpiles.

➤ These impacts are discussed in more detail in the topics 'Phytophthora dieback' and 'Wetland weeds' in Chapter 3, and within this topic under the headings 'Nutrients', 'Turbidity' and 'Pathogens'. The impacts of pesticides and metals is discussed within this topic under the headings 'Pesticides' and 'Metals'.

Wetland fauna including macroinvertebrates, fish, frogs, reptiles and birds may suffer physical injury or death as a result of ingesting litter/debris (from choking or poisoning), or by becoming entangled, trapped or smothered.

Indicators

The presence of litter and debris such as household rubbish, garden waste, car bodies, used chemical containers is evident as foreign material floating in the water or deposited on soil or vegetation.

Obvious signs may include injury, disease or death of fauna such as fish kills, birds swallowing or becoming entangled in fishing line or death of wetland vegetation due to increased turbidity, smothering, pathogens or physical damage. Not-so-obvious indicators of litter and debris on water quality such as increased turbidity, nutrients and introduction of pathogens, pesticides, metals and other toxic materials are discussed under the relevant section of this topic.

Managing litter and debris

Best practice management by particular industries, such as the building industry, can reduce the disturbance of sediment in the catchment. Stormwater management can reduce litter and debris in the catchment. Litter and debris in stormwater drains can be managed through the installation of structures (for example, 'trash racks') which are designed to trap rubbish before it enters receiving wetlands (Figure 48). These need to be cleared regularly to prevent build up of material, which impedes water flow and can lead to flooding. Where structural control options are not practical, litter and debris may need to be removed manually. This can be undertaken when water levels are lowest, allowing for better access into areas that would otherwise be inundated. Litter and debris can become trapped in native vegetation and therefore care should be taken when removing it in order to minimise damage to native plants. Community litter prevention programs can be very effective in preventing disposal of waste that may otherwise end up in local wetlands.

➤ Keep Australia Beautiful WA provides support and resources for litter prevention. See www.kabc.wa.gov.au for more information.

Figure 48. Structures to prevent litter and debris from entering drains and wetlands need to be cleared regularly. Photo – DEC.

Glossary

Acid neutralising capacity: a measure of the soil's inherent ability to buffer acidity and resist the lowering of the soil pH

Acid sulfate soils: includes all soils in which sulfuric acid is produced, may be produced or has been produced in quantities that can affect the soil properties. Also referred to as acid sulphate soils.

Acidity: the amount of acidity associated with all dissolved ions in a solution, expressed as an amount of pure calcium carbonate needed to neutralise these. Dissolved ions include hydrogen ions and commonly free dissolved metals such as aluminium, iron and manganese.

Active (or actual) acid sulfate soils: soils in which the sulfidic minerals have oxidised and the pH has fallen to very low levels

Acute toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent in a short time (usually less than 24 hours)

Adjuvant: includes substances such as surfactants, oils, penetrants and wetting agents

Adsorption: the adhesion of a substance to the surface of a solid or liquid

Aeration: the addition of oxygen to the water column of a wetland

Aerobic: an oxygenated environment (organisms living or occurring only in the presence of oxygen are aerobes)

Aestivating: being in a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Algae: a general term referring to the mostly photosynthetic, unicellular or simply constructed, non-vascular, plant-like organisms that are usually aquatic and reproduce without antheridia and oogonia, that are jacketed by sterile cells derived from the reproductive cell primordium; includes a number of divisions, many of which are only remotely related to each other

Algaecide: any chemical or biological agent intended to kill algae

Alkalinity: a solution's capacity to neutralise an acid, expressed as the amount of hydrochloric acid needed to lower pH of a litre of solution to pH 4.5. The concentration of bicarbonate (HCO_3^-), or when pH is greater than 8.3, the concentration of carbonate (CO_3^{2-}). Sometimes due to dissolved silicate, phosphate or ammonia in relatively high concentrations (tens of milligrams per litre).

Anoxic: deficiency or absence of oxygen

Bassendean Sands: (also known as the Bassendean Dunes) a landform on the Swan Coastal Plain, comprised of heavily leached aeolian sands, located between the Spearwood Dunes to the west and the Pinjarra Plain to the east

Benchmark: a standard or point of reference; a predetermined state (based on the values that are sought to be protected) to be achieved or maintained

Benthic: the lowermost region of a wetland water column; the organisms inhabiting it are known as benthos

Bioaccumulate: process in which tissues of an organism accumulate a chemical because uptake is greater than elimination and breakdown

Bioavailable: in a chemical form that can be used by organisms

Biodiversity: encompasses the whole variety of life forms—the different plants, animals, fungi and microorganisms—the genes they contain, and the ecosystems they form. A contraction of 'biological diversity'.

Biofilm: bacteria, microalgae, fungi and unicellular microorganisms enmeshed in a hydrated mucopolysaccharide secretion that sequesters ions and isolates microorganisms from the water column[101]. May be present on living and non-living surfaces and substrates.

Biological parameters: organisms that inhabit wetlands such as algae, macroinvertebrates, fish

Biomagnify: an increase in the concentration of a chemical along a food chain

Bioremediation: the use of microorganisms to break down environmental pollutants

Bloom: rapid, excessive growth, generally caused by high nutrient levels and favourable conditions

Buffering capacity: a measure of the soil's inherent ability to buffer acidity and resist the lowering of the soil pH

Carcinogenic: cancer-causing

Catchment: an area of land which is bounded by natural features such as hills or mountains from which surface water flows downslope to a particular low point or 'sink' (a place in the landscape where water collects)

Chemical parameters: chemicals found in water such as dissolved oxygen, pH, nutrients and pollutants

Chronic toxicity: sublethal or lethal impacts resulting from a single or multiple exposures to an agent over a longer time period (months or years)

Cyanobacteria: a large and varied group of bacteria which are able to photosynthesise

Damplands: seasonally waterlogged basin wetlands

Decomposition: the *chemical* breakdown of organic material mediated by bacteria and fungi, while 'degradation' refers to its *physical* breakdown. Also known as mineralisation.

Denitrification: the conversion of nitrate (NO_3^-) to elemental nitrogen (N_2) under deoxygenated conditions, facilitated by specialised bacteria

Detritus: organic material originating from living, or once living sources including plants, animals, fungi, algae and bacteria. This includes dead organisms, dead parts of organisms (e.g. leaves), exuded and excreted substances and products of feeding.

Diatom: a microscopic, single-celled alga with cell walls made of hard silica, freely moving in the open water and forming fossil deposits

Dystrophic: a wetland that suppresses increased algal, cyanobacterial and plant growth even at high nutrient levels due to light inhibition

Endemic: naturally occurring only in a restricted geographic area

Endocrine disruptor: a synthetic chemical that when absorbed into the body either mimics or blocks hormones and disrupts the body's normal functions

Endocrine system: a complex network of glands and hormones that regulates many of the body's functions, including growth, development and maturation, as well as the way various organs operate

Eutrophic: nutrient rich waters or soil with high primary productivity (plant/algal/cyanobacterial growth). From the Greek term meaning 'well nourished'.

First flush: the first rainfall for a period of time, resulting in stormwater dislodging and entraining relatively high loads of sediments, particulates and pollutants that have built up in the intervening period between rainfall events, and typically carrying a higher pollutant load than subsequent events

Flocculation: the joining of particles (small objects) into loose masses (floc) in water

Gnangara groundwater system: the groundwater system formed by the superficial, Leederville and Yarragadee aquifers located in northern Perth, east to Ellen Brook, south to the Swan River, west to the Indian Ocean and north to Gingin Brook

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater capture zones: the area within which any recharge (infiltrating water) eventually flows into the wetland

Groundwater plume: body of polluted water within an aquifer

High water soluble phosphorus fertilisers: products containing greater than 2 per cent total phosphorus and greater than 40 per cent of the total phosphorus as water soluble phosphorus

Impermeable: does not allow water to move through it

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site

Internal eutrophication: eutrophication of wetland surface waters as a result of changes in water quality without additional external supply of nutrients[42]

Invertebrate: animal without a backbone

Ion: an atom that has acquired an electrical charge by the loss or gain of one or more electrons

Iron ferrolysis: a process by which anoxic groundwater containing dissolved ferrous ions is exposed to air and ferrous irons are oxidised to ferric ions, which reacts with water to form orange-brown precipitates, gels or crusts of ferric oxyhydroxides, releasing free hydrogen ions in the process

Latent: dormant, inactive

Lethal effect: where exposure to an agent such as a toxin results in death

Limiting nutrient: the nutrient in an ecosystem which limits further growth because it is available at proportionately lower levels with respect to other nutrients needed for primary producers to increase their abundance

Luxury uptake: the process by which some organisms take up more nutrients than they need for current growth, instead storing them for future growth

Macroalgae: algae large enough to be seen with the unaided eye

Microalgae: microscopic algae

Midges: biting and non-biting species of a number of families within the true flies (Diptera) including the Chironomidae and Ceratopogonidae.

Mutagenic: mutation-causing

Net acidity: the degree of acidity in water, accounting for dissolved alkalinity (that is, acidity minus alkalinity, measured in units of $CaCO_3$ equivalent per litre)

Nitrification: the conversion of ammonia (NH_3) or ammonium (NH_4^+) to nitrate (NO_3^-) in freshwater wetlands under oxygenated conditions, facilitated by specialised bacteria, if conditions (pH, temperature, organic carbon availability) are suitable

NTU: nephelometric turbidity unit is a measure of the clarity of water. Turbidity in excess of 5 NTUs is just noticeable to most people.

Organism: any living thing

Oxidation: the removal of electrons from a donor substance

Particulates: in the form of particles (small objects)

Pathogen: any organism or factor causing disease within a host

Pesticide: any chemical or biological agent intended to kill animals or plants

Phenol: complex organic compounds derived from plant materials

Physical parameters: physical characteristics of water such as temperature, turbidity, colour

Potential acid sulfate soils: soils that can contain significant sulfidic material, which on oxidation can cause the pH of the soil to fall to very low levels

Precipitate: cause a substance to be deposited in solid form from a solution

Reference range: a quantitative and transparent benchmark appropriate for the type of wetland

Resilience: capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks

Scum: froth or floating matter on the water surface

Sediment: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology.

Sediment pore waters: water which is present in the spaces between sediment grains at or just below the land surface. Also called interstitial waters.

Setback: a minimum distance between a particular land use and a wetland. A setback does not necessarily preclude other land uses within that setback area, in contrast to a wetland buffer. Land uses associated with a relatively high potential for site contamination, nutrient export or alterations to wetland water regimes (for example, some forms of intensive agriculture, industry, some effluent treatment facilities and groundwater abstraction) may require setbacks greater than the wetland buffer.

Slightly disturbed: ecosystems that have undergone some changes but are not considered so degraded as to be highly disturbed. Aquatic biological diversity may have been affected to some degree but the natural communities are still largely intact and functioning. An increased level of change in physical, chemical and biological aspects of these ecosystems is to be expected.[13]

Species: a group of organisms capable of interbreeding and producing fertile offspring, for example, humans (*Homo sapiens*)

Stormwater: water flowing over ground surfaces, in natural streams and drains as a direct result of rainfall over a catchment. It consists of rainfall runoff and any material (soluble or insoluble) mobilised in its path of flow

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between the layers

Sublethal effect: where exposure to an agent such as a toxin is insufficient to cause death, but may result in other adverse impacts

Sulfate-mediated eutrophication: eutrophication of wetland surface waters as a result of changes in water quality associated with sulfate rather than additional external supply of nutrients

Surfactant: a substance that helps water or other liquid to spread or penetrate. Also known as a wetting agent or penetrant.

Swan Coastal Plain: a coastal plain in the south west of Western Australia, extending from Jurien south to Dunsborough, and the Indian Ocean east to the Gingin, Darling and Whicher Scarps

Teratogenic: causing malformations of an embryo or foetus

Thermal water pollution: the excessive raising or lowering of water temperatures above or below normal seasonal ranges in wetlands, waterways, estuaries or oceans as a result of the discharge of hot or cold effluents into such waters

Transpiration: the process in which water is absorbed by the root systems of plants, moves up through the plant, passes through pores (stomata) in the leaves and other plant parts, and then evaporates into the atmosphere as water vapour

Trigger values: quantified limits that, if exceeded, would indicate a potential environmental problem, and so 'trigger' a management response e.g. further investigation

Trophic: from the Greek word for 'feeding', it relates to food and nutrition

Trophic classification: the classification of an ecosystem on the basis of its productivity or nutrient enrichment. The three main trophic classes are oligotrophic, mesotrophic and eutrophic.

Tolerance limits: the upper and lower limit to the range of particular environmental factors (e.g. light, temperature, salinity) within which an organism can survive. Organisms with a wide range of tolerance are usually distributed widely, while those with a narrow range have a more restricted distribution.

Turbid: the cloudy appearance of water due to suspended material

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Water hardness: a measure of the concentration of calcium and magnesium ions in water, frequently expressed as milligrams per litre calcium carbonate equivalent

Water quality: the quality of water relative to its natural, undisturbed state

Water regime: the specific pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

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A guide to managing and restoring wetlands in Western Australia

Secondary salinity

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Secondary salinity' topic

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Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Ion: an atom with an electrical charge. Used to refer to dissolved salts such as sodium (Na+) or chloride (Cl-) in solution

Salinisation: the process of accumulation of salts in soils, waters or sediments

Salts: ionic compounds comprised of cations (positively charged ions, such as sodium, Na+) and anions (negative ions, such as chloride, Cl-)

What is secondary salinity?

Salinity is a measure of the concentration of **ions** in waters, soils or sediments.[1] **Salinisation** can be a natural process, originating from sea **salts** that become airborne and are transported inland and which gradually accumulate in inland soils over thousands of years, or from natural salt build-up through contact with saline water near the coast. These processes give rise to naturally saline soil and wetlands. There are many such naturally saline wetlands in Western Australia, and they support a range of ecological values. In contrast, **'secondary' salinisation** is a human-induced degrading process in which the salt load of waters or soils increases at a faster rate than would have occurred naturally, leading to secondary salinity. Secondary salinity can occur in both freshwater and naturally saline wetlands.

➤ For information about naturally saline wetlands, see the topic 'Conditions in wetland waters' in Chapter 2.

There are two main types of secondary salinisation in Australia; dryland salinisation and irrigation salinisation. Dryland salinity occurs on non-irrigated land (including wetlands) and usually results from broadscale clearing of native vegetation and its replacement with crops and pastures that use less water, while irrigation salinity occurs through the addition of irrigation water to a landscape. In both cases, a change to the water balance leads to accelerated land and water salinisation. In Western Australia the predominant form is dryland salinisation, which occurs in the inland agricultural zone of the south-west (Figure 1).

Irrigation salinisation occurs in the Ord Irrigation Area in the north-east of the state and some of the irrigation areas of the south-west[2], with salt scalds evident in some areas of the Harvey River catchment.[3] About 20 per cent of the southern Swan Coastal Plain (i.e. between Gingin to Dunsborough) is considered to be at risk.[4] However irrigation salinity is not nearly as widespread as dryland salinisation[5], and is not discussed further in this topic.

Background to secondary salinity in Western Australia

Secondary salinity is a major threat to **biodiversity** in south-western Australia[7] and poses a serious threat to the biodiversity and **ecosystem processes** occurring in many wetlands in south-west WA.

Even relatively small increases in the levels of water and sediment salinity can dramatically decrease the growth, reproductive capacity and survival of wetland plants and animals, and if salinity ranges cross critical **thresholds** (which vary between species) this may cause irreversible loss of species and communities. In addition, increased salinity is coupled with changes to wetland **water regime**, particularly an increase in water depth and loss of seasonal wetting and drying cycles, and the combined effects of these two stresses on wetland **organisms** are even more severe.

The main area of Western Australia that is affected by secondary salinity is the inland south-west agricultural zone, which extends from north of Geraldton to east of Esperance, and which lies to the east of the Darling Scarp within the 300 and 600 millimetre rainfall zones[9,10] (Figure 1). The western part of the inland agricultural area and the south coast east of Esperance are particularly affected.[9,10]

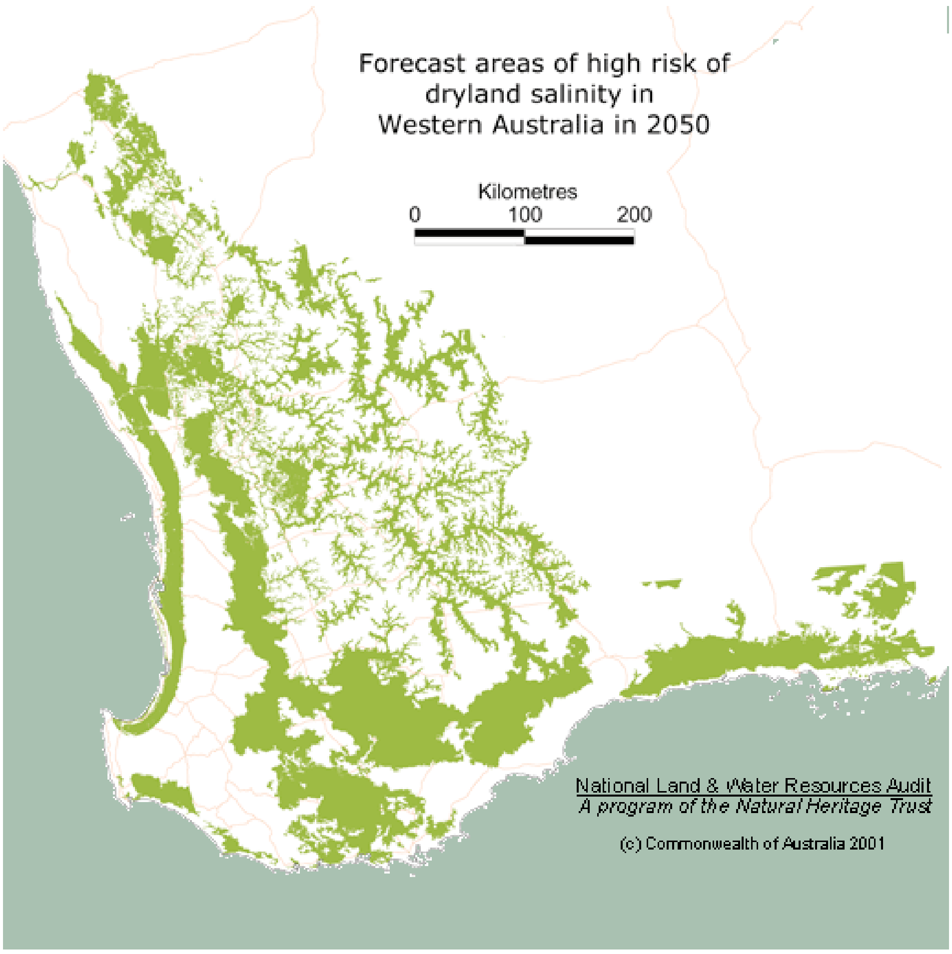


Figure 1. Forecast areas of high risk of salinity in 2050, based on the predicted extent of land at risk of high water tables (from Australian Natural Resources Atlas 2007[6]).

Biodiversity: encompasses the whole variety of life forms—the different plants, animals, fungi and micro-organisms—the genes they contain, and the ecosystems they form. A contraction of 'biological diversity'

Ecosystem: a community of interdependent organisms together with their non-living environment

Ecosystem processes: the complex interactions (events, reactions or operations) among biotic and abiotic elements of ecosystems that lead to a definite result[8]

Thresholds: points at which a marked effect or change occurs

Water regime: (of a wetland) the specific pattern of when, where and to what extent water is present in a wetland, including the timing, duration, frequency, extent and depth and variability of water presence[1]

Organisms: any living things (includes plants, animals, fungi and microbes)

Figure 2. (below) Two south-west Western Australian wetlands affected by secondary salinity. Photos - L Sim.

(a) Lake Mears, near Brookton

(b) Rushy Swamp, near Woodanilling

Dryland salinisation occurs over long time scales (decades to hundreds of years) and over very large areas, making it very challenging to manage. In 2001, the Land Monitor project estimated that the area of the state affected by salinity was about one million hectares and increasing at 14,000 hectares a year, based on 1996 data.[11] In total, 5.4 million hectares of the south-west are estimated to be at risk from dryland salinity.[11]

The number of wetlands potentially at risk is not known, as comprehensive mapping of all wetlands in south-west Western Australia is not complete. The landscape-scale processes driving secondary salinity mean that only limited intervention is usually possible at a wetland scale.

Along with its impacts on the environment, secondary salinity also has major economic implications, including the degradation of agricultural land and infrastructure such as roads and rural towns. This is accompanied by significant social impacts on rural communities, landholders and Aboriginal cultural heritage.[12]

What causes the salinisation of Western Australian wetlands?

Dryland salinisation within the south-west of Western Australia has developed as a result of the widespread clearing of **perennial** native vegetation and its replacement with **annual** crops and pastures which use less water. Most clearing took place between 1900 and 1930, and from 1950 to 1980.[13] Increases in water and land salinities in Western Australia were first noticed in the 1920s, however, the problem only became widely recognised throughout the inland south-west agricultural area several decades later.[13]

The inland south-west agricultural area is dominated by areas of naturally flat **landform**, low annual rainfall and high evaporation. These conditions have promoted the natural accumulation of airborne sea salts in the soils over hundreds of thousands of years.[10] Natural salinisation of many areas of the south-west occurred slowly before the landscape was disturbed by clearing, resulting in the development of naturally saline wetlands. In the Wheatbelt such sites of primary salinisation are estimated to have occupied less than 1 per cent of land area.[14] The rate of salinisation since land clearing and the areas affected by secondary salinity are much greater.[15] In areas of higher rainfall, lower evaporation and hillier landform (such as the tropical north, the Darling Scarp and areas of the south coast of Western Australia) the clearing of native vegetation has not had the same salinising effect.[10]

As described, dryland salinisation is linked to the clearing of native, perennial vegetation (such as trees) and its replacement with annual crop species (such as wheat).[10] This drives large-scale changes in **hydrology** – that is, the distribution and movement of water between the land surface, **groundwater** and atmosphere. Before broadscale land clearing, less than 1 millimetre per year of rainwater used to reach the groundwater in much of the inland south-west agricultural area; the rest was evaporated or **transpired** by vegetation, with the majority of water use in summer.[10] Most of the rainfall, except in large episodic events, infiltrated into the soils locally, with very limited surface flows (Figure 3(a)). The soils were also covered in a thin surface crust (a hard, water-repellent top layer), which prevented water from soaking in easily, and this crust has been disturbed by livestock and tilling for crops.[10] Both the removal of native perennial vegetation (particularly trees) and increased disturbance of the soil surface have resulted in increased amounts of water reaching the **groundwater tables**, causing them to rise (Figure 3(b), (c)). In consequence, both naturally saline groundwater and the salt stored in the soil profile are brought to the surface as the water rises.[10] The result is a significantly increased salt load in surface soils and in the region's fresh and naturally saline wetlands and waterways.[10] Rates of salinisation vary significantly across the region, but at Lake Bryde for example, salinity levels have increased rapidly with researchers identifying a ten-fold increase between 1981 and 1994.[16]

Wetlands often become salinised more quickly than other areas of the landscape because they are predominantly located in low-lying positions in catchments.[17] Saline water may enter wetlands directly from the underlying groundwater (Figure 3(b)). Wetlands that are not intercepted by the saline groundwater table may receive salty surface flows (Figure 3(c)). Many wetlands receive both saline groundwater and surface flows. As a result, most wetland types in the inland agricultural areas are affected by salinisation.

Few wetland types within the inland south-west agricultural area are considered to be at low risk of salinity and altered hydrology. These are typically higher in the catchments, for example, the bentonite wetlands in the Buntine-Marchagee catchment. They may be protected by geological features, for example, **gnammas** located on rocky outcrops and **perched** wetlands in vegetated catchments.[18] These wetlands should be managed as refuges for plants and animals vulnerable to salinisation.

Perennial: a plant that normally lives for two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Landform: a natural feature of a landscape such as a valley, mountain, basin or plain

Hydrology: the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Transpire (transpiration)**:** the loss of water from plants to the atmosphere through evaporation

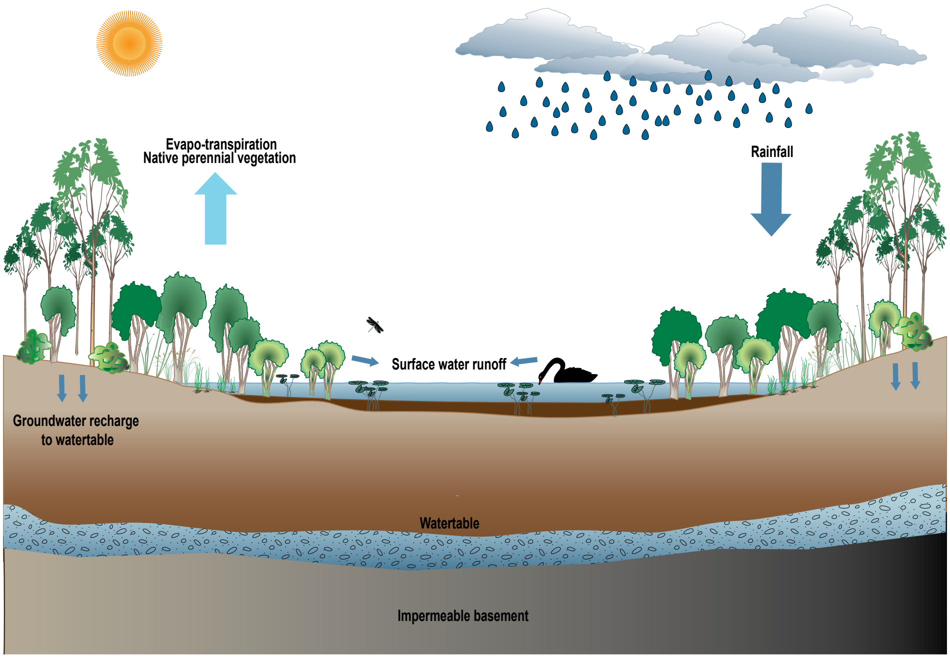
Groundwater table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone)

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyoongar origin

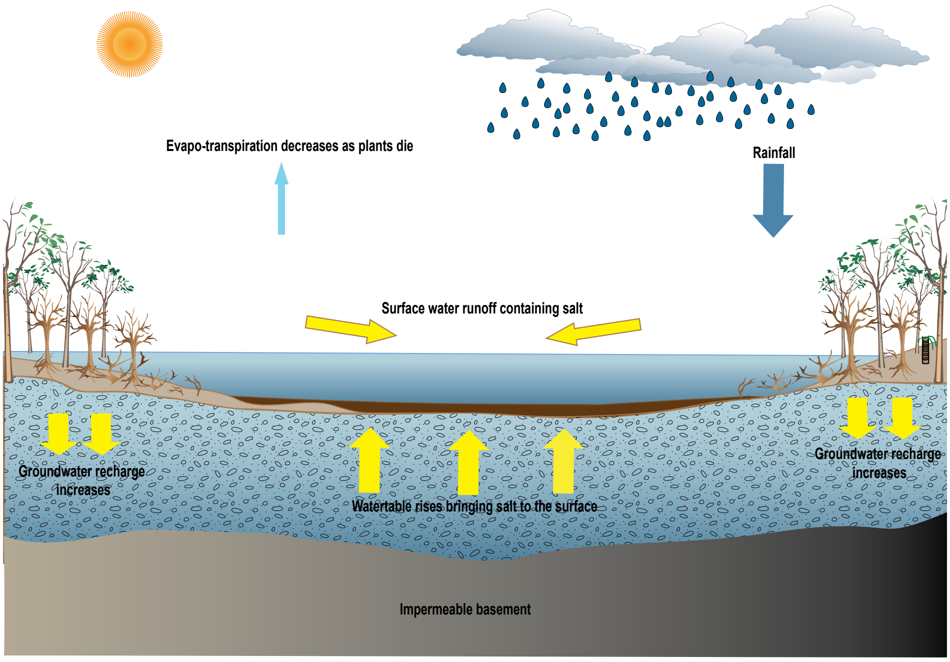
Perched: not connected to groundwater

In some areas that are affected by salinisation, freshwater seeps still exist, and along with wetlands less affected by salinisation, these may allow animals such as waterbirds to survive despite the salinity in the broader area, as they provide a source of fresh water for drinking.

Figure 3. (below) The distribution and movement of water and salt in wetlands of the Western Australian inland south-west agricultural area under (a) natural and (b) and (c) altered conditions after clearing.

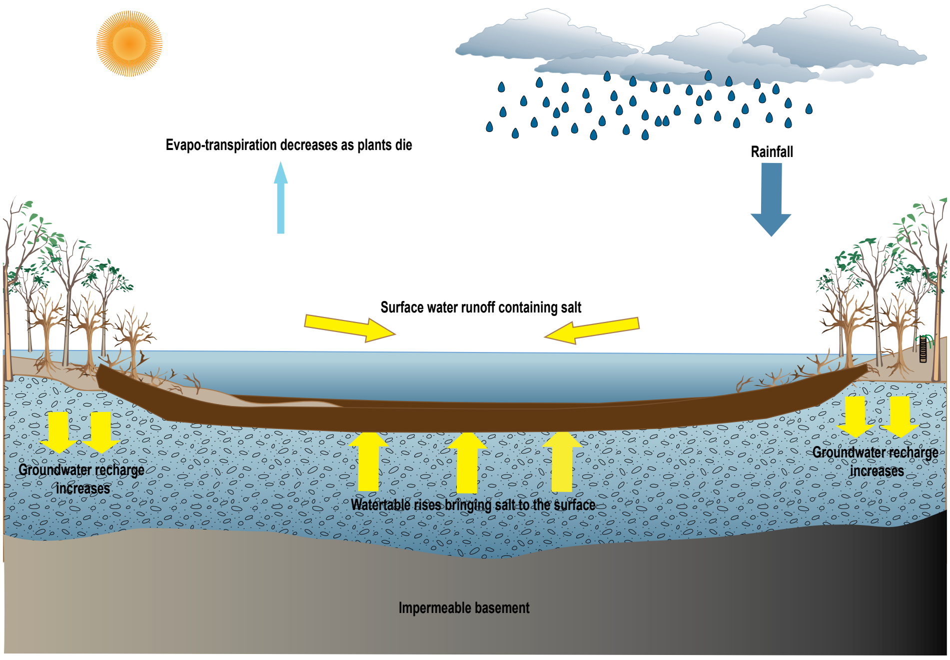


(a) Natural conditions of a wetland prior to clearing, showing low groundwater table, perennial vegetation and high transpiration rates.



(b) Altered conditions in a wetland after clearing, showing high groundwater table and low evapo-transpiration rates. In this scenario, saline groundwater is directly entering the wetland.

Figure 3. (continued)



(c) Altered conditions in a perched wetland after clearing, showing high groundwater table and low evapo-transpiration rates. In this scenario, the saline groundwater is not directly entering the wetland due to the presence of the impermeable clay layer. However it is reaching the soil surface and entering the wetland via surface flows.

Figure 3 depicts the process of secondary salinisation within landscapes that have relatively simple geological and hydrological profiles. In reality, the sub-surface characteristics and groundwater systems of the south-west of WA can be complex. To develop a better understanding of the conditions, specialist investigations including analysis of chemical isotopes and airborne electromagnetic surveying, such as that used in the Lake Warden catchment, may be used. Figure 4 shows more complex conditions present in many areas subject to secondary salinity.

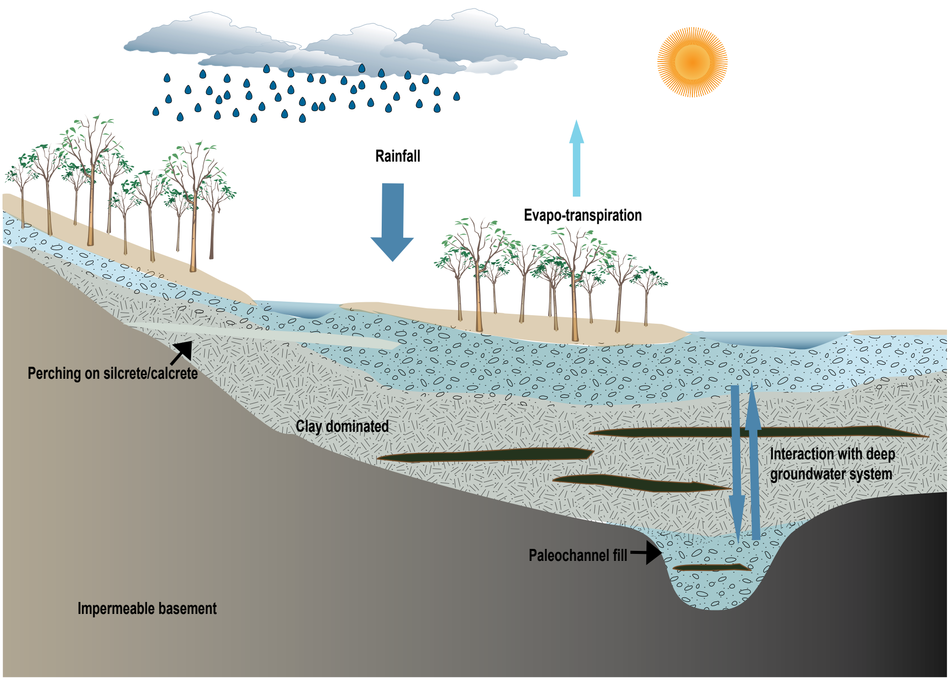


Figure 4. A representation of the complex, altered hydrological conditions present in areas of the agricultural zone within the zone of ancient drainage. Image – adapted from DEC.[19]

The general processes that lead to dryland salinity are similar throughout the inland south-west agricultural area, however, local and landscape variations in climate, landform, **geology** and the natural hydrology mean that the effect of land clearing and change in hydrology differ from place to place.

The trend of rising groundwater continues in high rainfall parts of the Wheatbelt and South Coast.[20] In contrast, the Environmental Protection Authority has reported that there is evidence to suggest that the drying climate in the south-west has lowered local groundwater levels in some places, slowing the rate of salinisation, especially in areas of the central and eastern Wheatbelt.[3] However the drying climate can create further stress on salinising systems, particularly perched wetlands, because the lack of rainfall deprives the plants and animals of the freshwater they require to survive and breed.

What effect does secondary salinity have on wetlands?

Dissolved salts occur naturally in fresh and naturally saline wetlands and play an important role in wetland chemical processes and the **metabolic functions** of wetland organisms, even when they are present in very low concentrations.[1,21,22] Furthermore, some species occurring in naturally saline areas are adapted to very high levels of salt. It is when a change in salinity level occurs very rapidly, or when a salinity threshold is reached for a particular species, that adverse effects on ecosystems may occur.[1,21,22]

Secondary salinisation can have significant impacts on the biological, chemical and physical components of both naturally fresh and naturally saline wetlands, and may ultimately cause a decline in biodiversity, the loss of **endemic** species, and changes in ecosystem processes. Naturally saline wetlands are not immune to the effects of secondary salinity, as it can alter the natural levels and ionic composition of salts to which the wetland plants, animals and **microbes** are adapted. The effects of secondary salinisation on wetlands are often particularly severe because they are coupled with significant and widespread changes in hydrology, and because they take place in an agricultural landscape where other pollutants such as nutrients, pesticides, acidic water and heavy metals are often also entering wetlands. Very little is currently known about how the combined effects of two or more threatening processes (for example, salinity and acidity) differ from those of salinity alone, although some work on the interaction between human-induced waterlogging and salinity has been done.[23] It is likely that the impact of multiple stresses on biodiversity and ecological processes is more severe than that of a single factor.

The biological, chemical and physical effects of salinisation are often interrelated, as the following sections describe.

➤ For additional detail on the effect of altered wetland water regime, see the topic ‘Managing wetland hydrology’ in Chapter 3.

➤ For additional detail on human-induced wetland acidity, see the topic ‘Water quality’ in Chapter 3.

Geology: the composition, structure and features of the Earth, at the surface and below the ground

Metabolic functions: the processes occurring within a living organism that are necessary to maintain life

Endemic: naturally occurring only in a restricted geographic area

Microbe: an organism that is too small to be seen with the unaided eye, for example, bacterium, some algae

Biological effects

The salinity ranges within which different species of wetland plants, animals and microbes survive, grow and reproduce are related to the salinities of their native environments. Organisms adapted to either naturally saline or freshwater conditions usually cannot tolerate large changes in the timing, duration, seasonality or range of salinities.[9,24] However, freshwater species are often sensitive to much smaller changes in salinity than salt-adapted species. The change from fresh to saline waters is generally accepted to occur at around 3 grams per litre (g/L) or 3 parts per thousand (ppt) of salinity.[24] This is the point at which marked changes in the types of plants and animals found in wetlands are expected. However, many salt-sensitive freshwater species may be unable to tolerate salinities as low as 1 part per thousand.[24]

Importantly, **juvenile** plants and animals are often much more susceptible to increased salinity levels than adults of the same species[24], therefore in order for a species to persist, salinities must be low enough during their development, as well as during reproductive phases, for **recruitment** to occur.

➤ For additional detail on salinity units, conversion and measurement, see the topic 'Conditions in wetland waters' in Chapter 2.

Vertebrates

The adults of many **vertebrate** species found in Western Australian wetlands are highly mobile, and can tolerate some increases in salinity levels if they can access alternative sources of fresh drinking water.[25,26,27] An example is the Australian shelduck (*Tadorna tadornoides*), which feeds at saline wetlands and is able to rid itself of excess salt it ingests through specially adapted nasal glands.[25] However, when breeding, Australian shelducks are dependent of fresh waters until their young develop an ability to rid their bodies of salt.[25]

Rather than restricting the community to a particular number of waterbird species, salinity appears to constrain the 'maximum potential number' of waterbird species occurring in agricultural zone wetlands, with **species richness** also being influenced by other factors such as water depth and density of emergent vegetation.[18] Even if an animal can tolerate some salinity change, it may still be lost from salinised wetlands due to the effect of the salinity on breeding or feeding habitats.

Another example of a moderately salt-adapted freshwater vertebrate is the oblong tortoise (*Chelodina colliei*), which is known to be able to tolerate estuarine level salinities if it has access to fresh water for breeding and long-term health (J Giles 2009, pers. comm.).[27] It does not possess a salt excretory gland (J Giles 2009, pers. comm.).

Only limited information is available about the tolerances of frogs to salinity in Western Australian wetlands, however, anecdotal information suggests that frog declines are associated with an increase in salinity.[13] The effect of increased salinity on populations of the spotted burrowing frog (*Heleioporus albopunctatus*) has been investigated in the inland south-west agricultural area, and there is some indication that there may be a decline in its numbers correlated with salinisation of its habitats, possibly related to the effect of salinity on eggs and tadpoles.[28] If this is the case, it is likely that other frog species in the region are also affected.

Juvenile: young or immature

Recruitment: addition of new individuals to a population (usually through reproduction)

Vertebrate: an animal with a backbone

Species richness: the total number of species (in a defined area)

Invertebrates

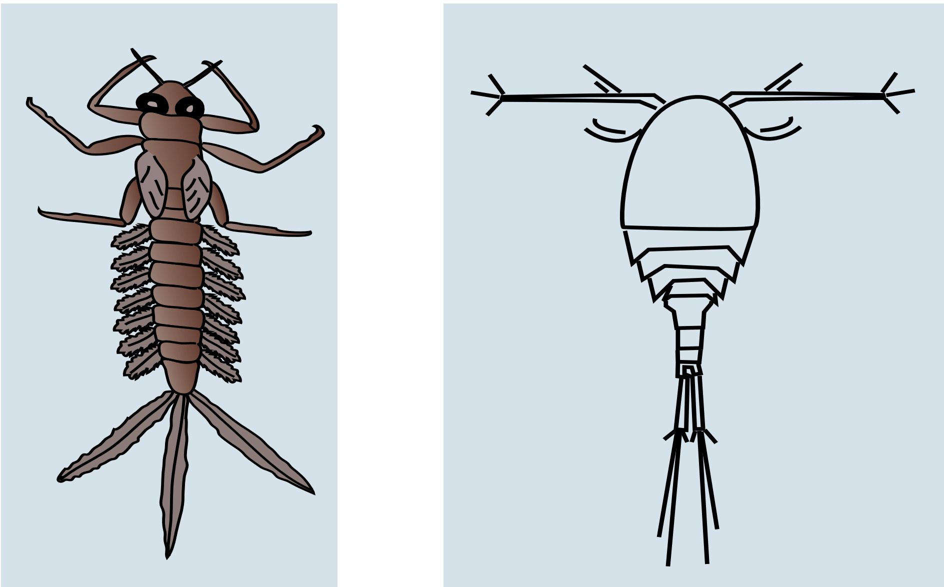
A few freshwater **invertebrate** species in south-western Australia are very salt tolerant, many are tolerant of mild salinity[9,29], but most, especially outside of the inland south-west agricultural zone, are largely restricted to freshwater (A Pinder 2009, pers. comm.). There is also a substantial number of salt-adapted fauna species called **halophiles** (from the Greek term for 'salt-loving') that show a preference for saline waters and many of these species are native to the south-west.[9,10] Many are restricted to naturally saline wetlands. These salt-adapted species are also threatened by salinisation, as salinity rises and hydrological regimes change.[9,30]

Despite some salt tolerance in the invertebrate fauna, the salinity changes occurring with salinisation have been too rapid and too large for freshwater species to adjust. Research[30] suggests that there are several salinity thresholds at which rapid loss of the Wheatbelt region invertebrate fauna occurs (in the higher rainfall areas of the south-west thresholds would be even lower). The most sensitive species are rapidly lost from wetlands with even very mild salinisation, leading to changes in the composition of the invertebrate fauna inhabiting the wetlands to more salt-tolerant species. Species richness (excluding halophiles, species that prefer very saline conditions) starts to decline at about 2.6 parts per thousand.[30] Those species that prefer saline waters decline in richness once salinity reaches above about 30 parts per thousand, though some will tolerate salinities many times that of seawater, which is around 35 parts per thousand. Even invertebrate groups with very high salt tolerances, such as the brine shrimp (*Parartemia* species) are showing declines in the Wheatbelt due to salinisation.[31] An example of a freshwater invertebrate group that contains many species sensitive to salinity increases is the insects (such as mayfly larvae), while groups like the **crustaceans** (such as copepods) tend to include a greater number of tolerant species (Figure 5).

Invertebrate: an animal without a backbone

Halophile: a species that shows a preference for saline habitat such as salt lakes

Crustaceans: a class of animals that have a hard exoskeleton (shell) and usually live in the water, for example, crabs, lobsters, yabbies



(a) **(b)**

Figure 5. Examples of (a) salt-sensitive (mayfly larvae) and (b) salt-tolerant (copepod) wetland invertebrate groups.

➤ For more information on invertebrates and the role they play in wetlands, see the topic 'Wetland ecology' in Chapter 2.

Plants

In general, freshwater wetland plant species tend to be sensitive to increases in salinity level and are rapidly replaced by salt-tolerant species as salinity increases.[24] In addition, changes to a wetland's salinity and water regime have different effects on **submerged** and **emergent** wetland vegetation due to their different tolerance ranges for these two factors. Many species of emergent vegetation (such as moonah (*Melaleuca preissiana*) and lake club-rush (*Schoenoplectus validus*), Figure 6) are perennial and feel the full effects of the combined stresses of increased salt and increased duration of waterlogging.[32,24] In contrast, freshwater submerged vegetation may be slightly protected from increased water in the wetland by being fully underwater, and annual submerged species can also persist through summer, when salinities levels are highest, as **dormant** seeds or **vegetative** parts such as **tubers**.[24] Despite this, in salinising wetlands, salinity levels quickly become too high for all freshwater organisms to survive. Even salt-tolerant plants such as species of *Ruppia* (Figure 6), *Lepilaena and Lamprothamnium* are lost when salinity levels exceed their tolerance limits.[33,14] Research[33] into salt-tolerant species of aquatic plants shows that their threshold for germination is 45 grams per litre, while the threshold for their survival is 90 grams per litre. At greater salinities, **phytoplankton** or **benthic microbial communities** (often visible as pink or purple mats formed by cyanobacteria and bacteria) are often the predominant primary producers. In permanently inundated wetlands, benthic microbial communities can dominate even at lower salinities.[14] Invertebrates, amphibians, reptiles and waterbirds reliant on plant-dominated wetland ecosystems may be lost when these changes occur.[14]

➤ For more information about plants and benthic microbial communities and the role they play in wetlands, see the topic 'Wetland ecology' in Chapter 2.

Loss of dryland vegetation surrounding wetlands and loss of emergent wetland vegetation can reduce the amount of protection the wetland has from wind and pollutants from surrounding land (such as nutrients), and can increase the amount of light and heat reaching wetlands. These are all factors that contribute to changes in the ecology of salinising wetlands.

Submerged: a plant that is entirely underneath the surface of the water

Emergent: a plant that is protruding above the surface of the water or, where a water column is not present, above the wetland soils (as distinct from floating or submerged plants)

Dormant: a state of temporary inactivity in which plants are alive but not growing

Vegetative: a stage or structure of a plant that is concerned with feeding, growth or asexual reproduction, rather than sexual reproduction

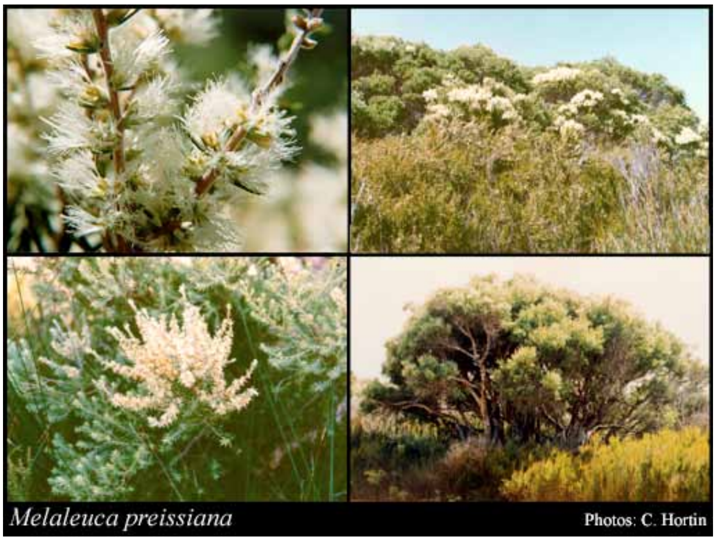
Tubers: specialised fleshy storage organs of the stem that are present in some plant species, usually found underground

Phytoplankton: Plankton (aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location) that are photosynthetic (for example, algae and bacteria)

Benthic microbial communities: bottom-dwelling communities of microbes (living on the wetland sediments)

Figure 6. (below) Examples of salt-sensitive and salt-tolerant wetland plant species. Photos – (a) C Hortin; (b) JF Smith; (c) J Thomas; (d) KA Shepherd; and (e) L Sim. Images (a) – (d) used with the permission from the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright.

Salt-sensitive species



(a) Moonah (*Melaleuca preissiana*) (emergent)

(b) Lake club-rush (*Schoenoplectus validus*) (emergent)

(c) Floating pondweed (*Potamogeton tricarinatus*) (submerged)

Figure 6. (continued)

Salt-tolerant species

(d) *Sarcocornia blackiana* (emergent)

(e) *Ruppia polycarpa* (submerged)

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from soil pore waters of inundated and waterlogged wetlands)

Flocculation: the joining of particles (small objects) into loose masses (floc) in water

Particulate: in the form of particles (small objects)

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Ionic composition: the particular ions making up a solution, usually expressed in terms of the relevant dominances of the major (most abundant) positively charged and negatively charged ions in a solution

Chemical effects

The chemical and physical effects of salinity on wetlands are often closely interrelated and can be difficult to separate. For example, in wetlands with **water columns**, salinity leads to increased **flocculation** of suspended **particulate** matter (including organic material and suspended sediments), and these larger particles then settle on to the wetland sediment.[24] This settling process leads, in turn, to increased light penetration into wetland waters, enabling better visibility and the potential for higher rates of predation of some organisms than under turbid conditions.[34] Increased light can also stimulate **photosynthesis**, leading to accelerated plant and algal growth, and may also increase heating of the water and penetration by ultraviolet rays. Flocculation can also make some important nutrients less available to wetland organisms. In particular, high levels of calcium (a naturally occurring salt) in the water column can affect the availability of the important nutrient phosphorus, as phosphate quickly binds to calcium carbonate and settles out.[35] A lack of biologically available phosphorus can restrict plant and algal growth.

Other chemical characteristics of wetland waters, such as the **ionic composition**, change as wetlands become more saline, and this can alter the relative dominance of different microbially driven processes such as **sulphate reduction** and **methanogenesis**. This changes the way that nutrients are cycled in a wetland, and has flow-on effects for the function of wetland food webs.

➤ For additional detail on the properties of wetland waters, including ionic composition and nutrient cycling, see the topic 'Conditions in wetland waters' in Chapter 2.

➤ For additional detail on wetland food webs, see the topic 'Wetland ecology' in Chapter 2.

Physical effects

The process of dryland salinisation can also lead to significant physical changes in wetlands, many of which are closely linked to chemical changes. Some of these effects are caused by excess water, some by excess salt and some by changes to the light penetration and temperature of the wetland waters.

As described earlier, the loss of vegetation together with changes to the chemical environment in salinised wetlands can increase the amount of light entering wetland waters. Increased light can increase the temperature of wetland waters, which may affect the metabolic processes of plants, animals and microbes. Higher water temperatures may alter the rates at which organisms grow and reproduce, the relative dominance of different organisms (some may be able to tolerate the new conditions better, and may out-compete others), and also have other flow-on effects, since temperature influences the solubility of dissolved gases such as oxygen and carbon dioxide.

Increased salinity in wetland waters may also cause wetlands to **stratify**. Salinity-driven **stratification** can lead to **anoxic** conditions at the bottom of the water column, and may lead to fish deaths and a change in microbial processes. This is because oxygen is much less **soluble** in saline waters than fresh waters, reducing its relative availability to wetland plants and animals.[36]

➤ For additional detail on stratification and on the effects of temperature change, see the topic 'Conditions in wetland waters' in Chapter 2.

In many permanently inundated saline wetlands, a thick mat of benthic microbial communities can develop over the **sediments**, and this layer may reduce or almost stop water exchange between groundwater and surface water.[37] This means that the wetland waters become increasingly saline over time, as the surface water evaporates and is not diluted by an inflow of fresher (although still saline) groundwater.

Another effect of the excess water associated with salinisation is increased flooding frequency and severity across the landscape. This occurs because much of the soil is already saturated with water, reducing its ability to 'soak' up large rainfall events. Instead of soaking into the soils, much of this excess water may become surface flood flows.[9,10]

In some cases, excess salt can lead to a decline in soil/sediment structure. Over time, the chloride ions in salinised soil may be flushed out, leaving high concentrations of sodium ions (sodium and chloride are the two most dominant ions in land and water salinity in Australia). This lead to the development of 'sodic' soils where the sodium ions attach to clay particles in the soil, meaning that when they are wet they can no longer stick together.[38] This makes them prone to **erosion** and collapse, especially if they are drained.

Excess salt may also lead to the creation of salt crusts on the base of wetlands, which can act as a physical layer shielding the sediments from the effects of solar radiation and exposure to air. Benthic microbial communities can survive underneath this layer of salt, and the crust can also prevent the seeds and eggs of wetland plants and animals from germinating or hatching.

➤ For additional detail on the effects of dissolved salts in wetlands, see the topic 'Conditions in wetland waters' in Chapter 2.

Sulphate reduction: the chemical process where sulphate is joined with hydrogen and gains electrons

Methanogenesis: the production of methane by microbes

Stratify: separate the water column into distinct layers

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between these layers

Anoxic: deficiency or absence of oxygen

Soluble: able to dissolve

Sediments: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology

Erosion: wearing away and movement of land surface materials (especially rocks, sediments and soils) by the action of water, wind or a glacier

What does wetland salinisation look like in Western Australia?

The first sign of wetland salinisation is usually the death of freshwater wetland vegetation, including emergent and submerged species.[13] A decline in water quality will also be evident if wetland water is used for livestock or domestic purposes. The loss of freshwater vegetation leads to bare areas around and inside wetland boundaries, which may later be colonised by salt-tolerant species, such as **samphires**. Increases in both salinity levels and the extent and duration of soil waterlogging can cause a decline in the health of emergent and dryland vegetation, although the effects may vary between species.[23] When they become more advanced, the effects of salinisation are very visually evident (Figure 7) due to the presence of **salt scalds** on the ground and the widespread death of trees and shrubs, and lumps of salt may even be seen floating in the waters of highly saline wetlands. Common signs of secondary salinity in and around previously freshwater wetlands include:

- dead trees and other woody shrubs (Figure 7(a, b))
- salt scalds on bare ground (Figure 7(c))
- deposits of solid salt in and around wetlands (Figure 7(d))
- disappearance of salt-sensitive plant species (Figure 7(e))
- appearance of salt-tolerant species such as samphires or salt bushes (Figure 7(f)).

Samphire: the common name for a group of succulent sub-shrubs and shrubs including *Tecticornia, Halosarcia, Sarcocornia, Sclerostegia, Tegicornia* and *Pachycornia*, belonging to the family Chenopodiaceae

Salt scald: a bare area of ground caused by secondary salinisation, in which vegetation has died and solid salt is visible

Figure 7. (below) Signs of dryland salinity in and around wetlands. Photos – (a), (c)–(f) L Sim, (b) M Cundy/DEC.

(a) Death of trees and other woody vegetation at Lake Mears, near Brookton

(b) Tree death in the Buntine-Marchagee Natural Diversity Recovery Catchment

Figure 7. (continued)

(c) Salt scald, Arthur River flats near Highbury

(d) Deposited solid salt at the Yenyening Lakes, near Brookton

(e) Loss of rushes/sedges around 'Rushy' Swamp, near Woodanilling

Figure 7. (continued)

(f) Samphires around Lake Mears, near Brookton

The effects and appearance of salinity may also change from year to year with the influence of variable rainfall on wetland water levels, salt loads and sediment/soil salinity. The most reliable way of assessing whether wetland waters or surrounds are affected by salinisation is to measure the water or soil salinity levels.

➤ For additional detail on salinity measurement, see the topic 'Conditions in wetland waters' in Chapter 2, and for monitoring methods, see the topic 'Monitoring wetlands' in Chapter 4.

➤ The salinity of a number of Western Australian wetlands has been monitored by DEC's and its predecessor agencies. See the *South west wetlands monitoring program report 1997–2010*[39] and *WetlandBase*[40] for more information.

At a much broader scale, remote sensing can be used to predict whether a wetland may be saline. A method for predicting whether a wetland is either 'fresh-subsaline' or 'saline' using remote sensing methods has been developed for use in the Avon natural resource management region.[41]

Managing and restoring salinising wetlands

Landscape-scale approaches

Landscape-scale salinity management focuses on the reduction of excess water in the landscape. The landscape-scale nature of the processes underlying dryland salinisation make it necessary to approach salinity management from a catchment perspective if it is to have a lasting effect on the conditions on ground. As a result, effective salinity management is often the result of coordinated effort across different regions and areas of expertise and can be very costly to implement.

A variety of complementary measures are typically required, that is, an 'integrated water management' approach. This calls for a sound understanding of the hydrological conditions and typically involves a range of studies including catchment and finer-scale surface water assessments, groundwater investigations, groundwater numerical models, soil mapping and the installation and maintenance of a bore network.

Table 1 summarises the broad approaches used to manage dryland salinisation at the catchment-scale in the inland south-west agricultural zone.

Table 1: Water management in the inland south-west agricultural zone - problems, causes and solutions. Reproduced with permission from K Wallace/DEC.

Water problems		
Surface water	**Groundwater**	**Water-borne**
• Waterlogging • Erosion (soil, drainage line, stream banks) • Increased recharge • Flooding, inundation and associated damage	• Groundwater rise, and all associated salinity problems • Increased surface flows from saline soils	• Siltation • Nutrient loading • Eutrophication • Spread of weeds • Pesticides • Water quality decline

Causal factors				
Biophysical changes (non-structural)	**Cultural structures**	**Natural structures**	**Episodic events**	**Interaction between causal factors**
• Replacement of natural veg. with annual crops and pastures • Changes in soil properties as a result of agriculture • Loss of storage and discharge function of natural wetlands • Degradation of nutrient sink function of wetlands	• Damage to roads, tracks • Damage to railway lines • Drainage works • Cultivation of drainage lines • Paving and other enhanced drainage in towns and urban areas	Topography, landform, soils, geology, and salts stored in soil profile will all have a range of impacts such as: • dykes impeding groundwater flow • natural surface barriers • sand bars • extensive flats and areas of low relief.	• High volume, high intensity rainfall events, particularly summer cyclones • High volume, long duration events; high volume and prolonged wet seasons • Wildfires and associated loss of vegetation cover • Extended periods with little or no rainfall	All the preceding factors interact. How they interact at a particular site, or within a particular sub-catchment or basin, will vary.

Solutions				
Engineering	**Revegetation and high water-use plants**	**Agronomic change**	**Enhanced storage**	**Protection of remnant native vegetation**
• Diversion structures (e.g. grade banks, diversion banks, levees) • Drainage structures (e.g. seepage interceptors, deep drains, w-drains) • Storage structures (see column dealing with enhanced storage) • Groundwater pumping	• Perennial woody vegetation • Perennial grasses and legumes • Stabilisation of stream banks • Nutrient stripping	• Contour farming • Continuous cropping • Phase cropping • Complete change of land use in prone areas, e.g., adopt productive saline systems and aquaculture • Salt land agronomy	• Increase dams up-slope and associated water harvesting • Increase valley storage • Evaporation basins • Regulation of flow to wetlands	For example: • fence remnant vegetation • control herbivores and omnivores • manage weeds.

Salinity management programs

One of the major programs for landscape-scale salinity management in WA that focuses on wetlands is the 'Natural Diversity Recovery Catchments' program developed under the State Salinity Strategy, which is aimed at protecting areas with high natural diversity that are threatened by rising water tables and salinisation, and focusing especially on wetlands. So far, six Natural Diversity Recovery Catchments exist:

- Buntine-Marchagee
- Drummond
- Lake Bryde complex
- Lake Muir-Unicup
- Lake Warden
- Toolibin Lake.

This program has been instrumental in pioneering many techniques for managing dryland salinity in WA. A central aim of salinity and landscape-scale water management in these catchments is to achieve integration between nature conservation and sustainable agricultural practices[19] (Figure 8).

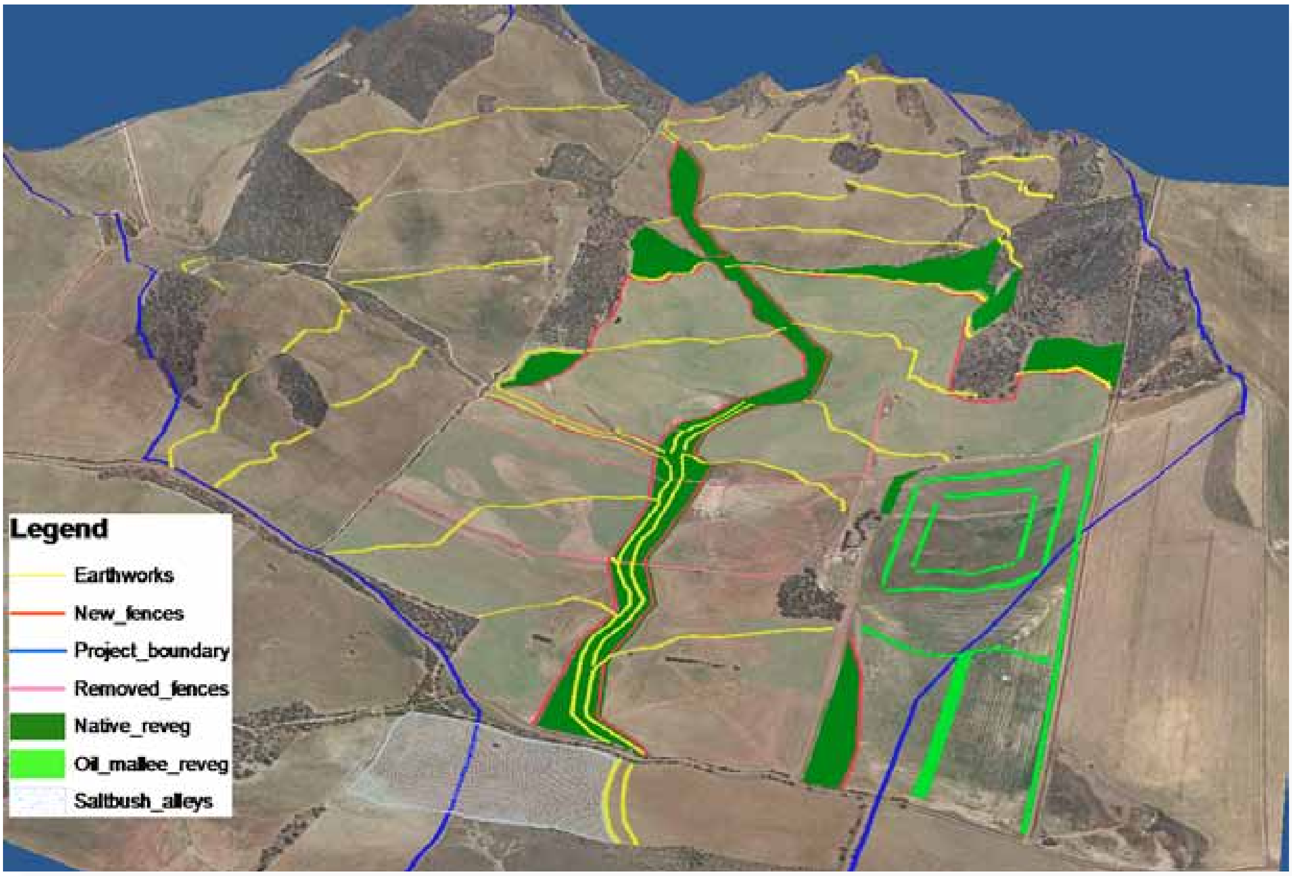


Figure 8. Integrated water management at the landscape scale has a positive effect on reducing salt, nutrient and sediment export to downstream wetlands. Engineering and biological options are integrated to optimise gains in water management (surface and groundwater) and agricultural productivity in this 800-hectare demonstration area in the Buntine-Marchagee. Note the elevations are exaggerated. Image – R Dawson/DEC.

➤ Information on DEC's Natural Diversity Recovery Catchments can be found at DEC's website.[42]

Another major state government program, which focuses on landscape-scale salinity management more broadly, is the Engineering Evaluation Initiative led by the Department of Water. It examines a range of potential mitigation options including deep drains, groundwater pumping and surface water management, safe saline water disposal and regional drainage planning.

➤ More information on the Engineering Evaluation Initiative is available from the Department of Water website.[43]

Intervention measures for wetlands

The management and restoration of salinising wetlands is complex and requires a detailed understanding of site hydrology and ecology. In cases where resources are more limited, such as when managing wetlands on private land in areas outside of large catchment-scale restoration projects, it may be more realistic to aim to assist the wetland ecosystem to adapt in the face of a threat that is unlikely to lessen, or to maintain current conditions if possible. This approach is described in the case study in this topic entitled 'Meeking Lake – wetland management at a local scale'.

The reality is that even within managed catchments, it is likely that it will not be possible to tackle secondary salinity at every wetland. Prioritisation is typically required to decide which wetlands should receive intervention measures and which will miss out.

The majority of wetlands affected by secondary salinity within the inland south-west agricultural area are already significantly altered and, as such, relatively unchanged wetlands are rare. Wetlands that have been salinised for several decades have arguably now become a 'new' type of ecosystem, and may resemble naturally saline wetlands more than naturally fresh wetlands, although there are also likely to be differences between naturally and secondary saline systems. However, although salinised wetlands are degraded in terms of their original values, they may still provide important services in the landscape, such as nutrient cycling, water retention, and drought refuge.

Importantly, there is evidence to suggest that further salinity increases could actually have significant detrimental effects on many salinising wetlands if they lead to the loss of the (salt-tolerant) submerged plant communities that dominate these systems.[14] These plants provide habitat for invertebrates, food for vertebrates such as waterbirds, and store nutrients, which would otherwise be free to feed algal blooms. Therefore, a critical goal is to stop salinities from exceeding the threshold level at which these submerged plants are lost from the system. The concept of 'alternative stable states' suggests that re-establishing these submerged vegetation communities may not be as simple as lowering the salinity level again, making it even more important not to cross the threshold in the first place.[44,45]

➤ Funding, training and other resources are available for landholders and wetland managers tackling secondary salinity and altered hydrology. For more information see the topic 'Funding, training and resources' in Chapter 1.

➤ A detailed example of an integrated approach to the management of a catchment with multiple valuable wetlands can be found in the *Buntine-Marchagee Natural Diversity Recovery Catchment Recovery Plan: 2007–2027*.[19]

Intervention techniques at the wetland scale

Key water management and restoration techniques for use in and around salinising wetlands include:

- retaining and restoring remnant vegetation
- revegetating
- controlling surface water inflows
- flushing
- dewatering
- pumping
- drainage
- creation of evaporation basins and sacrificial wetlands.

These are outlined in Table 2.

Expert advice is required to design and carry out management interventions, particularly those that relate to altered hydrology. Ideally, any salinity management activities should be undertaken as part of a comprehensive wetland management plan, which also addresses other management issues or degrading processes and their associated management activities. It is strongly encouraged that a management plan is prepared, when managing any wetland, however basic it may be.

➤ For additional detail on preparing a wetland management plan see the topic 'Planning for wetland management' in Chapter 1.

Legal requirements associated with draining and pumping water

It is very important to be aware of the legal requirements associated with draining and pumping water for salinity control purposes. These activities are primarily regulated under the *Soil and Land Conservation Act 1945*. The environmental harm provisions of the *Environmental Protection Act 1986* also apply. Further regulations may apply, for example, within proclaimed surface water areas and waterway conservation areas. For additional detail on legal requirements associated with the control or modification of ground and surface water for salinity control purposes see the topic 'Legislation and policy' in Chapter 5.

Table 2. Key water management techniques for use in and around salinising wetlands

Action	Purpose	How it is achieved	Figure	Considerations	Case studies/key resources
Retaining and restoring remnant wetland and dryland vegetation	Maintain existing water use	Fencing off remnant vegetation from livestock; covenanting of remnant vegetation	Figure 9	• A cost-effective salinity management tool • Provides the dual function of maintaining biodiversity and ecosystem function	Example: fencing of remnant vegetation in the integrated water management demonstration catchment, Buntine-Marchagee[46] Resource: 'Managing wetland vegetation' topic, Chapter 3
Revegetating areas around wetlands	Increase water use	Planting and maintaining perennial woody vegetation e.g. endemic natives, perennial pastures, saltbush, oil mallees	Figure 10	• Yields short to long-term changes on water table and salinity levels. Can prevent further concentration of salts in the short-medium term, and reduce water levels in the longer term (e.g. a decade or more) • Critical to select suitable revegetation sites and vegetation. Site selection factors include geology, soil, size and part of the landscape • Preferable to use species local to the area that also meet the landowner's agricultural land use objectives	Example: revegetation in the integrated water management demonstration catchment, Buntine-Marchagee[46] Resource: Revegetation guidelines on DEC website.[47] Includes case studies of numerous revegetation projects Resource: 'Managing wetland vegetation' topic, Chapter 3
Controlling surface water inflows	Prevent saline water entering wetland	Installing and managing structures to bypass or divert salty water	Figure 11	• Often reduces total amount of inflows. This can cause environmental impacts to the wetland, which can be exacerbated by periods of sustained drought or sustained reduced rainfall due to climate change • May have significant downstream impacts (see evaporation basins and sacrificial wetlands, below) • Requires environmental approval to ensure that no significant environmental impacts occur	Example: Toolibin Lake surface water diversion channel and separator gate
Wetland flushing	Remove some accumulated salts from wetland	Using fresher water, making use of an inflow and outflow		• Less common technique in WA as wetlands are not as commonly connected to permanently flowing river systems as in eastern Australia	Example: Toolibin Lake outlet control system

Table 2. Key water management techniques for use in and around salinising wetlands

Action	Purpose	How it is achieved	Figure	Considerations	Case studies/key resources
Wetland dewatering	Lower wetland water levels	Pumping wetland water out of wetland	Figure 12	• Requires environmental approval to ensure that no significant environmental impacts occur • May have significant downstream impacts (see evaporation basins and sacrificial wetlands, below)	Example: Lake Wheatfield dewatering, Lake Warden Wetland System, Esperance
Groundwater pumping	Lower groundwater table	Pumping groundwater from the site and disposing elsewhere	Figure 13	• Feasibility needs to be assessed by an experienced hydrologist • Very expensive to establish and run; requires power • Buys time; can be feasible in combination with longer-term techniques such as revegetation • May have significant downstream impacts (see evaporation basins and sacrificial wetlands, below) • Requires environmental approval to ensure that no significant environmental impacts occur	Example: Toolibin Lake groundwater pumping
Landscape drainage	Remove excess surface water or shallow groundwater from landscape	Constructing and maintaining earthen drains and waterways	Figure 14	• Works need to be designed by an experienced hydrologist • Suitability of site is dependent of the geology and hydrology of the area • Groundwater drains involve a higher level of intervention, cost and maintenance than surface water drains • May have significant downstream impacts (see evaporation basins and sacrificial wetlands, below) • Requires environmental approval to ensure that no significant environmental impacts occur	Example: constructed grassed waterway, integrated water management demonstration catchment, Buntine-Marchagee[46] Example: Toolibin Lake, Dulbining constructed waterway
Creation of evaporation basins, selection of sacrificial wetlands	Dispose saline water generated via pumping, drainage etc	Constructing/ selecting a site for evaporation and development of saline crust or brine	Figure 15	• The location of the basin/wetland must be optimal to minimise transportation required, while ensuring that plumes do not reach the wetland being managed • Requires environmental approval to ensure that no significant environmental impacts occur	Example: Toolibin Lake, Taarblin Lake saline groundwater disposal

Figure 9. Fencing to help protect remnant vegetation. Retaining existing native vegetation is a cost-effective measure for salinity management. Photo – G Mullan/DEC.

Figure 10. (below) Revegetation with native species to help manage altered hydrology in the Buntine-Marchagee catchment (a) using oil mallee eucalypts as a prospective commercial crop (b) using *Atriplex amnicola* (river saltbush), a stock fodder, in groundwater discharge areas and (c) using mixed shrubs and trees chosen for their resilience, structural diversity and genetic integrity in areas of low agricultural productivity. Photos – G Mullan/DEC.

(a)

(b)

Figure 10. (continued)

(c)

Figure 11. Controlling surface water flows into Toolibin Lake using a separator gate. It captures and diverts low volume, high salinity flows, preventing them from entering the wetland. Photo – L Mudgway/DEC.

Figure 12. (below) Dewatering of Lake Wheatfield (a) pipeline entry point at Lake Wheatfield (during installation, prior to being submerged); (b) pipeline exit point at Bandy Creek. Photos – (a) K Oswald/DEC; (b) J Lizamore/DEC.

(a)

Figure 12. (continued)

(b)

Figure 13. (below) (a) Pump and (b) tank to pump groundwater at Toolibin Lake. Photos – R McKnight/DEC.

(a)

(b)

Figure 14. A landholder inspects a constructed grassed waterway in full flow in the Buntine-Marchagee catchment – a part of the landscape-scale integrated water management approach. Photo – K Stone.

Figure 15. (below) (a) Lake Taarblin, which receives saline discharge from Toolibin Lake (b) a saline discharge point at Lake Taarblin. Photos – M Lee/DEC.

(a)

(b)

case study

Toolibin Lake – wetland restoration at a catchment scale

Toolibin Lake is a large (493-hectare), tree-dominated, brackish-freshwater wetland located 40 kilometres east of Narrogin in the central inland south-west agricultural area[48] (Figure 16). It is located at the top of a chain of nine wetlands that form part of the Northern Arthur River drainage system within the Upper Blackwood River catchment.[49] It is the only major wetland in the chain not to have salinised.[50] The wetland is located within a system of 'A' class nature reserves managed by the DEC, but the wider catchment has been extensively cleared for agriculture, and is affected by dryland salinisation.[48]

Figure 16. Aerial view of Toolibin Lake, June 2008. Photo – DEC.

Toolibin Lake is recognised as a wetland of international significance, being listed under the Ramsar Convention on the basis of it being the last, large wetland dominated by *Casuarina obesa* and *Melaleuca strobophylla*, and due to its important waterbird habitat, particularly the significant number of breeding waterbird species it can support when full or close to full.[51,52] It is also listed as an (endangered) threatened ecological community under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, and is also identified by DEC as a critically endangered community.[48] The wetland is recognised as the best remaining representative of a 'Perched wetland of the Wheatbelt region with extensive stands of living sheoak and paperbark across the lake floor' that still retains a significant proportion of living trees[48] (Figure 17).

(a)

(b)

Figure 17. (a) *Casuarina obesa* and (b) *Melaleuca strobophylla* stands at Toolibin Lake. Photos – R McKnight/DEC.

case study

Prior to salinisation, this was a common wetland type in the region, but increased salinity has impacted heavily on these wetlands. The absence of water in recent years has significantly impacted on waterbird use of the wetland.[48] In recognition of its high natural diversity values and the threat posed by secondary salinity, Toolibin Lake was listed in 1996 as one of the first 'Natural Diversity Recovery Catchments' under the State Salinity Action Plan.[49]

Toolibin Lake was historically a perched freshwater wetland, with the groundwater table located 15 metres below the wetland bed. It is filled through surface flows in years of above-average rainfall, or when there are significant summer rainfall events. Depending on rainfall, the wetland may not fill for a number of years, but after a large rainfall event, it may remain full for several years. When Toolibin Lake is full, it can reach a maximum depth of 2 metres, after which it overflows into other wetlands downstream.[49] Since overflowing in 1996, it has only partially filled once, in summer 2006. This is due to very low rainfall over the past decade and the installation of a diversion gate to divert saline surface water flows, which reduces the amount of water entering the lake.[19]

Salinity in the wetland has increased over the past decades as a result of catchment clearing, due to increasingly saline surface water inflows from surrounding land and a rise in the saline groundwater level almost to the level of the wetland bed.[49] The wetland appears to have some protection from salinisation from direct groundwater intrusion due to the presence of an unconsolidated clay layer under the wetland, however the wetland vegetation is still vulnerable to the combined effects of salinity and increased waterlogging.[23]

Recovery actions

A detailed recovery plan was developed for Toolibin Lake in 1994[53] and a review of this plan is underway. A range of key recovery works have been carried out since 1994, as outlined below.

To reduce groundwater recharge:

- protection and revegetation of remnant vegetation in the catchment
- changes to agricultural practices, including the introduction of contour farming (tillage across slopes that follows the topographic contour, or close to it) and sustainable, high-water use crops such as woody perennials.

To manage surface water:

- reductions in agricultural waterlogging, particularly via the installation of surface water drains
- diversion of highly saline inflows around Toolibin Lake via a separator gate and diversion channel
- increased salt export out of the wetland, by constructing an outlet control system to manage outflows
- construction of Dulbining waterway to reduce the impact of increasing surface flows, waterlogging and inundation, and to reduce salt storage in the catchment.

To increase groundwater discharge from the wetland:

- groundwater pumping to lower the water table beneath the wetland.

Regular monitoring of biological and physical parameters is carried out at Toolibin Lake to assess the success of these management actions against a range of key criteria. In 2002, it was estimated that an 80 per cent reduction in salt load entering the lake had been achieved.[54] Furthermore, a depth to groundwater of greater than 1.5 metres has been achieved. Yet while there has been a positive effect of actions designed to lower the watertable under the wetland, many of the biological and water quality criteria have been made difficult to assess due to the lack of rainfall to fill the wetland since the early 1990s.[55] To date, the overall condition of mature vegetation has either stabilised or continued to decline in areas, with limited regeneration (Figure 19). A range of studies and an adaptive management approach is being carried out.

➤ For more information about Toolibin Lake, please contact the Conservation Officer (Toolibin Lake), Narrogin District Office, DEC. Telephone: (08) 9881 9200.

case study

Figure 18. (below) Examples of management actions being implemented in the Toolibin Lake NDRC (a) Toolibin Lake showing diversion channel on western side, (b) view of 'Chadwick's Block', which was purchased by DEC and revegetated, (c) waterway from Dulbining Lake to Toolibin Road North to improve water conveyance through to Toolibin, (d) catchment revegetation works. Photos – DEC.

(a)

(b)

(c)

(d)

Figure 19. Recruitment of *Melaleuca strobophylla* at Toolibin Lake. Photo – J Higbid/DEC.

case study

Meeking Lake – wetland management at a local scale

Meeking Lake is a 25-hectare seasonally inundated wetland situated on private land north of Darkan in the central inland south-west agricultural area. It is thought that it is gradually becoming more saline. The property is not located within a catchment with a dedicated integrated catchment-scale restoration program.

By fencing out livestock and revegetating the wetland, the landowners have reduced the threats to it and improved its condition. While these actions will not reduce the rate of salinisation, they may assist the wetland ecosystem to adapt to the changing conditions.

A narrow fringe of wetland vegetation surrounds the water on all sides. The landholders have fenced and revegetated the northern and eastern sides of the wetland. A road lies to the west, while there is paddock to the north and woodland to the east and south. Meeking Lake was historically fresh however over the past twenty years it has experienced increased water salinities (M Steddy 2004, pers. comm.), accompanied by tree deaths and the recruitment of salt-tolerant species including *Ruppia polycarpa* and *Melaleuca viminea*.

Figure 20. Meeking Lake. Photo – L Sim.

Impacts of catchment-scale clearing

It appears likely that Meeking Lake has salinised both via groundwater intrusion at its edges (although not through the main bed of the wetland), and via overland flow of surface water from nearby salinised land (T Mathwin 2004, pers. comm.). Water salinities measured at the wetland between 2002 and 2004 usually ranged from 7 to 30 parts per thousand.[56] Without intervention, the wetland is likely to continue to become more saline (T Mathwin 2004, pers. comm.). It is not known how quickly it has become salinised, however the persistence of turtles and frogs (D Steddy 2004, pers. comm.), and the health of the wetland vegetation suggest that the change has been gradual, and that a critical threshold for the loss of these species has not yet been reached.

case study

Retained wetland values

Despite the change from fresh to saline water, Meeking Lake still supports a diversity of healthy wetland vegetation including *Melaleuca viminea*, *M. lateritia*, *Baumea articulata* and *Typha* species, and a relatively diverse fauna including resident breeding oblong tortoises (*Chelodina colliei*, Figure 21), gilgies (*Cherax quinquecarinatus*) and small fish. When the wetland is inundated, it is covered in a dense bed of submerged plants, dominated by *Ruppia polycarpa, Lamprothamnium macropogon* and *Lepilaena preissii.*[56]

Figure 21. Juvenile oblong tortoise (*Chelodina colliei*) at Meeking Lake. Photo – C Mykytiuk.

Topic summary

- Secondary salinity is a major threat to wetland and terrestrial biodiversity within the south-west agricultural zone, and it operates over very large scales. The main area of WA that is affected by secondary salinity is the south-west agricultural area, which extends from north of Geraldton to east of Esperance, within the 300 and 600 millimetre rainfall zones.
- The removal of native perennial vegetation and its replacement with annual crop species has led to a rise in groundwater levels. Rising groundwater brings salt stored in the soil profile to the surface, salinising lands and waters.
- The large-scale causes of salinity make management of wetland salinisation and the restoration of salinising wetlands very difficult.
- When the concentrations of dissolved salts get much higher or change very quickly, significant impacts on biological, chemical and physical components of wetlands can result. The effects of increased salinity are heightened by the accompanying changes to wetland hydrology.
- Most wetland types in the inland south-west agricultural area are affected by salinisation unless they are protected by special geographic or geological features, for example, perched wetlands in vegetated catchments and on rocky outcrops.
- Common signs of salinity include:
    - death of trees and other woody vegetation
    - salt scalds on bare ground
    - precipitated salt in and around wetlands
    - loss of salt sensitive species
    - appearance of salt-tolerant species (for example, samphires or salt bushes)
    - changes to wetland vegetation (species)
    - water or soil salinity testing (most reliable).
- The management and restoration of salinising wetlands is often complex and costly, and is most effective if approached as part of integrated catchment management. If resources are limited, it may be more feasible to focus management actions on the maintenance of existing wetland conditions or adaptation to a new state, rather than aiming for restoration.
- Intervention at wetlands may include:
    - retaining and restoring remnant vegetation
    - revegetating
    - controlling surface water inflows
    - flushing
    - dewatering
    - pumping
    - drainage
    - creation of evaporation basins and sacrificial wetlands.

  Authorisation is necessary to undertake the majority of these measures.

Sources of more information on understanding and managing secondary salinity in wetlands

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Glossary

Annual: a plant that completes its life cycle within a single growing season (from germination to flowering, seed production and death of vegetative parts)

Anoxic: deficiency or absence of oxygen

Benthic microbial communities: bottom dwelling communities of microbes (living on the wetland sediments)

Biodiversity: encompasses the whole variety of life forms–-the different plants, animals, fungi and microorganisms–-the genes they contain, and the ecosystems they form. A contraction of 'biological diversity'

Crustaceans: a class of animals that have a hard exoskeleton (shell) and usually live in the water, for example, crabs, lobsters, yabbies

Dormant: a state of temporary inactivity in which plants are alive but not growing

Ecosystem: a community of interdependent organisms together with their non-living environment

Ecosystem processes: the complex interactions (events, reactions or operations) among biotic (living) and abiotic (non-living) elements of ecosystems that lead to a definite result[8]

Emergent: a plant that is protruding above the surface of the water or, where a water column is not present, above the wetland soils (as distinct from floating or submerged plants)

Endemic: naturally occurring only in a restricted geographic area

Erosion: wearing away and movement of land surface materials (especially rocks, sediments and soils) by the action of water, wind or a glacier

Flocculation: the joining of particles (small objects) into loose masses (floc) in water

Geology: the composition, structure and features of the Earth, at the surface and below the ground

Gnamma: a hole (commonly granite) that collects rainwater, forming a wetland. This word is of Nyoongar origin

Groundwater: water occurring beneath the ground surface in spaces between soil grains and pebbles and in fractures or crevices in rocks

Groundwater table: the upper surface of the groundwater in an unconfined aquifer (top of the saturated zone)

Halophile: a species that shows a preference for saline habitat such as salt lakes

Hydrology: the properties of the Earth's water, particularly the distribution and movement of water between the land surface, groundwater and atmosphere

Invertebrate: an animal without a backbone

Ion: an atom with an electrical charge. Used to refer to dissolved salts such as sodium (Na+) or chloride (Cl-) in solution

Ionic composition: the particular ions making up a solution, usually expressed in terms of the relevant dominances of the major (most abundant) positively charged and negatively charged ions in a solution

Juvenile: young or immature

Landform: a natural feature of a landscape such as a valley, mountain, basin or plain

Metabolic functions: the processes occurring within a living organism that are necessary to maintain life

Methanogenesis: the production of methane by microbes

Microbe: an organism that is too small to be seen with the unaided eye, for example, bacterium, some algae

Organisms: any living things (includes plants, animals, fungi and microbes)

Particulate: in the form of particles (small objects)

Perched: not connected to groundwater

Perennial: a plant that normally lives for two or more growing seasons (from germination to flowering, seed production and death of vegetative parts)

Photosynthesis: the process in which plants and some other organisms such as certain bacteria and algae capture energy from the sun and turn it into chemical energy in the form of carbohydrates. The process uses up carbon dioxide and water and produces oxygen.

Phytoplankton: plankton (aquatic organisms floating or suspended in the water that drift with water movements, generally having minimal ability to control their location) that are photosynthetic (algae and bacteria)

Recruitment: addition of new individuals to a population (usually through reproduction)

Salinisation: the process of accumulation of salts in soils, waters or sediments

Salinity: a measure of the concentration of ions in waters, soils or sediments

Salt scald: a bare area of ground caused by secondary salinisation, in which vegetation has died and solid salt is visible

Secondary salinisation: a human-induced process in which the salt load of soils, waters or sediments increases at a faster rate than would have occurred naturally

Sediment: in general terms, the accumulated layer of mineral and dead organic matter forming the earth surface of a wetland. Used interchangeably in this guide with the terms 'wetland soil' and 'hydric soil', although all three of these terms have more specific meaning in wetland pedology

Soluble: able to dissolve

Species richness: the total number of species (in a defined area)

Stratify: separate the water column into distinct layers

Stratification: the division of the water column into distinct layers called the epilimnion (top), the metalimnion (middle) and the hypolimnion (bottom), due to differences in water density between these layers

Submerged: a plant that is entirely underneath the surface of the water

Sulphate reduction: the chemical process where sulphate is joined with hydrogen and gains electrons

Thresholds: points at which a marked effect or change occurs

Transpire (transpiration)**:** the loss of water from plants to the atmosphere through evaporation

Tubers: specialised fleshy storage organs of the stem that are present in some plant species, usually found underground

Vegetative: a stage or structure of a plant that is concerned with feeding, growth or asexual reproduction, rather than sexual reproduction

Vertebrate: an animal with a backbone

Water column: the water within an inundated wetland that is located above the surface of the wetland soils (as distinct from sediment pore waters of inundated and waterlogged wetlands)

Water regime: (of a wetland) the specific pattern of when, where and to what extent water is present in a wetland, including the timing, duration, frequency, extent, depth and variability of water presence[1]

Personal communications

Name	Date	Position	Organisation
Dr Jacqueline Giles	3/05/2009	Wetland ecologist	Department for Environment and Heritage, South Australia
Tim Mathwin	2004	Hydrologist	Department of Agriculture and Food, Western Australia
Adrian Pinder	2009	Senior Research Scientist	Department of Environment and Conservation, Western Australia
Dana Steddy	2004, 2009	Landholder, Meeking Lake	
Murray Steddy	2004, 2009	Landholder, Meeking Lake	

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A guide to managing and restoring wetlands in Western Australia

Phytophthora dieback

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Phytophthora dieback' topic

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Contents

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Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Phytophthora dieback: the introduced plant disease caused by ***Phytophthora cinnamomi***, which results in the decline or death of susceptible plants

Phytophthora cinnamomi: an introduced water mould that attacks the roots of susceptible plant species, resulting in the decline or death of the plant

Pathogen: any organism or factor causing disease within a host

Introduction

Phytophthora dieback refers to the introduced plant disease caused by ***Phytophthora cinnamomi*** (pronounced fy-tof-thora – meaning plant destroyer in Greek). The impacts of Phytophthora dieback were first detected in Western Australian forests in the 1920s. The **pathogen** itself, a water mould, *P. cinnamomi*, was identified in the mid 1960s and since then management procedures have been introduced to combat the disease and minimise its spread.

The arrival and spread of *P. cinnamomi* in WA has been catastrophic for the plants and animals of many south-western ecosystems, including wetlands (Figure 1). As many as 2,300 of the estimated 5,700 native plant species in the south-west are susceptible to, and often killed, by the pathogen. Phytophthora dieback has been recognised as a key threatening process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. It is now considered to be a bigger threat to Western Australia's natural ecosystems than salinity and is estimated to cost the Australian economy $160 million each year.[1] In addition, *P. cinnamomi* has caused major problems for road construction, timber harvesting, mining and other industries since researchers realised that the movement of soil is the most likely method of spread of the pathogen.

There are several other species of *Phytophthora* present in native vegetation in the south-west of WA, including *P. cryptogea, P. multivora* and *P. nicotianae*, but their extent and impact on native vegetation is unclear.

Figure 1. The effects of Phytophthora dieback in a seasonally waterlogged wetland near Busselton in the south-west of WA. Photo – C Mykytiuk/DEC.

Dieback: the progressive dying-back of a plant as a result of disease or unfavourable conditions

Historically, Phytophthora dieback has also been known as 'dieback' and 'jarrah dieback'. The use of these names has contributed to the confusion about the disease. For example, the term '**dieback**' is used in other parts of Australia to refer to tree decline caused by factors such as salinity, drought and insect damage. Furthermore, *P. cinnamomi* affects a large number of native and introduced plant species in addition to jarrah (*Eucalyptus marginata*). To overcome this confusion the term 'Phytophthora dieback' is now used.[2]

What is Phytophthora dieback?

As previously mentioned, Phytophthora dieback refers to the plant disease caused by the introduced pathogen *P. cinnamomi. Phytophthora cinnamomi* is a microscopic soil-borne organism belonging to the **Oomycetes** or 'water moulds'. As the name suggests, the organism depends on moist conditions that favours its survival, reproduction and dispersal.

Phytophthora cinnamomi lives in both soil and plant tissue. It invades the roots of plants from the surrounding soil to obtain nutrients and moisture for growth and reproduction. It grows as microscopic-sized filaments, **mycelium**, on the surface of plant roots.[3] The pathogen extends these microscopic filaments into the major roots of susceptible species causing cell breakdown and the formation of lesions (areas that appear dead or rotten – see Figure 2). This reduces the ability of a plant to take up and transport water and nutrients and usually results in plant death.[3] In very susceptible species, such as banksias, death may occur within weeks, while in moderately susceptible species such as jarrah (*Eucalyptus marginata*), the tree may not die until a year or more after infection. Moderately susceptible and resistant species such as flooded gum (*E. rudis*) have the ability to 'wall off' the infection to prevent further spread of the mycelia, with varying degrees of success.[4]

Phytophthora cinnamomi mycelia need environmental conditions to be favourable to grow within a plant root. For instance, there is little growth when the water content of the plant tissue is below 80 per cent. The pathogen is able to survive within dead plant roots and dry soils, by producing tough long-lived spores known as chlamydospores. These allow the pathogen to persist more easily during the dry summer months of south-west WA.

Oomycetes: the group of fungae-like organisms known as the water moulds

Mycelium: the vegetative part of a fungus, consisting of microscopic threadlike filaments known as hyphae

Figure 2. A *Phytophthora cinnamomi* lesion in a sheoak (*Allocasuarina*) trunk with the bark removed. Photo – Dieback Working Group.

extra information

Phytophthora cinnamomi life cycle

Phytophthora cinnamomi feeds on living plant roots and stems. It invades the roots of plants to get the nutrients it needs. This invasion and growth within the plant reduces the plant's ability to transport water and nutrients, often resulting in death of the host plant.

Phytophthora cinnamomi is able to reproduce through the production of microscopic fruiting bodies which release spores. Four types of spores are produced—sporangia, zoospores, chlamydospores and oospores (Figure 3 and described below).

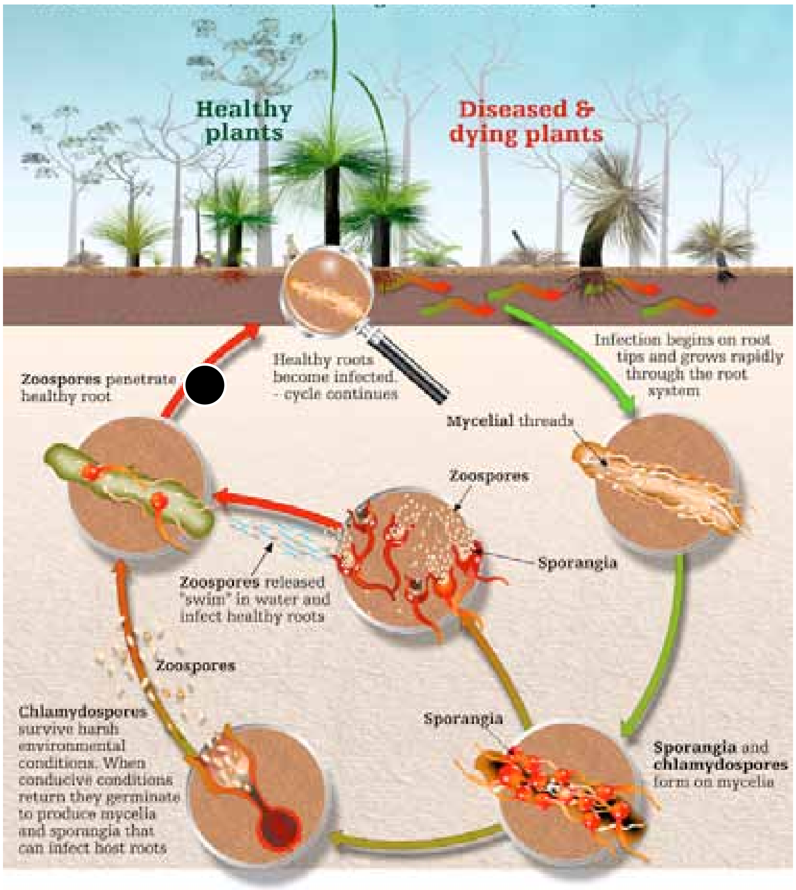

Figure 3. Life cycle of *Phytophthora cinnamomi.* © Dieback Working Group.[5]

Sporangia

Sporangia are the largest of all the spores and are produced under favourable temperature and soil moisture conditions. Zoospores are produced internally in sporangia and are released into soil once the sporangia reach maturity.

Zoospores

Zoospores are short-lived and fragile, but are produced in large numbers under moist soil conditions and are probably the cause of most new infections. Produced by sporangia, zoospores have flagella (tails), which allow them to swim very short distances (25–35 millimetres) in standing water or in films of water in soil pores. They can also be carried along in moving water over large distances. As they move through the soil, zoospores are attracted to the tips of plant roots, where they lodge, and then **germinate** (begin to grow, usually after a period of dormancy) to produce germ tubes which penetrate roots. Once inside the plant, the germ tube develops into mycelia which grow within the roots of susceptible plants, and may grow from plant-to-plant via root contact points. This root-to-root growth is the main cause of spread of a Phytophthora infestation in an upslope direction.

Chlamydospores

These are much larger than zoospores and are tough and long-lived (within dead plants and the soil). They are produced within plant roots in response to drying conditions, and are the 'resting' phase of the water mould. Chlamydospores are resistant to drying-out and are one of the mechanisms the pathogen has developed to help it survive adverse conditions. They may be transported in root fragments or soil and then germinate to cause a new infection when they encounter warm, moist conditions. Germinated chlamydospores may produce sporangia, more chlamydospores, or mycelia which directly infect roots.

Oospores

Oospores are produced through the sexual recombination of two different forms of the pathogen (A1 and A2 mating types). The sexually produced oospores are round and thick-walled, and are considered highly resistant to degradation. In some Phytophthora species, oospores are an important mechanism of surviving harsh environmental conditions. Although both mating types do occur together in some infested sites in WA, there is limited evidence of sexual recombination, and thus oospore production, occurring in the natural environment in this state.

What causes the spread of Phytophthora dieback in Western Australian wetlands?

Phytophthora cinnamomi is transported by two main mechanisms. The first is the movement of its spores through free water (including groundwater in coarse-textured soils and water-filled root channels), or by root-to-root contact between plants.[6] The second is through the movement of infected soil or plant material around the landscape. It is the movement of infected soil and plant material that has caused the large-scale spread and devastating impacts of Phytophthora dieback in the south-west of WA.

Phytophthora dieback is able to spread quickly down slopes and cover long distances if infected water is able to move freely. Its movement is much slower up slope and on flat ground (around one metre per year) as movement is generally restricted to root-to-root contact. Any action or process, including water movement, which transports soil in the landscape can also potentially transport the pathogen to a new site. Wetlands that are located in the lowest points in the landscape, and receive water from throughout the catchment, are at a high risk of being infested by *Phytophthora cinnamomi*.

The main cause of the spread of infected soil and plant material is transport by humans and some animals. *Phytophthora cinnamomi* can be carried by animals such as horses and wild pigs, often in soil attached to hooves and fur. It is transported by: humans on boots, in the muddy tyres of vehicles travelling along infested tracks, in plant pots, through earth moving and some vegetation clearing activities, and road construction.[2]

Warm, moist soil provides ideal conditions for the spread of *P. cinnamomi*. These conditions enable the pathogen to produce millions of zoospores. The zoospores are then attracted to plant roots as they seek out moisture and nutrients, swimming through soil water.[2]

High risk activities for transporting *Phytophthora cinnamomi*

Activities with a high risk of transporting *Phytophthora cinnamomi* include:

- removal of groundwater and surface water from wetlands potentially contaminated with *P. cinnamomi* for activities such as dewatering, irrigation and fire fighting
- transport of soil to and from wetlands potentially containing the pathogen
- fire break construction, which can result in the movement of soil around a property and between properties[1]
- revegetation activities that may potentially introduce *P. cinnamomi* to an area if the potting mix or soils used are contaminated with the pathogen
- movement of equipment and vehicles for a range of purposes, including the construction and maintenance of linear corridors such as roads, railways, gas pipelines and powerlines.

What effect does Phytophthora dieback have on wetlands?

Effects on vegetation

Over 40 per cent of the native plants in south-west WA are susceptible to Phytophthora dieback.[7] In field studies of south-western plant communities the families with the highest proportion of susceptible species were: Proteaceae – banksia family (92 per cent); Epacridaceae – heath family (80 per cent); Papilionaceae – pea family (57 per cent); and Myrtaceae – myrtle family (16 per cent) (Table 1).

Very little research has been undertaken on the effects of Phytophthora dieback on wetlands. Many common wetland plant species in the south-west such as flooded gum (*Eucalyptus rudis*), moonah (*Melaleuca preissiana*) and white myrtle (*Hypocalymma angustifolium*) are resistant to Phytophthora dieback (see Figure 4). Yet common species such as swamp peppermint (*Taxandria linearifolia*), swamp banksia (*Banksia littoralis*) and swamp teatree (*Pericalymma ellipticum*) have been identified as being susceptible (see Figure 5). Field observations have suggested that many wetland species are resistant to the disease (C Dunne 2008, pers. comm.), hence wetland plant communities often don't exhibit signs of Phytophthora dieback. Although many wetland species may be resistant to Phytophthora dieback, they may still act as resistant hosts for the pathogen (C Dunne 2008, pers. comm.).

Table 1. Examples of wetland species susceptible to Phytophthora dieback in the south-west by plant family

Family	Species – scientific name	Species – common name
Proteaceae	*Adenanthos obovatus*	Basket flower
	Banksia littoralis	Swamp banksia
Epacridaceae	*Sphenotoma gracilis*	Swamp paper-heath
Papilionaceae	*Jacksonia horrida*	-
Myrtaceae	*Melaleuca thymoides*	-
	Verticordia densiflora	Compacted featherflower

Garden species susceptible to Phytophthora dieback

A number of garden and horticultural plants are susceptible to *Phytophthora cinnamomi* including:

- apple, peach, apricot and avocado trees
- roses
- camellias
- azaleas
- proteas
- rhododendrons[8,9]

Figure 4. (below) Common south-west wetland species resistant to Phytophthora dieback. Photos – (a) ND Burrows and SD Hopper; (b) C Horton; (c) M Seale and J Stevens. Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 4/2/2009.

(a) Flooded gum (*Eucalyptus rudis*)

(b) Moonah (*Melaleuca preissiana*)

(c) White myrtle (*Hypocalymma angustifolium*)

Figure 5. (below) Common south-west wetland species susceptible to Phytophthora dieback. Photos – (a) BA Fuhrer, M Hancock, A Ireland and E Wajon; (b) I and M Greeve, C Hortin and T Tapper; (c) A Ireland and M Hislop. Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright, accessed 4/2/2009.

(a) Swamp peppermint (*Taxandria linearifolia*)

(b) Swamp banksia (*Banksia littoralis*)

(c) Swamp teatree (*Pericalymma ellipticum*)

case study

Critically endangered wetlands threatened by Phytophthora dieback

The following information has been taken from the then Department of Conservation and Land Management (CALM) (2005).[10]

The 'Shrublands on southern Swan Coastal Plain ironstones' (Busselton ironstone community) is a species-rich plant community of seasonally inundated wetlands with ironstone and heavy clay soils on the Swan Coastal Plain near Busselton (Figure 6). The community is recognised as being critically endangered on the list of threatened ecological communities endorsed by the Western Australian Minister for Environment. In 1995 there were only thirteen known occurrences of the Busselton ironstone community totalling 90 hectares. As a result of further surveys, the area of these occurrences has been found to be bigger than first thought and two additional occurrences have been identified bringing the total area of the community to almost 140 hectares.

The ironstone soils on which the Busselton ironstone community occurs are extremely restricted in distribution on the Swan Coastal Plain. They occur only on the eastern side of the Swan Coastal Plain along the base of the Whicher Scarp near Busselton. The heavy soils of this area are particularly useful for agricultural purposes. It has been estimated that around 97 per cent of vegetation on the eastern side of the Swan Coastal Plain has been cleared.

Much of the species diversity of the Busselton ironstone community is made up of annuals and **geophytes** (land plants that survive unfavourable periods by means of underground food storage organs, for example, rhizomes, tubers and bulbs). Typical and common native species are the shrubs *Kunzea* aff. *micrantha, Pericalymma ellipticum, Hakea oldfieldii, Hemiandra pungens* and *Viminaria juncea,* and the herbs *Aphelia cyperoides* and *Centrolepis aristata*. The community contains a number of taxa that are listed as priority or declared rare flora (DRF) by the Western Australian Government and are either totally confined or largely confined to these areas.[10]

Major threats to the community include Phytophthora dieback, clearing, too frequent fires, weed invasion, hydrological changes, and possibly salinisation. A number of plant species that occur in the community are very susceptible to Phytophthora dieback, including *Banksia nivea* subsp. *uliginosa* (Figure 7). All but one of the fifteen occurrences of the plant community are thought to be infected with the disease.[10] As such, Phytophthora dieback has the potential to seriously impact the 'Shrublands on southern Swan Coastal Plain ironstones'.

Figure 6. Busselton ironstone community. Photo – C Mykytiuk/DEC.

Figure 7. Death of *Banksia nivea* subsp. *uliginosa* (in the foreground) from Phytophthora dieback in an occurrence of the Busselton ironstone community. Photo – A Webb/DEC.

When *P. cinnamomi* invades communities dominated by species from the Proteaceae family, such as banksias and grevilleas, substantial changes in plant abundance and floristic structure may be observed. However, the effect of Phytophthora dieback on a plant community can vary greatly, depending both on the species composition of a particular community, and on the prevailing environmental conditions. It has been found that within the portion of the south-west land division that receives more than 800 millimetres mean annual rainfall, plant communities respond to Phytophthora dieback in one of four distinct ways:

1. No apparent disease at all (Figure 8).
2. An extremely destructive epidemic of root rot.
3. A variable epidemic within the dominant tree component of the jarrah forest, characterised by:
   a. irregular and often prolonged death of trees ranging from early localised mass collapse, through delayed and patchy deaths, to no apparent effect on the health of the jarrah overstorey
   b. high sensitivity to subtle differences in soil characteristics particularly those affecting drainage.
4. Replacement of forest with open woodland.[11]

The loss of native vegetation as a result of Phytophthora dieback (both within and surrounding a wetland) can have a number of detrimental impacts including:

- increased erosion and sedimentation
- reduced water quality
- loss of biodiversity, both directly and through loss of habitat and food for native fauna.

➤ For additional detail on the impacts of vegetation loss, see the topic 'Managing wetland vegetation' in Chapter 3.

Figure 8. Wetland vegetation infested with *Phytophthora cinnamomi* but showing no signs of the disease. Photo – R Lynch/DEC.

Effects on native animals

Changes in plant community composition and structure caused by *P. cinnamomi* may adversely affect associated groups of animals and soil biota by altering the availability of food resources and habitat (Table 2). Large herbivores such as western grey kangaroo (*Macropus fuliginosus*) and western brush wallaby (*M. irma*) may become more common, while smaller animals such as bandicoots and frogs may suffer from loss of refuge, with the more open vegetation giving them less protection from predators.

Pollinators reliant on susceptible plant species as key nectar sources, such as western pygmy-possum (*Cercartetus concinnus*) and honey possum (*Tarsipes rostratus*) may become rare or extinct in areas which have lost many species as a result of being infested for a long time. Insect pollinators may also be adversely affected by a reduction in nectar-producing plants, which in turn may affect the reproductive success of surviving plants dependant on the pollinators.

Table 2. Potential effects on fauna due to vegetation loss from Phytophthora dieback (based on Wilson, 1994[12])

Effects on vegetation	Effects on fauna
Loss of susceptible plants in the understorey and midstorey	Direct loss of food sources such as seeds, nectar and pollen
	Indirect loss of food sources such as invertebrates
Decline in plant species richness and diversity	Loss of food for species that prefer floristically rich vegetation
	Loss of seasonal food
Decrease in plant cover, increase in bare ground, erosion	Loss of habitat for species dependant on thick ground cover
	Increased predation risk
	Changes to microclimate
Decrease in canopy cover	Loss of food for tree-dwelling species
Decrease in litter fall	Decline in litter invertebrates
	Decline in invertebrate food sources for insectivores
Post-infection increase in frequency of resistant species	Changes in food webs

What types of Western Australian wetlands are commonly affected by Phytophthora dieback?

Phytophthora dieback is now widespread throughout the south-west of WA (Figure 9). In general, *Phytophthora cinnamomi* is restricted to areas in the south-west of the state receiving at least 400 millimetres of average annual rainfall; between Eneabba in the north and Cape Arid near Esperance in the east. It may, however, exist in slightly drier regions in water retaining sites such as wetlands and waterways. The pathogen causes the greatest impact in areas that receive more than 600 millimetres of annual rainfall. *Phytophthora cinnamomi* does not establish on coastal limestone soils of high pH (although other species of Phytophthora may) suggesting that wetlands on this substrate are unlikely to be infected.[13]

The degree to which plant communities are infested by *P. cinnamomi* is dependant on several factors, including the length of time the disease has been present, the history of land use, species susceptibility and landscape and soil factors. The location of many wetlands low in the landscape means that they have a high likelihood of being infested if *P. cinnamomi* is located within their catchments, particularly if infested waterways or other drainage lines direct surface water into them. If food and oxygen are available, and temperature, chemistry and microflora are not inhibitory, *P. cinnamomi* is also able to survive in groundwater.[14] Other than the jarrah forest, little is known of the movement of *P. cinnamomi* in groundwater. Although *P. cinnamomi* can be transported via groundwater for more than a couple of metres in the jarrah forest, the same movement may not occur elsewhere and the spread of the pathogen from one infested wetland to another wetland via groundwater may not occur (B Shearer 2009, pers. comm.). There are three basic requirements for the rapid, long-distance, lateral (sideways) dispersal of *P. cinnamomi* through groundwater:

1. the soil structure must be porous enough (full of holes) to allow spores to move through[15]
2. groundwater flow must largely be lateral (sideways)[16]
3. the connections between larger groundwater pores must be unbroken over significant distances.[17]

Figure 9. Distribution of Phytophthora dieback in the south-west of WA. © Dieback Working Group.

Extent of infestation

According to conservative estimates, 15–20 per cent of the jarrah (*Eucalyptus marginata*) forest has been infested by *P. cinnamomi,* with the proportion considerably higher in the wetter, north-western part of the forest.[13] Around 60 per cent of the montane shrublands and banksia and mallee woodlands of the 116,000-hectare Stirling Range National Park are infested, as are perhaps 70 per cent of the seasonally inundated banksia woodlands in the Shannon and D'Entrecasteaux national parks.[13] In contrast, largely because of restricted vehicular access, less than 0.1 per cent of the 328,000-hectare Fitzgerald River National Park is infested with *P. cinnamomi,* even though a large part of it receives more than 400 millimetres annual average rainfall.[13] There are a number of wetlands in the south-west that have been identified as being impacted by Phytophthora dieback. These include: Lake Logue near Eneabba; Lake Warden in Esperance; numerous wetlands on the southern Swan Coastal Plain ironstone (Busselton area); and wetlands within Jandakot Regional Park and Lightning Swamp bushland in the Perth metropolitan area.

Recognising the symptoms of Phytophthora dieback

The first step in the management of Phytophthora dieback is determining whether it is present or absent, and if it is present, identifying which parts of a site are infested.

Indicator species

The first indication that *P. cinnamomi* has spread into a new area is the death of 'indicator species' (Figure 10). An indicator species is a plant species which is reliably susceptible to *P. cinnamomi* (i.e. the disease usually kills that species). Common indicator species in wetlands include the swamp peppermint (*Taxandria linearifolia*), swamp banksia (*Banksia littoralis*), and swamp teatree (*Pericalymma ellipticum*). The distribution and composition of indicator species will vary from place to place according to vegetation type.

➤ Lists of Western Australian native species both susceptible and resistant to Phytophthora dieback are available on the Centre for Phytophthora Science and Management website. This list includes both dryland and wetland species. www.cpsm.murdoch.edu.au[18]

Figure 10. Deaths of oak-leaved banksia (*Banksia quercifolia*) in a seasonally waterlogged wetland within D'Entrecasteaux National Park on the south coast of WA.
Photo – Dieback Working Group.

Other causes of plant decline or death

Plant decline and death may be caused by factors other than Phytophthora dieback. When assessing a site for the presence of Phytophthora dieback using indicator species, it is important to be able to discount other causes of plant death or decline such as:

- insect attack
- changes to surface water or groundwater levels
- poor soil or water quality (including nutrient enrichment, acid sulfate soils and secondary salinity)
- the honey fungus *Armillaria luteobubalina*
- fire
- nutrient deficiencies.

If Phytophthora dieback 'resistant species' such as flooded gum (*Eucalyptus rudis*), moonah (*Melaleuca preissiana*) and white myrtle (*Hypocalymma angustifolium*) are dying, then it is likely that the cause is something other than *P. cinnamomi*.

Epicormic: (of a shoot or branch) growing from a previously dormant bud on the trunk or limb of a tree

When affected by Phytophthora dieback, moderately susceptible plant species such as jarrah (*Eucalyptus marginata*) may show symptoms of crown decline including the yellowing of leaves and death of primary leaf-bearing branches.[19] **Epicormic** buds may shoot, forming new branches along existing branches, with the leaves on these tending to be smaller than on the primary branches. Over time, epicormic branches will decline, resulting in an overall thinning of the crown.[19] Trees showing symptoms of crown decline may take a number of years to die. In some cases, apparently healthy trees (in groups or individually) can suddenly collapse and die.

Interpreters

The personnel who carry out the tasks of detection, diagnosis and mapping of Phytophthora dieback are known as 'interpreters' because they interpret disease symptoms to draw conclusions about the health of the vegetation. By recognising disease symptoms and observing the pattern of indicator species deaths, interpreters can build up a picture of the history and future progress of the disease at a particular site. As the pathogen spreads through an area, some or all susceptible plants become infected and die. Consequently, there will be a spread of ages in the plants that have succumbed to Phytophthora dieback, ranging from more recent deaths with yellowing or brown leaves, through to older leafless stags, and finally to remnant stumps in the ground.

Apart from a knowledge of common indicator species, interpreters need to be able to assess the influence of landscape position, soils and drainage on the development of the disease and to be able to distinguish the effects of Phytophthora dieback from those of drought and other diseases of native vegetation such as *Armillaria*.

Aerial photography

Since 1986, 230-millimetre (1:4,500) colour aerial photographs have been used for mapping the position of *P. cinnamomi* disease boundaries in WA. Given sufficient disease expression (dead and dying plants) at the time of photography, an interpreter can make decisions about the disease status of an area (that is, whether *P. cinnamomi* has caused the deaths). Field visits to view the symptoms and sampling of recently dead plants are used to verify the interpretation of aerial photographs.

Ground stripping

Ground stripping involves interpreters walking an array of parallel lines through the bush to determine whether disease caused by *P. cinnamomi* is present and to record its position. It is used in areas which are not suitable for interpretation using 230-millimetre aerial photography or when such photography is not available. Field maps and **GPS** units are used to record the position of infected plants and the boundaries of infested areas. Boundaries are demarcated with painted yellow tree blazes or ‘dayglo’ orange flagging tape (Figure 11).

GPS: global positioning system, an accurate worldwide navigational and surveying facility based on the reception of signals from an array of orbiting satellites

Figure 11. Sample being taken from a dead tree for laboratory testing to determine the presence of *Phytophthora cinnamomi.* Photo – M Pez/DEC.

Sampling to determine the presence of *Phytophthora cinnamomi*

To confirm the accuracy of the interpretation of disease symptoms, samples of root and lower stem material as well as adjacent soil can be taken from recently dead plants (Figure 12). Long-dead plants are unlikely to return positive results from sampling even if *P. cinnamomi* killed the plant. Collected material can then be sent to an analytical laboratory for testing. Laboratories offering this service can provide detailed instructions on how to take a sample, store and transport the collected materials to them.

Laboratories are able to determine the presence of *P. cinnamomi* using either the baiting or direct plating method. 'Baiting' involves mixing soil from the sample bag with distilled water in a container and then floating cotyledons (imillimetresature leaves) of *Eucalyptus sieberi* (which have purple undersides) on the water. If after five to ten days the cotyledons have lost their purple colour the sample is presumed to be infected with *P. cinnamomi*. 'Plating' is then carried out by placing the cotyledons on antibiotic **agar** in a **petri dish**. Plated baits are left for a maximum of three days and if *P. cinnamomi* is not evident after this time, the plates are discarded, and the samples are recorded as negative.

It is important to note that a negative result from a sample does not mean that the site is free of pathogen. A negative result only means that the pathogen was not captured in the sample. Multiple samples of a site may be required before a positive result can be obtained.

Agar: a gelatinous substance obtained from any of various kinds of red seaweed and used to grow cultures of fungi and other microorganisms

Petri dish: a shallow covered dish used for the culture of fungi and other microorganisms

Figure 12. A DEC interpreter marking the boundary of an area infested with *Phytophthora cinnamomi* with yellow tree blazes and orange flagging tape. Photo – Dieback Working Group.

Mapping Phytophthora dieback

Interpreters generally produce two main types of maps, a *P. cinnamomi* occurrence map and a *P. cinnamomi* protectable areas map, both of which are accompanied by a written report. The *P. cinnamomi* occurrence map shows disease distribution, and is used as a basis for the *P. cinnamomi* protectable areas map and a *P. cinnamomi* hygiene management map. Three categories are shown on a *P. cinnamomi* occurrence map: uninfested, uninterpretable and infested (Table 3).

A *P. cinnamomi* protectable areas map shows areas which are disease free, and which are considered to be able to be protected from the establishment of new centres of infestation (arising from the activities of humans) through the implementation of hygienic management practices (Figure 13). The *P. cinnamomi* hygiene management map is jointly prepared with the land manager as part of the protectable areas *P. cinnamomi* hygiene planning process, and forms part of the *P. cinnamomi* hygiene plan. The frequency at which these maps need to be produced will be influenced by the circumstances at a particular wetland.

Table 3. *Phytophthora cinnamomi* occurrence categories used in maps

<table>
<tr><td>Unmappable
Areas that are sufficiently disturbed so that Phytophthora cinnamomi occurrence mapping is not possible at the time of inspection</td><td colspan="2">Further categorisation may be possible after variable regeneration periods for different types of disturbance</td></tr>
<tr><td rowspan="3">Mappable
Natural undisturbed vegetation. Phytophthora cinnamomi occurrence mapping is possible</td><td>Infested</td><td>Area that a qualified person had determined to have plant disease symptoms consistent with the presence of Phytophthora cinnamomi</td></tr>
<tr><td>Uninfested</td><td>Area that a qualified person had determined to be free of plant disease symptoms that indicate the presence of Phytophthora cinnamomi</td></tr>
<tr><td>Uninterpretable</td><td>Area where indicator species are absent or too few to determine the presence or absence of Phytophthora cinnamomi</td></tr>
</table>

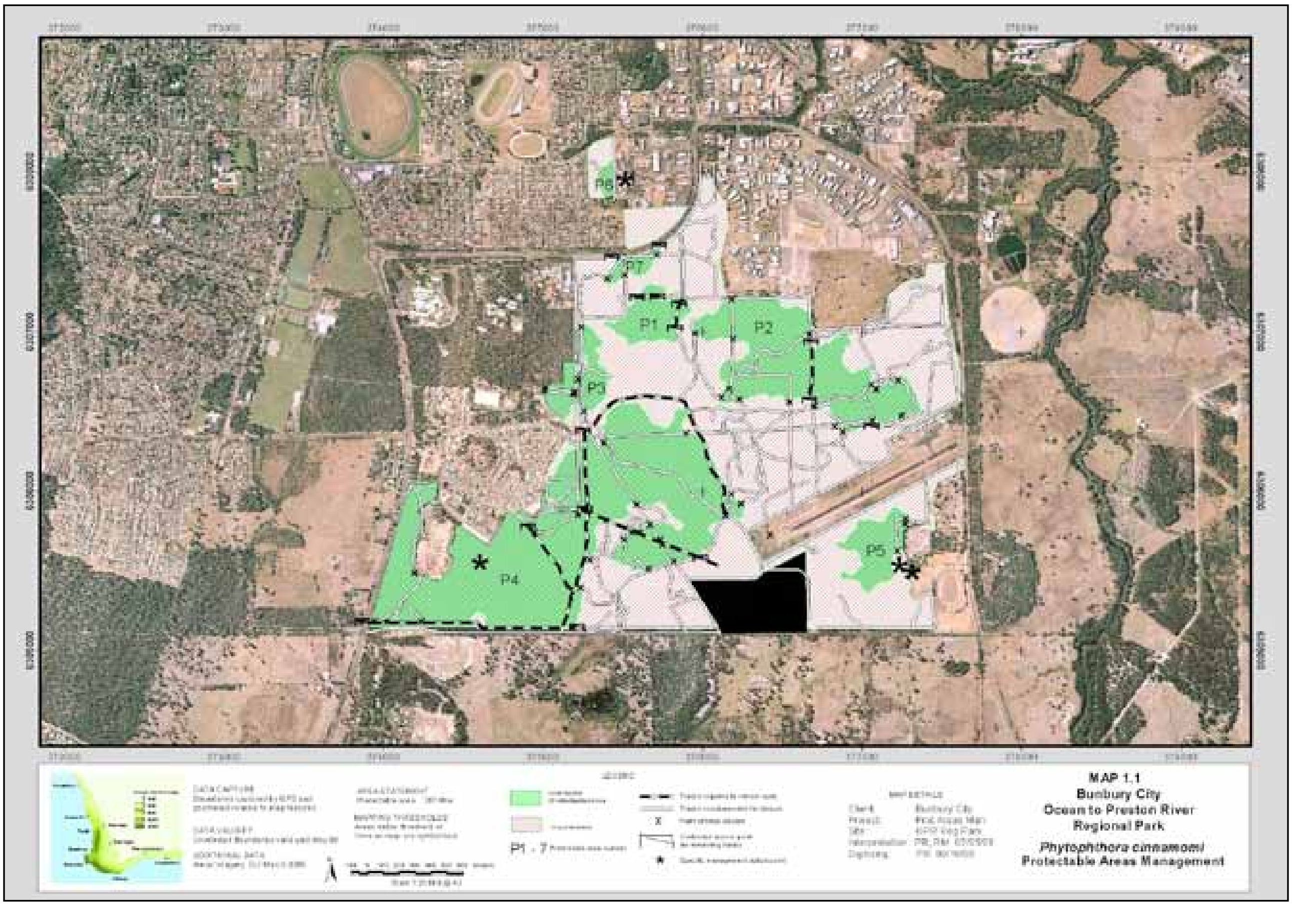

Figure 13. A protectable areas map produced for Manea Park in Bunbury. Map produced by Glevan Consulting for the City of Bunbury.

Key management techniques for tackling Phytophthora dieback in wetlands

Phosphite: an aqueous solution of mono- and di-potassium phosphite used to protect plants against Phytophthora dieback

The management of Phytophthora dieback in wetlands can be summarised into three steps:

1. Assess the site and map Phytophthora dieback occurrence
2. Prepare and implement management procedures
3. Treat plants with **phosphite**.

Assessing a wetland for Phytophthora dieback

As described above, there are a number of ways of assessing a wetland for the presence of Phytophthora dieback, which include field assessment, analysis of aerial photography and laboratory testing of plant and soil samples. A key component of an assessment is determining the distribution of Phytophthora dieback at a site and recording this information in a *P. cinnamomi* occurrence map.

As a number of common wetland species are resistant to Phytophthora dieback and may not show symptoms of the disease, many wetlands may be considered to be 'uninterpretable' with regard to detecting the presence of *P. cinnamomi.* It may therefore be necessary to test plant and soil samples in a laboratory to confirm the presence or absence of *P. cinnamomi* at wetland sites. If a wetland is located low in the landscape and Phytophthora dieback has already been positively identified within the catchment, it can be assumed with reasonable confidence it already is or soon will be infested. In such cases it may be considered unnecessary to have wetland plant and soils samples tested in the laboratory.

More information on assessing a wetland for the presence of Phytophthora dieback is available in the sections: 'Recognising the symptoms of Phytophthora dieback' and 'Sources of more information on managing Phytophthora dieback in wetlands' within this topic.

Preparing and implementing management procedures

Once present, *P. cinnamomi* cannot be eradicated from an area. As such, the management of Phytophthora dieback is focused on minimising the spread of the pathogen. How Phytophthora dieback is managed at a wetland depends largely on knowing if it is present and having an understanding of its distribution. Whether Phytophthora dieback is present at the site or not, or is spread throughout an entire site or located in an isolated section, all management procedures are based on minimising the movement of soil, plant material and water (hygiene management), and on protecting plants by treating them with phosphite.

➤ Excellent examples of how to manage Phytophthora dieback in different scenarios are provided in: Dieback Working Group (2008). *Managing Phytophthora dieback in bushland: A guide for landholders and community conservation groups.*[2]

The basic steps in preparing and implementing Phytophthora dieback management procedures include:

- Identifying areas which are free of Phytophthora dieback and have a high likelihood of being maintained as such ('protectable areas') and focusing hygiene management on them
- Implementing hygiene protocols to minimise the spread of Phytophthora dieback including signage, boot-cleaning stations, vehicle and equipment washdowns (see Figure 14)
- Setting a timeframe for re-assessing areas for the presence of Phytophthora dieback and preparing up-to-date occurrence maps
- Utilising up-to-date occurrence maps to review the effectiveness of management procedures.

A number of guidelines for the best practice management of Phytophthora dieback have been produced for a variety of land managers including landholders and community groups, local government and state government agencies. A list of the best practice guidelines that have been produced for each of these groups is included in this section. Please note that the documents listed may be of use to land managers beyond the targeted group.

It is also worth noting that the guidelines listed below have been written with dryland bushland rather than wetlands in mind. When relating management guidelines to wetlands it is important to keep the following points in mind:

- If Phytophthora dieback is present in a catchment area, wetlands located low in the landscape within that catchment have a high likelihood of being infested.
- When preparing management guidelines which deal with restricting the movement of water, it is important to consider the implications of restricting water movement on the wetland water regime.

➤ For additional detail on wetland water regime see the topic 'Wetland hydrology' in Chapter 2.

(a)

(b)

Figure 14. Phytophthora dieback hygiene management activities: (a) signage; and (b) boot-cleaning station. Photos – Dieback Working Group.

Guidelines for the best practice management of Phytophthora dieback

For landholders and community groups:

Dieback Working Group (2008). *Managing Phytophthora dieback in bushland: A guide for landholders and community conservation groups.*[2]

For local government:

Dieback Working Group (2000). *Managing Phytophthora dieback: Guidelines for local government.*[20]

For state government and other agencies:

Department of Conservation and Land Management (2003). Phytophthora cinnamomi *and disease caused by it: Volume I Management guidelines.*[3]

Department of Conservation and Land Management (2004). *Best practice guidelines for the management of* Phytophthora cinnamomi *(Draft).*[11]

Treating plants with phosphite

Phosphite, an aqueous solution containing phosphorus, has shown great promise in the battle to preserve rare and endangered Western Australian native plants under threat from *P. cinnamomi*. Depending on how it is applied, phosphite can provide protection for vulnerable plant species against the disease for up to ten years. Phosphite is an environmentally safe, inexpensive chemical that is systemically transmitted throughout treated plants and has a very low toxicity to animals.

Fungicide: a substance that kills fungi

Fungistat: a substance that inhibits the growth and reproduction of fungi without destroying them

How it works

The mode of action of phosphite is not fully understood. At high enough concentrations, phosphite will act directly on *P. cinnamomi* as a **fungicide** or **fungistat** to either kill or halt its growth. This direct effect appears to occur within the *P. cinnamomi* organism, but it also appears that the progress of infection by *P. cinnamomi* is halted when it comes into contact with phosphite in plant tissue. This may be because high phosphite concentrations interfere with the way that phosphorus is used by the pathogen for survival. The application of phosphite may also trigger the plant's self-defence mechanism, causing it to wall-off and isolate the invaded root cells. Plants in poor health which are treated in time have been shown to fully recover and remain healthy for a number of years.

History of use

Previously called phosphonate, phosphite has been used to protect avocado, pineapple and cocoa crops against Phytophthora disease since the 1970s. In the late 1980s Department of Conservation and Land Management research staff began investigating whether the fungicide provided any protection to Western Australian native plant species. Phosphite solution was injected into jarrah (*Eucalyptus marginata*) and several banksia species, and the treatments showed considerable promise; slowing and stopping the growth of the pathogen within the plants under attack.[21]

Research efforts continued over the next decade and included field trials in locations ranging from the northern sandplains near Eneabba to Fitzgerald River National Park east of Albany. Aerial application of phosphite to native plant communities was tested for the first time in 1993 in several reserves near Albany and proved a success. Aircraft allow for relatively cheap and rapid treatment of entire plant communities containing rare plant species, and are suitable for areas where the ruggedness of the terrain would make ground application prohibitively expensive.

How it is applied

Phosphite is applied via stem injection (to trees with a diameter at chest height of 10–14 centimetres or greater[22]), or as a spray by aerial or ground application (Figure 15). One drawback with aerially applied phosphite is that protection normally only lasts for about two years, whereas stem injection may provide protection for up to ten years. There are two main strategies for its application. Firstly, phosphite can be applied in an already infested area to protect susceptible plants that have not yet been infected or help already infected plants to recover.[23] Secondly, phosphite can be used strategically for effective protection ahead of an advancing 'front' of *P. cinnamomi*. A 30–40-metre-wide swathe of phosphite can be applied in front of an advancing *P. cinnamomi* infestation to prevent root-to-root transfer of the pathogen across the barrier.[22] If the infested area is upslope of the area to be protected the protective swathe would need to be wider than if it is downslope. This is because of the possibility of overland or subsurface transport of *P. cinnamomi* zoospores for considerable distances downslope following rainfall. In contrast, movement of an infestation upslope is generally slower, being mainly caused by root-to-root contact between plants.

Figure 15. (below) Application of phosphite via (a) spraying; and (b) stem injection. Photos – Dieback Working Group.

(a)

(b)

Applying phosphite in wetlands

If applying phosphite, or any other chemical, in wetlands or other natural environments it is important to minimise any off-target impacts such as the unwanted decline or death of plants or animals. It is also important to be aware that when phosphite is applied as a spray, by aerial or ground application, it is mixed with a wetting agent to help droplets hold onto leaf surfaces until they are absorbed. There are significant risks associated with the use of wetting agents in wetlands and other aquatic environments including toxic effects on tadpoles.[24,25] As such, it is essential that any off-target impacts of wetting agents are also minimised.

➤ For more information on reducing the off-target impacts of the application of chemicals see the topic 'Wetland weeds' in Chapter 3.

The off-target impacts of chemicals (including wetting agents) can be reduced and the effectiveness of application increased by:

- selecting the correct application method (which will depend on the type and size of plants being targeted, for example, using stem injection where possible)
- applying the chemical under ideal environmental conditions (for example, dry, still wind conditions to minimise spray drift and timing the application while susceptible fauna aren't in a critical life phase such a reproduction)
- carefully following the manufacturer's instructions.

Wetting agent: a substance that helps water or other liquid, to spread or penetrate (also known as a surfactant or penetrant)

The future

Research into phosphite and its application is continuing. Among the areas requiring additional investigation is the refinement of application rates, times and frequencies for different vegetation types. Phosphite cannot eradicate *P. cinnamomi* from an area once it has established. However, by boosting the ability of plants to ward off infection, it does provide some ability to protect endangered plants that might otherwise become extinct in the wild within a few years. Nevertheless, the major strategy for limiting the environmental damage caused by the pathogen remains the prevention of the transport of infested soil into uninfested areas, by means of quarantine and the maintenance of high standards of hygiene.

Monitoring the success of management and restoration techniques

Monitoring is a key component of wetland management and restoration. The information collected through monitoring can be used to assess if management is successful, and if not, to adapt or modify the management (adaptive management).

In order to monitor the success of Phytophthora dieback management techniques it is recommended that up-to-date Phytophthora dieback occurrence maps are prepared. The frequency at which these maps need to be produced will be influenced by the circumstances at a particular wetland. Specialist advice should be sought from an interpreter or other specialist for more information. As Phytophthora dieback impacts wetland vegetation, it is recommended that vegetation also be monitored to assess the effectiveness of management activities.

➤ Additional detail on monitoring wetland vegetation is provided in the topic 'Monitoring wetlands' in Chapter 4.

case study

Manea Park – a collaborative approach to Phytophthora dieback management

Manea Park is approximately 500 hectares in size and is managed by the City of Bunbury for conservation purposes. The reserve contains more than 150 hectares of wetlands including damplands, palusplains and sumplands. The reserve also contains two threatened ecological communities, which are both listed as vulnerable. Both of these communities are wetlands (Figure 16).

Much of the flora of Manea Park is highly susceptible to Phytophthora dieback and, as such, an investigation into its distribution within the park was conducted by the then Department of Conservation and Land Management in 2001. This survey found that up to half of Manea Park was infested with the disease, including many of the wetland areas and some heavily degraded dryland areas. In 2007, the City of Bunbury secured funding from Project Dieback to have Manea Park reassessed and mapped by a consultant. The results from the survey undertaken by Glevan Consulting in 2008 strongly mirrored the results of the 2001 assessment and show that Phytophthora dieback has spread very little since the original mapping exercise in 2001.

The survey undertaken in 2008 found that the vegetation in around 36 per cent of the survey area was sufficiently disturbed (by factors such as clearing and grazing) that *P. cinnamomi* mapping was not possible at the time of inspection, and was otherwise referred to as 'unmappable'. This 36 per cent included many of the wetlands within the reserve. Of the area that was able to be mapped, approximately 22 per cent was found to be infested with *P. cinnamomi.*[26] The survey also found that it was predominately low-lying wetlands in the north-west of the park that were infested. Although many wetland plant species are resistant to Phytophthora dieback, impacts of the disease have been observed in a number of the wetlands in Manea Park, including those recognised as threatened ecological communities, with deaths of swishbush (*Viminaria juncea*), swamp banksia (*Banksia littoralis*) and swamp teatree (*Pericalymma ellipticum*) recorded (Figure 17).

In mid-2008 the City of Bunbury decided to take the next step in protecting Manea Park from Phytophthora dieback by developing management strategies for dieback-free areas or 'protectable areas' in the reserve. Limited areas of wetland were included within the identified protectable areas, as most of the wetland areas within the reserve were identified as either being infested with *P. cinnamomi* or unmappable.

Management strategies for protectable areas were developed at a workshop with key stakeholders including the Department of Environment and Conservation, Department for Planning and Infrastructure, Project Dieback, the Friends of Manea Park and the City of Bunbury's consultant. It was agreed that track closure and the control of track access were the most effective strategies available. To complement these strategies it was also agreed to erect interpretive signage at strategic points throughout the park to explain the current *P. cinnamomi* infestation status and the management strategies implemented to control its spread.

To manage those areas already infested by *P. cinnamomi*, phosphite treatment will be undertaken in a number of places, including the wetland areas. This treatment will assist in reducing the loss of plant species in these high conservation value areas.

For further information contact the City of Bunbury Environmental Officer.

Figure 16. One of the threatened ecological communities in Manea Park near Bunbury. Photo – C Mykytiuk/DEC.

Figure 17. Deaths of swamp banksia (*Banksia littoralis*) in one of the threatened ecological communities in Manea Park. Photo – C Mykytiuk/DEC.

Whether or not to manage Phytophthora dieback in a wetland

When deciding whether or not to manage Phytophthora dieback at a wetland, there are a number of factors that should be considered, which will help focus the decision-making process. These include:

- **What are the values under threat from Phytophthora dieback?**

  Example: Which plants species are susceptible to Phytophthora dieback? What will be the impact of the loss of these species?

  If the values under threat from Phytophthora dieback are significant, managing dieback will be a higher priority.

- **How practical and effective will management (hygiene management and treatment with phosphite) be?**

  Example: Does Phytophthora dieback already occur throughout the site? Is the wetland located low in the landscape within a catchment already infected with Phytophthora dieback?

  If management actions are unlikely to be effective in controlling and/or reducing the impact of Phytophthora dieback at the site, it may not be a good use of resources to implement these actions.

- **Will management protect the values under threat?**

  Example: Are the values under threat from Phytophthora dieback, already threatened by a potentially more significant degrading process such as altered hydrology? Is the wetland already so significantly impacted by Phytophthora dieback that management will not achieve improvements?

  If managing Phytophthora dieback is not going to be sufficient to protect the values under threat because they're threatened by something else, or because the site is already severely impacted by Phytophthora dieback, it may not be a good use of resources to implement these actions and instead resources may be better directed towards managing another degrading process.

- **How urgent is the need for action – at what rate is Phytophthora dieback diminishing wetland values?**

  Example: Is Phytophthora dieback causing a rapid and significant loss of plants? Is the loss of plants from Phytophthora dieback relatively slow over time?

  Threats that are having a rapid impact would generally be a higher priority for management than threats that act very slowly.

- **What are the financial and other costs (such as time and labour) of carrying out management activities?**

  Example: How do financial and other costs of Phytophthora dieback mapping and hygiene management weigh up against the values under threat? How do the financial and other costs of phosphite treatment weigh up against the values under threat?

  Management will be most cost effective and beneficial if the site has high values, and the cost of management actions is relatively low.

- **Taking into account the management of other threats or degrading processes – what is the most logical sequence for undertaking management actions?**

  Example: If it is planned to close tracks or paths as part of a hygiene management plan, it should be determined whether the paths are needed for other management activities, such as providing access to remove car bodies or other rubbish?

  All threats and degrading processes need to be documented for the site, and any possible links between these identified prior to planning on-ground management.

In some situations, it may be necessary to make decisions regarding the management of Phytophthora dieback across multiple wetlands within one landscape or management area. In these situations, the questions listed above will still be a useful guide to decision-making. Often it is most effective to focus resources on those wetlands that are minimally degraded and still have high values, as intervention is likely to be most successful, and have most conservation value at these sites.[21]

In an ideal situation, any management activities should be undertaken as part of a comprehensive wetland management plan which would address other management issues or degrading processes and their associated management activities. It is strongly encouraged that a management plan is prepared, however basic it may be.

➤ For additional detail on preparing a wetland management plan see the topic 'Planning for wetland management' in Chapter 1.

Topic summary

- Phytophthora dieback refers to the introduced plant disease caused by the microscopic soil-borne organism *Phytophthora cinnamomi*.
- *P. cinnamomi* invades the roots of plants, killing cells, reducing the ability of a plant to take up and transport water and nutrients, often resulting in the death of the plant.
- Many common wetland species are susceptible to Phytophthora dieback, however field observations have suggested that a large number of wetland species are resistant to *P. cinnamomi*, hence wetland plant communities often don't exhibit signs of Phytophthora dieback disease.
- The loss of native vegetation as a result of Phytophthora dieback can have a number of detrimental impacts on wetlands including increasing the risk of erosion and sedimentation, reducing water quality, loss of biodiversity, loss of habitat and food for native fauna and a subsequent decline in native fauna.
- The fact that most wetlands are located low in the landscape means that they have a highly likelihood of being infested if Phytophthora dieback is located within their catchments.
- Once present, *P. cinnamomi* cannot be eradicated from an area. As such, the management of Phytophthora dieback is focused on minimising the spread of the pathogen to disease-free areas.
- The management of Phytophthora dieback is based on minimising the movement of soil, plant material and water, and protecting plants by treating them with phosphite.
- The management of Phytophthora dieback in wetlands can be summarised into three steps:
    1. assess the site and map Phytophthora dieback occurrence
    2. prepare and implement management guidelines
    3. treat plants with phosphite.
- When deciding whether or not to manage Phytophthora dieback at a wetland, there are a number of factors that should be considered including the values under threat, how practical and effective will management be, and the financial and other costs (such as time and labour) of carrying out management activities.

Sources of more information on managing Phytophthora dieback in wetlands

Websites

Dieback.org.au
www.dieback.org.au
Information on the impacts of Phytophthora dieback and its management. Designed to be a one-stop shop for information on how to manage Phytophthora dieback.

Dieback Working Group
www.dwg.org.au
Information on the impacts of Phytophthora dieback and its management.

Project Dieback
www.dieback.net.au
Information on the impacts of Phytophthora dieback, maps of its distribution within the south-west, and lists of susceptible and resistant species in the South Coast NRM region.

Centre for Phytophthora Science and Management
www.cpsm.murdoch.edu.au
Information on Phytophthora dieback research, links to national best practice guidelines, and list of susceptible and resistant species.

Department of Environment and Conservation
www.dec.wa.gov.au (search for 'Phytophthora')
Information on the impacts of Phytophthora dieback and its management, state government Phytophthora dieback policy, Phytophthora dieback Atlas.

Department of Sustainability, Environment, Water, Population and Communities
www.environment.gov.au (search for 'Phytophthora')
Information on Phytophthora dieback management and threat abatement.

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W O'Gara, K Howard, B Wilson and GESTJ Hardy (2005). *Management of Phytophthora cinnamomi for biodiversity conservation in Australia: Part 2 National best practice guidelines.*[6]

Glossary

Agar: a gelatinous substance obtained from any of various kinds of red seaweed and used to grow cultures of fungi and other microorganisms

Dieback: the progressive dying back of a plant as a result of disease or unfavourable conditions

Epicormic: (of a shoot or branch) growing from a previously dormant bud on the trunk or limb of a tree

Fungicide: a substance that kills fungi

Fungistat: a substance that inhibits the growth and reproduction of fungi without destroying them

Germinate: begin to grow, usually following a period of dormancy (resting phase)

Geophytes: land plants that survive unfavourable periods by means of underground food-storage organs, for example rhizomes, tubers and bulbs

GPS: global positioning system, an accurate worldwide navigational and surveying facility based on the reception of signals from an array of orbiting satellites

Mycelium: the vegetative part of a fungus, consisting of microscopic thread-like filaments known as hyphae

Oomycetes: the group of fungae-like organisms known as the water moulds

Pathogen: any organism or factor causing disease within a host

***Phytophthora cinnamomi*:** an introduced water mould that attacks the roots of susceptible plant species, resulting in the decline or death of the plant

Phytophthora dieback: the introduced plant disease caused by *Phytophthora cinnamomi*, which results in the decline or death of susceptible plants

Petri dish: a shallow covered dish used for the culture of fungi and other microorganisms

Phosphite: an aqueous solution of mono- and di-potassium phosphite used to protect plants against Phytophthora dieback

Wetting agent: a substance that helps water or other liquid, to spread or penetrate (also known as a surfactant or penetrant)

Personal communications

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A guide to managing and restoring wetlands in Western Australia

Managing wetland vegetation

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

‘Managing wetland vegetation’ topic

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Recommended reference

When referring to the guide in its entirety, the recommended reference is: Department of Environment and Conservation (2012). *A guide to managing and restoring wetlands in Western Australia*. Department of Environment and Conservation, Perth, Western Australia.

When specific reference is made to this topic, the recommended reference is: Department of Environment and Conservation (2012). ‘Managing wetland vegetation’, in *A guide to managing and restoring wetlands in Western Australia*, Prepared by J Nichol, Department of Environment and Conservation, Perth, Western Australia.

Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

INTRODUCTION

Wetland plants are an important part of the state's biological diversity. It is estimated that wetland **taxa** form more than 20 per cent, or 3,000 of Western Australia's approximate 12,500 flora.[1]

The **vegetation** also constitutes part of the wetland **ecosystem**, playing a key role in many physical, biological and chemical **wetland processes**, helping to maintain a stable ecosystem and defining a wetland's **ecological character**. As such, vegetation change can significantly influence the long-term health and values of a wetland.

WA's wetlands can be degraded by a range of threatening processes that impact upon wetland flora and vegetation. This is telling in the number of wetland **ecological communities** that are threatened: thirty-three of WA's sixty-nine threatened ecological communities are wetland communities defined or reliant on (vascular) plant taxa.[1] Weeds are usually prevalent in wetlands that have been subject to disturbance.

Vegetation changes can either occur naturally or because of human influences. This topic focuses on managing human-caused vegetation change in natural wetlands. Most human-caused vegetation changes are detrimental and can lead to further degradation of a wetland ecosystem. This topic outlines the steps wetland managers can take to manage native wetland vegetation in order to maintain a wetland's natural values. The information in this topic applies to the management of vegetation that is currently degraded, or that is in good condition or within acceptable limits of change, so as to prevent the vegetation becoming degraded.

Specifically, this topic is designed to assist wetland managers to:

- identify the three main types of vegetation change that occur within a wetland and determine the type and extent of these changes in a given wetland
- determine an appropriate level of intervention
- plan management actions.

Requirements for revegetating or rehabilitating wetlands as a condition of development approval, an offset, or a vegetation conservation notice under the *Environmental Protection Act 1986* or relevant planning legislation are not addressed in this topic. These mechanisms may have specific requirements, such as completion criteria and specific timeframes.

➤ For guidance on these matters, see:

- *Rehabilitation of terrestrial ecosystems*[2]
- *Guidelines checklist for preparing a wetland management plan*[3]
- Chapter B4 of *Environmental guidance for planning and development*[4]

Taxa: a taxonomic group (the singular being taxon). Depending on the context, this may be a species or their subdivisions (subspecies, varieties etc), genus or higher group.[6]

Vegetation: combinations of plant species within a given area, and the nature and extent of each area

Ecosystem: a community of interdependent organisms together with their non-living environment.

Wetland processes: the dynamic physical, chemical and biological forces within a wetland, including interactions that occur between wetland organisms, within the physical/chemical environment, and interactions of these

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Ecological community: naturally occurring biological assemblages that occur in a particular type of habitat

There is no substitute for maintaining the natural characteristics of wetland vegetation. Regeneration and revegetation activities may never completely re-establish natural wetland processes.[5] Prevention, and maintaining or improving the **resilience** of the vegetation, are key strategies. In the absence of vegetation changes, wetland managers can manage wetland vegetation by:

- keeping a watch for vegetation change, particularly weeds
- managing the dryland surrounding the wetland (sometimes designated as a **wetland buffer**) to help protect the wetland from potential impacts from surrounding land uses and to help maintain its natural processes
- retaining, or where possible, reinstating **ecological linkages**
- where warranted, surveying the wetland vegetation and considering contingencies such as seed storage that can be used in the event of significant vegetation change.

➤ Programs providing funding, labour, training and technical guidance for wetland vegetation management are outlined in the topic 'Funding, training and resources' in Chapter 1.

It is strongly recommended that anyone intending to carry out regeneration or revegetation activities consider doing so within the framework of a wetland management plan. A wetland management plan provides a structured way of deciding on priorities and tasks to make the process as effective, efficient and successful as possible. For large, complex or significant wetlands it is invaluable.

➤ Further guidance in provided in the topic 'Wetland management planning' in Chapter 1.

Resilience: capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

Ecological linkage: a network of native vegetation that maintains some ecological functions of natural areas and counters the effects of habitat fragmentation[6]; a series of (both contiguous and non-contiguous) patches of native vegetation which, by virtue of their proximity to each other, act as stepping stones of habitat which facilitate the maintenance of ecological processes and the movement of organisms within, and across, a landscape[7]

extra information

WA's wetland vegetation: background information

WA's wetland plants are remarkable and important for many reasons. Wetland flora contributes to the incredible biodiversity and endemism found in WA, in parts of the Kimberley, Pilbara and Goldfields regions, and in the south-west, which is a centre of exceptionally high species richness and endemism and is one of the world's 25 biodiversity hotpots.[2]

For more information on WA's wetland vegetation and flora refer to:

- the topic 'Wetland vegetation and flora' in Chapter 2, which documents the remarkable vegetation and flora of WA's wetlands
- the topic 'Wetland ecology' in Chapter 2, which provides information on the ecological role played by wetland vegetation.

In seeking to provide guidance on managing the vegetation of WA wetlands, there are many limitations to how specific or detailed the information can be. The vegetation in WA's wetlands ranges from forests to tiny moss pillows, extremely diverse to fairly limited, and relatively well-documented to those containing flora not yet documented by science.

Useful contacts and resources for additional information include:

- *Restoring Natural Areas in Australia* (Buchanan 2009)[8]
- Florabank's Native Vegetation Management Tool: www.florabank.org.au
- The Australian Association of Bush Regenerators www.aabr.org.au

extra information

WA's wetland vegetation: background information (cont'd)

- Revegetation Industry Association of WA www.riawa.com.au
- Wildflower Society of Western Australia http://members.ozemail.com.au/~wildflowers/policies.htm
- Greening Australia[9] http://live.greeningaustralia.org.au/nativevegetation/pages/page116.html
- *Restoring Perth's Banksia woodlands* (BGPA, in preparation)

WHAT ARE THE MAIN TYPES OF VEGETATION CHANGE IN WA WETLANDS?

Changes to natural wetland vegetation can be categorised into three main types:

- composition
- structure
- density.

These are defined below.

Composition

A 'composition' change is any change to the assemblage of individual plant species within a plant community or group of communities (see Figure 1 and Figure 4). Examples of a 'composition' change include:

- a plant species is lost from the community
- a new plant species enters the community
- a plant species is replaced in the community with another plant not found in the original community

A possible result of a 'composition' change is the establishment of a new assemblage of plants, so the community itself has been altered.

Figure 1. Impacts to this wetland have resulted in a change in composition, with weeds replacing native species in the understorey. Photo – C Mykytiuk.

Structure

A 'structure' change is any change to the configuration or arrangement of a plant species within a community. A community consists of a suite of species, and one or more of those species may become more dominant over others, but the same suite of species remains (as opposed to a change in 'composition') (see Figure 4).

For example, a wetland may became more saline over time, allowing one species already found in the plant assemblage to become more dominant because it is more tolerant of the more saline environment. For example, samphires may already be present in the community but may become more dominant with increasing salinisation.

Similarly, if abstraction of groundwater causes the death of a significant proportion of trees of a particular species in a forested wetland (that is, supporting canopy with greater than 70 per cent cover), the change in structure from a forest to a woodland (which supports less than 70 per cent cover) would constitute a change in structure. In addition to trees, other life forms in WA wetlands are shrubs, herbs, grasses, sedges and climbers; and layers in WA wetlands include shrubland, herbland, grassland, sedgeland and combinations of these.

Structural change can also be natural, with relative species dominance changing over time as a community 'matures' following a disturbance, such as a flooding event or fire. This is known as succession in a plant community. It is important to understand the cause of structural changes in a community, and determine if this is natural or not, and if management intervention is required, or not.

It is important to keep in mind that many wetlands naturally do not have a stereotypical zonation from an inundated central area vegetated with aquatic plants and extending out to sedges, shrubs and trees (as shown in Figure 17). Particularly in waterlogged wetlands, there is often a mix of these types of plants throughout, with plant patterning reflecting smaller-scale habitats within these wetlands (Figure 2 and Figure 3).

Figure 2. Wetland vegetation of a seasonally waterlogged wetland.

Figure 3. Wetland vegetation of a seasonally waterlogged wetland.

Biomass: the total mass of biological material (living or dead), usually expressed as live or dry weight per unit area or volume

Senescence: the natural aging and subsequent death of an organism

Density

A 'density' change is any change to the total amount of plant material or **biomass** in a wetland. Examples of a density change include a reduction in density due to the removal of plants through clearing or **senescence**, or an increase in the density due to re-growth following a fire.

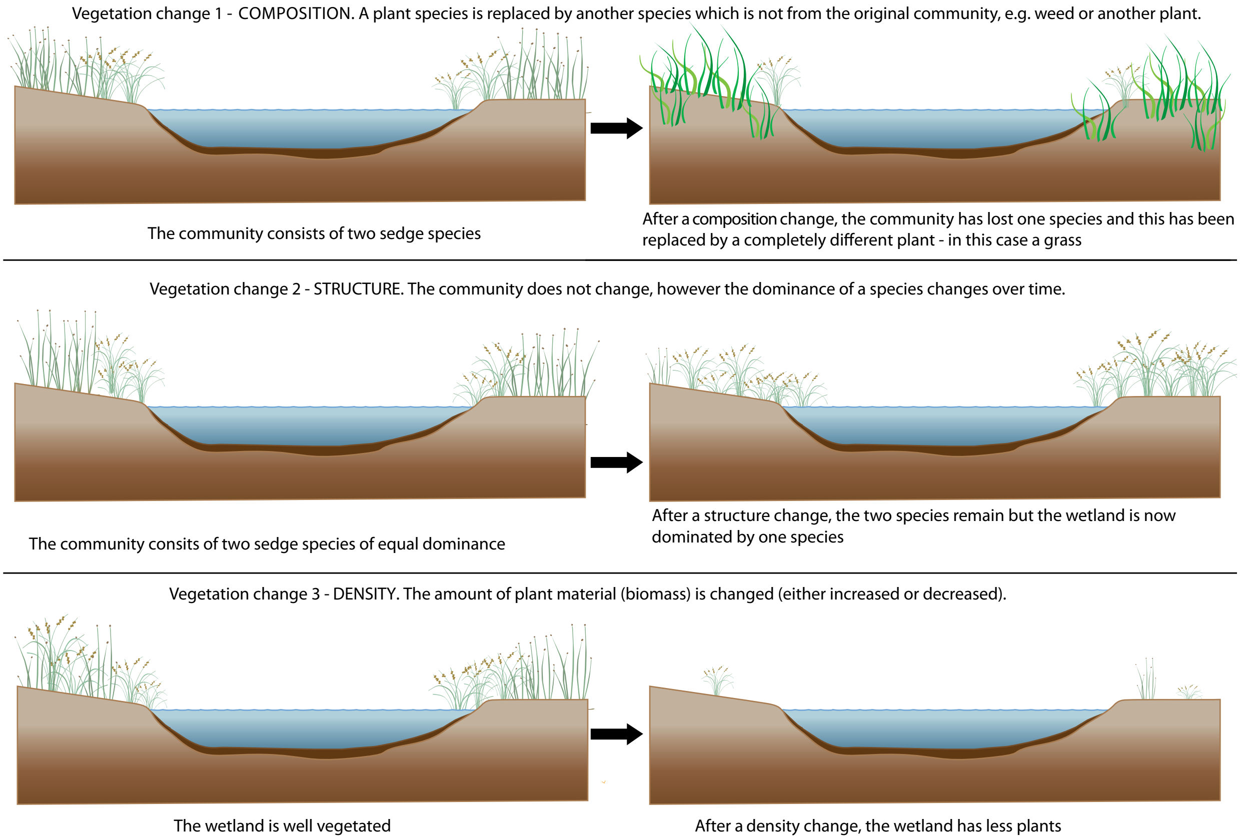

Figure 4. Schematic representation of the three main types of vegetation change in wetlands.

The reasons for vegetation change are often complex and vegetation change itself may result in the generation of other threats developing over time, which may then lead to further vegetation change occurring. For example, clearing resulting in a 'density' change to wetland vegetation, may allow the introduction of weeds leading to 'composition' and 'structure' changes. Figure 5 schematically represents clearing as a vegetation change and how this event may lead to other vegetation change events occurring over time.

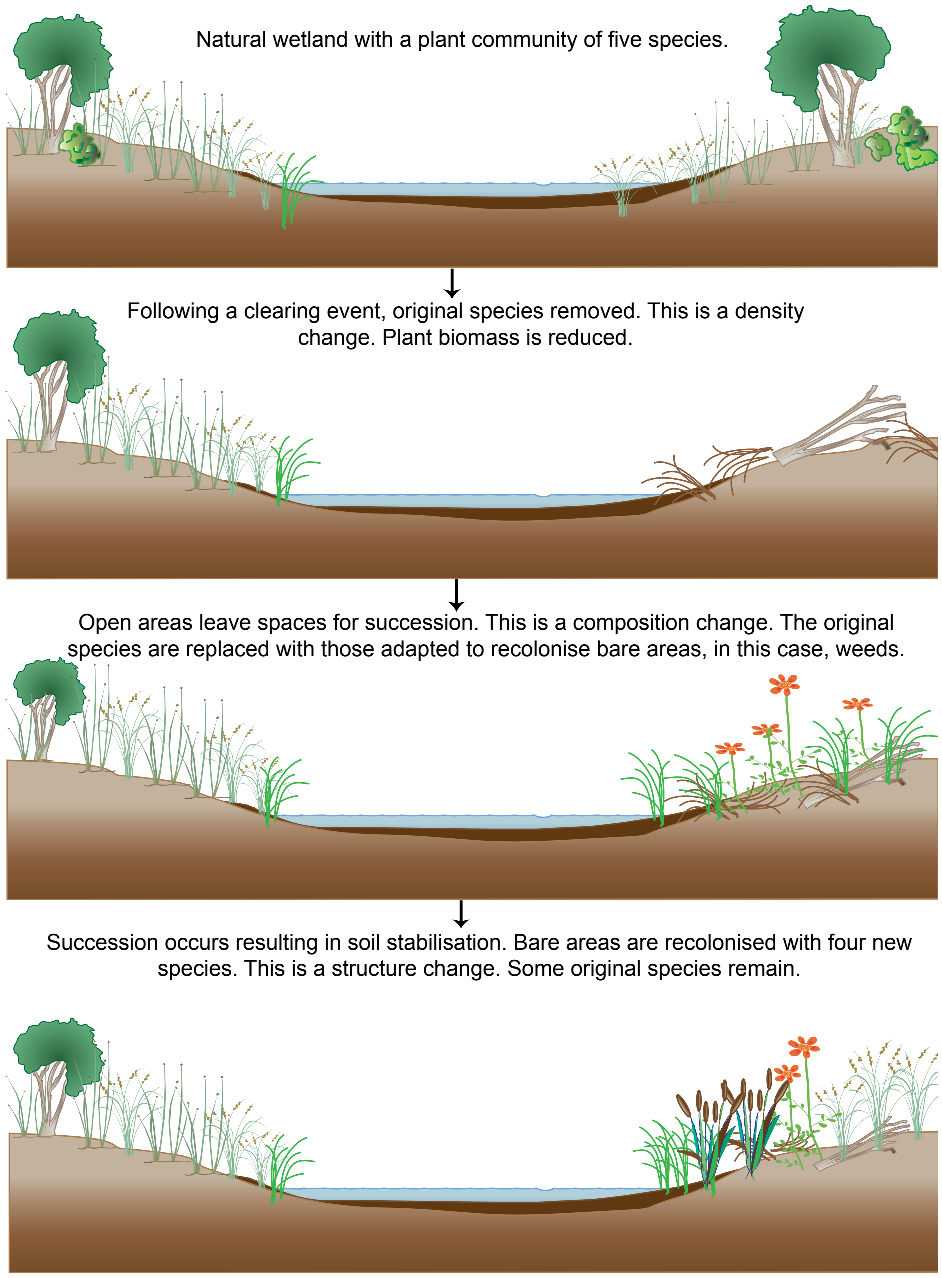

Figure 5. Vegetation clearing leading to other vegetation changes.

Natural responses to change: colonisation and succession

Succession is defined as progressive change in species composition and/or structure that occurs following disturbance of a site.[10] It can be caused by a natural or human-induced event such as fire, clearing or grazing. Following the disturbance event, the changed physical environment is colonised by a series of plant communities until the vegetation reaches a final 'equilibrium state'. Initially, colonising plants (or 'pioneers' or 'disturbance opportunists') grow, develop and modify the environment so that other plants can successively join or replace the initial colonisers, until the maximum number of species exist in that environment.[11] Initial colonising plants are those that are adapted to respond rapidly to opportunities for growth and survival in highly disturbed environments.

Colonising plants in WA wetlands include species such as wattles (*Acacia*), stinkwoods (*Jacksonia*) and spearwood (*Kunzea*) species which are mid-storey plants that produce large volumes of seed (Figure 6 and Figure 7). These seeds remain viable for long periods in readiness to germinate in response to an environmental change such as fire or sudden exposure to light that is significant enough to trigger germination, and start the process of succession. These plants can grow very rapidly and prolifically in order to take advantage of the good growing conditions and lack of competition from other native plants and weeds (Figure 8). Many succession species also have relatively short life spans, for example, many *Acacia* species and stinkwood (*Jacksonia sternbergiana*) live approximately 14–20 years, as opposed to some long lived slow growing species such as jarrah (E*ucalyptus marginata*) which can live up to 400 or more years.[12] When colonisers die off, conditions are often suitable for other species to regenerate. Coloniser species may also enhance the site conditions for later species – for example the legumes (*Acacia* species and pea plants such as *Jacksonia*) are able to 'fix' atmospheric nitrogen, increasing the nitrogen available in the soil for other species.

Figure 6. Panjang (*Acacia lasiocarpa*) is a common succession species in areas of the south west of WA. Photos – M Hislop (main) M Hancock (close up). Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright.

Figure 7. Stinkwood (*Jacksonia sternbergiana*) is a common succession species in areas of the south west of WA. Photos – K C Richardson (main), R Davis (inset). Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright.

However, dense, very old stands of some coloniser species and an absence of other species may indicate that the seed bank of other species is likely to be exhausted. It isn't uncommon for landowners to express a desire to 'get rid of' these species in the belief that they are preventing other plants from establishing. However, such dense stands may be natural and part of the structural arrangement of vegetation in specific habitat types within or surrounding a wetland. These colonising plants play an important role and should not be prematurely removed for aesthetic reasons if the natural wetland vegetation is to be retained. For example, following establishment, acacias and stinkwood stabilise the soil, develop soil nutrients, and provide shade and habitat for a period of time before other more long-lived wetland understorey and overstorey species such as flooded gum (*Eucalyptus rudis*) can establish and gradually out-compete the succession species.

Figure 8. Prolific growth of *Kunzea* sp. has occurred in the older area (left hand side) of a firebreak within a seasonally waterlogged wetland, in the southern Perth suburb of Forrestdale. Photo – J Higbid/DEC.

IDENTIFYING VEGETATION CHANGE

Monitoring will allow vegetation change events to be identified and may help to determine the cause of the change and effects of the change.

Identifying change of wetland vegetation through visual observations over time can provide considerable information on the nature and extent of vegetation changes. Examination of aerial maps and photographs from monitoring points over time are other simple methods of identifying change.

- Google Earth www.google.com/earth supplies a free software program that provides online access to aerial photography covering WA. Some areas have many years of aerial photography (time series), which can assist with identifying vegetation change.
- Aerial photography can be viewed and purchased from Landgate's Map Viewer www.landgate.wa.gov.au/bmvf/app/mapviewer/ and NearMap www.nearmap.com.

To determine wetland vegetation change accurately, the following characteristics of wetland vegetation can be monitored regularly to determine the degree and rate of the change:

- extent
- species composition
- structure (height class and dominance); and
- vegetation density (percentage cover)[13]

These observations will provide information on how rapidly the changes are occurring. This information is important in decision-making for undertaking intervention projects which are discussed in detail later in this topic.

If time or money is not available for monitoring vegetation and other wetland parameters, photo points may be useful in determining if changes are occurring. Photo points are simple, fast and relatively cheap to establish. The drawback of photos is that they only provide an indication that a change is occurring or has occurred and may not enable that change to be quantified. Photos such as those in Figure 9 showing weeds being controlled in a wetland are useful as monitoring points for noticing changes over time. Small, incremental changes may be difficult to detect in monitoring photos, and it may take a number of years before change is noticeable.

Figure 9. Photo monitoring is an effective way of capturing information at a point in time. This photo series shows the extent of *Watsonia meriana* var. *bulbillifera* within Brixton St wetland in response to weed management over a period of six years. Photos - K Brown/DEC.

➤ For a guide to photo points for monitoring purposes, see the Land for Wildlife program's Wildlife Note No. 9 *Photographic monitoring of vegetation*.[14]

➤ For additional detail on monitoring wetland vegetation and other parameters please see the topic 'Monitoring wetlands' in Chapter 4.

Technology now offers opportunities to monitor vegetation in new ways, making use of aerial photography and high-resolution digital airborne imagery to detect indications of canopy change, water use and plant health. These techniques may be suitable for large, complex wetlands or those in remote or inaccessible areas.

➤ For more information, see CSIRO (www.csiro.au/Organisation-Structure/Divisions/Land-and-Water/Environmental-Earth-Observation.aspx)

Where monitoring has not taken place and the vegetation prior to change was not documented, it is likely that it will need to be inferred. Photographs and aerial photographs can provide insight; if this information isn't available it may be useful to examine a suitable benchmark or **reference wetland** that shares the same characteristics as the wetland in question. Alternatively it can be very useful to gain historical insight from people familiar with the wetland in the past, who may be able to identify changes that have occurred and their causes.

Reference wetland: a wetland used to provide a model for planning a management project

Dynamic: a process or system which is characterised by constant change or activity

WHAT ARE THE EFFECTS OF VEGETATION CHANGE ON WETLANDS?

Vegetation change can significantly impact on the physical, biological or chemical processes existing within a wetland. Detrimental changes to vegetation in a wetland can occur at different rates, be subtle or substantial, involve different plant species, and will have a varied impact on wetland condition and functionality.[5] The effects of vegetation change may include:

- changes to habitat for native animals, fungi, algae and bacteria
- changes to the overall level of primary production by plants, resulting in changes to food webs that provide native animals, fungi and bacteria with food/energy
- changes to the chemical characteristics of the water. For example, a change in the amount of tannins in the water, and in the uptake of nutrients in the wetland with resulting changes to the types and density of algae
- changes in the physical structure of the wetland. For example, rates of erosion and sedimentation determined by vegetation can affect the bathymetry of a basin
- localised extinctions of plant species and vegetation communities

➤ For more information on the ecological role played by wetland vegetation, see the topic 'Wetland ecology' in Chapter 2.

WHAT CAUSES VEGETATION CHANGE IN WA WETLANDS?

Plants respond to a range of factors, such as water regime, soil wetness, salinity, pH, temperature, light, nutrients and competition.[15] These factors fluctuate within wetlands because of a variety of natural or human-induced events.

Natural causes

Due to the **dynamic** nature of wetlands in WA, managers should expect some natural vegetation change and allow for subtle changes over time.[16] Natural vegetation changes occur in wetlands in response to events such as drought, floods, cyclones, boom and bust animal populations, and fire caused by lightning strikes. These affect vegetation germination, growth and survival and can result in natural short, medium or long-term changes to composition, structure and density of vegetation. For example, a detailed study of the Becher wetlands in Rockingham found that fluctuations in structure and density of populations of the annual groundcover gota kola (*Centella asiatica*, Figure 10), occurred regularly over five years as local climatic and flooding conditions varied.[17]

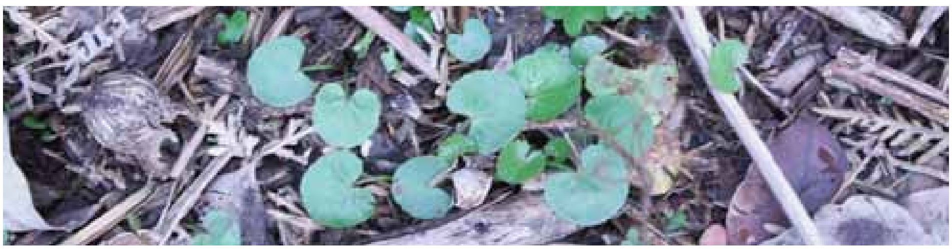

Figure 10. *Centella asiatica* density and structure was shown to fluctuate naturally over time in the Becher wetlands. Photo - J Nichol/DEC.

Human causes

Some of the most common human-induced causes of vegetation change are:

- weed infestations
- grazing by livestock or other introduced or nuisance animals
- manual clearing
- fire
- disease
- altered hydrology
- salinity
- other changes to water quality including **eutrophication** and acidification.

It is not uncommon for a wetland to have been subject to more than one cause of vegetation change over time or at the same time. For example, in urban areas, many wetlands were historically grazed, causing altered hydrology and water quality, and weed invasion. Once urbanised, altered fire, hydrology, water quality and weeds continue to cause vegetation change.

Table 1 below summarises how these **threatening processes** can affect vegetation. Many of these causes of vegetation change are covered in detail in other topics of this guide.

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plant material (phytoplankton, macrophytes or both). May occur naturally over geological time or may be human-induced.

Threatening processes: processes that threaten the survival, abundance or evolutionary development of a native species or ecological community

Table 1. Common threats to wetlands and examples of their effect on wetland vegetation.

Activity or threat to wetland	Type of change to vegetation	Example	More information
Clearing - manual	Density	Plants are manually removed via a machine, so extent of vegetation altered	
	Structure	Clearing removes the understorey species and changes the arrangement	
	Composition	Clearing activity transports weeds into the community which then outcompete native species	
Livestock and feral animals	Density	High nutrient levels cause algae to proliferate, out-competing native plants and reducing total plant biomass in the wetland.	See the topic 'Livestock' and 'Introduced and nuisance animals' in Chapter 3
	Structure	Areas of the wetland are preferentially spot grazed by horses, while droppings are left in another area	
	Composition	Palatable species that are selectively grazed are lost from the wetland. Weeds are introduced in faeces.	
Weeds	Density	Typha (*Typha orientalis*) invades a population of bare twigrush (*Baumea juncea*) which is much slower growing. The typha spreads and vegetation density in the community alters as the typha is much denser (has a higher biomass).	See the topic 'Weeds' in Chapter 3.
	Structure	Typha (*Typha orientalis*) invades a population of bare twigrush (*Baumea juncea*) which is much slower growing. The typha spreads and vegetation structure changes- the *Baumea* dies off because it has been taken over and only a small remnant remains	
	Composition	Typha (*Typha orientalis*) invades a population of bare twigrush (*Baumea juncea*) and the baumea cannot compete for sunlight and dies. It is completely replaced in the community by the typha	
Phytophthora dieback	Density	Potentially greater biomass due to severe weed invasion post-infection	See the topic 'Phytophthora dieback' in Chapter 3
	Structure	Increased dominance of resistant native and weed species	
	Composition	Loss of susceptible plant species from the wetland	

Activity or threat to wetland	Type of change to vegetation	Example	More information
Secondary salinity	Density	Salinity of water increases causing some wetland plants which are not tolerant to die, reducing overall cover	See the topic 'Secondary Salinity' in Chapter 3.
	Structure	Where saline water is highest; many plants of non-tolerant species are dying and more tolerant species are taking over and dominating, changing the vegetation structure	
	Composition	More saline tolerant weed species move into areas where plants have died.	
Eutrophication (increased nutrients)	Density	Quality of water changes causing some wetland plants which are not tolerant to die reducing overall cover	See the topic 'Managing Water Quality' in Chapter 3.
	Structure	More tolerant species or ones which thrive in high nutrient environments then take over and dominate, changing the vegetation structure	
	Composition	Weeds, which have more tolerance for high nutrient levels, move into the plant community	
Altered hydrology	Density	Reduced water depth means some plants die reducing overall cover of vegetation leaving bare areas	See the topic 'Managing hydrology' in Chapter 3
	Structure	More tolerant species spread and take over from other species	
	Composition	Dryland species from different plant assemblage or weed species spread into drier zones.	
Altered fire regime	Density	Fire can kill individual plants, decreasing density. Plants may germinate in response to fire, increasing density. Either way, vegetation density is altered by fire events	
	Structure	Fire may favour burning particular species in a community over others, thereby altering the dominance of some species over time. Relative species presence will change over time with succession.	
	Composition	Fire tends to favour fire-tolerant species and disadvantage fire-sensitive species. Fire events kill vegetation allowing areas to be opened up for plants potentially not from the local community to invade. Some weedy plant species thrive in fire environments.	

Clearing of native vegetation

Clearing is regulated under the *Environmental Protection Act 1986*. Under section 51A of the Act, clearing is defined as:

(a) the killing or destruction of; or

(b) the removal of; or

(c) the severing or ringbarking of trunks or stems of; or

(d) the doing of any other substantial damage to,

some or all of the native vegetation in an area, and includes the draining or flooding of land, the burning of vegetation, the grazing of stock, or any other act or activity, that causes —

(e) the killing or destruction of; or

(f) the severing of trunks or stems of; or

Clearing of native vegetation (cont'd)

(g) any other substantial damage to,

some or all of the native vegetation in an area.

The Act establishes it to be an offence to cause or allow clearing of native vegetation unless it is done in accordance with a clearing permit, or is exempt. The Environmental Protection (Clearing of Native Vegetation) Regulations 2004 describe the administration of permits.

The regulations apply to all native vegetation including native aquatic or terrestrial vegetation, but not vegetation in a plantation or which was intentionally sown, planted or propagated unless that vegetation was sown, planted or propagated as required under law.

The taking of flora, including seeds, flowers, stems and all other parts of native plants, is regulated under the *Wildlife Conservation Act 1950*. On Crown land, taking of flora for any purpose requires a licence. On private property, the taking of flora requires the land owner's permission, and a licence is required for the sale of any flora that is taken. For further information on flora licences, contact DEC. Clearing that is done in accordance with a licence issued by DEC under the *Wildlife Conservation Act 1950* does not require a clearing permit.

For information on legislation relating to native vegetation clearing, please see the topic 'Legislation and policy' in Chapter 5.

MANAGING DETRIMENTAL VEGETATION CHANGE

There are two main phases when managing detrimental vegetation change:

1. addressing the causes of the vegetation change
2. managing the vegetation

Addressing the causes of detrimental vegetation change

The first step of managing detrimental vegetation change is addressing the cause of the change. This entails identifying the cause and then deciding whether to:

- stop or minimise the cause
- prevent the cause from re-occurring
- take no action at all

Even when the outcome of this step is to take no action at all, it is an essential step which determines how to proceed. If this is not taken into consideration, efforts at regeneration and revegetation may fail, be more expensive, less efficient and even detrimental to a wetland environment.

Many wetland managers in the Wheatbelt face the issue of vegetation change caused by secondary salinity. Secondary salinity is a complex, landscape-scale issue and its management typically involves change in land use across landscapes and a range of expensive intervention measures that are beyond the scope of many wetland managers. If the catchment is not identified as being a priority for biodiversity recovery by regional or state organisations, it is highly unlikely that there will be potential to achieve the vegetation composition, structure and density that existed prior to secondary salinisation. In this scenario, establishing that secondary salinisation of the wetland cannot be halted is the first step in determining the way forward. Wetland managers can then establish whether natural colonisation of native salt-tolerant species is likely to occur and if so, they can prioritise activities to reduce threats to regeneration, such as salt-tolerant weeds and livestock grazing, so that **adaptation** to changing conditions occurs without being compromised by threats that can be managed.

Table 3 cross-references the relevant topics of this guide which provide guidance on addressing the causes of vegetation change.

Table 2. Information on how to manage the cause of vegetation change

Threat to vegetation	Information on how to manage this threat
Weeds	'Wetland weeds' topic, Chapter 3.
Grazing by livestock	'Livestock' topic, Chapter 3
Damage by introduced and nuisance animals	'Introduced and nuisance animals' topic, Chapter 3
Altered hydrology	'Managing hydrology' topic, Chapter 3
Phytophthora dieback	'Phytophthora dieback' topic, Chapter 3
Secondary salinity	'Secondary Salinity' topic, Chapter 3
Eutrophication (increased nutrients)	'Water quality' topic, Chapter 3
Acid sulfate soils	'Water quality' topic, Chapter 3

Weeds require a special mention, because as well as being a cause of vegetation change, weed invasion is also an outcome of every other type of vegetation change listed above. The planning of weed management should be coupled with planning of native vegetation management. The location, size of the area, amount of weeds to be controlled and rate of control should be dictated by the resources available and the rate at which natural regeneration or revegetation is expected to occur following the removal of weeds. The **Bradley method**[16] is effective, that is, working from more intact areas of vegetation towards more degraded areas. This allows natural regenerative processes within the environment to assist with regeneration and revegetation.

Managing vegetation

Deciding whether to actively manage the vegetation

Once the cause of vegetation change has been addressed (identified, stopped, reduced, prevented in future or not acted upon), the wetland manager can aspire to either:

1. **restore** the wetland vegetation composition, structure and density as much as possible, or

2. **rehabilitate** the wetland to create a new, self-sustaining native plant community that can survive in the altered environmental conditions, while still being as close to the original community as possible.

Alternatively, following an examination of these options, it may be determined that the scope for restoration and rehabilitation is too limited and the costs too high to proceed with either option. A decision may then be made to manage the wetland to limit further loss of wetland values. Ultimately, it is necessary for wetland managers to ensure that they are directing limited resources to those sites that achieve the best possible nature conservation outcomes.

Adaptation: the process by which an organism becomes fitted to its environment

Bradley method: working from the most intact parts of a bushland area out towards more degraded areas, to allow natural regeneration to occur, for example, when weeding

Restoration: returning an ecological community to its pre-disturbance or natural state in terms of abiotic conditions, community structure and species composition

Rehabilitation: the re-establishment of ecological attributes in a damaged ecological community although the community will remain modified

Thresholds: points at which a marked effect or change occurs

Revegetation: return vegetation (indigenous or otherwise) to an area

Private landowners may decide it is a priority to rehabilitate their wetland. Public land managers with responsibility for large areas of land (multiple wetlands), and other organisations involved in regional land management activities, typically need to prioritise sites to be managed. Some basic principles include prioritising:

- wetlands that are of high conservation value
- wetlands that are in better condition before those in worse condition
- wetlands that are improving by themselves rather than deteriorating
- those that will take less work to get back to a more natural state.[18]

The decision to restore, rehabilitate or to take a minimalist approach (including not to act at all) needs to be made early on in the management process in order to manage expectations and to set realistic objectives for the long-term management of the vegetation change event. It is also important to note that the required level of intervention may alter over time and will require frequent re-evaluation.[16]

From a nature conservation perspective, restoration is always most desirable, but it is often not feasible. It will depend on whether it is possible to address the cause of the vegetation change and how significant changes to the wetland and its vegetation are. The development of a management plan that describes the objectives for the wetland is a good way to work logically through this decision-making process.

➤ A process for wetland management planning is described in the topic 'Wetland management planning' in Chapter 1.

The rate at which a vegetation change event occurs can be a strong indicator of whether an intervention response is the most appropriate action. Rapid vegetation changes often signify that a critical **threshold** has been reached.

A rapid rate of vegetation change is also likely to allow for opportunities for other threatening processes to occur which may exacerbate the vegetation change event or degrade the wetland further.

The more that vegetation changes, the more challenging it may be to instigate meaningful intervention, the greater the effort required and therefore potentially the higher the management costs.[19,10] Early detection and evaluation of change is vital for preserving existing vegetation and values.[16,20]

The cumulative effect of allowing wetlands with small vegetation change events to continue to degrade is likely to result in additional management costs in the future.

Managing vegetation: choosing regeneration or revegetation

If a wetland manager has determined that either restoration or rehabilitation is feasible, they can usually choose one or more of the following three strategies:

1. where possible, allow for the natural processes such as regrowth and recruitment within the wetland to repair the vegetation; known as 'regeneration'
2. carry out activities to optimise natural regeneration processes that repair the vegetation; known as 'assisted regeneration', including fire, smoke and smoked water
3. where necessary, introduce plants/seeds to the wetland that are adapted to the new conditions following the vegetation change event; known as **revegetation**.

Wherever regeneration potential exists, it should always be the default option. Regeneration provides much greater potential for achieving self-sustaining wetland ecosystems and a far greater chance of approximating the natural diversity of a wetland. Natural and assisted regeneration techniques are natural and non-invasive/minimally invasive respectively. They are also cost-effective.

Figure 11. A wetland near Yanchep, north of Perth, where following a fire, the potential for natural regeneration is likely to be high, unless actual acid sulfate soil generation has occurred. Photo – T Calvert/DoE.

Endemic: naturally occurring only in a restricted geographic area

Propagate: grow plant specimens from parent material

Revegetation is usually required only when a wetland will continue to degrade or will remain in a degraded state without human intervention. Revegetation tends to require significantly more resources and time. Being an invasive technique, it also poses risks that regeneration does not. There are also significant limits to our ability to achieve natural diversity through revegetation. For example, in the area encompassing Perth and surrounds (Moore River to Dunsborough), 74 per cent of the 1,187 native wetland plant taxa are **endemic** to WA.[1] Many of these taxa have not yet been successfully **propagated** (bred) and so are not able to be used in planting programs.

Assessing the potential for natural regeneration

The wetland manager plays no active role in natural regeneration, other than monitoring, and where necessary, working to reduce threatening processes. Natural regeneration is the least invasive, and potentially cheapest way to reverse detrimental vegetation change.

Regeneration uses the natural processes such as regrowth and recruitment to repair the vegetation. Understanding the potential for regeneration of wetland vegetation involves assessing the resilience and reproductive capacity of the wetland vegetation following a vegetation change event.

Natural regeneration is more likely to occur when the cause of vegetation change is a natural process, such as fire, and where this process is not compounded by other impacts. Where fire has occurred, for example, the best approach is to carry out regular inspections to ensure that the area is not being invaded by weeds, and that the fire has not resulted in the generation of actual acid sulfate soils (Figure 11).

Regeneration may or may not result in similar composition, structure and density of wetland vegetation compared to its original state. The vegetation change event may have changed the conditions required for one of these aspects to be achieved. For example, *Phytophthora cinnamomi* can kill individuals of species that are susceptible to the pathogen, changing the vegetation composition; similarly the export of nutrients in ash following a fire may limit the density of regrowth.

This principle does not always apply when altered hydrology has caused the death of mature plants in a tree population. These mature species may be adapted to the existing water regime and may be lost as a result of changes to hydrology, if changes are too fast or too extreme for them to adapt. However, their progeny may develop root morphologies suitable to the new water regime, allowing a plant population to survive even if individuals are lost.

It is important to take into account the timeframes required for regeneration processes, for example, the season in which plants germinate, vegetatively reproduce or re-grow.

As described earlier, colonisation and succession are natural processes of recovery.

Regeneration is reliant upon:

- a source of healthy seed or **propagules**
- a receptive seed bed
- suitable climatic conditions
- suitable water regimes
- protection from grazing/impacts of animals
- low competition from weeds or other native plants
- the absence of harmful pathogens or other disease organisms

Regeneration occurs via:

- the release of seed during/after the event
  For example, modong (*Melaleuca preissiana*) are prolific seed producers and produce a seed rain each season. The seeds are very small and can germinate in large numbers in response to episodic events such as heavy rainfall and fire, where these provide opportunities for germinants to establish. The majority of wetland shrubs and trees in WA are long-lived and experience episodic **recruitment** events under the right conditions. Assessing seed production and viability will help establish the likelihood of germination of seed-setting species.
- suitable conditions for remaining individuals to produce seed after the event
- suitable conditions for re-growth of existing individuals via **epicormic** buds (Figure 12), **lignotubers** etc.
- suitable conditions for vegetative growth to occur via **rhizomes** or **stolons**
- This is particularly relevant for many **sedges**.
- suitable conditions for re-growth of existing individuals via **underground storage organs** such as bulbs, tubers and corms.
- Underground storage organs such as bulbs, tubers and corms allow plants to renew. These organs allow plants to enter a state of dormancy where conditions are extreme, such as during drought and fire. The underground storage organs of some species can remain dormant in the soil for years and still remain viable, and for some, sprouting is stimulated by fire. Twenty-two percent of wetland flora in the southern Swan Coastal Plain (the Perth metropolitan region and surrounds from Moore River to Dunsborough) renew from underground storage organs.[1] If these remain unaffected by detrimental change, a significant amount of regeneration can occur.
- the soil seed bank being intact and viable
- The **soil seed bank** is more likely to be intact if the soil hasn't been disturbed. This factor will affect the degree to which species will germinate from soil seed banks (Figure 13).

Propagule (plant): any part of a plant from which a new plant can grow, including seeds, bulbs and rootstocks

Recruitment: addition of new individuals to a population (usually through reproduction)

Epicormic buds: dormant vegetative buds that are embedded beneath the bark, which have a regenerative function after crown destruction

Lignotuber: a large woody swelling of the plant stem that occurs at and below the soil surface. Regrowth from lignotubers can occur following fire, drought and grazing.[22]

Rhizomes: stems that are buried underground

Stolons: stems that usually run horizontally along the soil surface

Sedge: tufted or spreading plant from the families Cyperaceae, Centrolepidaceae, Hydatellaceae, Juncaginaceae, Restionaceae, Juncaceae, Typhaceae and Xyridaceae. In these plants the leaf sheath is generally not split, there is usually no ligule, the leaf is not always flat and there is an extended internode below inflorescence. Some sedges are also known as rushes.

Underground storage organs: specialised fleshy organs such as corms, bulbs and tubers that allow plants to flourish in nutrient deficient soils or to die back and enter a state of dormancy when conditions are extreme, such as during fire or drought[23]

Soil seed bank: the natural storage of seeds, often dormant, within the soil

Figure 12. Epicormic growth of a fallen *Melaleuca rhaphiophylla* at Maramanup Pool, Baldivis, south of Perth. Photo – J Higbid/DEC.

Figure 13. The degree to which the soil has been disturbed will have an effect on how viable the soil seed bank is. Photo – L Perera.

Seed dispersal mechanisms: the means by which plants distribute their seeds, for example via wind, water, birds and insects

➤ *Are there seeds in your wetland*?[21] describes how to assess the seed bank in a wetland's sediment. This can be used to help determine which species' seeds are present and their viability.

- suitable **seed dispersal mechanisms** occurring to enable seeds to reach the area Many wetland plants disperse seeds using wind, water and animal vectors. Some have a wide distribution in many areas of WA and beyond. For example, the sedge *Juncus kraussii* subsp. *australiensis* occurs along the coast from east of Esperance to north of Shark Bay. Its seed is small and easily distributed by wetland birds that travel long distances. Long distance dispersal creates disjunct populations of the sedge in wetlands in what are effectively 'islands' of suitable habitat surrounded by a much drier landscape.[1]

  Other species rely on water to transport their seeds. For example, *Aponogeton hexatepalus* seeds germinate in the season they form and when water is present they can float to new locations[1] in a wetland or possibly to a different wetland. If the wetland is connected to 'upstream' wetlands, waterways or even drains, some influx of propagules is possible.

Understanding which of the wetland's species use these dispersal mechanisms can provide an understanding of the potential opportunities and timeframes for natural dispersal to occur.

Fire-responsive: plants which have seed pods that open, seeds that germinate, or epicormic buds or lignotubers that resprout in response to a fire event. Some of these responses are triggered by the chemicals produced in smoke during the fire event.

Carrying out assisted regeneration

The two main types of assisted regeneration are:

- managed fire to produce a mosaic of burnt and unburnt areas over time
- smoke and smoked water.

Managed fire

In some instances, fire could be used to promote conditions suitable for regeneration of native plants. Fire can potentially stimulate seed germination, reduce the impacts of weeds (if managed)[24] and encourage the regeneration of mixed age vegetation.[25] Using fire as an assisted regeneration technique for vegetation change events is complex, and must take into account factors such as frequency, season, intensity, pattern and post-fire environmental conditions, as well as legality. Its use can be controversial as it may cause as many problems as it can potentially address, including further damaging existing vegetation as well as destroying seed banks and encouraging more weeds.

Burning is a form of clearing (see 'Clearing of native vegetation' earlier in this topic for the definition of clearing). Where vegetation is proposed to be burnt and the purpose is not exempt, a clearing permit under the *Environmental Protection Act 1986* is required.

➤ For more information, see *A guide to burning under the native vegetation clearing provisions.*[26]

Smoke and smoked water

An alternative to fire is applying smoke or smoked water to the wetland environment to promote plant germination. Using smoke on wetland areas is a relatively non-invasive technique which can be applied fairly cheaply to areas with **fire-responsive** vegetation. Fire-responsive plants are species which have seed pods that open in response to the heat and drying effect of a fire, and/or seeds that have enhanced germination in response to the chemicals produced in smoke during a fire event.[27,28] The chemicals that encourage seed germination are encapsulated in smoke or contained within a water medium and applied directly to the vegetation or soil, avoiding the need for fire. Smoke and smoked water can greatly assist in the germination success of many native seeds, and if the technique is applied correctly can result in regeneration events.[27] Sites to be planted or direct seeded can also be prepared before planting with smoke or smoked water so that seedlings planted can benefit from smoke germination chemicals. Site preparation is described in more detail in the revegetation section of this topic.

➤ The Botanic Gardens and Parks Authority of Western Australia has pioneered much of the research into the application of the chemical in smoke responsible for seed germination. A range of scientific journal articles on the subject are listed on the website: www.bgpa.wa.gov.au.

➤ For further information on using smoked water see:

- Geographe Community Landcare Nursery website[29]
- Greening Australia's *Seed germination data sheet*[30]

Carrying out revegetation

There are three key revegetation techniques:

- brushing
- direct seeding
- planting.

Revegetation is a broad topic. Many techniques are in use, and much has been written about it. When reading such literature, remember that revegetation occurs across many different ecosystems for many different reasons. The following is a very quick overview of key considerations for the purposes stated in this topic.

Brushing

Brushing involves harvesting seed-bearing branches of local plants (either during seeding season, or at any time for plants that hold their seed within their canopy in woody fruits) and laying these branches in chosen regeneration areas. When branches from shrubs and trees from genera such as *Melaleuca, Eucalyptus*, *Casuarina*, *Agonis*, *Astartea*, *Pericalymma* and *Banksia* are laid out, they drop seeds when the branch dries out, increasing the number of seeds present, and the woody material and leaf litter from the branches suppress emergent weeds and protect the regenerating seedlings from other degrading processes such as erosion or strong winds. Brushing is often applied in bare areas where weed control or slashing has occurred and the site requires protection while the brushed species have a chance to regenerate over time when conditions are most suitable.

Plant materials, such as stems, can harbour the pathogen *Phytophthora*, which causes the devastating Phytophthora dieback. It is essential that all brushing materials be carefully selected to avoid spreading Phytophthora dieback. A site assessment by a professional dieback assessor may be appropriate.

It is also important to ensure that the sourcing of brushing material be done carefully and sensitively, so as to minimise environmental impact. The taking of flora, including seeds, flowers, stems and all other parts of native plants, is regulated under the *Wildlife Conservation Act 1950*. On Crown land, taking of flora for any purpose requires a licence. On private property, the taking of flora needs to be authorised by the land owner, and a licence under that Act is only required if the flora is taken for sale. For further information on flora licences, contact DEC.

Clearing of native vegetation is regulated under the *Environmental Protection Act 1986*. Clearing that is done in accordance with a licence issued by DEC under the *Wildlife Conservation Act 1950* does not require a clearing permit.[31] Furthermore, the definition of 'clearing' under the *Environmental Protection Act 1986* does not include the taking of plant material where it does not cause any substantial damage to the plant. Thus, the careful and selective cutting of brush material (or the collecting of seed) should not require a clearing permit under the *Environmental Protection Act 1986*. Making use of plant material cleared for firebreaks or access tracks is also a good way to minimise impacts.

➤ For more information, see the following information sources:

- disease hygiene standards: the topic 'Phytophthora dieback' in Chapter 3
- regulations: see the text box 'Clearing of native vegetation' earlier in this topic

Direct seeding

Direct seeding involves placing viable seeds into a wetland and promoting their germination. The success of direct seeding relies upon appropriate seed collection, storage and preparation to maximise viability and germination success[32], site preparation and sowing. These last two factors are discussed in greater detail in the 'Revegetation' section of this topic.

Seed may be applied directly as cleaned seed that has been tested and, if appropriate, treated to achieve a pre-determined germination rate for the establishment of defined vegetation species composition and density. Alternatively, seed may be applied through indirect means, such as brushing (see above), or through the spreading of weed-free topsoil (applicable in dryland environments, such as areas surrounding wetlands).

Direct seeding can be suitable in weed-free areas of wetlands, although not on steep slopes if erosion is a risk. However, although direct seeding may be significantly cheaper than planting seedlings, it has had a mixed success rate in WA and in particular on the Swan Coastal Plain (the coastal area from Jurien – Dunsborough), due to a variety of reasons, including unsuitable approaches and site preparation.[33] Direct seeding success stories overwhelmingly involve adequate site preparation and post-seeding site management such as weed control, to allow the seedlings to germinate in the absence of other threats.[34] In many instances, although the process appears cheap, the outcomes are too poor to warrant the effort or resources invested. This is most often due to a lack of understanding about WA growing conditions in individual wetland environments, such as challenging soils and weather conditions. Other challenges include low seed viability and seed predation by birds, ants and other animals.[5] Because many of these factors cannot be controlled, wetland managers should compare opportunities for seeding activities with other methods of revegetation prior to commencement.

Seeding may also be used in conjunction with planting, to provide the opportunity for greater species diversity and natural plant establishment outcomes, while not relying only on effective seed germination and establishment for revegetation success. It is also important to note that seed sown may remain dormant for a number of years before germinating, achieving positive revegetation outcomes over a longer time frame.

Where it is important to determine the likelihood of success prior to proceeding with large-scale direct seeding, one possible approach is to trial the use of direct-seeding on a smaller scale.

➤ Many, but not all, native plants have successfully been direct seeded. For further information about direct seeding and types of species which can be direct seeded, refer to:

- the *Seed Notes for Western Australia*[35], which provide information on individual species as well as licensing and storage www.dec.wa.gov.au/content/view/3303/1808/

- *Florabank*, www.florabank.org.au, an information internet portal providing knowledge from research and practice in native species seed management for native seed suppliers, buyers, landholders and other NRM stakeholders

There are different ways to sow seed, including hand planting, niche seeding, broadcasting, machine planting and hydromulching. Many of these will not be appropriate in relatively intact wetland areas. Pre-seeded matting is excellent for steep embankments, providing both erosion control and seeds together. Seeds are spread onto an appropriate fibremulch and germinated. The seeding can occur in a nursery or on-site. If done at a nursery, it is only suitable for seeding of sedges and other monocots because the matting needs to be rolled up to transport (like roll-on lawn) to the site.[18]

Treating seeds prior to or following sowing can be very beneficial. The seeds of different species respond to different treatments, including smoke and smoke products, acid, cold stratification and heat. Seed suppliers often provide these treatment services.

➤ The range of direct seeding methods and seed treatments are outlined in Florabank, along with references for more details. See www.florabank.org.au> Seed Knowledge> Native Vegetation Management Tool> Direct seeding.

Planting

Planting techniques include:

- planting seedlings grown in seedling trays or tube stock
- strip or mat planting, useful in highly erosive sites and where there is the potential for waterbirds to pull plants out of the ground
- long-stem planting, where seedlings are grown to a height of 1 metre or more, and three quarters of the length of the plant is buried. (www.environment.nsw.gov.au/resources/grants/Longstemguide.pdf)

Preparing or pre-ordering stock from an accredited supplier in due time is essential. Collecting, treating and sowing seed of local provenance is a lengthy process which needs to be factored in to the works schedule. As a guide, standard tubestock of trees and shrubs should be no more than 7–8 months old, while sedges should be 10 months old.[18] At this age, tubestock should develop extensive root systems when planted and sedges will be engaged in lateral spread rather than vertical extension only, enabling rapid coverage of planted areas.[18]

Hand planting equipment includes trowels, spades, tree spades, mattocks, powered augers, pottiputkis, Hamilton treeplanters and Hamjam borers.[8] A range of mechanical equipment has been developed and is commercially available, but these are often not suitable for use in sensitive wetland sites.

Poor planting techniques by untrained volunteers can lead to poor establishment and higher mortality rates in seedlings. A short demonstration prior to the commencement of planting at volunteer days can put everyone at ease and reduce this potential problem.

Waterbirds such as ducks, coots, swans and occasionally herons can uproot sedges and consume submerged plants before they have established, quickly undoing lots of painstaking work. A trial exercise may help to determine whether it is likely to pose a problem at a site. Strip or mat planting can help reduce waterbird damage by weighting plants down. Bird netting may be warranted for large sites where waterbird damage is a known problem. For small-scale plantings, wire enclosures can be used for the first few months until plant roots are well established.[18] In both cases, the materials need to selected and installed with great care to ensure that there is no inadvertent injury or death to animals or humans.

➤ For more information on planting techniques, see:

- Florabank: www.florabank.org.au> Seed Knowledge> Native Vegetation Management Tool> Tubestock planting.
- *Revegetation techniques: a guide for establishing native vegetation in Victoria*[36] at: http://live.greeningaustralia.org.au/nativevegetation/pages/pdf/Authors%20C/13_Corr.pdf

Common problems

Some of the most common problems encountered by people revegetating wetlands include:

- not reducing the weed load before planting and not being prepared for follow-up weeding over long timeframes
- not factoring in enough time to get seeds/seedlings ready in time for planting
- planting at the wrong time of the year, or there being unpredictable weather
- underestimating the mortality rate of plantings, and overestimating the success rate of direct seeding
- seedlings being planted badly because people planting are unfamiliar with the procedure
- waterbirds such as ducks, coots, swans and occasionally herons uprooting sedges and consuming submerged plants
- vandalism, often by children

Some tips on these problems are outlined in the sections below.

Revegetation: key considerations

There are a number of details to consider when revegetating, including species choice, diversity and provenance. Timing of replanting activities, costs and post-planting maintenance are also key considerations.

When seeking to emulate the pre-vegetation change environment, the main considerations are:

- site preparation
- hygiene practices to avoid introducing weeds and diseases
- avoiding impacts to animals
- choosing the most suitable species
- aiming for original species diversity and density
- planting in the most appropriate locations
- deciding on the planting density
- minimising excessive damage to existing wetland values;
- using additives to soils during planting or seeding
- post-planting or seeding maintenance.

Site preparation

Preparing an area for replanting or direct seeding is an important step in ensuring revegetation success. Prior to both seeding and planting, the site should be cleared of weeds, as weed species will compete with natives for space and light.[37] The location, size of the area, amount of weeds to be controlled and rate of control should be dictated by the resources available and the rate at which revegetation is expected to occur following the removal of weeds. The Bradley method[16] is effective, that is, working from more

Figure 14. Arum lily (Zan*tedeschia aethiopica*) has taken over this area following the removal of bracken (Pteridium *esculentum*). Photo - J Nichol/DEC.

intact areas of vegetation towards more degraded areas. This allows natural regenerative processes within the environment to assist with regeneration and revegetation. Doing the job right to begin with saves considerable time and resources; managing weeds amongst seedlings can be time consuming and difficult.

If there is a diverse assemblage of weeds on site, or persistent weed vectors, it may take a number of years to eradicate or control them to levels suitable to undertake planting. Just as there is natural succession in native species, the same can be true of weeds. Removing one suite of weeds may just result in suitable conditions for another (Figure 14). It may take a number of years to eradicate or control weeds to levels suitable to undertake planting. Post-seeding and planting weed control is also critical.

➤ Weed control techniques for WA wetlands are described in the topic 'Wetland weeds' in Chapter 3.

Preparing the ground is an aspect of site preparation where particular care needs to be taken in relation to wetlands. Many techniques, such as deep ripping, furrowing and mounding are appropriate for paddocks being rehabilitated and in farm forestry sites, but are generally not appropriate in wetlands due to their impact on wetland soil.

Revegetation hygiene practices: weed and disease free seeds, plants and propagules, vehicles and equipment

It is critical to take steps to avoid introducing pathogens that cause disease and weeds. For example, Phytophthora dieback, which is caused by *Phytophthora* species, can have devastating effects on the vegetation of wetlands and surrounding dryland. *Phytophthora cinnamomi*, for example, can be brought into a site in infected soil, water and plant materials (including dead plant material such as bark and mulch).

It is essential that hygiene standards be observed in all aspects of revegetation programs to minimise the spread of weeds and Phytophthora dieback.

➤ For more information, see the topic 'Phytophthora dieback' in Chapter 3.

Avoiding impacts to animals

Planting disturbs the soil. It is important to consider that animals, or their eggs, may be present in the soil, including burrowing crayfish, frogs (Figure 15), turtles, and a wide range of small invertebrates. It is also important to consider the impact that soil disturbance may have on water quality, and how this may affect species that are sensitive to turbid conditions or to being covered in sediment. For example, fine particulate matter suspended in water can affect many aquatic species, including fish, by clogging, coating or abrading respiratory structures such as gills.

➤ For more information on wetland animals, see the topic 'Wetland ecology' in Chapter 2.

Figure 15. The burrow of a white-bellied frog (*Geocrinia alba*), a critically endangered frog, is susceptible to soil disturbance. Photo - K Williams/DEC.

Species diversity

When seeking to emulate the vegetation that was present prior to a vegetation change, species diversity will be an important consideration. Unless the wetland had a low diversity or the vegetation was well documented, determining the diversity prior to vegetation change event can be a difficult task. Photographs and aerial photographs can provide insight; if this information isn't available it may be useful to examine a nearby wetland of the same or similar type.

Some wetlands naturally support a low diversity of native vegetation. For example:

- some primary saline wetlands
- some wetlands with an overstorey that has a closed canopy and a dense leaf litter
- permanently inundated areas with deep water
- those where benthic microbial communities are prevalent

In situations where the original species will no longer survive, it is necessary to choose an alternative suite of species. This may be necessary when a wetland:

- has become more saline, such that plants with a greater salt-tolerance are necessary. Freshwater wetlands generally have a higher diversity of species than those of saline wetlands.[1]
- is infected with a pathogen such as *Phytophthora cinnamomi*, such that Phytophthora dieback resistant plants are necessary. As over 40 per cent of native plants in south-west WA are susceptible[39], this is likely to limit species diversity.
- has a significantly altered hydrology, such that plants with different water requirements are necessary. This is less likely to alter species diversity.

Provenance: the place of origin[42]

Figure 16. A simple planting regime with low diversity of species may be justifiable in some circumstances, particularly where it is intended to continue the rehabilitation over time. Photo – DEC.

- the water quality is significantly altered, such that tolerant plants are necessary. Some plant species are known for having greater tolerance to higher nutrient levels or for their ability to remove excess nutrients, such as lake club-rush (*Schoenoplectus validus*), salt rush (*Juncus kraussii* subsp. *australiensis*) and tall spikerush (*Eleocharis sphacelata*).[16]

When considering the introduction of locally native species that were not present in the wetland prior to the vegetation change, it is important to ensure that the benefits of their introduction are greater than potential disadvantages (e.g. weediness).

Another important consideration is that not all wetland plants can be supplied for use in revegetation projects, because many have not yet been successfully propagated (bred).

Other circumstances may also constrain the ability to achieve the original species diversity. In particular, the condition of a site may mean that the resources required to prepare the site, manage weeds and achieve the desired species diversity is beyond those available. In some highly degraded sites that have been determined to be a priority for revegetation, it may be necessary to begin with a simple planting regime (Figure 16) to initiate the rehabilitation of the site, within the scope of the available resources.

Plant choice: provenance and ecotype

When seeking to emulate the vegetation that was present prior to a vegetation change, wetland managers will be sourcing seeds or seedlings of the species that were present. However, it is important to take this a step further by sourcing seeds and other propagules (seeds, seed inundated mud or sediments, plant cuttings, plant roots or rhizomes[19,40]) of local **provenance**, that is, local origin. A species' genetic variation over a geographic range can reflect the ecological conditions in which the species has evolved. A compelling reason for ensuring local provenance of propagules is that in WA the genetic variation within plant species can change over short distances, meaning that the wetland itself is the best choice to source propagules, followed by wetlands as geographically close to it as possible.[41] Recent research indicates there are some circumstances when it may be beneficial to broaden the provenance for revegetation activities, for example, when there is a need to build in greater tolerance in the vegetation to cope with environmental changes; these should be considered on a case-by-case basis. For more information, see www.florabank.org.au> Seed Knowledge> Native Vegetation Management Tool> Design – Species and provenance selection.

Many wetland plants have closely related species that inhabit dryland. Furthermore, many taxa have distinctive wetland and dryland **ecotypes**, and a number of these ecotypes are proving to be valid discrete taxa. Correct ecotype is an important consideration.[2]

Care should be taken during collection of genetic materials from local intact wetlands to not cause further damage to these wetlands by taking too much.[19] To prevent damage, seed collection and harvesting of plant genetic material is regulated in WA. Collections must be made in a manner that protects existing plants, with only limited materials being taken. The taking of smaller quantities of propagating material from a greater number of plants also increases the genetic diversity of material being used for revegetation, thereby increasing the health and diversity of the vegetation being established.

Revegetation practitioners must also have permission to collect plant material from land managers prior to any site visit, and should ensure that all collection sites are protected from damage caused by collecting activities.[32,40] Particular care needs to be taken to prevent spread of plant diseases and incidental destruction of vegetation by vehicular movement.

The laws governing flora conservation are contained within the *Wildlife Conservation Act 1950* and Regulations. These are administered by DEC. Flora is protected and may or may not be able to be harvested under particular conditions relating to the level of protection required. Licenses are required for collection on Crown land and the commercial use of flora, and different licenses exist depending on the purposes for collection. Permission is also required from the land manager, including for private property.

➤ For specific information on the details for licensing and laws surrounding flora collection, please go to the flora licensing webpage[43] on DEC's website: www.dec.wa.gov.au/management-and-protection/plants/flora-licensing.html

➤ The Revegetation Industry Association of WA (Inc)[44] has information on seed collection: www.riawa.com.au

It is estimated that tens of thousands of sedges have been used in revegetation projects in wetlands in the Perth region that have been propagated by tissue culture, often used without reference to provenance and with extremely narrow genetic diversity due to using a small number of clones.[45] However, it has been demonstrated that it is possible and relatively easy to produce large numbers of some WA sedges from seed and in doing so maintaining genetic diversity.[45]

Planting and seeding in the right spot

Plant germination and survival depends upon a range of factors, such as **water regime**, soil wetness, salinity, pH, temperature, light, nutrients and competition.[15] These factors vary over time and space. That is, they change with seasons and shorter and longer term drivers; and they change over a geographic area.

Identifying the optimal establishment zone of a plant should take into account the most important factors. Water regime is particularly variable within a wetland and this factor is a strong determinant of where a plant would naturally germinate. If the water regime is intact, planting replacement vegetation becomes more straightforward as seeds or plants can be located where they were previously found.

This approach accounts for the water requirements of species. Even a basic understanding of a plant's **water requirements** will help. Knowing whether a plant is always, sometimes or never submerged under water is a good start. If it is sometimes submerged, knowing the minimum and maximum inundation it can tolerate is important. If it is never submerged, knowing its tolerance to waterlogging and completely dry soil is critical.

Ecotype: a genetically distinct geographic variety, population or race within a species which is adapted to specific environmental conditions. Typically ecotypes exhibit differences in morphology or physiology stemming from this adaptation, but are still capable of breeding with adjacent ecotypes without loss of fertility or vigour.

Water regime: the pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, duration, frequency, extent and depth, and variability of water presence

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Figure 17 below provides an example of the vegetation of a wetland that is permanently inundated, showing a classic series of plant types from the centre of the basin to the outer extent of the seasonally waterlogged area of the wetland. The series of plant types, from submerged to emergent plants, occur in zones. This diagram is an example only; there are many patterns of diversity and structure of vegetation in wetlands, including many which do not support classic zonation, for example, as shown in Figure 2 and Figure 3. For example, a seasonally inundated basin wetland may have less aquatic plants and more fringing vegetation than a wetland with standing permanent water such as a lake. The vegetation patterning will therefore vary depending on the type of wetland, its water regime and historical impacts.

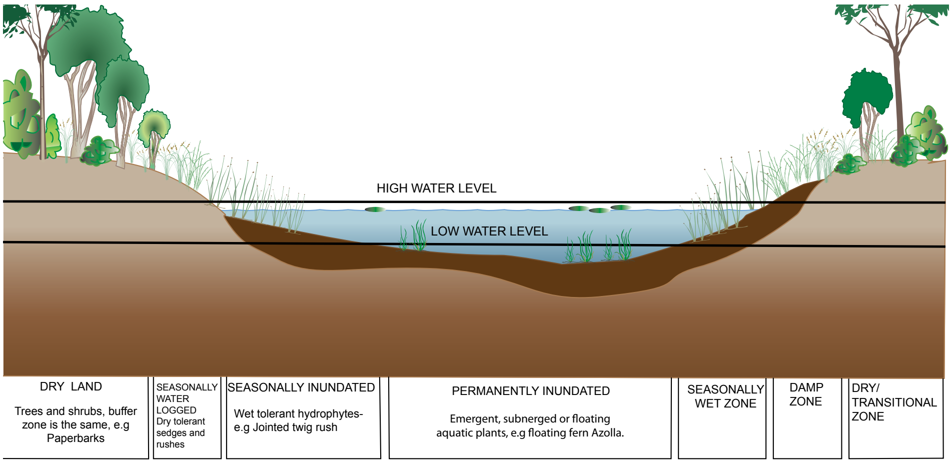

Figure 17. Zonation of plants in a permanently inundated wetland. Adapted from work by Denise Crosbie, Cockburn Wetlands Education Centre (2006).

In 2000, a study was carried out on the water levels and duration of inundation or waterlogging being experienced by sixty wetland species at wetlands on the Swan Coastal Plain.[46] The results of this study have been used to inform the management of a number of wetlands in the greater Perth area. For example, the common wetland tree *Melaleuca rhaphiophylla* was found, on average, to exist at a maximum water depth of 0.006 metres above the ground and minimum water depths of 2.14 metres below the ground. However, the maximum water depth at which the tree was found during the study was 1.03 metres, while the minimum water level at which it was found was 4.49 metres below the ground. It was found to live in wetlands that are inundated on average 2.15 months of every year, but the longest period was 9.4 months of every year. This information is useful in that it provides wetland managers with a coarse indication of the maximum and minimum thresholds for the species' survival. Of equal importance, it shows that there is a great deal of variation amongst a species. However, identifying the water regime that supports a species is not as simple as defining the extreme measures (maximum and minimum). Simply maintaining the water level between a maximum and minimum height is a simplistic approach, because variability in water level is important for plant reproduction and other aspects that determine the ecological character of the site. Since this study, further studies have been undertaken across the broader south-west, resulting in updates to this water range data. Studies have also been undertaken in other areas of the state, as listed below.

➤ Information on water requirements for planting include:

- *A guide to emergent wetland plants of south-western Australia*[47] is an excellent resource, providing a guide to the habitat location, optimum and maximum water depth and mean annual water level tolerated by thirteen native sedges, as well as their seasonal flooding range.

- *Water regime for wetland and floodplain plants: a source book for the Murray-Darling Basin*[48] is, as the name suggests, focused on eastern states species, but does describe the germination requirements of *Eucalyptus camaldulensis* in detail, as well as those of *Muehlenbeckia florulenta*, *Eragrostis australasica*, *Eleocharis acuta* and *E. sphacelata*, *Typha domingensis* and *Cyperus gymnocaulos*.
- Although more technical in nature, a range of water requirement studies of wetland plants may also be useful. In WA, research into the water requirements of wetland organisms has focused on the Gnangara and Jandakot groundwater mounds in the greater Perth region[46,49,50], the Blackwood and Scott Coastal Plain groundwater areas[51], and Ramsar wetlands. Riparian studies that include wetland species in the Pilbara and Kimberley have also been the subject of a number of studies (for example, Loomes[52,53,54]).
- *Establishing samphires in the Avon catchment*[55]

Even when optimally planted, the best efforts of a wetland manager can be confounded if exceptionally wet or dry conditions occur during the growing season – some death of plants is to be expected, although contingencies such as watering may assist in minimising plant losses.

Deciding on planting and seeding density

Replicating the original density can be informed by examining part of the site which has not experienced a vegetation change or by examining a nearby similar, intact wetland, often referred to as a 'benchmark' site.

Planting should attempt to mimic the natural environment as much as possible, but managers should be aware that planting in densities greater than 10 plants per square metre can be very costly and time consuming.

The natural density of wetland vegetation varies widely between wetlands, even those with similar characteristics or in close proximity to each other. This makes it difficult to provide even rules of thumb about appropriate planting densities. Denser is not always better, for example, bare patches between areas of vegetation are often important habitat for a range of reptiles.

Published rules of thumb/actual densities include:

- 2-3 seedlings per square metre in poor and very poor sites
- a rough guide of 500:50:5 herbs or sedges:shrubs:trees for each 100 square metres for riparian vegetation (that is, vegetation associated with waterways) in south-west WA[56,18]
- where only sedges and rushes are being used, a rate of 6-9 tubes or cells per square metre. More sedges/rushes per square metre can be used to achieve dense stands faster, if budgets allow. For a larger stock size, such as blocks or strips of sedges/rushes, densities are normally determined by site characteristics and budget constraints. The closer the blocks and strips are planted, the quicker they will grow to meet each other and create dense stands.
- for direct seeding, determine the seed viability, allow 50 per cent mortality of seedlings, and calculate the required seed lots accordingly (this service is available from some commercial seed operators).[18]

In the south-west of the state, as a rule of thumb, an average loss of up to 80 per cent of all germinants of direct-seeded trees and shrubs can be expected after two years, therefore seed should be sown at a rate of twenty germinable seeds per square metre.[18] The average mortality rate of planted trees and shrubs is estimated to be 30–50 per cent.[18] Over-seeding and over-planting (also known as saturation planting) is often used in anticipation that a certain percentage of the seeds or plants will not survive in the short to medium term. This technique has the added benefit of reducing the area available for weed establishment during the seedling establishment phase.

Timing of seeding and planting

Seeding

As a rule of thumb, seeding should occur prior to the main rains[56]) to give establishing plants the greatest period before drought stress occurs. This is roughly late summer/early autumn in the south-west of WA, but can differ yearly. The wetland environment can hold water for longer periods than dryland areas, giving new plants a longer establishment period. However, in wetland environments it is important to be aware that surface water flows may wash away seeds. More intense rainfall events can also lead to inundation and poor seedling survival.

Planting

The optimal planting time can depend on the type of plant and whether it is to be planted into an area subject to inundation or waterlogging.

As a rule of thumb, in the tropical climate of northern WA, it is appropriate to plant at the start of the rains, in summer, when rainfall events are common and the soils are moist and yet still warm.

In the south-west of WA, the Mediterranean climate means that most plantings are ideally undertaken in late autumn, at the beginning of the rainfall season, when the soil is moist and still warm and more rain is to be expected. However, winter planting of waterlogged soils and the edges of inundated zones, and early summer planting of zones where inundation is giving way to waterlogging, has been found to work at some sites (for an example, see the case study 'Challenges in wetland rehabilitation at Bibra Lake' at the end of this topic). In inundated wetlands in the south-west of WA, many wetland sedges are planted in spring/summer when water levels are receding (if in the water column) Sedges may be dormant over winter and as a result their roots may not establish as well. This means they can be susceptible to damage by high-energy winter storm events that cause waves and erosion. Similarly they may not be tall enough to avoid being submerged, leading to death.

To water or not to water?

There are many opinions about whether or not to water seedlings in the dry seasons following their germination/planting. As outlined above, planting in the optimal establishment zone of a plant should minimise the need for watering. Over and above this, whether or not it is appropriate in a given situation depends on many factors including:

- seasonal rainfall variations
- soil conditions
- species chosen

Watering can influence the root development of a plant. If, as a seedling, the plant is watered often, it is less likely to establish deep roots to find water. When watering ceases, the plant will have less ability to find water for itself, and will lose vigour and may die unless it can develop a suitable root system.

Wetland managers may consider a limited period of watering, for example, over the first one or two summers, to encourage establishment and minimise potential plant death. In seasons with lower than normal rainfall watering is likely to be required to achieve acceptable plant establishment rates. Optimal watering is infrequent, deep watering, to encourage deep root systems, and watering the base of plants (the root zone) rather than its leaves or branches. Watering can be logistically challenging and expensive.

Soil improvers, fertilisers and plant guards

As a general rule, soil improvers and fertilisers should not be used in wetlands. Native plants have adapted over thousands of years to local soils, hydrology and climatic conditions. Many improvers and fertilisers contain nutrients in much higher amounts than can be tolerated by native species.

The application of gypsum, or dihydrous calcium sulphate ($CaSO_4 2H_2O$), is often suggested for clay or sodic soils to improve soil structure, such as sites subject to secondary salinity, which causes the soil structure to become compacted, and the growing environment for the local plants is changed. Gypsum addition will replace the sodium (Na) ions with calcium (Ca) ions which help to open the soil structure and improve soil permeability. However, this will only be effective in the longer term where the source of the salinity has been addressed and no further sodium is entering the wetland system. If this is not feasible, then the short term benefit and cost of gypsum addition is hard to justify.

The wetland origins of many soil conditioners

Gypsum, or dihydrous calcium sulphate ($CaSO_4 2H_2O$), is a natural product of many wetlands in WA, particularly in the Wheatbelt, the south-west and Goldfields region. Gypsum deposits in wetlands and in the dunes on the southern and south-eastern shores over time; it is estimated that deposits have been forming up to 35,000 years ago in some WA wetlands.[38] In WA it has been mined since 1921 using methods such as excavators (dry excavation) and sub-aqueous dredges. As well as being mined for use as soil conditioners, gypsum is mined for a multitude of uses, including drywalls, plasters, and fertilisers. Similarly, bentonite clay is mined from WA wetlands for use as a soil wetter as well as a range of other industrial and domestic applications.

Plant guards, such as those shown in Figure 18, can reduce grazing by animals such as rabbits, kangaroos and uprooting by waterfowl such as purple swamphens (*Porphyrio porphyrio*).[25] Guards can be costly and time consuming to install, and have limited benefit if not well maintained. Their use comes with the understanding that they will need to be manually removed, when plants are big enough, and if plastic like the ones shown below, generally prior to summer to prevent killing plants by overheating them (the use of mesh plant guards may minimise this issue).

Figure 18. a) plant guards can help to protect plants from people and other animals;
b) unmanaged plant guards may stifle plants or result in over-heating. Photos - J Nichol/DEC.

Timeframes

In natural wetland environments, plants interact with other physical, biological and chemical factors such as climate, soils and hydrology to grow, establish and undertake ecological function over long periods. How long it may take to revegetate a wetland and re-establish these processes is therefore a matter for consideration for wetland managers to manage projects and balance resource allocations.

Another factor to take into account when considering timeframes is the predicted numbers of plants surviving to adulthood following a revegetation project, based on natural attrition and the recognition that revegetation is an artificial process and plants will not always survive. Whilst detrimental vegetation change may occur in wetlands over short periods of time (1–5 years), it is widely recognised that ecological processes will not be reinstated within similar timeframes.

Symbiosis: a condition in which two organisms live in a mutually beneficial partnership

Mycorrhiza: a symbiotic association between a fungus and the roots of a plant, from which both fungus and plant usually benefit

The role of fungi and lichen

Fungi are multi-celled organisms that are neither plants nor animals (fungi is the plural, fungus singular). Fungi include an extremely wide range of organisms including macrofungi such as mushrooms, toadstools, puffballs, coral fungi, earthstars and truffles, and an even broader range of microfungi.

Fungi occur in most environments, however, some fungi species are much more prevalent in wetlands than other areas, such as certain species of macrofungi that fruit most abundantly on paperbark (*Melaleuca*) trees, and the predominantly microscopic aquatic fungi, which rely on free water for some part of their life cycle.

Studies worldwide show that a large number of wetland plants are partnered with mycorrhizal fungi[57,58] and WA is no exception—including but not limited to *Melaleuca, Astartea, Isoetes, Cotula, Viminaria, Myriophyllum, Nymphoides, Nymphaea, Pericalymma, Livistona, Pandanus, Ruppia* and *Eucalyptus*.[59] In recent decades there has been developments in the understanding of mycorrhizal associations with sedges, and the major role they play in phosphorus dynamics.[58]

Many fungi form a close association with plants in which both parties benefit (**symbiosis**) from an exchange of nutrients and sugars. This relationship is known as **mycorrhiza** and the roots of the associated plants are referred to as mycorrhizal roots. These mycorrhizal roots are connected to networks of microscopic thread-like structures developed by the fungi known as hyphae or mycelia, which explore and exploit a far greater area of the soil than uncolonised roots alone. These networks take up nutrients, such as phosphorus, and transport the nutrients back to the plant. Two main types of mycorrhiza occur: endomycorrhiza, where the fungi penetrate the plant's cell wall, and ectomycorrhiza, where the fungi are external to the plant cells. Endomycorrhiza are formed mainly by microfungi and can be present in permanently flooded soils, while ectomycorrhiza are formed by many macrofungi and appear to be sensitive to inundation.[60]

The significance of these beneficial plant-fungi partnerships needs to be considered when planning wetland revegetation. Research has found that healthy natural woodlands have a greater diversity of native fungi than degraded woodlands or revegetated agricultural lands, and that most native fungi are not self re-establishing in degraded or cultivated land, at least in the short to medium term.[61] Mycorrhizal fungi suitable for some plant species is now being made available by commercial suppliers. These fungi are mostly applicable to a range of non-woody plants. Inoculum specifically for use in revegetation for many natural Australian ecosystems with woody plants is not available. Inoculum obtained from similar vegetation in the local area is considered likely to be the most suitable. For more information, see the fungi information in the topic 'Wetland ecology' in Chapter 2, which provides a list of sources of additional information.

Lichen, cyanobacteria, bryophytes, mosses and liverworts form biological soil crusts. These crusts can help to reduce erosion, control water flow through soils, enhance soil nutrition and provide niches for plant seedlings and invertebrates.[62]

Inappropriate management techniques

Care should be taken when undertaking revegetation activities to ensure that the act of revegetation itself does not adversely impact on the condition of the wetland.

Some potential adverse impacts of wetland vegetation management include:

- planting or seeding when natural regeneration is possible. Trampling, weed spread, plant loss, soil compaction and introduction or spread of disease are all risks brought to bear unnecessarily.
- removing dead trees, logs and leaf litter, as these still function as habitat for native plants, animals, fungi, lichen and bacteria. Over time they are broken down and their nutrients are recycled.

case study

Restoring vegetation: the importance of weed control over the long term

John Lombardo was resigned to weeds and dying plants on his private property of 3 hectares in Wandi, thirty-two kilometres south of Perth. Over fifteen years, John had observed the wetland becoming increasingly infested with weeds such as arum lily (*Zantedeschia aethiopica*), perennial veldt grass (*Erharta calycina*) and Sydney golden wattle (*Acacia longifolia*). These weeds were causing composition changes in the wetland, displacing native plants.

In 2005, WWF agreed to fund some work on the property over a three year period, via its 'Wetland Watch' program. The project included the preparation and implementation of a management plan. Implementation included funding for controlling weeds, undertaking minor revegetation and controlling rabbits to allow regenerating plants to establish.

Management strategies - weed, plant and weed again

For the next four years, John undertook a number of weed control and assisted regeneration activities to improve the condition of the wetland vegetation. Specific wetland weeds were targeted for reduction or eradication. The herbicide Fluazifop-p-butyl (the active ingredient in 'Fusilade'), was sprayed over the entire site for several years to target non-native grasses without damaging the existing sedges, rushes and other natives. This controlled the veldt grass and paspalum (*Paspalum dilatatum*). Arum lilies on the property were also treated using other targeted herbicides and woody weeds such as the Sydney golden wattle were hand-removed.

Rabbits were controlled on site by baiting with Pindone. The baiting control was successful for several years in reducing the rabbit populations. However, the rabbits did return, so plant guards were placed around all new planted seedlings. Over time and with perseverance, the wetland began to naturally regenerate, with rushes and sedges growing from existing areas and seedlings of *Kunzea* and *Astartea* springing up once the areas were cleared of weeds (Figure 19, Figure 20).

Ongoing weed monitoring and management

The wetland now has more diversity of wetland species, which John regularly monitors when making his daily walk around the paths (Figure 21). During these walks, John observes any emergent woody weeds such as the Sydney golden wattle and removes the seedlings on the spot. Frequent, short visits to see changes and notice if weeds are spreading is a good technique to ensure work is achieved with limited time allocated. This method is labour intensive, however, John considers the success of the regeneration is well worth the ongoing management.

case study

Figure 19. Natural regeneration of *Casuarina* sp. following consistent weed control and other assisted regeneration activities.
Photo - J Nichol/DEC.

Figure 20. Natural regeneration of sedges following consistent weed control and other assisted regeneration activities.
Photo - J Nichol/DEC.

John also uses his daily walks in summer to assess whether or not he should water some of the revegetation sites he is working in. John calls his watering frequency "summer rain", in that he only puts around 20 millimetres of water on the wetland areas infrequently, no more than once a month, so as not to cause weeds to germinate or increase the spread of plant disease. John has noticed the plants in these areas do survive the hot summer conditions better.

Ongoing maintenance and monitoring

John's wetland continues to slowly regenerate, following his regime of controlling grasses two to three times per year, annual arum lily control and ongoing woody weed management. He has turned areas from old tracks to stands of *Melaleuca*, *Kunzea* and *Astartea*. Whilst the work is labour intensive the site is small enough to be managed with John and his wife undertaking limited tasks once or twice a week, breaking down the workload into manageable amounts and areas. John hopes to carry out more weed control and management in the future, and looks forward to the return of more native flora and fauna, such as blue wrens (*Malurus cyaneus*), at his property.

Figure 21. Mr John Lombardo showing regeneration on his property in Wandi. Photo - J Nichol/DEC.

PLANNING VEGETATION MANAGEMENT

Planning for vegetation management can be logistically challenging. It often involves long timeframes, overlapping tasks, and substantial resources. A schedule of works is a good way to structure tasks and understand timeframes, and should take into account all of the below factors.

Climatic variations, inferior seeds, incorrect planting methods, storm events, flooding, drought, weeds or varied water quality parameters are just some of the unpredictable influences which will affect the outcomes of a revegetation activity, yet many revegetation projects do not account for these factors. For example, in natural wetlands, native plant seeds may lay dormant within the sediment for years or even decades before the right combination of physical and chemical conditions for germination occur. Yet many projects are planned with the expectation that an entire area will be revegetated in only a few years, without any allowances for the unpredictability of nature. Planning for a project, and measuring its success, needs a timeframe of several years rather than months.

Wetland managers should therefore recognise the complexity of such a task during goal and objective setting, and resource allocation, in order to more accurately predict how long a revegetation project may take, and what will constitute a 'success'.

Planning should account for plant deaths through natural attrition and other causes. Undertaking strategic management activities like overplanting or using several techniques at once, such as direct seeding and revegetation may help reduce the potential for setting unrealistic expectations. Managers should always remember that revegetation is merely a tool used for managing wetlands which are too degraded to regenerate naturally and that success may need to be measured after a long period of time to measure if wetland processes have been restored as a result of the revegetation.

Ideally, wetland management should form part of an overall wetland management plan. A plan can identify priority wetland management actions and where, when and how these should be undertaken.

➤ A process for wetland management planning is described in the topic 'Wetland management planning' in Chapter 1.

Contingency planning

The planning process may identify collecting and storing seeds or other plant propagules as a suitable contingency action, particularly if there is a high risk to the wetland vegetation, or if individual species are rare or difficult to harvest. Seed storage facilities are provided by revegetation businesses companies and a number of non-government conservation organisations.

case study

Challenges in wetland rehabilitation at Bibra Lake

Adapted from a case study prepared by Denise Crosbie (Cockburn Wetlands Education Centre) and Norm Godfrey (Wetlands Conservation Society)

Bibra Lake is a permanently inundated wetland in Perth's southern suburbs. Extensive weeding and planting has been carried out in Bibra Lake.

Getting started

The inundated area of Bibra Lake fluctuates from season to season and year to year. Different wetland plants and weeds are associated with different zones in the wetland, and this has implications for rehabilitation activities. Maps were prepared to gain a better understanding of the site conditions including water levels, topography, type and extent of existing native vegetation and weeds. Weed control was then planned and implemented and planting initiated.

Trials and tribulations

During the early days of rehabilitation at Bibra Lake the following problems were encountered:

- timing of grants restricted the ability to order seedlings early and thus limited species availability
- chemically treated weeds did not mulch down in time for planting
- numerous seedlings needed replanting because they were established in the slashed weed biomass instead of the soil
- late plantings (September) required summer watering of the seasonally waterlogged zone
- secondary weed invasion was extensive
- planted sedges were predated by waterbirds.

Although wetland trees and tall shrubs were able to be established in weedy environments (though they grow more slowly), the object was to re-introduce understorey and attain a reasonably 'self-sustaining system' through dedicated weed control efforts.

Revegetation

Due to the dynamic nature of wetlands, many native plants may be growing outside of their optimal establishment zone. Be careful! Look at historical water data for the wetland, and at other wetland sites prior to planting. It is also difficult to predict future water levels, and during some years plants may lost – this is part of the challenge.

Wetlands plants grow rapidly and are much quicker to reward you than their slower bushland counterparts. The planting efforts at Bibra Lake included:

- saturation planting to out-compete the weeds
- planting transitional, waterlogged and upper seasonally inundated zones during winter months
- staging planting of the lower seasonally inundated zones following a fall in water level (approximately November onwards)
- organising planting days after the maximum water levels
- removing tree guards the following winter to avoid summer predation by rabbits
- propagating locally sourced seed and establishing a wetland seed production area for future supplies

case study

Figure 22. The site post-spraying, being prepared for planting. Photo – D Crosbie/Cockburn Wetlands Education Centre.

Figure 23. Seedlings were planted with tree guards and weed mats to combat weed regrowth. Photo – D Crosbie/ Cockburn Wetlands Education Centre.

case study

Figure 24. Secondary weed growth – weed regrowth was less where mulch had been applied. Photo – D Crosbie/ Cockburn Wetlands Education Centre.

Figure 25. The site two years later following planting. Photo – D Crosbie/Cockburn Wetlands Education Centre.

case study

So, can we really bring back the understorey?

Unfortunately there are no quick solutions when it comes to rehabilitation activities. The understorey is looking fantastic, bandicoot diggings are evident, and the frogs and birds are breeding. Bushy starwort, spear thistle, nutgrass and lotus invade bare areas where saturation planting has not been achieved. Our knowledge is growing and we need to continue long-term monitoring and evaluation to determine the true outcomes of our trials.

Established in 1993, the Cockburn Wetlands Education Centre is an independent, not-for-profit community organisation dedicated to wetlands, restoration activities, environmental education, youth services and facility hire. Numerous volunteers implement the centre's activities along with the assistance of a small band of dedicated staff. The centre lies in the suburb of Bibra Lake, 15 kilometres south of Perth. It provides the gateway to Beeliar Regional Park which contains twenty-seven wetlands within two parallel wetland chains.

GLOSSARY

Adaptation: the process by which an organism becomes fitted to its environment

Biomass: the total mass of biological material (living or dead), usually expressed as live or dry weight per unit area or volume

Bradley method: working from the most intact parts of a bushland area out towards more degraded areas, to allow natural regeneration to occur, for example, when weeding

Clearing: any act that kills, removes or substantial damages native vegetation in an area. This includes severing or ringbarking of trunks or stems, draining or flooding of land, burning of vegetation and grazing of stock or any other act or activity that causes damage to some or all of the native vegetation in an area

Community: a general term applied to any grouping of populations of different organisms found living together in a particular environment

Dynamic: a process or system which is characterised by constant change or activity

Ecological community: naturally occurring biological assemblages that occur in a particular type of habitat

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region

Ecological linkage: a network of native vegetation that maintains some ecological functions of natural areas and counters the effects of habitat fragmentation[oo]; a series of (both contiguous and non-contiguous) patches of native vegetation which, by virtue of their proximity to each other, act as stepping stones of habitat which facilitate the maintenance of ecological processes and the movement of organisms within, and across, a landscape[7]

Ecosystem: a community of interdependent organisms together with their non-living environment

Ecotype: a genetically distinct geographic variety, population or race within a species which is adapted to specific environmental conditions. Typically ecotypes exhibit differences in morphology or physiology stemming from this adaptation, but are still capable of breeding with adjacent ecotypes without loss of fertility or vigour.

Endemic: naturally occurring only in a restricted geographic area

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plant material (phytoplankton, macrophytes or both). May occur naturally over geological time or may be human-induced.

Fire-responsive: plants which have seed pods that open, seeds that germinate, or epicormic buds or lignotubers that resprout in response to a fire event. Some of these responses are triggered by the chemicals produced in smoke during the fire event.

Functioning ecosystem: a community of interdependent organisms together with their non-living environment. A functioning ecosystem is one which has a full suite of these normal resources and functions successfully, interacting within an ecosystem all of the time to maintain a stable sustainable system over time.

Mycorrhiza: a symbiotic association between a fungus and the roots of a plant, from which both fungus and plant usually benefit

Propagate: grow plant specimens from parent material

Propagule (plant): any part of a plant from which a new plant can grow, including seeds, bulbs and rootstocks

Provenance: the place of origin[42]

Recruitment: addition of new individuals to a population (usually through reproduction)

Reference wetland: a wetland used to provide a model for planning a management project

Rehabilitation: the re-establishment of ecological attributes in a damaged ecological community although the community will remain modified

Resilience: capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks

Restoration: returning an ecological community to its pre-disturbance or natural state in terms of abiotic conditions, community structure and species composition

Revegetation: return vegetation (indigenous or otherwise) to an area

Senescence: the natural aging and subsequent death of an organism

Succession: progressive change in species composition and/or structure that occurs following disturbance of a site

Symbiosis: a condition in which two organisms live in a mutually beneficial partnership

Taxa: a taxonomic group (the singular being taxon). Depending on the context, this may be a species or their subdivisions (subspecies, varieties etc), genus or higher group

Threatening process: processes that threaten the survival, abundance or evolutionary development of a native species or ecological community

Thresholds: points at which a marked effect or change occurs

Turbid: the cloudy appearance of water due to suspended material

Vegetation: combinations of plant species within a given area, and the nature and extent of each area

Water regime: the pattern of when, where and to what extent water is present in a wetland. The components of water regime are the timing, duration, frequency, extent and depth, and variability of water presence

Water requirements: the water required by a species, in terms of when, where and how much water it needs, including timing, duration, frequency, extent, depth and variability of water presence

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

Wetland processes: the dynamic physical, chemical and biological forces within a wetland, including interactions that occur between wetland organisms, within the physical/chemical environment, and interactions of these

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A guide to managing and restoring wetlands in Western Australia

Introduced and nuisance animals

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Introduced and nuisance animals' topic

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Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Introduction

A wide variety of fauna (animals) may use a particular wetland or be wetland-dependent, including mammals, reptiles, fish, birds, frogs, and **aquatic invertebrates** (such as insects, snails and crayfish). Protecting, maintaining and encouraging native fauna populations at a wetland involves managing the wetland in such a way as to provide suitable habitat (an area or environment where conditions are suitable for the survival of an organism, taxon or community) for such fauna. Managing a wetland to maintain its natural state (in general terms: good water quality, healthy vegetation and unaltered hydrology) will help to maintain suitable habitat for the wetland's natural suite of fauna (Figure 1).

Figure 1. A wetland in Forrestdale which provides habitat to its natural suite of fauna due to good water quality, healthy vegetation and unaltered hydrology. Photo – C Mykytiuk/WWF.

Maintaining or improving habitat for the natural suite of native fauna often involves preventing or controlling introduced and nuisance animals. These will be predators and/or competitors of native fauna and will also degrade the habitat available for native fauna.

There are many species of introduced animals found throughout Western Australia. In fact, introduced animals may be found in almost every area of the state, with wetlands being no exception. Introduced animals may threaten **biodiversity**, degrade habitats and may have severe economic and social impacts. Some species of native fauna can seriously impact wetlands and surrounding land when in unnatural numbers, and in these circumstances may be considered 'nuisance fauna'. This topic briefly describes the introduced and nuisance species that may be present at a wetland, including **feral livestock**, the impacts these may have, and the management strategies available to address these animals.

Aquatic invertebrates: those animals without a backbone (such as insects, worms, snails, molluscs, water mites and larger crustacean such as shrimps and crayfish) that live in or on water for at least one phase in their lifecycle

Biodiversity: a contraction of the words 'biological' and 'diversity', encompassing the whole variety of life forms—the different plants, animals, fungi and microorganisms—the genes they contain, and the ecosystems they form

Feral animals: introduced animals that have escaped, or have been released, from domestication and returned, partly or wholly, to their wild state

Livestock: introduced domestic ungulate (or hoofed) animals

What are nuisance fauna?

Nuisance fauna are native animals that naturally occur at a site, but which have reached a population size that is causing harm to the environment or humans. Examples include kangaroos, Australian white ibis and midges, which can all reach unnatural numbers as a result of human alterations to the environment. Mosquitoes are also labelled nuisance insects, but they are an exception: the population of many species of mosquitoes can grow rapidly and disperse far from wetlands under the right natural conditions.

➤ For guidance on managing nuisance midges and mosquitoes, see the topic 'Nuisance midges and mosquitoes' in Chapter 3.

What are introduced animals?

The term 'introduced animals' refers to those animal species that have been intentionally or unintentionally brought into a region where they do not historically occur, usually facilitated by humans. In the Australian context, this definition includes both non-Australian animals as well as animals that are native to Australia but have been introduced from one area within the country or state to another. For example, common yabbies *(Cherax destructor albidus)* have been introduced to dams in WA from the eastern states. Some introduced animals may also be considered invasive animals, which are rapidly spreading introduced animals that out-compete native fauna for habitat.

Introduced animals are a problem because they are able to rapidly increase in numbers without natural predators or diseases to keep the population in check. Many of the introduced animals in Australia are large animals such as pigs (*Sus scrofa*) or camels (*Camelus dromedarius*). The wild ancestors of these domestic animals evolved among large predators such as the big cats, bears and wolves. In Australia, where these predators do not occur, introduced animals were able to easily establish themselves. The only natural control of most introduced animals in Australia is drought. Introduced animals numbers increase during good seasons and decline rapidly during dry times. During dry times in particular, terrestrial introduced animals seeking water are more likely to congregate around wetlands. Australia's extended evolutionary and biogeographic isolation has resulted in its native fauna being naïve and vulnerable to introduced animals, particularly predators.[1]

Since European settlement (if not before), humans have facilitated the spread of introduced animals to Australia. In a twenty-year period spanning 1860–80 more than sixty vertebrate animal species were released in Australia.[2] Many of these introductions were deliberate, in an attempt to make the European settlers feel more at home by bringing European animals to the country.[3] There were even acclimatisation societies set up solely for the purpose of spreading animals such as rabbits (*Oryctolagus cuniculus*), birds and deer for the 'benefit' of the country.[3] Animals such as rabbits and red foxes (*Vulpes vulpes*) were often released for recreational hunting while European carp (*Cyprinus carpio*) were introduced for ornamental display in garden ponds. Many other animals such as house mice (*Mus musculus*) and rats (*Rattus* spp.) were introduced into Australia accidentally on settlers' ships, while domestic animals such as cats (*Felis catus*), horses (*Equus caballus*) and camels were released from captivity into the wild.

Since the realisation that introduced animals can be harmful to Australia's environment and native fauna, introductions have mostly been accidental, although some intentional introductions (for example for hunting and fishing) still occur. Many animals kept as pets or livestock have become feral animals after straying from the properties they were kept on or after being deliberately abandoned. Animals may also be introduced to new areas by travelling unnoticed with tourists and vehicles transporting food and other products, or even by hitching a ride on debris in waterways: cane toads (*Bufo marinus*) have been reported to be 'surfing' down the Ord River by as much as 20 kilometres a night.[4]

Many of the aquatic introduced animals that occur in wetlands in WA were probably introduced as a result of aquarium and aquaculture ventures. For example, blackworm (*Lumbriculus variegatus*), commonly sold as live fish feed, and aquarium snails are commonly found in wetlands in metropolitan areas. Yabbies and brine shrimp (*Artemia* spp.) are commonly used in the aquaculture industry to feed juvenile fish in hatcheries.

Most introduced fish populations result from intentional releases, for example, of domestic aquarium fish that have been 'set free', or fish released by recreational fishers to enhance recreational fishing. Notably, eastern gambusia (*Gambusia holbrooki*) were deliberately introduced into Australian wetlands and waterways as a **biological control** agent for the control of mosquitoes in the 1920s.[5] They may now be found in most drainage channels and many wetlands along the south-western coast of WA, particularly in metropolitan areas. They were referred to as 'mosquito fish' but unfortunately they are thought to have actually benefited mosquito populations by eating the native insects which would otherwise prey on mosquito larvae. So it appears that they are quite aptly named – their genus name *Gambusia* is derived from the Cuban Spanish term *gambusino*, meaning 'useless'. Eastern gambusia also out-compete native fish for food and attack competitors including tadpoles and fish by damaging their fins.

Biological control: the control of an introduced plant or animal by the introduction of a natural predator or pathogen, usually bacteria, viruses or insects, or by biological products such as hormones

Amphibians: the class of animals to which frogs, toads and salamanders belong. They live on land but develop by a larval phase (tadpoles) in water.

Another notable deliberate introduction is the cane toad. Cane toads were introduced to northern Queensland from Hawaii in 1935 in an unsuccessful attempt to control cane beetles, a pest of the sugar cane industry. Having no natural enemies, the toads spread west into the Northern Territory and south into New South Wales. Cane toads have since crossed the Western Australian border in the northern part of the state. The poisonous toads are considered a threat to Western Australian native frogs and other fauna through predation, competition and lethal ingestion.

Finally, some introduced species have slipped in to Australian wetlands undetected by catching a ride on other introduced species. This is the most likely mode of entry for a European ostracod (*Physocypria* sp.), which was discovered in Lake Jolimont, Perth in 2010. It is thought that the ostracod was introduced when pet goldfish were released into the lake.[5]

Which introduced animals can occur at a wetland?

Table 1 provides a list of introduced animals that are known to occur at wetlands in WA. Which of these species actually occur at a wetland will depend on a number of factors, including the location of the wetland within WA and the available habitat at the wetland.

When assessing the risk of an introduced species inhabiting a particular wetland, it is important to keep in mind that factors such as climate change may alter that risk in the future. For example, some feral fish species may expand in range if wetlands and waterways become warmer or more saline in the future as a result of climate change.

Table 1 groups the introduced animals according to those that are, and are not, dependent on wetlands for their survival. 'Wetland dependent' introduced animals are those that are restricted to or dependent on wetlands for their existence. This category is dominated by aquatic species and **amphibians**. Those introduced animals that are 'not wetland dependent' are visitors to wetlands.

Table 1. Introduced animals that are known to occur at wetlands in Western Australia

	Common name	Latin name	Known distribution in WA	Identification guide	Reporting
Wetland dependent					
Birds					
	Mute swan	*Cygnus olor*	Avon River, Northam	Field guide to Australian birds[7]	-
	Domestic waterfowl	*Various*	Metropolitan areas	Field guide to Australian birds[7]	-
Amphibians					
	Cane toad	*Bufo marinus*	Kununurra	DEC pamphlet Is it a cane toad?[8]	Cane Toad Hotline 1800 084 881 Kimberley residents: DEC's Kununurra Office (08) 9168 4200
Reptiles					
	Red-eared slider turtle	*Trachemys scripta elegans*	Perth. Known occurrences have been removed.	Red-eared slider: Animal pest alert No 6/2009[9]	Department of Agriculture and Food 1800 084 881 Or DEC on 9334 0292.
Fish					
	Eastern gambusia	*Gambusia holbrooki*	South-west (widespread)	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	One-spot live bearer	*Phalloceros caudimaculatus*	Perth metropolitan area	Field guide to the freshwater fishes of Australia[5]	FISHWATCH service 1800 815 507
	Tilapia	*Oreochromis mossambicus*	Gascoyne-Lyons river system	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Pearl cichlid	*Geophagus brasiliensis*	Perth metropolitan area (primarily Bennett Brook and Altone Park)	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Goldfish	*Carassius auratus*	South-west	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Swordtail	*Xiphophorus hellerii*	Irwin River, south-east of Geraldton	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Guppy	*Poecilia reticulata*	Northern Western Australia	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Redfin perch	*Perca fluviatilis*	South-west	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	European carp	*Cyprinus carpio*	South-west	Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
	Brown trout	*Salmo trutta*	South-west	Field guide to the freshwater fishes of Australia[5]	FISHWATCH service 1800 815 507
	Rainbow trout	*Oncorhynchus mykiss*	South-west	Field guide to the freshwater fishes of Australia[5]	FISHWATCH service 1800 815 507
Invertebrates					
Crayfish	Common yabbie	*Cherax destructor albidus*	South-west, Hutt and Bowes Rivers (north of Geraldton). Native to eastern states	Identifying freshwater crayfish in the south west of WA[11] Aquatic invaders publication[10]	FISHWATCH service 1800 815 507
Crayfish	Smooth marron	*Cherax cainii* (previously known as *Cherax tenuimanus*)	Hutt River, Esperance, Kalgoorlie (human-aided range extensions). Native to south-west. Considered a threat in particular areas of the Margaret River only, where it is a threat to the hairy marron	A field guide to freshwater fishes, crayfishes and mussels of south-western Australia[161]	FISHWATCH service 1800 815 507
Crayfish	Redclaw	*Cherax quadricarinatus*	Kimberley. Native in Northern Territory and Queensland	A field guide to freshwater fishes, crayfishes and mussels of south-western Australia[161]	FISHWATCH service 1800 815 507

	Common name	Latin name	Known distribution in WA	Identification guide	Reporting
• Snails	Tadpole snail	*Physa acuta*	South-west	-	FISHWATCH service 1800 815 507
• Snails	Great pond snail	*Lymnaea stagnalis*	South-west coastal	-	FISHWATCH service 1800 815 507
	Brine shrimp	*Artemia franciscana* and *A. parthenogenetica*	South-west and coastal WA	-	FISHWATCH service 1800 815 507
	Blackworm	*Lumbriculus variegatus*	Metropolitan areas		FISHWATCH service 1800 815 507
	Some naidid worms	Some species within the Naididae family of worms including *Branchiura sowerbyi*	Metropolitan areas	-	FISHWATCH service 1800 815 507
	Physocypria (ostracod)	*Physocypria sp.*	Lake Jolimont	-	FISHWATCH service 1800 815 507
Not wetland dependent					
Mammals					
	Cat	*Felis catus*	All of WA	-	-
	Red fox	*Vulpes vulpes*	Southern half of state and Pilbara coast	-	-
	Domestic dog	*Canis lupus familiaris*	Pastoral areas	-	-
	Fallow deer and red deer	*Dama dama* and *Cervus elephus*	South-west	Rusa deer: Animal pest alert[12]	Department of Agriculture and Food 1800 084 881
	Camel	*Camelus dromedarius*	Inland/arid areas	-	-
	Horse	*Equus caballus*	Arid rangelands and Kimberley	-	-
	Donkey	*Equus asinus*	Inland, Pilbara and Kimberley	-	-
	Goat	*Capra hircus*	Semi-arid to arid pastoral areas (Midwest and Goldfields)	-	-
	Pig	*Sus scrofa*	South-west, Kimberley and some in Midwest and Pilbara	-	Department of Agriculture and Food 1800 084 881
	Rabbit	*Oryctolagus cuniculus*	All of WA other than Kimberley	-	If present on offshore islands report to DEC Wildcare Hotline 9474 9055
Rodents	Black rat	*Rattus rattus*	South-west and along north-west coast	-	If present on offshore islands report to DEC Wildcare Hotline 9474 9055
Rodents	Brown rat	*Rattus norvegicus*	Coastal cities of south-west	-	If present on offshore islands report to DEC Wildcare Hotline 9474 9055
Rodents	House mouse	*Mus musculus*	All of WA	-	If present on offshore islands report to DEC Wildcare Hotline 9474 9055

Detecting introduced animals

Introduced animals may be difficult to see at a wetland, but they will usually leave some signs of their presence. Signs of introduced mammals may include grazed vegetation, trampled vegetation in the form of 'runways' which they may regularly use, scats, burrows, tracks (footprints), eroded banks, diggings and signs of wallowing in mud or water. Scats and tracks are particularly useful as they may be used to identify the type of animal that is present more accurately than by using other signs (Figure 2).

➤ The book *Tracks, scats and other traces: A field guide to Australian mammals*[13] is useful for identifying which introduced mammals are present at a wetland.

➤ The Wildlife Note *Sand Pads – using tracks to monitor fauna*[14] describes how to create a sand pad for monitoring purposes.

Figure 2. (a) Tracks preserved in clay at Shirley Balla Swamp in Banjup. Photo – J Lawn/DEC. (b) Fox den at Lake Joondalup. Photo – N Hamilton/DEC.

(a)

(b)

Introduced aquatic species can be harder to detect through observation alone. At least twenty-two species of introduced fish are known to occur in Australia's fresh waters.[5] Of these, at least ten species are found in Western Australian wetlands (see Table 1).

Sophisticated techniques are also being employed to detect some animals and monitor their movements. For example, global positioning system (GPS) collars are being used to monitor foxes and feral cats in Leschenault Peninsula Conservation Park. Sniffer dogs are being used to detect cane toad fronts (Figure 3). Genetic testing of feral pig populations is being used to identify populations that have been transported to new areas by humans for hunting.

Figure 3. Nifty the cane toad detector dog works with DEC State Cane Toad Initiative technical officer Sandy Fleisher to seek out the invading fronts of cane toads in the Kimberley. Photo – M Andrews.

Threatening process: a process that threatens, or may threaten, the survival, abundance or evolutionary development of a native species or ecological community

What effect do introduced and nuisance animals have on wetlands?

There are many reasons for controlling introduced animals. Certain species have devastating impacts on the Australia environment. The effects of introduced species on populations of native fauna has been recognised in the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* with the inclusion of rabbits, feral goats, foxes, feral cats, feral pigs and cane toads on the list of key **threatening processes** in Australia. From a range of serious environmental issues, the Environmental Protection Authority has assigned introduced species the highest priority ranking for policy development, management action and investment in the *State of the Environment Report: Western Australia 2007*.[15]

extra information

Socio-economic impacts of introduced animals

While this topic is focused on the management introduced animals for wetland conservation, managing introduced animals can also maintain or improve the economic, social, aesthetic or recreational values of a wetland. The impacts of introduced animals include reduced water quality, vegetation loss, soil disturbance and a loss of biodiversity, which may indirectly contribute to a wetland becoming less attractive for tourism and recreation, and in turn lead to a reduction in economic assets.

Introduced animals using, or living in, a wetland can also impact on surrounding land uses. Camels can seriously damage pastoral and community infrastructure. The great pond snail (*Lymnaea stagnalis*) is a host for liver fluke (*Fasciola* spp.), which is an internal parasite that affects humans and many herbivorous mammals including sheep and cattle. The disease caused by liver fluke, fasciolosis, occurs in humans in some parts of the world. It can also cause severe agricultural production losses and death in livestock. These are but a few of the wide-ranging effects of introduced animals on land uses surrounding wetlands.

Introduced animals may impact a wetland primarily in two ways: by affecting other animals within the wetland, and by affecting the wetland environment itself.

Herbivores: animals that chiefly eat plants

Omnivorous: feeding on both plants and animals

Effects on native fauna

Introduced predators can have devastating effects on the fauna found at a wetland. Introduced animals may directly affect native fauna in a number of ways, the most obvious of these being predation of native fauna. Other impacts include aggressive and competitive behaviour towards native fauna, the spread of diseases, causing behavioural changes in native animals, and hybridising with native fauna. Each of these effects is discussed below in more detail.

Predation

Feral cats and foxes prey on native birds, mammals and reptiles. Feral cats alone have been implicated in the elimination of twenty-three native animal species in Australia.[16] Foxes have also been responsible for the disappearance of many native fauna species and are affecting the survival of many other species of mammals, reptiles and birds.[1,17,18,19,20] In Perth's urban wetlands, foxes have been implicated in the lack of and reduced recruitment of oblong turtles (*Chelodina colliei*) (also known as long-necked or snake-necked turtles) in some urban wetlands. They are known to dig up and eat turtle eggs. Feral cats and foxes are attracted to wetlands by the large numbers of fauna in these areas, particularly when waterbirds are breeding.

The presence of introduced **herbivores** at a wetland may indirectly affect its native fauna. For example, large populations of rabbits and rodents may attract cats and foxes to the wetland, putting native species at risk. Rabbits and rodents are a major component of the diet for both feral cats and foxes.[21,22,23,24]

Pigs are **omnivorous** and consume a wide range of flora as well as fauna.[25] Feral pigs are active predators of native birds, reptiles (including their eggs), frogs and invertebrates within the soil such as earthworms. Other introduced predators include rodents which may prey on eggs, small reptiles and even juvenile birds.[26,27] Eastern gambusia eat insects that prey on mosquito larvae, and so change the composition of the aquatic invertebrate community within a wetland. Eastern gambusia also eat the eggs of native fish. Carp rarely eat other adult fish but do eat fish eggs or larvae. In a laboratory study yabbies were found to prey on and show strongly aggressive behaviour towards tortoise hatchlings.[28] These results suggest yabbies could be harmful to juvenile tortoises and have the potential to pose a serious threat to some tortoise populations and species.

Juvenile and adult cane toads feed on a broad variety of small prey, predominantly ground-dwelling invertebrates. The bulk of the diet is usually ants, beetles and termites, although they can eat anything that fits in their mouth, including a wide variety of insects, frogs, small reptiles, mammals and birds.[29] Cane toads are thought to consume approximately 200 food items per night, far more prey than most native frogs ingest in the same period.

Competition

Introduced animals may compete with native fauna for food, shelter or breeding habitat (Figure 4). They are also often more aggressive and so displace native fauna. Yabbies (*Cherax destructor albidus*) are known to compete with the native marron (*Cherax cainii*) and gilgies (*Cherax quinquecarinatus* and *C. crassimanus*) for shelter in clay substrates. Access to these clay substrates is important for marron as it provides protection from predators and cannibalism.[30,31] Yabbies have been shown to directly compete with *C. cainii* for food resources and are also expected to outcompete native crayfish when present.

Figure 4. Introduced ducks chasing a native pacific black duck (*Anas superciliosa*), affecting the native duck's choice of habitat and access to potential mates. Photo – A Nowicki/DEC.

Some native fauna, such as bilbies (*Macrotis lagotis*), require a constant supply of carbohydrate-rich seeds and roots.[32] If these are all consumed by introduced herbivores then the native fauna are at risk. Feral pigs eat fungal fruit-bodies, which are also eaten by several small mammal species[33,34], including the Gilbert's potoroo (*Potorous gilbertii*) and southern brown bandicoot (*Isoodon obesulus*). In the eastern states, such competition is a particular threat to the endangered long-footed potoroo (*Potorous longipes*), the diet of which is more than 80 per cent fungal fruit-bodies.[34] Introduced fish often compete with native fish. For example, carp compete strongly with other fish and aquatic invertebrates for food and habitat, affecting the diversity and abundance of these fauna in the water.[30]

Competition among animals may involve very aggressive behaviour, resulting in injury or even death. For example, eastern gambusia and tilapia are very aggressive fish and will nip the fins and eyes of native fish. Even if they do not kill the victim, the injuries sustained by native fish may eventually prove fatal due to their weakened state and susceptibility to infection which may affect their ability to find food or avoid predators.

Cane toads are unique as they have a lethal defence mechanism. All stages of the cane toad's life cycle—eggs, tadpoles, toadlets and adult toads—are poisonous.[29] Cane toads have venom-secreting poison glands (known as parotoid glands) or swellings on each shoulder from which poison is released when the toads are threatened.[29] Native predators are not used to frogs being poisonous as no species of native frog in WA has this defence mechanism. Because of this naivety among native fauna, cane toads could devastate the native fauna populations of a wetland.

The red-eared slider (*Trachemys scripta elegans*) is one of the top 100 'World's Worst' invaders as determined by the International Union for the Conservation of Nature and is considered a major threat to biodiversity (Figure 5). It is native to the United States and Central America and is a popular turtle in the pet industry in some countries. Red-eared sliders were brought to Australia in the 1960s and 1970s.[35] Many were released into the wild after owners discovered their aggressive nature and tendency to bite and they are now an invasive pest in several states. In Australia, owning red-eared sliders is banned because of the threat the turtle poses to wildlife. In Australia, they compete with native turtles for food, nesting areas and basking sites; and by eating hatchlings and carrying diseases that can infect native turtles, while in England they have been reported to damage waterbird nests when using them as basking sites.[9] Even at low numbers they have the potential to create large populations; females can live for forty years, laying up to seventy eggs annually.[36] It is likely that red-eared sliders are still being kept illegally as individuals have been found and removed in the Perth region, including at Tomato Lake and Hyde Park, on three occasions in recent times.[37]

Figure 5. The red-eared slider turtle (*Trachemys scripta elegans*) is a serious threat to native fauna in Western Australian wetlands. Photo – P Lambert/DEC.

Disease

Introduced animals may carry diseases, parasites or pathogens to which native fauna are very susceptible. The following examples are just some of the many diseases that may be transmitted by introduced animals.

Cats are known hosts of the parasite *Toxoplasma gondii* which is responsible for the disease toxoplasmosis.[38] Symptoms of toxoplasmosis have been found in more than twenty species of mammals and the disease has been speculated to be a cause of decline of carnivorous marsupials.[39] Toxoplasmosis can also be transmitted to humans. Symptoms include lethargy, poor coordination, blindness and possible death.[40]

Feral cats and foxes are carriers of *Spirometra erinacei*, which causes muscular haemorrhage, damage to soft tissue and may cause death in native fauna.[41] Feral cats are also carriers for the disease sarcosporidiosis which may be transferred to native fauna, livestock and humans.[18] Pigs are potential carriers for many diseases that are transferable to livestock, native fauna and humans, including foot and mouth disease and tuberculosis[25] and hydatids, which has spread to the local western grey kangaroo (*Macropus fuliginosus*) population at Glen Eagles Forest.

Fish that are translocated from other bioregions, states or countries are potentially carriers of diseases and parasites. Some of the more serious fish diseases include epizootic ulcerative syndrome (red spot disease), irodovirus, goldfish ulcer disease, epizootic haematopoietic necrosis (redfin virus or EHNV), viral encephalopathy and retinopathy (nodavirus or VER), and infectious hypodermal and haematopoietic necrosis (in crustaceans). EHNV is a type of iridovirus which has the potential to affect fish, reptiles and amphibians. Fish such as redfin perch, rainbow trout, silver perch, and eastern gambusia are known to be susceptible to EHNV, and it is thought that most native Australian fish are also susceptible. Signs of disease or significant numbers of dead fish in wetlands should be reported to the Department of Fisheries WA, by calling FISHWATCH on 1800 815 507.

Yabbies are also known to carry many diseases and parasites, the most serious and widespread of which is the parasite *Thelohania parastoci*, which causes disease in native crayfish.[40,41,42] Infection by this parasite causes destruction of muscle tissue and reduced movement. This can lead to mortality by reducing the ability of infected crayfish to compete with healthy crayfish and increasing their risk of predation.

Feral animals can also spread disease to domesticated animals. For example, feral horses can carry exotic diseases such as equine influenza and African horse sickness, which are serious threats to domestic horses. They can also carry tick fever, which can infect domestic horses and cattle.[42] The management of feral populations can be of benefit to both conservation and agriculture.

Hybrids: the results of interbreeding between two animals or plants of different species

Grazing: feeding on grasses and other low-growing herbaceous vegetation

Browsing: feeding on leaves, twigs or bark from non-herbaceous (woody) plants, such as trees and shrubs

Behavioural changes

Just the presence of some introduced animals, particularly predators, at a wetland may influence the well-being of native fauna by changing their behaviour. Activities such as foraging for food or seeking mates generally make an animal more prone to predation or aggression from other species. If native fauna can detect (for example, through smell) their predators such as feral cats or foxes, they might change where and how often they eat, what time of the day they are active, or with whom they choose to mate.[62,63,64,65] Such changes to an animal's behaviour can mean that it doesn't get the optimal food or habitat and that it uses too much energy which, ultimately, can affect its health, reproductive success and chances of survival.

Hybridisation

Some introduced animals are able to interbreed with native animals to produce **hybrids**. Large-scale hybridisation reduces the genetic integrity of the species being hybridised and may eventually result in the pure form of the species becoming extinct.

This may one day be the fate of dingoes (*Canis lupus dingo*), which are relatively rare in their pure form, as most have hybridised with domestic dogs. Predation and hybridisation by wild dogs has been listed as a key threatening process in New South Wales.[43] Domestic waterfowl may also breed with native waterfowl. For example, introduced mallard ducks (*Anas platyrhynchos*) can interbreed with native pacific black ducks to produce fertile hybrid offspring, which can go on to produce more hybrids.[44]

Effects on the environment

Changes to the environment will often indirectly affect the fauna that live at, or visit, a wetland by changing the habitat available or limiting food resources.

Vegetation loss

Many introduced animals are herbivores that remove plants, including below-ground plant parts. Herbivores remove the leaves from plants and sometimes uproot the whole plant. Continual **grazing** or **browsing** can reduce native plant diversity, structural complexity of vegetation and degrade wetland habitats. Camels, for example, are voracious herbivores; they can browse 80 per cent of arid land plant species (Figure 6).

Figure 6. Camels at a wetland in the Rudall River area of the Pilbara. Camels have serious detrimental effects to wetlands in arid to semi-arid areas of Western Australia. Photo – B Ward/DEC.

As introduced animals often prefer to eat fresh growth, continual grazing and browsing can limit the growth and spread of new plants. Introduced animals may also trample plants in and around wetlands causing damage to, or removal of, the plants. In droughts, large herds of over one hundred camels may congregate on available water. This causes overgrazing, trampling, pugging and fouling of wetlands. Feral livestock may also strip bark off trees or rub up against trees, causing tree death by ringbarking. This is true of male feral deer, which can severely damage trees when rutting. In the eastern states, deer have had major impacts on endangered freshwater wetland communities.

The removal of plants by heavy grazing or browsing can mean that there is less food, shelter and reproductive habitat available for native animals. The loss of native vegetation may also allow weeds to establish, reduce biodiversity, and may lead to soil **erosion** and water quality problems through increased run-off.

Weed dispersal

Introduced animals are often highly mobile and may bring weed **propagules** to a wetland. Disturbance of habitats caused by introduced animals may also facilitate the invasion and spread of weeds.[34] The introduction and spread of weeds at a wetland can affect the composition of plant communities, thereby reducing the available habitat for native fauna. Weeds can also increase the threat of fire at a wetland by increasing the fuel load.

➤ For additional detail on the impacts and management of weeds, see the topic 'Wetland weeds' in Chapter 3.

Spread of pathogens and viruses

As well as weeds, introduced animals may spread pathogens such as *Phytophthora cinnamomi*, a microscopic soil-borne organism belonging to the water moulds. This introduced organism is responsible for the decline and death of native vegetation, known as Phytophthora dieback. For example, there is evidence that feral pigs can carry *P. cinnamomi* on their hooves[45], and that the spread of the pathogen can be associated with soil disturbance and reduction of litter cover by pigs.[46] Furthermore, chewing and other damage to tree trunks may facilitate infection of vegetation by the fungus and other diseases.[34] The typically omnivorous diet of pigs also leads to the passage of *P. cinnamomi* infected plant material through their digestive system, providing an additional means of spreading the pathogen among native vegetation.[47]

➤ For additional detail, see the topic 'Phytophthora dieback' in Chapter 3.

It is thought that introduced aphids are the source of an introduced virus, the bean yellow mosaic virus, which is decimating an aquatic herb species in the Swan River in Perth. Water ribbon (*Triglochin* sp.) was once common along the river foreshore and played an important ecological role by filtering nitrates and phosphates from the river. It is now restricted to a few isolated pockets near Guildford.[48]

Soil disturbance

Introduced animals may cause land degradation by disturbing the soil at a wetland. Soil compaction or erosion is often a consequence of overgrazing by introduced animals or direct damage from **pugging**, rooting, digging, burrowing or wallowing. These actions can have major impacts on flora and leaf litter, particularly after rain when the ground is softer.[34]

Soil disturbing activities are particularly a problem at wetlands. Feral pigs wallow in mud during hot weather, causing significant damage to wetlands. Such actions can create **turbid** conditions and/or **sedimentation** of the water.[34] Muddy water with a high **turbidity** allows less light to penetrate the water to plants and algae, which causes

Erosion: the gradual wearing away and movement of land surface materials (especially rocks, sediments, and soils) by the action of water, wind, or a glacier

Propagule: any part of a plant from which a new plant can grow, including seeds, bulbs and rootstocks

Pugging: depressions, hoof prints or 'pug' marks made in wet soil by trampling animals

Turbid: the cloudy appearance of water due to suspended material

Sedimentation: the process by which soil particles (sand, clay, silt, pebbles and organic materials) suspended in water are deposited or settle to the bottom of a water column.

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column.

reduced plant growth or plant death. As sediments begin to settle, they smother animals living on the bottom by clogging their gills and causing problems for filter-feeders; coat organic deposits and algae upon which aquatic animals depend for food and cover; and fill in aquatic habitats.[49,50]

Water quality decline

As mentioned above, introduced animals can affect the water quality of a wetland by impacting on wetland soils and vegetation. In addition to this, introduced animals affect the water quality of a wetland by defecating and urinating in or near the wetland.[34] Even animals that mostly live terrestrially and only visit wetlands, such as cats, foxes or pigs, will congregate around water points and are likely to foul the water with their wastes. Such activities may have a number of flow-on effects such as changed nutrient levels, leading to **eutrophication** of the wetland and algal blooms.

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plant material (phytoplankton, macrophytes or both). May occur naturally over geologic time or may be human-induced

Eutrophication of a water body may lead to nuisance midge and mosquito problems. The management of these nuisance fauna may further affect the water quality of a wetland. For example, some poisons used at wetlands as a method of controlling nuisance mosquitoes and midges have the potential to pollute to the water and cause harm to other fauna.

➤ For additional detail on management of mosquitoes and midges see topic 'Nuisance midges and mosquitoes' in Chapter 3.

The presence of introduced animals at a wetland may lead to soil disturbance that may lead to an increase in the turbidity of the water in a wetland. Carp and goldfish vigorously stir up sediment while feeding, which can change the suitability of the wetland for other species as well as potentially releasing phosphorus locked in the sediments.[51]

➤ For additional detail on the impacts of poor water quality and its management see the topic 'Water quality' in Chapter 3.

Goldfish (*Carassius auratus*) have also been found to stimulate the growth of some toxic cyanobacteria species that pass through their gut, such as *Microcystis aeruginosa*.[52] Under the right conditions species such as *Microcystis* can form blooms which can cause significant ecological impacts in wetlands. An increase in cyanobacteria can in turn provide goldfish with an abundant food source, creating the potential for an ongoing cycle of ecological impacts. Researchers found this to be an issue of significant concern for the Vasse River in the south-west of WA.[53]

Who is repsonsible for managing introduced and nuisance animals?

At the private property level, landowners and/or managers are responsible for introduced animal damage control (that is, damage to agricultural products such as crops, and to infrastructure such as fences and water points). If declared pests of agriculture are present on private property, landowners are compelled to control the species under the *Agriculture and Related Resources Protection Act 1976*. There are some exceptions to this, which relate to the control of native fauna species. Native fauna species can only be controlled if DEC approves control via a licence, an open season or declares a species' status to be 'unprotected' (Table 2 provides more information about this).

While individual landowners have this responsibility, animals generally do not restrict their movements to property boundaries and so effective management of introduced animals usually involves cooperation between landholders, community groups, councils and regional management authorities.

Landowner assistance

Private landholders can receive assistance with introduced animal management activities from a range of government and non-government programs.

For example, DEC's *Healthy Wetland Habitats* program: eligible landowners on the Swan Coastal Plain can receive funding to manage introduced species. For more information telephone the *Healthy Wetland Habitats* program coordinator on (08) 9334 0333.

➤ For more information on various programs that provide landowners with assistance, see the topic 'Funding, training and resources' in Chapter 1.

Community initiatives

The community is at the forefront of a range of on-ground management initiatives. The 'Red Card for the Red Fox' program is one such initiative that was started in 2003 by two community landcare groups working together, but has steadily developed into a statewide program and attracted funding and technical support from regional natural resource management organisations and government. In 2009, 5,000 foxes, 2,500 rabbits and 230 feral cats were shot as part of this program.[54]

Another successful community-initiated program, the Lake Muir/Denbarker Community Feral Pig Eradication Group, is the subject of a case study entitled 'Fighting feral pigs on the South Coast' presented later in this topic.

State government programs

Various Western Australian government agencies coordinate and participate in on-ground control, regulation, research and monitoring of introduced species.

The WA Department of Agriculture and Food (DAFWA) coordinates the management, control and prevention of introduced species; the prohibition and regulation of the introduction, spread and keeping of certain plants and animals for the protection of agriculture and related resources generally. DAFWA coordinates surveillance and research into vertebrate animal pests and regulates the introduction and spread of introduced species via the *Biosecurity and Agriculture Management Act 2007*. It operates the Pest and Diseases Information Service, which provides information on pests and diseases that affect community and industry well-being in WA, and provides advice on options for control of introduced species. It can provide information on when a licence is required, procedures to follow to obtain licences and the conditions that need to be adhered to when undertaking control activities.

The Department of Fisheries is responsible for controlling the introduction and spread of introduced fish and crayfish, and regulating fishing and fish stocking of state water bodies. It maintains the noxious fish species list and operates the FISHWATCH Service, which is responsible for receiving reports of sightings of freshwater pest species, including introduced freshwater crustaceans. It should be used to notify the Department of Fisheries of mass fill kills as well as reporting illegal fishing activity.

DEC protects and regulates interactions with Western Australian fauna, including fauna surveys and control of nuisance populations of native fauna under the *Wildlife Conservation Act 1950*. DEC manages the *Western Shield* program, which is the world's largest introduced predator control and biodiversity conservation program. *Western Shield* involves 1080 baiting of about 3.5 million hectares in the south-west of WA, allowing native fauna to be reintroduced to their former range. So far, the program has been successful in bringing at least thirteen native species back from the brink of extinction.[15] The State Cane Toad Initiative is also run by the department.

There is limited strategic monitoring of invasive species by state government departments across the state's large geographic area. DAFWA has recently published a monitoring framework for ecologically significant invasive species for natural resource management groups in WA.[55]

Although the control of introduced animals is not currently coordinated nationally, a number of national programs are in place.[56] Two of the national organisations dealing with pest animal control are the Vertebrate Pests Committee and the National Introduced Animal Control Program. The Invasive Animals Cooperative Research Centre was also formed in 2005 and combines the collective knowledge of forty-three research, industry, environmental, commercial and government organisations.

What are the legal requirements for managing introduced and nuisance animals?

Ethical treatment of animals

All introduced and nuisance animal control programs in WA must consider the ethical treatment of animals. Their treatment is governed by the *Animal Welfare Act 2002*, which prohibits cruelty to, and other inhumane or improper treatment of animals. Control and euthanasia are to be conducted humanely and legally, be target specific, and cause no suffering to target or non-target fauna. In order to achieve this, the people undertaking these activities must be competent and, where necessary, licensed to do so.

Industry best practice standards

Adhering to codes of conduct and standard operating procedures ensures that activities are humane, legal and in accordance with best practice standards.

Codes of conduct and standard operating procedures

Code of practice for the capture and marketing of feral animals in Western Australia, Department of Local Government and Regional Development (2003).[57]

A large number of codes of conduct and standard operating procedures for the humane capture, handling or destruction of introduced animals in Australia are available from Department of Sustainability, Environment, Water, Population and Communities website (www.environment.gov.au).[58]

DEC's standard operating procedures for monitoring (which includes trapping that may be extended to control operations) are available from the DEC website (www.dec.wa.gov.au).[59]

Permits, licences and laws relevant to animal control

Most introduced and nuisance animal management activities require authorisation, generally in the form of a permit, licence or exemption. Table 2 below provides a guide to the most common permits and licences. Table 3 lists other relevant laws which must be observed when undertaking animal management activities.

Table 2. A guide to some of the permits and licences required for a range of introduced and nuisance animal management activities

Note 1: in addition to the below, individuals must be authorised to enter any property at which activities are to be conducted.

Note 2: this information may change over time. It is important to keep up to date with legal requirements associated with introduced animal management activities.

Activity	Permit/license/approval required	Regulating authority	Legislation	For more information
Native fauna licence surveys (including macroinvertebrates)	A licence is required under Regulation 17, 'Licence to take fauna for scientific purposes'. It is referred to as a 'Regulation 17' licence.	Department of Environment and Conservation	*Wildlife Conservation Act 1950*	Application for licence to take fauna for scientific purposes[60]
	A 'Scientific exemption' permit is required under Regulation 178 to take some freshwater species including fish and crayfish for scientific purposes.	Department of Fisheries	*Fish Resources Management Act 1994*; Fish Resources Management Regulations 1995	Contact the Department of Fisheries
Culling of native species for conservation purposes (e.g. kangaroos, Australian white ibis)	A licence is required under Regulation 15, 'Licence to take fauna for educational or public purposes'. It is referred to as a 'Regulation 15' licence. This licence is not required when a species is unprotected by virtue of an open season or restricted open season notice.	Department of Environment and Conservation	*Wildlife Conservation Act 1950*; Wildlife Conservation Regulations 1970	Application for a Regulation 15 licence – to take fauna for education or public purposes (fauna relocations and/or education)[60]
Use of traps for land-based non-native species	A permit is required to use any type of trap or snare in some metropolitan and outer metropolitan areas. The permit is requested via an 'Application to Trap Declared Animals'. Individual local government authorities may also have requirements.	Department of Agriculture and Food	*Agriculture and Related Resources Act 1976*; Agriculture and Related Resources Protection (Traps) Regulations 1982	Contact the Department of Agriculture and Food
Use of bird traps	A licence is required under Regulation 11, 'Licence to take avian fauna for sale'. It is referred to as a 'Regulation 11' licence.	Department of Environment and Conservation	*Wildlife Conservation Act 1950*; Wildlife Conservation Regulations 1970	Refer to the Fauna licensing page of DEC's website[60]
Use of firearm	A licence from the Western Australian Police is required to possess, carry and lawfully use a firearm.	Western Australia Police	*Firearms Act 1973*	www.police.wa.gov.au[61]

Activity	Permit/license/approval required	Regulating authority	Legislation	For more information
Use of pesticides (including 1080, fumigants and rotenone)	All instructions on the label of the pesticide container regarding the safe use, storage and disposal of registered products must be followed.	Department of Health	*Health Act 1911*; Health (Pesticides) Regulations 1956	
	A 'Minor Use' or 'Emergency' Permit is required to use a pesticide on a species not identified on the label or in situations not stated on the label.	Australian Pesticides and Veterinary Medicines Authority	*Agricultural and Veterinary Chemicals Code Act 1994*	www.apvma.gov.au/publications /fact_sheets/docs/permits.pdf www.apvma.gov.au/permits
	1080: Trained landholders and land managers can purchase bait products containing 1080 once baiting approval has been obtained through a formal process from the. Only trained and licensed personnel can prepare and mix baits.	Department of Agriculture and Food	*Agriculture and Related Resources Act 1976*	Landholder information for the safe use and management of 1080[62]
Removal of introduced freshwater species of fish and crustaceans from wetlands	An exemption, approval or authority for the purpose of 'fish stock depletion or enhancement' is required under Section 7 of the Act. Alternatively, the department may deem that a recreational fishing licence is required. It is a contravention of the Act to be in possession of most fishing equipment at wetlands in the state without an exemption from the CEO of the Department of Fisheries. Section 104 of the Act specifies that noxious fish listed in Schedule 5 of the Regulations must not be kept in a person's possession or be allowed to remain alive.	Department of Fisheries	*Fish Resources Management Act 1994*; Fish Resources Management Regulations 1995	Contact the Department of Fisheries Recreational fishing: refer to the most current recreational fishing guide on freshwater angling for the bioregion from www.fish.wa.gov.au
Relocation, introduction or reintroduction of freshwater species of fish and crayfish	An exemption is required under Section 7 of the Act for scientific research, fish stock depletion or enhancement; or the collection, keeping, breeding, hatching or culturing of rare and endangered fish. Written authority is required under regulation 176 of the Regulations to bring into the state, or a particular area of the state (i.e. translocate from another area or bioregion), a live fish of a species not endemic to the state or area of the state.	Department of Fisheries	*Fish Resources Management Act 1994*; Fish Resources Management Regulations 1995	
	A 'Regulation 15' licence is needed to move native species.	Department of Environment and Conservation	*Wildlife Conservation Act 1950*	
Shockwaves	A valid Shotfiring permit is required to employ shockwaves. Only fully trained, accredited and licensed operators can carry out this procedure. It is the responsibility of the shotfirer to ensure that all operations undertaken are compliant.	Department of Minerals and Petroleum Resources	*Explosives and Dangerous Goods Act 1961*; Western Australian Explosives Regulations 1963	Department of Minerals and Petroleum Resources

Table 3. General requirements when undertaking animal management activities

Activity	Requirement	Regulating authority	Legislation
All animal management activities	Humane and proper treatment of animals.	Department of Local Government and Regional Development	*Animal Welfare Act 2002*
All activities being undertaken by an employee	Requires employers to identify potential hazards and to develop strategies to minimise the risk of injury or disease. Requires employees to ensure their own safety by following instructions and correctly using any safety equipment provided.	Department of Consumer and Employment Protection, WorkSafe	*Occupational Safety and Health Act 1984*; Occupational Safety and Health Regulations 1996
Activities which, if implemented, are likely to have a significant effect on the environment	Referral of thse proposals to the Environmental Protection Authority.	Environmental Protection Authority	*Environmental Protection Act 1986*
Noise due to shooting	Noise associated with the use of firearms.	Department of Environment and Conservation	Environmental Protection (Noise) Regulations 1997
Removal of non-native species from DEC-managed land	Authority from DEC is required under Regulation 18.	Department of Environment and Conservation	Conservation and Land Management Regulations 2002

How to manage introduced and nuisance animals

There are two main strategies for the management of introduced animals in wetlands:

1. prevention, typically using barriers such as fences, screens and nets to prevent access to a wetland
2. control, using one or more methods, to either reduce the population size or eradicate the population.

As with any threat to a wetland, the best management strategy is to avoid it in the first place. However, if introduced animals become established at a wetland, the best thing to do is to remove those animals. Complete removal of a population of a particular introduced animal may not always be feasible. In this case, population control may still be an option to reduce the introduced animal population to low numbers. Both activities need to be complemented with prevention methods to prevent new or additional individuals from reaching the wetland.

Prevention strategies are particularly relevant for introduced animals for which there are currently no approved control methods available. Introduced aquatic snails, brine shrimp, blackworm and naidid worms cannot be removed from a wetland once established (C Francis 2009, pers. comm.). However, the impact of these species on wetlands is generally limited and so removal of these introduced animals may not be the highest priority.

The decision to undertake management at a wetland should only be made after a management planning process has been completed and a management plan prepared, however basic it may be. Undertaking a management planning process will involve examining all of the threats at a site and assessing which of these is a priority for management. For example, if altered hydrology and introduced animals such as cats are issues at a wetland, it may be determined that managing altered hydrology is a high priority issue and until this is addressed no action will be taken to manage the introduced animals.

➤ For guidance on wetland management planning, see the topic 'Wetland management planning' in Chapter 1.

Any management of introduced animals at a wetland, be it prevention or control, requires an integrated approach. Animals generally do not restrict their movements to property boundaries and so effective management of introduced animals will often involve cooperation between landholders, community groups, councils and regional management authorities.

Considerations when selecting management techniques

When choosing a method to control a population of introduced animals, some key requirements should be considered. It must be:

- Legal: relevant legal approvals, licences and permits should be obtained and conditions of the licence or approvals understood before any management action is undertaken.
- Informed: make sure that the target species is not, in fact, a similar-looking native species.
- Without, or at an acceptable level, of adverse side effects: the environment and native animals should not be adversely affected.
- Feasible in the long term: that is, it will actually stabilise or reduce numbers over long periods. It is common for people to discover that the required frequency and duration of the control activity (for example, baiting or trapping) is often much greater than anticipated.
- Part of the bigger picture: working to control a species at a site is often futile if they are not being controlled in adjacent areas. Coordinated action at a broad scale is usually most effective.
- Undertaken with an awareness of consequences: it is common for the removal of one introduced species to cause another introduced species to increase in numbers (for example, numbers of cats often increase when fox numbers are controlled). A well-planned strategy will address this.
- Cost-effective: management should be economical in terms of the values or benefits gained in return for the money spent.
- Humane: the animals themselves should not suffer and violence should be avoided.
- Internationally acceptable: that is, the management method adopted should not affect the same or similar species in other countries. This is especially true of any immunocontraceptive (sterilisation-causing) organism that is spread by a carrier.

Quick guide to the prevention and control options by animal

Table 4. Summary of key management options by animal

Note 1: preventative actions such as wetland restoration, community education, awareness and legal avenues are applicable to all introduced animals and as such are not addressed in the table.

Note 2: as there are no approved/effective control measures available for introduced aquatic snails, brine shrimp, blackworm and naidid worms, these are not addressed in the table.

	Prevention	Control						
Animal	**Barriers (page 24)**	**Trapping (page 26)**	**Shooting (page 36)**	**Poisoning (page 37)**	**Fumigating (page 40)**	**Shockwaves, electrofishing (page 41)**	**Manipulating habitat and food (page 42)**	**Removing manually (page 44)**
Domestic waterfowl		•	•					
Australian white ibis			•				•	
Cane toad		•						•
Red-eared slider turtle		•	•					•
Introduced fish	•	•		•		•	•	•
Introduced crayfish		•					•	
Cat	•	•	•	•				
Red fox	•	•	•	•	•		•	
Domestic dog	•	•	•	•				
Kangaroo	•		•					
Deer	•		•					
Camel	•	•	•					
Horse	•	•	•					
Donkey	•	•	•					
Goat	•	•	•					
Pig	•	•	•	•				
Rabbit	•	•	•	•	•		•	
Rodents		•		•				

Prevention

Prevention is the most important and effective strategy in managing introduced animals, as controlling introduced species is often difficult, if at all possible. Prevention of the establishment of introduced animals at a wetland includes:

- maintaining or restoring wetlands
- community awareness and education
- legislation
- physical barriers.

These preventative measures should be combined with surveillance activities. Depending on the risk of introduced species and the threats they pose to the wetland, the level of surveillance may range from casual observation to comprehensive surveys.

➤ For guidance on wetland monitoring, see the topic ‘Wetland monitoring’ in Chapter 4.

Maintaining and restoring wetlands

The conditions within modified and degraded wetlands can favour the establishment and domination of some introduced species. For example, some degraded wetland habitats can be more favourable for introduced fish such as the eastern gambusia (*Gambusia holbrooki)* than native species.[63] Maintaining or restoring the natural ecosystem may help prevent such species from establishing or out-competing the native species.

Community awareness and education

Many of Australia's introduced animals were introduced by humans, either directly or indirectly through domestic or livestock 'escapes'. Community awareness and education provide valuable tools for the prevention of further introductions. Education and awareness-raising programs may be aimed at preventing new introductions or encouraging community members to monitor for new invasions. The public may be informed not to release pets (particularly aquarium fish or rabbits) and to ensure pet cats and dogs are sterilised, kept on a lead at all times while outdoors and don't roam freely through wetlands. The public should also be aware of the impacts of deliberately releasing animals such as pigs or fish for hunting and recreational purposes.

There are many tools available to raise the level of community awareness and education. The print, broadcast and internet media can be powerful allies in educating the public on environmental matters. Awareness-raising campaigns are often most successful when they are targeted at specific groups because information can be tailored to the activities, needs and challenges of the group. A good example of an online resource targeted at educating young people is 'Aquatic Invaders', developed by the Queensland Fisheries Service as an education module available online[64] for teachers of upper primary and lower secondary students.

There is much scope for involvement of children and youth in introduced animal monitoring and management. Young people comprise nearly 30 per cent of the global population and will be the decision-makers of the future.[65] Their way of thinking about the environment is already shaping the world of tomorrow and, just as importantly, can shape the views of their parents. Therefore, it is important that community education and awareness of managing introduced animals at wetlands is inclusive of a range of age groups and is extended to all demographic groups. A good example of a hands-on education campaign targeted at high school students is presented in the case study 'Restocking native fish in Masons Gardens Lake, Dalkeith' at the end of this topic.

Activities aimed at raising community awareness may be as simple as installing signs at a wetland informing the public of the impacts of introduced animals. Alternatively, printed material with information on the effects of released and abandoned pets on the environment could be provided to local pet shops for distribution to customers. Collaboration could also be gained from pet shop owners by asking them to commit to accept any unwanted pets as an alternative to 'releasing' them. The Perth Cichlid Society (www.perthcichlid.com.au) offers to take care of any unwanted fish and provides a list of local fish stores that have agreed to accept unwanted fish.

Raising awareness of the issues and management methods relating to introduced animals in wetlands can encourage greater community participation in management actions as well as prevention. Involving organisations and communities in introduced animal management can create a sense of stewardship towards the wetland, ease hardship through collaboration, and provide a forum for new ideas and greater participation.

Communities can be involved in all aspects of managing introduced animals within a wetland. For example, eastern gambusia were discovered by Waterwatch volunteers in Ilparpa Swamp south of Alice Springs in 2000. This discovery allowed the volunteers to quickly remove the eastern gambusia from the wetland before they became a problem.[66]

Endemic: naturally occurring only in a restricted geographic area

Since then, Waterwatch has been educating the community about the impacts of releasing pet fish into waterways and wetlands. The local community continues to be vigilant for new incursions of eastern gambusia. This example shows the importance of ensuring members of the public are capable of correctly identifying introduced animals, even if they have not occurred in the area previously. It also reiterates the value of creating a sense of 'ownership' of a wetland.

Legislation

There are a number of legal avenues available to prevent introduced animals from becoming established at a wetland. These range from legislation at the state government level, through to local government authority laws, and privately enforced regulations within residential developments.

State legislation

At present the key legislation for preventing the introduction and spread of certain animal species is the *Agriculture and Related Resources Act 1976* (ARRP Act), which is administered by DAFWA. The Act provides for the management, control and prevention of certain animals, for the protection of agriculture and related resources generally. In particular, it categorises a range of introduced animals, known as 'declared animals', into one of six possible categories, each with a corresponding requirement of management, control or prevention.

➤ The list of declared animals is available on DAFWA's website (www.agric.wa.gov.au).[67]

The AARP Act is one of seventeen existing Acts that will be replaced by the *Biosecurity and Agriculture Management Act 2007* (BAM Act). While the BAM Act has been enacted, its regulations and other subsidiary regulatory instruments are not yet in place. One of the main purposes of the BAM Act is to prevent new animal and plant pests and diseases from entering WA, and to manage the impact and limit the spread of those already present in the state. The application of the BAM Act covers biosecurity threats to agricultural activities, as well as threats to the environment, to public safety and amenity, to fishing and pearling activities, and to commercial activities related to agriculture, fishing and pearling.

Controls on the introduction and spread of introduced fish and crayfish are governed by the Fish Resources Management Regulations 1995, which is administered by the Department of Fisheries. Under Regulation 176 of the regulations it is illegal to introduce any fish into a site where the species is not **endemic** without the written authority of the Chief Executive Officer of the Department of Fisheries. Translocation of non-endemic fish without written authority may incur a significant penalty. Fish listed as noxious must not be kept in a person's possession and cannot be released, relocated or kept alive. If caught they must be destroyed.

➤ The list of fish species that are restricted for importation and spread (the 'noxious fish' list) is available from the Department of Fisheries website (www.fish.wa.gov.au).[68]

In 2009, the state government proposed the introduction of statewide cat control legislation to assist in reducing the number of unwanted cats in WA. In mid-2010 the Department of Local Government initiated public consultation on a domestic cat act.[69] This follows on from the disallowance of the City of Joondalup's *Cats Local Law 2008* by the Legislative Council in 2009 on the basis that some of the law's provisions should be applied on a statewide level rather than be isolated to a single local government area, notably in relation to the compulsory sterilisation of cats.[70]

Local government controls

At the local government level, some legal restrictions can be placed on domestic animal owners to register and identify their pets (using tags or microchips), limit the number of certain animals per household, prevent the release of these animals and reduce the impacts of straying animals.

Local governments can use one or more mechanisms at their disposal to place restrictions on domestic animals near environmentally sensitive areas. Local laws can be instated. For example, 'cat prohibited areas' are designated under the *Keeping and Control of Cats Local Law 1999* within the City of Stirling. Wetlands identified as cat prohibited areas include Star Swamp, Carine Swamp, Lake Gwelup, Herdsman Lake and Jackadder Lake (Figure 7).

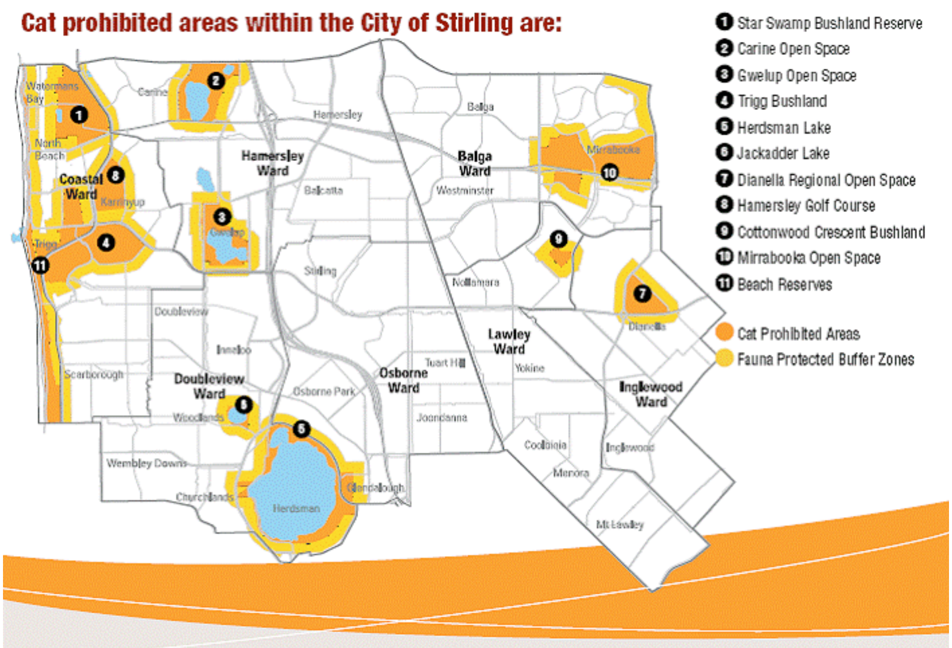

Figure 7. Cat prohibited areas in the City of Stirling.[71] Image courtesy of the City of Stirling.

Alternatively, controls within local planning schemes may be used. For example, a number of areas within the City of Albany are zoned as 'conservation zone' in the City of Albany *Town Planning Scheme No. 3*. Cats and rabbits may not be kept within these areas on the basis that they pose a threat to native flora and fauna.

Many local councils currently encourage voluntary sterilisation of pet cats and dogs by offering subsidies for the procedure.

Private residential developers may place a restrictive covenant on their land that places restrictions on keeping animals. Churchman Book Estate, within the City of Armadale, has prohibited the keeping of cats on the land. This covenant has been put in place to prevent pet cats from roaming and hunting wildlife in the nearby Armadale Settlers Common, an environmentally sensitive area. However, restrictive covenants generally have an 'expiration date' after which time the restrictions lapse.

While creating and implementing legislation may be beyond the scope of wetland managers, they may lobby local and state government for the establishment of laws regulating key problem species. Introduced animals may be controlled by limiting their movement, restricting ownership and by requiring sterilisation.

Physical barriers

An effective way to prevent introduced animals from damaging a wetland is to prevent them from entering altogether. Constructing physical barriers is often the simplest and most effective way to combat introduced animals. Of course, barriers are only effective if they serve to keep introduced animals out, not in. If breached, barriers may actually increase the risk of vulnerability of endangered fauna species by preventing their escape from the predator. If introduced animals are found within the confines of a barrier, it may be necessary to remove them using the methods discussed later in this topic. Continual monitoring for new incursions is essential.

A range of barriers is available, including fencing, screens and netting, depending on the animal being targeted. Fencing is the most commonly utilised type of barrier.

Fencing

There is a myriad of fence designs available for use in excluding introduced animals. The type of fence chosen will depend on the type of animal to be excluded. It is generally understood that no fence will be 100 per cent effective all of the time. Electric wires may be used to improve the effectiveness of this barrier but are rarely a successful deterrent on their own. Fences may be damaged by large animals or by falling vegetation and so monitoring, maintenance and repair of the fencing will be required. The base and corners of a fence, as well as gates and waterway crossings, are often the weak points of a fence that will be exploited by introduced animals. Special attention should be paid to ensure these features are maintained and are functional. The high costs of establishing and maintaining some types of exclusion fencing, such as feral cat-proof enclosures, generally limit their use to the management of threatened or endangered species, such as the protection of the endangered western swamp tortoises (*Pseudemydura umbrina*) at Twin Swamps and Ellen Brook nature reserves in Bullsbrook and Upper Swan respectively.

➤ For more information on the types of fencing that can be used to exclude foxes and feral cats, rabbits, goats, pigs and wild dogs, see the *Catalogue of fence designs* available on the Department of Sustainability, Environment, Water, Population and Communities website.[72]

➤ For more information on fencing suitable for camels, see *Camel control using alternative fencing* available on the Northern Territory government website.[73]

A fence should provide an effective physical barrier to the targeted introduced animals while minimising detrimental effects on the native fauna of the area. Generally the fence should be placed at a distance from the wetland. This will allow native fauna to use both the wetland and adjacent dryland if required. For example, female oblong turtles (*Chelodina colliei*) can lay their eggs at some distance from wetlands (the distance varies). If the fence is placed too close to the wetland, they may die from dehydration or predation while persisting in their efforts to get past the fence to their intended nesting site.[74] Similarly, if fences are too close to the wetlands, they may be within the flight path of large birds, increasing their risk of entanglement.

Fencing can alter or restrict the movement of native fauna in and out of a wetland, alter their dispersion and foraging patterns, and cause entanglement and electrocution. It can also create a significant hazard to wildlife in the event of a bushfire.[75] Mesh, barbed, plain and electric wire fences have caused injuries and deaths of bats, kangaroos, wallabies, small mammals, waterbirds, birds of prey and owls. Wetland fences can pose a higher risk of entanglement or injury when they are new, where they cross animal flight paths and tracks into a wetland and where they are less visible at the boundary between low pasture and taller native vegetation. The top and bottom wires are where animals most often come in contact with the fence, with small animals such as echidnas and snakes being killed by electrified wires close to the ground. These problems can be minimised by choosing a fence type and location that increases fence visibility and by installing native animal access ways, such as gates. In areas where entanglement is a problem, fence visibility can be increased by attaching metal tags, old CDs, tin cans or aluminium pie dishes to the top two wires.

➤ For more information on ways to reduce the impact of fences on native species, see *Wildlife Friendly Fencing Guidelines*[76] and DEC Fauna Note 32 *Fencing and gates to reduce kangaroo damage.*[77]

Screens and nets

Where a waterway (such as a creek, stream or river) or drain flows into a wetland, barriers in the form of large screens or mosquito nets may be fitted to prevent the movement of introduced fish. Screens and netting may also not be effective for juveniles or eggs as these will still pass through the barrier. Sometimes, such barriers may be teamed with traps to remove introduced fish from a waterway (see the section 'Fish traps' for more information). A number of screens are currently available such as vertical travelling screens that remove debris whilst preventing passage of a range of fish sizes. These options are currently being assessed to control downstream colonisation of the pearl cichlid from wetlands on Bennett Brook and Ellen Brook (S. Beatty pers. comm.).

Control

It is very difficult to completely prevent introduced animals from entering a wetland, particularly if they are terrestrial or highly mobile. In some situations, the most feasible option may be to carefully monitor the wetland and promptly remove any new intruders before the introduced animals have a chance to start reproducing and to become established. Therefore, a key component in preventing the establishment of introduced animals at a wetland is appropriate surveillance. Wetlands should be observed for signs of newly occurring introduced animals as often as possible, whether it be on a casual or opportunistic basis, or as part of a dedicated monitoring program.

➤ For information on designing a monitoring program, see the topic 'Monitoring wetlands' in Chapter 4.

Once an introduced animal has become established at a wetland, and is having an impact either on the wetland itself or on the native animals that reside there, the best course of action is to remove the animal in question from the wetland. Introduced animals may be controlled by:

- trapping
- shooting
- poisoning
- fumigating
- using shockwaves
- electrofishing
- manipulating habitat or food
- removing the animals manually
- using fertility control.

The choice of the best method of removal will depend on the animal itself as well as factors such as the environment in which they are found (for example, open or closed vegetation) or population size. In some cases, such as the control of rabbits, a combination of removal methods may be necessary. The eradication or removal of introduced animals may not always be possible; for example, there is no approved method of removing introduced aquatic invertebrates such as brine shrimp. This reaffirms the importance of prevention when managing wetlands for introduced animals.

Nocturnal: primarily active during the night

In some scenarios, the control options available may be more environmentally damaging than the introduced species being controlled. This can be the case where non-target impacts of the control method are high even when carried out by a professional, for example, the use of some pesticides, the creation of shockwaves at some wetlands and the removal of some habitats. A proposed control activity which, if implemented, is likely to have a significant impact on the environment, requires referral to the Environmental Protection Authority, in accordance with the *Environmental Protection Act 1986*. A careful risk analysis should always be undertaken, considering the following:

- What are the values under threat from the introduced species?
- What are the potential off-target impacts to the wetland of each relevant form of control? How can the potential off-target impacts be minimised?
- Do the potential off-target impacts outweigh the benefits of control of the introduced species?

Many of the control options also require forethought regarding the handling and disposal of carcasses. Carcasses should never be buried within or close to wetlands, other aquatic environments or drinking water catchments due to the risk of contaminating the water, nor close to roads due to the road safety risks posed.

Trapping

Trapping may be used to control most introduced animals but can be time consuming and labour intensive and is therefore best suited for control of small populations or individuals. The success of trapping will depend on the species being targeted and the design of the trapping program. The choice of appropriate traps and trap sites will maximise the chance of capture and also minimise the distress caused to any animal caught, be it target or non-target. The use of some types of traps requires authorisation; see Table 2 for more information on the authorisations required.

Traps should be set in a place where the targeted animals are most likely to encounter the trap. Attractants such as edible bait, odours or sounds may be used to lure the introduced animals into the trap. The type of bait used will depend on the diet of the introduced animals. Meat baits such as chicken wings are appropriate for carnivores and most other mammals will be attracted to ‘universal bait’ (a mixture of rolled oats, peanut butter, honey and sometimes sardines).

Traps will need to be checked often (at least in the morning and late afternoon) to prevent suffering from heat, thirst, starvation, exposure or shock. The trapped animal will be stressed and may injure itself while trying to escape. Frequent checking is particularly important where non-target fauna may be caught (which is likely in most cases). To minimise non-target fauna being caught, traps should be opened to correspond with the time of day the target animals are active. For example, if **nocturnal** animals are being targeted, traps should be opened shortly before sunset and checked as soon as possible after sunrise.

Once caught, the animal may be humanely euthanased. Traps may potentially cause significant suffering or even death and so care should always be taken to ensure the welfare of the trapped animal. This is particularly important to ensure non-target native animals are released unharmed. Traps should always be placed to avoid exposure to the elements, particularly heat or direct sunlight, flooding and predation (including predation by ants). Shade cloth or hessian can be wrapped around wire cages and aluminium folding traps to provide shelter. Some bedding material can also be provided in traps to provide protection from cold weather. The location of all traps should be accurately recorded and marked, and the information readily available in case the trapper is unable to check the traps. It is also important to check each trap every time it is set to ensure it is functioning properly.

There are several different types of traps available. The trap should be selected based on how suitable it is for the species being targeted and the trapping location, as well as logistical factors. Table 5 identifies which traps are suitable by species.

Table 5. The types of traps most suitable for capture of introduced animals affecting wetlands

Introduced animal	Trap yards	Wire/steel cage traps	Aluminium folding traps	Jawed traps	Fish traps	Nets	Basking turtle traps	Cane toad traps
Domestic waterfowl						•		
Cane toad								•
Red-eared slider turtle						•	•	
Introduced fish					•	•		
Introduced crayfish						•		
Cat		•						
Red fox		•		•				
Domestic dog				•				
Camel	•							
Horse	•							
Donkey	•							
Goat	•							
Pig		•						
Rabbit		•		•				
Rodents			•					

Euthanasia of trapped animals must be conducted humanely and legally and cause no suffering to the animal. In order to achieve this, the people undertaking these activities must be competent and, where necessary, licensed to do so.

➤ See *Methods of euthanasia*[78] for suitable techniques for euthanasia of trapped introduced fauna.

Holding yards

Holding yards are used for capturing and holding very large animals such as camels, horses, donkeys and goats for short periods. Holding yards may be fixed or portable. Mobs and herds of animals can be mustered (herded) to holding yards. Additionally various attractants, such as food or water, can be used to entice the animals into trap yards, a form of holding yard. Once in a trap yard, the animals can be trapped by using 'spears' or a trip wire to close the gate. Spears made of steel pipes or timber saplings are held up by wires at the gate. The spears point inwards into the yard. Animals may push their way through the spears which will move sideways slightly, but when they try to leave the yard the spears will point against them.

➤ Standard operating procedures for mustering and trapping feral horses and goats are available from the Department of Sustainability, Environment, Water, Population and Communities website.[58]

➤ A model code of practice for the destruction, capture, handling and marketing of feral livestock is available online from CSIRO.[79]

Wire or steel cage traps

Wire or steel mesh cage traps are available in a variety of sizes, from traps suitable for rats or rabbits (although these are unlikely to enter a trap) to those large enough for pigs. For example, a dog-sized cage is 120 x 60 x 60 centimetres and is made of 2.5-millimetre welded wire with a mesh size of 50 millimetres. There are two types of cage traps: treadle-activated and hook-activated. Treadle-activated traps have a metal plate at the base of the cage which is connected to the cage door. When an animal steps on the treadle, either a hinged swing-style or a drop down guillotine-style door will close shut. The other type involves the bait being placed on a hook. When the animal pulls on the hook, it triggers the door to close behind the animal.

Foxes, feral cats and wild dogs are very wary of entering cage traps. However, the use of cages to trap feral pigs has been found to be quite successful. DAFWA identifies panel, box and silo traps (Figure 8) used with vertical, side-hinged and funnel gates as suitable for use in trapping feral pigs.

➤ For DEC's standard operating procedures for cage traps, see *Standard Operating Procedure 9.2 Cage traps for live capture of terrestrial vertebrates*.[80]

➤ For information on traps suitable for feral pigs, see DAFWA's Farmnote No. 36 *Feral pig control by trapping*.[81]

Figure 8. Pigs trapped in a silo trap with a funnel gate (also referred to as a 'figure 6 trap') in a wetland in the Lake Muir – Denbarker area of Western Australia. Photo - Lake Muir/Denbarker Community Feral Pig Eradication Group.

case study

Fighting feral pigs on the south coast

Feral pigs (*Sus scrofa*) are found in many parts of WA, particularly in the south west and the Kimberley. They favour a wide range of habitats in medium to high rainfall areas and require thick vegetation cover and access to water[82], so are often found in and around wetlands.

Feral pigs cause considerable damage to natural environments such as wetlands through rooting and trampling, which causes physical damage and erosion, and destroys soil fauna (Figure 9). Rooting also reduces ground cover and can cause vegetation change and open areas for weed invasion. Feral pigs consume plants, prey on native fauna (such as frogs, small mammals, reptiles, insects, worms and birds), destroy their habitat and out-compete them for habitat and food. They wallow in wet areas, churning up sediment and fouling the water with faeces and urine. Recent studies also suggest feral pigs can facilitate the spread of the *Phytophthora cinnamomi* pathogen responsible for Phytophthora dieback, as well as other pathogens and diseases.[82]

Figure 9. Evidence of pig damage at a wetland in Pingrup. Pigs cause wetland soil erosion and compaction, providing suitable conditions for introduced weeds to invade. Photo – M Barley/DEC.

Plants that have tuberous roots and which grow in wetlands, such as sundews (*Drosera* spp.) (Figure 10) and orchids (such as *Caladenia* spp.), are often impacted by feral pigs.[83] Large pigs will dig furrows up to 20 centimetres wide throughout feeding sites to dig for tubers and roots. Such behaviour causes erosion and soil compaction, forms trails and destroys wetland vegetation. It appears feral pigs are particularly attracted to sensitive areas of a wetland located around surface water following germination of spring flora species.[84]

Figure 10. *Drosera huegelii*, a species of sundew from the south-west of WA, is eaten by feral pigs. Photos – C Hortin and E Wajon. Image used with the permission of the Western Australian Herbarium, DEC (http://florabase.dec.wa.gov.au/help/copyright), accessed 12/05/2010.

Wetland fauna are threatened by feral pig invasion. Pigs destroy the habitat of species such as quokkas and bandicoots that require dense vegetation for protective habitat. Frog species, such as the sunset frog (*Spicospina flammocaerulea*) found in isolated peat wetlands in the Warren Region north of Walpole and Denmark (Figure 11), are at risk from habitat destruction and being eaten by pigs.

Figure 11. The sunset frog (*Spircospina flammocaerulea*), which is threatened by feral pigs. Photo – K Bain/DEC.

case study

Community action

In 2001, a number of local landholders in the Lake Muir and Denbarker area recognised the growing threat of feral pigs to the south-west and decided to undertake a pilot eradication project in the area, which supports natural areas of high conservation value including the Frankland River and the Ramsar-listed Lake Muir.

The success of the trapping program during the five-month pilot demonstrated the benefit of the project and the Lake Muir/Denbarker Community Feral Pig Eradication Group was formed.

Collaborative action has been a cornerstone of the group's success. A range of project partners and stakeholders have been involved, including local landholders; DAFWA and DEC; South Coast NRM Inc; Green Skills Inc; the shires of Denmark, Plantagenet, Manjimup and Cranbrook; Great Southern Limited; ITC Limited; Walpole-Nornalup National Parks Association and the Wilson Inlet Catchment Committee Inc.

This integrated stakeholder approach has been highly successful in identifying and eradicating feral pig populations, because it combines resources and provides opportunities for coordinated management across property boundaries.[83]

The group's committee has found that trapping is the most appropriate method for the Lake Muir/ Denbarker area (Figure 12) and that trapping is most efficient in late summer to early autumn, when water and feed supplies are low. A 'figure 6' silo trap is generally most effective at catching a group of pigs at a time, complemented by traps with a drop gate for pigs too large to enter the figure 6 traps. To maximise trapping success, pre-feeding is employed to encourage pigs to become accustomed to traps prior to trapping. The experience of the group is that inadequately controlled shooting and hunting poses a risk of scattering pigs and training them to avoid humans. The group reports that shooting by organisations such Sporting Shooters' Association of Australia complements trapping, however, communication between organisations has been vital to minimise duplication of effort and disturbance to each other's programs.

Figure 12. Feral pigs trapped by the group. Photo – Lake Muir/Denbarker Community Feral Pig Eradication Group.

The coordinated trapping approach is contributing significantly to the reduction of feral pigs in the area. In the 2007 and 2008 seasons, 225 pigs (including sows carrying a total of 165 unborn pigs) were dispatched.[84] In 2009, 169 pigs were dispatched. This high number reflects refinements in tracking and trapping techniques as well as the addition of new areas under trapping (M Muir 2010, pers. comm.). In autumn of 2010, 139 pigs (including sows carrying 75 unborn pigs) were dispatched.

Despite successful control of local populations of feral pigs, re-invasion is a constant threat because illegal dumping still occurs and because feral pigs can travel significant distances. The group therefore maintains a long-term perspective, with ongoing monitoring and treatment of areas remaining a priority.

The group has seen many advances in the fight against feral pigs since its formation in 2001. A number of groups have formed to fight feral pigs in other areas, and the Southern Feral Pig Advisory Group has recently been formed as an 'umbrella group' for these groups. In addition, a pilot nationally recognised training course has been developed to provide accreditation for feral pig trappers. These initiatives support the ongoing fight to control feral pigs in WA.

For more information on the Lake Muir/ Denbarker Community Feral Pig Eradication Group, go to www.feralpig.southcoastwa.org.au.

Note: this case has been prepared in consultation with the Lake Muir/Denbarker Community Feral Pig Eradication Group.

Aluminium folding traps

Aluminium folding traps, often called Elliott traps after the manufacturer, are small metal boxes that are easily folded up when not in use (Figure 13). Aluminium folding traps operate on a treadle mechanism. The hinged door folds inwards to allow the animal to walk over it and onto the treadle. The door then springs shut, trapping the animal. Aluminium folding traps are small and come in two sizes: A and B. These traps are mainly used for capturing small mammals such as house mice.

Figure 13. A typical set-up of an Elliott aluminium folding trap covered hessian. The trap is placed in a shady position under vegetation cover. Photo – A Nowicki/DEC.

➤ For DEC's standard operating procedures for Elliot traps, see Standard Operating Procedure 9.1 *Elliott traps for live capture of terrestrial vertebrates*.[85]

Jawed traps

Jawed traps can be used to trap foxes, rabbits and wild dogs. Foxes and wild dogs are very wary of entering cage traps, and so the use of jawed traps may achieve a higher success rate than cage traps. Even so, jawed traps are generally considered to be an ineffective tool for general population control of foxes, rabbits and wild dogs; they are generally used to control small, isolated populations, hard-to-catch individuals or following a baiting program.[86,87,88,89] Furthermore, as with most traps, jawed traps are not target-specific and can catch animals such as birds, kangaroos, wallabies, echidnas, goannas, wombats, possums, bandicoots, quolls and sheep[88]; as well as humans, therefore the decision to use jawed traps should take this into account.

The main benefit of jawed traps is that the animal is unaware of the trap until it is caught. The traps are buried into the ground in the set position. They operate by snapping two 'jaws' shut when an animal steps on the treadle plate or 'pan'. The pan is usually adjustable to suit the animal being targeted.

Jawed traps come in two main types: leg-hold and foot-hold (often called 'soft-catch'). The difference between leg-hold and foot-hold traps is that leg-hold traps are much larger and often catch the animal higher up on the leg, which can cause major trauma. Foot-hold traps seize the animal across the tougher padded area of the foot and are therefore preferred.

Jawed traps have evolved substantially since the early steel-jawed models. The traps in use today have padded, offset and/or laminated jaws. Offset jaws have been altered to leave a gap between the trap jaws, allowing greater blood flow to the animal's foot. Laminating traps expands the thickness of the trap which increases the surface area of the jaw on the animal's foot. Doing so reduces the injury caused to the trapped animal and also increases holding efficiency. Only padded-jaw traps can be used for fox and rabbit control.[88,87,86] For trapping of wild dogs, traps that cannot be serviced daily must be wrapped in hessian that is impregnated with strychnine crystals to prevent prolonged suffering.[89]

➤ Standard operating procedures for trapping of foxes, rabbits and wild dogs using jawed traps are available from the Department of Sustainability, Environment, Water, Population and Communities website.[58]

Fish traps

It is important to seek advice from the Department of Fisheries before attempting to use any equipment, including traps, to catch introduced fish or crustaceans within Western Australian wetlands. An exemption from the department is required for trapping activities.

Generally, fish traps and nets are considered to be relatively ineffective for eradicating introduced fish and crustaceans. This is because the biology of most introduced species makes the containment of such organisms, especially their reproductive material, extremely difficult (B Bardsley 2010, pers. comm.).

However, traps may be used to significantly reduce introduced fish populations. Box-mesh traps, like the one shown in Figure 14, can be used in wetlands to trap introduced fish such as eastern gambusia (*Gambusia holbrooki*). These were used by students of Shenton College to trap and remove eastern gambusia in Dalkeith (for more information, see the case study 'Restocking native fish in Masons Gardens Lake, Dalkeith' at the end of this topic).

Figure 14. A box mesh trap used to capture eastern gambusia. Photo – C Lawrence/Department of Fisheries.

Both the design and placement of fish traps can help reduce the entrapment of non-target species. For example, it is important to ensure that the trap opening is small enough to exclude turtles from entering.

Traps such as carp separation cages can be used to catch introduced fish in waterways or drains feeding into wetlands. The carp separation cage encourages European carp (*Cyprinus carpio*) to jump over a wall into a separate trap with a hinged lid, preventing escape. Recent laboratory trials of a 'finger style' carp push trap in South Australia have shown promise as a carp management option.[90] Cages and barriers may be used together to improve introduced fish management (see 'Barriers' for more information).

Nets

There are three main types of nets that can be used to catch introduced animals within wetlands: hand-held nets, mist-nets (for birds) and netted traps (for water-dwelling animals). Hand nets consist of conical netting attached to a hoop on the end of a rigid handle. The use of a hand-held net is fairly labour-intensive and so a netted trap or mist-net may be preferred.

Mist nets and netted traps are stationery. Steps should always be taken to ensure that these traps can easily be located. For underwater traps, this may be achieved by attaching a buoy to the trap. Careful consideration of non-target animals is required when using netted traps.

Mist net traps are fine nylon or polyester nets which are suspended between two upright poles. The grid size of the mesh netting varies according to the size of targeted birds. The net is practically invisible to birds, which fly into the net and remain caught until released. Birds will entangle themselves in the net and so continual monitoring and expert handling of caught birds is required. Mist nets have a high likelihood of non-target capture, further emphasising the need for frequent surveillance.

Netted traps come in a variety of designs including drop nets, hoop nets, yabbies pots or turtle traps. All designs consist of a rigid frame covered in mesh netting. The traps may be baited. Care should be taken when hauling a trap out of water to avoid disturbing the wetland sediment. Drop nets are constructed from two hoops joined by a cylindrical or cone-shaped net bag. Introduced crayfish are generally trapped with drop nets. Hoop nets are similar to drop nets but only have one hoop with a conical-shaped net attached to it. Yabbie pots are constructed from rigid wire and netting and have two fixed entrance funnels. They come in two shapes: rectangular and 'opera house', which is a semi-circular design. Opera house traps must be used with extreme care, as they can entrap rakali, also known as native water rats (*Hydromys chrysogaster*), which drown if caught. It is important to seek advice from the Department of Fisheries before attempting to use any equipment, including nets, to catch introduced fish or crustaceans within Western Australian wetlands. An exemption from the department is required for trapping activities. In 2007 the Minister for Fisheries granted an exemption for the use of fish traps within Lake Kununurra to allow commercially available 'opera house' style traps, specially modified to target redclaw, to be used to trap the introduced freshwater crayfish redclaw (*Cherax quadricarinatus*).[91]

Turtle nets are similar to yabbie pots but have been modified to allow turtles to reach the surface of the water to breathe air. Turtle nets are collapsible with a rectangular frame, two entrance funnels, and netting.[92] The netting forms a cylindrical shape and extends upwards by about 2 metres. The upper end of the cylindrical netting is tied with a cord to a tree branch or a stake above the water surface, allowing the trapped turtles to swim for air while remaining trapped.

Basking turtle traps

As well as the netted trap design outlined above, there are several basking trap designs and most consist of a floating basking platform with a net or wire basket attached underneath.[93] Turtles climb up the sides of the trap to bask on the platform and are captured in the net after leaving the platform. The sides of the trap are sloped inward to facilitate entry and prevent escape.

Cane toad traps

Cane toads may be removed at all stages of their life cycle. While eggs can only be removed by hand, cane toad tadpoles and adults can be trapped.

Tadpoles of any frog species can be trapped using funnel traps placed under water. These come in a myriad of designs, including cylindrical or box traps constructed from mesh galvanised wire, traps made from plastic beverage bottles, collapsible nylon mesh traps, and traps made with acrylic plastic sheet.[94,95,96,97,98] All of these designs operate by allowing tadpoles to enter the trap through one or two funnels, but not allowing the tadpoles to escape.

A variety of traps have been developed for capturing adult cane toads. These are generally cage traps, traps made of solid metal walls, or traps that are a combination of cage and solid walls. Kununurra and Wyndham residents can currently obtain cane toad traps from the Shire of Wyndham/East Kimberley depot for a small deposit for use on their properties.

Although extensive trapping of adult cane toads has been undertaken in the Kimberley, a number of issues have been identified with this method. These include maintenance and service of traps in remote areas; damage by fire, theft, vandalism, livestock and wildlife; capture of non-target species; and the need to position traps very close to or in water. DEC recognises that cane toad traps may play a role as a surveillance tool at and ahead of the main front and may be required by community members as a tool to keep toads out of backyards. To maximise their effectiveness, a combination of lights, baits and acoustics (that is, playing toad calls in order to attract others) is recommended to attract cane toads to the traps.

The use of fences may also improve the effectiveness of cane toad traps. Deflection fencing, which involves a barrier set up to direct toads towards traps, has been trialled for the control of cane toads (Figure 15). While the specific fence design and application are still being developed, temporary barrier fencing may also play a role in the exclusion of cane toads from strategic sites that are of special significance such as mound springs.

➤ For more information on the control of cane toads, see the DEC website at www.dec.wa.gov.au/canetoads.

Figure 15. Deflection fencing in use during the Stop the Toad Foundation's 2009 'Great Toad Muster'. Photo – A Shanahan.

Shooting

Nuisance kangaroos and larger introduced animals, such as camels, goats, horses, pigs, foxes, cats, rabbits and even red-eared slider turtles may be shot. In most cases, this will be lethal to the animal. Tranquiliser guns may be used if the aim is to translocate the animals, which may be an option for nuisance kangaroos. This can be expensive, with prices around $1,000 per kangaroo quoted in the metropolitan area of Perth. Shooting may be conducted on the ground. Aerial shooting is best suited for large-scale population control, particularly in remote and/or inaccessible areas. A team is required for aerial shooting, including a shooter, a pilot and a spotter/counter who locates the animals and records the number of animals shot.

Shooting can be a humane method of introduced animal control when it is carried out by experienced and skilled shooters (and pilots in the case of aerial shooting). Introduced animals should only be shot when they can be clearly seen and are within range, and using the correct calibre firearm and ammunition. Correct shot placement (aiming for the brain or heart) is very important and wounded animals should be promptly located and killed.

➤ Standard operating procedures on how to humanely shoot introduced animals species are available from the Department of Sustainability, Environment, Water, Population and Communities website.[58]

If carried out correctly, shooting can be the most humane method of removing introduced animals. It is also one of the most cost-effective methods available, particularly when population densities are high. However, shooting is often only a short-term solution and may have to be combined with other management methods such as exclusion fencing.

case study

Managing the nuisance kangaroo population at Thomsons Lake Nature Reserve

Kangaroos are prolific breeders and, due to a reduction in predation and a greater availability of food on cleared land, are able to quickly increase in population size until they can no longer be supported by the habitat.[99] Kangaroos form nuisance populations at golf courses, ovals and on farmland but generally they are not a major issue at wetlands. Large populations of kangaroos can readily form when they are unable to disperse due to fencing or insufficient corridors of native vegetation. In recent years, this has occurred at Thomsons Lake Nature Reserve in southern metropolitan Perth, which is fenced to protect waterbirds from predation by foxes and cats. Following the installation of the vermin-proof fencing in 1993, the population of western grey kangaroos (*Macropus fuliginosus*) within the reserve increased from twenty to thirty individuals to approximately 1,100 kangaroos by 2006. The kangaroos were causing extreme harm by overgrazing the understorey of the wetland and dryland vegetation. Kangaroos were culled (shot) in 2006 in accordance with the kangaroo management program for the reserve[100] and with the approval of the Conservation Commission of Western Australia and the support of the community-based Beeliar Regional Park Community Advisory Committee.[101] Translocation of the kangaroos was considered but rejected on the basis that it was not a feasible or practical option because of the unacceptable level of stress it would place on the animals, as well as causing unnatural pressures on any areas to which they could be relocated.

Poisoning

Poison may be applied within and around wetlands in two forms. The poison may be applied either directly, a method mainly used for controlling introduced fish and aquatic invertebrates; or through bait delivery, a method mainly used for terrestrial mammals.

When using poisons

Any chemical or biological agent intended to kill animals, such as a poison, is a **pesticide**. Extreme care must be taken to ensure that the use of pesticides does not constitute an offence or cause environmental harm. In WA, anyone who uses pesticides is bound by the Health (Pesticides) Regulations 1956. These regulations were developed to provide protection for the applicator, the public and the environment from misuse of pesticides. Pesticide labels are written in accordance with the Regulations and therefore any pesticide user has a legal obligation to read and follow instructions on the label. By law and without exception, pesticides cannot be used in any manner contrary to that described on its label without the permission of the Australian Pesticides and Veterinary Medicines Authority.[102] The label provides instructions for use, for the protection of the environment, information about storage and disposal and recommendations for personal protective equipment. Anyone proposing to apply a pesticide to a natural area of conservation value should have appropriate authorisation and should undertake training in the correct preparation, handling, application, transport and storage of pesticides. Legislation regarding the use of chemicals is under review and in future this may become a legal requirement.

Direct application

Rotenone

The most common poison used to control introduced fish is rotenone. Rotenone is an odourless chemical which occurs naturally in the roots and stems of several plants such as the jicama vine plant.[103] Commercial products containing the extract are used to poison fish, which are then easily collected because they swim to the surface of the water seeking oxygen.

Rotenone is primarily used for the control of introduced fish. However, it is a broad-spectrum pesticide, that is, it is toxic to many species including a number of aquatic fauna, such as tadpoles and a range of aquatic invertebrates. Rotenone is mildly toxic to humans and other mammals. This higher toxicity in fish and insects is because rotenone is easily taken up through the gills or trachea, but not as easily through the skin or through the gastrointestinal tract. The compound breaks down when exposed to sunlight. Rotenone persistence in natural waters is reported to vary from a few days to several weeks, depending on the season.[104] Rotenone is widely considered to have only minor and transient environmental side-effects and is considered by many researchers and institutions to be the most environmentally friendly fish poison.[104]

At this time, most methods of introduced fish control are unable to exclusively target a single species. As such, native fish will be at risk when controlling introduced fish. There has been some research into developing rotenone in bait form, which could then be targeted at individual species such as carp.[105] However, this method still requires further development.

Piscicide: a chemical substance which is poisonous to fish

In Australia, rotenone can only be used as a **piscicide** if permission to do so is granted by the Australian Pesticides and Veterinary Medicines Authority in the form of a 'minor use' permit (see Table 2 for more information). In the United States of America, where rotenone has been in use for many years, the American Fisheries Society has recently published standard operating procedures for the use of rotenone.[106] The New Zealand Department of Conservation has published a review of rotenone which includes a recommended protocol when considering its use as a piscicide.[104]

A proposal to use rotenone requires an environmental assessment as to whether it is acceptable at a particular wetland. As with any pesticide, the risk to all fauna needs to be identified and considered as part of this assessment. Important risk factors include whether the wetland is open or closed (that is, there is no overland flow into or out of the wetland); whether native fish and other susceptible native species may be present; and timing of the application to reduce impacts on native fauna present (for example, rotenone is known to be more toxic to tadpoles than adult frogs).[107] Another option to minimise the impacts on native fauna is to ensure that native species are removed from the control area for later restocking, or that there are nearby breeding populations which can naturally repopulate the area.[108]

➤ The use of pesticides and the removal and reintroduction of freshwater species is subject to regulation. For more information, see Table 2 and the section of this topic entitled 'How to manage the impacts of introduced animals'.

Among other methods, rotenone was successfully used in the control (but not eradication) of pearl cichlids (*Geophagus brasiliensis*) in the Perth metropolitan area. The cichlids were first discovered in March of 2006 and steps were taken to limit their spread in a range of water bodies at Altone Park, the Altone Park Golf Course irrigation ponds, drainage systems and natural streams such as Bennett Brook.[109,110] Rotenone has also been successfully used to control and eradicate populations of goldfish from billabongs near the Warren River and the Margaret River (S. Beatty pers. comm.).

Baiting

Baiting is an option often favoured for the control of foxes and rabbits. Baits may also be used for the control of introduced mice and rats. Baiting techniques for feral cats have improved rapidly in the last decade, however the use of Eradicat® in WA is currently limited to an experimental permit by DEC.

The primary method of control of foxes is by spreading baits containing the compound 1080 (sodium monofluoroacetate). There are two types of 1080 baits: dried meat baits and sausage baits. Meat baits are made by injecting 1080 into various meats (usually kangaroo or horse meat) which are left to sun-dry until at least a hard crust forms. Sausage baits are semi-dry meat baits whereas the traditional dried meat baits are fully dried. Spreading 1080 baits for fox control can be done by manually laying out the baits along set transects or by mass aerial dispersal. Baiting is an effective way of controlling foxes as they readily scavenge and frequently take up baits.[115,38,116] There has been substantial research in improving the effectiveness and safety of 1080 baiting in Australia including assessing the attractiveness and palatability of various types of baits.[116,117,118]

One of the main concerns when applying any lethal control methods is the impact on non-target species, particularly pets and native species. Native south-west Australian fauna are least at risk of fatalities associated with 1080 bait consumption. Monofluoroacetic acid, from which 1080 baits are derived, occurs naturally in the legume genus Gastrolobium. Over the millennia fauna of the area have co-evolved with the plants to develop a very high tolerance to the compound.[111,112] However, native carnivores and scavengers such as dingoes, quolls, goannas and some birds are at risk of consuming 1080 baits.[113] Some strategies can be employed to reduce the risk of bait uptake by non-target species, for example, by burying the baits to prevent birds from picking up the baits.[113,114,115] It must be noted that quolls readily dig up baits just as foxes do.[115,116]

➤ The use of baits containing 1080 is regulated. An excellent guide to the use of 1080 is *Landholder information for the safe use and management of 1080.*[62]

Baiting is now recognised as the most effective method for controlling feral cats when there is no risk posed to non-target species.[117] Historically baiting programs for feral cats were ineffective, principally because the baits used were for other introduced predators such as foxes and wild dogs and were unattractive to cats. In response, DEC researchers conducted an extensive series of trials which have led to the development of the feral cat bait known as 'Eradicat®'.[129,130]

Baiting campaigns using Eradicat® have proven to be an effective method in reducing feral cat numbers and it is now used by DEC as a control tool for feral cat management at a number of mainland sites in arid and semi-arid regions.[118] A recent project has gone a long way to demonstrating that the sustained control of introduced predators (both feral cats and foxes) in the southern rangelands can also be achieved using this bait.[119]

Baiting may also be used to control rabbit and rodent populations. The bait material used is either oats or carrots. Poison is then applied to the baits, usually 1080 or Pindone. Pindone is a registered rabbit poison that was originally developed for rodent control and is available in two forms: powder or liquid.[120] Pindone bait is preferred for use in urban and urban/rural areas as it has an antidote, vitamin K1, and is generally safer to use than 1080 where non-target domestic animals are at risk.[121,120,122] However, Pindone poses a greater risk to wildlife than 1080.[120] Therefore, choice of poison will depend on where the introduced animal control is being conducted. Only 1080 should be used where non-target wildlife are likely to be exposed to the bait, or considered to be at risk.

extra information

Baiting for rabbits

Baiting is generally only the first step in rabbit control and should be carried out in conjunction with warren ripping and/or fumigation.

Rabbit baiting is most effective in the late summer/early autumn. This is when natural causes and deliberately introduced viruses used as biological controls (such as myxomatosis or rabbit calicivirus disease) will have reduced the population, food availability is at a minimum, young rabbits are old enough to emerge from their warrens, and the breeding season is over so rabbits will range over greater distances.[121,120] The best area to lay baits for rabbits is close to their warren, however, they do feed up to 400 metres from their warren. The results of a rabbit control program can be greatly improved by laying unpoisoned baits, known as free feeding, once or twice before laying poison baits. Free feeding allows the rabbits to acquire a taste for the baits and encourages them to feed on a new food source.[121,120] Following baiting, all uneaten bait and rabbit carcasses should be collected (for up to 8–12 days following baiting) to make sure non-target animals aren't harmed by ingestion of either the bait or poisoned carcasses.

Fumigation

Fumigation may be used for the control of rabbits either following or as an alternative to warren ripping, which is undertaken after poisoning. Burrows dug out by foxes as shelter for their cubs (natal dens) may also be fumigated. Fumigation is considered to be less humane than poisoning with 1080. Therefore, it is desirable to fumigate only after a poisoning program has been completed, when the density of rabbits or foxes is low.[123]

Fumigation involves the introduction of toxic fumes into a burrow where it is inhaled by the inhabitants, leading to their death. There are two types of fumigation: pressure fumigation, in which the fumigant gases or vapours are generated outside the burrow and are forced into the burrow under pressure, usually from a pump or fan; and diffusion (or static) fumigation, where tablets are placed in active burrows and the gas generated is allowed to diffuse through the burrow.[124,125,123] Toxins used for fumigation include chloropicrin, carbon monoxide, carbon dioxide, calcium cyanide and phosphine.[124]

Phosphine has been widely used for diffusion fumigation and remains the preferred toxin for fumigation of rabbits. Phosphine is a gas which is released from aluminium phosphide tablets when they react with moisture.[125] Damp soil conditions give the best results when using this method of fumigation.[126]

Fumigation with carbon monoxide has been developed as a humane alternative to phosphine.[127] Carbon monoxide gas causes unconsciousness and rapid death without pain or discomfort. Carbon monoxide fumigant cartridges, such as DEN-CO-FUME®, are now registered for use in controlling foxes in natal dens. The cartridges contain carbon and sodium nitrate, which combust to produce carbon monoxide once the cartridge is ignited. Carbon monoxide has a similar density to air and quickly disperses throughout the available space and is not readily adsorbed by soil. DEN-CO-FUME® is widely used to control foxes in natal dens across Australia, but is not yet registered for use in rabbit warrens. Using car exhaust fumes is not an acceptable method of producing carbon monoxide as adequate gas concentrations cannot be achieved and exhaust contaminants cause severe irritation before death. The exhaust gases produced may also be unacceptably hot.[128,123,123]

Diffusion fumigation is preferred over pressure fumigation. Chloropicrin, used for pressure fumigation, is considered to be highly inhumane and its use is not recommended. It causes intense irritation of the respiratory tract and profuse watering of the eyes for a considerable period before death. Additionally, the process of pressure fumigation is slow and cumbersome, and only suitable for small areas.[129]

When fumigating, it is important that rabbits or foxes are inside the burrow and the burrow is sealed to prevent the gas from escaping. Rabbits will have multiple entrances to their warrens and so each of these will need to be located and sealed. The fumigants used are highly toxic to humans and great care should be taken at all times. Furthermore, care should be taken to ensure that the inhabitants of the burrow are, in fact, rabbits as recent research by the Bandicoot Refuge Project has found that quenda take refuge in rabbit burrows to avoid predators.

➤ Fumigation is the application of a gaseous pesticide; see the information under 'Poisoning' in this topic for more information about the legal requirements associated with pesticide use.

➤ Standard operating procedures for fumigating fox dens and rabbit warrens are available from the Department of Sustainability, Environment, Water, Population and Communities website.[58]

Shockwaves

Underwater explosions may be used to reduce the number of introduced fish in wetlands.[108] These explosions, caused by very small charges from detonating cords, create shockwaves in the water which kill fish by rupturing their internal swim bladders. Shockwaves were used in combination with other methods to reduce the number of pearl cichlids (*Geophagus brasiliensis*) in the Swan River system in 2006.[109]

This method is relatively inefficient for eradicating introduced fish, and its use should be restricted to environments where other methods are not viable, or where a combination of methods is required for successful eradication.

This method may affect other aquatic fauna in the wetland, including native fish, aquatic mammals, amphibians, and reptiles. Therefore the proposed use of shockwaves is subject to regulation and may trigger the *Environmental Protection Act 1986*.

The use of shockwaves must only be undertaken by a suitably qualified and licensed practitioner.

➤ The removal of freshwater fish species and the use of shockwaves are subject to regulation. For more information, see Table 2 of this topic.

Electrofishing

Electrofishing (also called electric fishing) is a method used to stun fish in the water to allow for easy collection. Electrofishing uses an electric current, delivered into the water by two electrodes (an anode and a cathode), to attract and immobilise fish.[130] There are three types of electrofishers: backpack models, towed barge models and boat mounted models (sometimes called stunboats). Electrofishing is only effective in water shallower than approximately 2.5 metres and in water with a conductivity range of between 10 and 5,000 microsiemens per centimetre (µS/cm); (for comparison, seawater is around 50,000 microsiemens per centimetre).[131]

➤ For more information on conductivity, refer to the topic 'Conditions in wetland waters' in Chapter 2.

When fish encounter the electric current, galvantotaxis occurs, which is an uncontrolled muscular convulsion that makes the fish swim toward the anode. When performed correctly, electrofishing results in no permanent harm to fish, which return to their natural state in as little as two minutes after being stunned. However, great skill is required by the operator to avoid harming fish. Electrofishing can cause harmful effects on fish that are often not externally obvious or fatal, such as spinal injuries and haemorrhages.[132] Because it requires the use of high voltage electricity in and around water, electrofishing equipment is highly specialised and relatively expensive.[130] The risk of injury to both operators and observers is such that an *Australian code of electrofishing practice* has been established. This prescribes the required standards in operator training and certification, equipment and operational practices.

➤ For guidance on electrofishing activities, see the *Australian code of electrofishing practice*.[133] For information on regulations governing the removal of freshwater fish, see Table 2 of this topic.

The annual control program of the goldfish population in the Vasse River involves boat electrofishing. More than 1,200 goldfish have been removed with no native fish deaths recorded in follow-up surveys.

Manipulating habitat and food

Rabbits, foxes and fish can be controlled by manipulating their habitat. Limiting the Australian white ibis' access to unnatural food sources, such as rubbish dumps and rubbish bins, can help ensure that the size of populations dependent on these food sources at wetlands are controlled.

In the case of rabbits and foxes, habitat manipulation refers only to the specific 'habitat' the animals have created, namely their burrows. Rabbit warrens and fox natal dens may be ripped or destroyed with small explosives. This is often used as part of a control program that includes baiting and possibly fumigation. Destroying burrows discourages rabbits and foxes from returning to the area.

➤ Standard operating procedures for rabbit warren destruction by ripping or explosives are available from the Department of Sustainability, Environment, Water, Population and Communities website.[58]

Draining a wetland of water may remove introduced fish. This is an option that must be considered a last resort only and must only be undertaken if legal. It requires an environmental assessment to determine whether it will have a significant environmental impact, taking into account all aspects of the wetland's hydrology, ecology (particularly native aquatic fauna) and chemistry (particularly acid sulfate soils), and may trigger the *Environmental Protection Act 1986*.

While draining a wetland for two to three days may be effective at removing many species of introduced fish, it is likely to kill most if not all native fish and other aquatic fauna within the wetland. There is not a lot of published data on the effectiveness of this method; however anecdotal reports are that a number of attempts at natural wetlands have proven ineffective. It was used to successfully eradicate eastern gambusia (*Gambusia holbrooki*) from the significantly modified wetland, Ilparpa Swamp, in the Northern Territory. After the eastern gambusia were discovered by Waterwatch volunteers, the swamp was pumped dry and was refilled to capacity by rains two weeks later.[66] This method may also be used for carp when they are present in isolated wetlands.

Draining a wetland will not eradicate yabbies. Extreme manual removal (with an excavator) or the use of chemicals may work[134], but these techniques obviously have the potential to create a significant environmental impact.

➤ There are legal requirements regarding the alteration of drainage into or out of wetlands and the alteration of wetland water regimes. For further information, see the topic 'Legislation and policy' in Chapter 5.

case study

Managing nuisance ibis populations

Australian white ibis (*Threskiornis molucca*) are a native species with the potential to form nuisance populations in some areas of WA (Figure 16).

Figure 16. An Australian white ibis (*Threskiornis molucca*). Photo – T Chapman/DEC.

As a scavenging species with a generalised diet, they have adapted well to urban environments.[135] Large numbers of the Australian white ibis can cause damage to wetlands and out-compete native species for food and nesting resources. Booragoon Lake, in southern metropolitan Perth, provides habitat for a large number of waterbirds and is one of the few urban breeding sites for pied cormorants (*Phalacrocorax melanoleucos*). Australian white ibis are also abundant at the lake and are considered nuisance fauna as their large numbers are out-competing pied cormorants for habitat. The nesting habits of the ibis are also damaging wetland vegetation, in particular, the *Melaleuca teretifolia.*[74] The local population of ibis has grown to nuisance size due to an abundant food source in the form of a nearby rubbish dump.[74]

A range of methods have been employed to control nuisance populations of Australian white ibis in Australia. Limiting access to unnatural food sources, such as rubbish tips and bins, is a key measure. Various methods of exclusion from these food sources are available including the use of netting (Figure 17), barriers, ibis-proof litter bins and preventing people from feeding them. These can be combined with complementary measures including limiting water sources and loafing sites, scaring and spotlighting them, shooting them and oiling eggs. There has also been research into a contraceptive pill to be implanted under the skin of captured birds.

➤ For more information on management options for nuisance populations of the Australian white ibis, as well as associated legal requirements, see *Prevention and control of damage by animals in WA: Australian white ibis* Threskiornis molucca.[135]

Figure 17. Ballina landfill in NSW, where netting has been shown to reduce local Australian white ibis populations significantly. Photo – K Patrick/Ecosure.[136]

Manual removal

Manual removal of introduced animals is generally considered to be the most environmentally sensitive method of removal, with few unwanted side effects. As the name suggests, it involves directly removing introduced animals from a wetland. While this can be a labour-intensive process, it may also be the most feasible method available in sensitive environments. It may also be the simplest method of removal in small wetlands or when only a few individuals of the introduced species are present.

One such method of manual removal is the use of dip nets to remove introduced fish from a wetland. This is generally a labour-intensive process and often less efficient than traps (at one site it was found that traps caught five times more fish than hand nets[137]). Care should be taken to ensure that only introduced fish are removed from the wetland and that any native fish that are caught are returned unharmed. Even if it appears that all adults have been removed, repeated fishing attempts may be required, as some individuals may have remained in the form of eggs or juveniles. Populations of warm-water species are smaller[138] and many species are not in reproductive mode in cooler months. However, this advantage is counteracted by the fact that activity and therefore 'catchability' is also diminished. In the dry season water levels are reduced and the concentration of introduced fish is increased. As such, timing should be assessed depending on the habitat and target species. The only known successful eradication of eastern gambusia from a natural aquatic system in WA was achieved by intensive dip netting in a pool in the upper Margaret River catchment that prevented its colonisation into the high conservation value upper reaches when winter flows resumed (S. Beatty pers. comm.). However, dipping is usually far less effective than use of larger nets (such as seine nets) or trapping in larger systems.

All noxious fish species must be destroyed on site. For other species, the Perth Cichlid Society (www.perthcichlid.com.au) offers to accept unwanted fish and provides a list of local fish stores that have agreed to accept unwanted fish. Alternatively, introduced species of fish that are not listed as noxious species may be disposed of humanely by refrigerating them in water until they stop moving, and then moving the container to the freezer overnight. This method has been endorsed by the RSPCA WA Inc.[10]

Experience has shown the most efficient and effective way to remove cane toads is to simply pick them up.[139] Cane toad 'musters' with high levels of community participation have been effective in reducing the number of cane toads present in WA (Figure 18) and was used to successfully eradicate the local population of cane toads in Port Macquarie, New South Wales. The use of deflection fencing may help to make hand collection more efficient.[140] The timing of hand collection is also an important factor as cane toads concentrate around water points during the dry season, making collection easier. Cane toads exude poison from the glands at their shoulders and so care should be taken when handling the toads. Gloves should be worn and care should be taken to avoid the poison getting into eyes, nose or mouth and pets should be removed from the area.

Figure 18. Volunteers counting and sorting cane toads manually collected during the Stop the Toad Foundation's 2009 'Great Toad Muster' in the Kimberley.
Photo – M Andrews.

Once collected, cane toads may be taken to an allocated disposal facility (usually a DEC office or veterinary clinic) or euthanased. It is essential that members of the public are completely certain of the identification of the animal they have captured prior to euthanasing it, as up to two-thirds of suspected cane toads turn out to be harmless native frogs.[8] Cane toad carcasses are still toxic so they should be disposed of carefully—either by burial in a location where it cannot be dug up by other animals, especially pets; or by incineration.

➤ For more information on the control of cane toads, see the DEC website at www.dec.wa.gov.au/canetoads.

Fertility control

Fertility control options may be considered as a means of maintaining low numbers of introduced animals. Immunocontraception is one method of fertility control where the animal's immune system is made to mount an attack against a part of their own reproductive system such that they become infertile. This could be against eggs, sperm or a hormone necessary for successful reproduction.[141]

Trials of immunocontraception, though promising, have shown limited success. This method requires multiple injections to be made to the animals, either directly or by using dart guns. This makes immunocontraception impractical and raises the issue of costs versus benefit. Orally delivered (using baits) immunocontraception is being investigated, particularly for foxes and feral cats. The high uptake rate of 1080 bait by foxes indicates that this form of control has potential.[142]

For immunocontraception to cause rapid population decline, a large proportion of breeding females need to be sterilised.[143] Some animals which have undergone contraception or vaccination have been found to reproduce, which implies that genetic selection for animals which do not respond to the vaccine is possible.[141] These are the issues that must still be resolved before any form of fertility control for introduced species can be used widely in Australia.

How to manage the impacts of introduced animals

Reintroduction: the deliberate release of a species in an area which is part of its natural historical range but in which it no longer occurs

As previously mentioned, introduced animals can have a number of detrimental impacts on wetlands, including:

- predation and competition with native fauna
- spread of diseases, plant pathogens and weeds
- degradation of native vegetation
- soil disturbance
- reduced water quality.

After introduced animals have been 'controlled' (numbers reduced or completely eliminated), a wetland may require additional management to address the impacts of the introduced animals. If a wetland is in good condition, it may be able to recover naturally. If a wetland has been severely degraded and natural recovery is unlikely, active management may be required. In these circumstances, management of both the wetland vegetation and fauna is likely to be required.

If significant vegetation loss or the complete loss of a particular plant species has occurred at a wetland and recruitment is not occurring naturally, revegetation may be considered.

➤ For additional detail on managing wetland vegetation see the topic 'Managing wetland vegetation' in Chapter 3.

If fauna have disappeared from a wetland because of the impacts of introduced animals and they do not return to the wetland after the introduced animals have been removed, **reintroduction** of the native fauna may be possible. Reintroductions should only be attempted after all threats (not just introduced animals) to the animal in question have been removed from the wetland and when it is unlikely that these threats will return.

Reintroduction programs are often stressful and dangerous to the fauna being moved, may result in the inadvertent spread of harmful diseases and pathogens, and may result in the loss of genetic integrity of an existing population. As such, reintroduction is an option that should only be considered in collaboration with the relevant authorities, typically DEC and/or the Department of Fisheries. The reintroduction, relocation (translocation) and introduction of animals into new areas are subject to regulations administered by these departments (see Table 2 for more information).

case study

Restocking native fish in masons gardens Lake, Dalkeith

A proactive partnership between a school and local and state government has achieved a significant reduction in the numbers of introduced fish in Masons Gardens Lake in Dalkeith.

In 2009 enthusiastic representatives from the City of Nedlands, Department of Fisheries and Shenton College developed an innovative project to remove introduced fish and address nuisance mosquito problems and algal blooms in the wetland, while providing the students of Shenton College with a living classroom in which to develop a range of skills and gain hands-on experience (Figure 19).

As part of an investigation into the ecology of the lake, seventy students used fish traps, scoop nets and drop nets to conduct a baseline survey of the fish population. During this survey they found the introduced eastern gambusia (*Gambusia holbrooki*) (Figure 20) co-inhabiting the wetland with native pygmy perch (*Edelia vittata*) and Swan River goby (*Pseudogobius olorum*) that were stocked by Murdoch University's Freshwater Fish Group in 2004 for the City of Nedlands.

Based on the information gained from the baseline surveys, the project partners opted to remove the eastern gambusia using traps because traps have a relatively low impact on the native fish population and wetland and are safe for use by students, unlike poison, shockwaves and electrofishing. They decided to manage the excess mosquitoes and algae in the wetland using biological remediation techniques rather than using pesticides and herbicides, which at best address the symptoms rather than the causes, and often create a range of other problems in wetlands.

The students conducted an intensive trapping regime over a three-month period using box-mesh traps to remove as many eastern gambusia as possible. It is estimated that the students removed 80 per cent of the eastern gambusia from the wetland, and at the end of trapping the ratio of eastern gambusia to native fish had fallen from 156:1 to 30:1. In comparing the efficiency of methods of capturing eastern gambusia, students found that traps caught five times more fish than hand nets. The students were able to raise awareness in the local community about the project and their findings via the local paper and a student podcast.

It is anticipated that the reduction in eastern gambusia will enable the native fish population

Figure 19. Dr Craig Lawrence from the Department of Fisheries with Shenton College students and (background) City of Nedlands staff Rob Burton and Vicki Shannon, at Masons Gardens Lake. Photo – W. Russell/courtesy of the Community Newspaper Group.

case study

Figure 20. The introduced eastern gambusia, *Gambusia holbrooki*. Photo – C Lawrence/Department of Fisheries.

in the wetland to increase. To assist the recovery of the native fish population in Masons Gardens Lake, species including pygmy perch (*Edelia vittata*), western minnow (*Galaxias occidentalis*) and smooth marron (*Cherax cainii*) were stocked into the wetland using carefully selected genetic stocks bred at the Aquaculture and Native Fish Breeding Laboratory at The University of Western Australia. These species were chosen on the basis that they are endemic to the catchment and could be supplied from the laboratory. The breeding program was an extensive and highly technical process designed to ensure that the genetic vigour of the fish was maintained. Following breeding, the individuals were carefully acclimatised to temperature and water quality of Masons Gardens Lake, and the conditions in which they were transported to the wetland (such as oxygen levels in the water) were carefully managed to maximise their survival rate in the wetland. It is proposed that Shenton College students continue ongoing monitoring of the recovery of the native fish population and trapping of introduced species to ensure their rehabilitation efforts have a long-term effect in their adopted wetland. As the eastern gambusia is a prolific breeder, it is very important that ongoing control continues.

It is hoped that by increasing the number of native fish in the wetland, nuisance mosquito problems can also be reduced, because native fish consume mosquitoes and their larvae. It is also hoped that the native fish species will consume algae, thereby contributing to the reduction of algal blooms; this is currently being evaluated.

Furthermore, the reduction in the numbers of eastern gambusia should indirectly lead to a reduction in algal blooms. This is because eastern gambusia prey on water fleas (*Daphnia carinata*), an aquatic macroinvertebrate that feeds primarily on algae. The loss of water fleas from the wetland can lead to algal blooms, which in turn provides an abundant food source for mosquitoes and midges, which can stimulate population booms.

In these ways, it is hoped that the biological remediation program improves the condition of the wetland while reducing the need to resort to the application of pesticides and herbicides in the wetland in the future.

This project, which is improving the habitat of the native fish population and the condition of the wetland using low-impact management techniques with the participation of local students, is an inspiring model for future wetland management initiatives.

Note: this case study has been compiled from information in a report by Shenton College students[137] and personal communication with Dr Craig Lawrence. The methods employed in this project were undertaken in compliance with regulations governing the management of freshwater fish and crustaceans; see Table 2 for more information.

Sources of more information on managing nuisance and introduced animals

General

Department of Agriculture and Food Western Australia
www.agric.wa.gov.au
Information on introduced animals considered pests to agriculture and the environment, including a list of declared pest species and information on management options, is provided on the Department of Agriculture and Food website.[144]

Feral.org.au
www.feral.org.au
Website and database containing information on vertebrate pest animal species in Australia and New Zealand.

Invasive Animal Cooperative Research Centre
www.invasiveanimals.com
Australia's largest integrated invasive animal research program.

Codes of conduct and standard operating procedures

Department of Local Government and Regional Development (2003) *Code of practice for the capture and marketing of feral animals in Western Australia*[57]

Various codes of conduct and standard operating procedures for the humane capture, handling or destruction of introduced animals in Australia published by the Department of Sustainability, Environment, Water, Population and Communities[58]

DEC's Standard Operating Procedures for monitoring (which includes trapping that may be extended to control operations) may be found on the DEC website[59]

Department of Health (2009). *A guide to the management of pesticides in local government pest control programs in Western Australia*[145]

Species-specific

Australian white ibis

Department of Environment and Conservation (2007). *Prevention and control of damage by animals in WA: Australian white ibis* Threskiornis molucca[135]

Camels, feral

Department of Agriculture and Food (2000). Farmnote No. 122/2000 [Reviewed 2008] *Feral camel*[146]

Cane toads

Cane Toads in Oz
www.canetoadsinoz.com

Department of Environment and Conservation (2009). *Cane Toad Strategy for Western Australia 2009–2019*[139]

Department of Environment and Conservation
www.dec.wa.gov.au/canetoads

Kimberley Toad Busters
www.canetoads.com.au

Northern Australian Frogs Database System
www.frogwatch.org.au

Stop the Toad Foundation
www.stopthetoad.org.au

Cats, feral

NSW Department of Primary Industries. *Model code of practice for the humane control of feral cats*[75]

Donkeys, feral

Department of Agriculture (2000). Farmnote No. 121/2000 [Reviewed 2007] *Feral donkey*[147]

Fish and crayfish, introduced

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Goats, feral

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Horses, feral

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Kangaroos

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Livestock, feral

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Pigs, feral

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Rabbits, feral

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Turtles, introduced

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Monitoring

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Reporting introduced animal sightings

Pest and Disease Information Service: 1800 084 881

FISHWATCH service, Department of Fisheries: 1800 815 507

Glossary

Aquatic invertebrates: those animals without a backbone (such as insects, worms, snails, molluscs, water mites and larger crustacean such as shrimps and crayfish) that live in or on water for at least one phase in their life cycle

Amphibians: the class of animals to which frogs, toads and salamanders belong. They live on land but develop by a larval phase (tadpoles) in water.

Biodiversity: a contraction of the words 'biological' and 'diversity', encompassing the whole variety of life forms—the different plants, animals, fungi and microorganisms—the genes they contain, and the ecosystems they form

Biological control: the control of an introduced plant or animals by the introduction of a natural predator or pathogen, usually bacteria, viruses or insects, or by biological products such as hormones

Browsing: feeding on leaves, twigs or bark from non-herbaceous (woody) plants, such as trees and shrubs

Endemic: naturally occurring only in a restricted geographic area

Erosion: the gradual wearing away and movement of land surface materials (especially rocks, sediments, and soils) by the action of water, wind, or a glacier

Eutrophication: the nutrient enrichment of a water body, which can trigger prolific growth of plant material (phytoplankton, macrophytes or both). May occur naturally over geologic time or may be human-induced

Feral animals: introduced animals that have escaped, or have been released, from domestication and returned, partly or wholly, to their wild state

Grazing: feeding on grasses and other low-growing herbaceous vegetation

Habitat: an area or environment where conditions are suitable for the survival of an organism, taxon or community

Herbivores: animals that chiefly eat plants

Hybrids: the results of interbreeding between two animals or plants of different species

Introduced animals: species of animals that have been intentionally or unintentionally brought into a region where they did not historically occur, usually facilitated by humans

Livestock: introduced domestic ungulate (or hoofed) animals

Nuisance fauna: native animals that naturally occur at a site, but which have reached a population size that is causing harm to the environment or humans

Nocturnal: primarily active during the night

Omnivorous: feeding on both plants and animals

Pesticide: any chemical or biological agent intended to kill animals or plants

Piscicide: a chemical substance which is poisonous to fish

Propagule: any part of a plant from which a new plant can grow, including seeds, bulbs and rootstocks

Pugging: depressions, hoof prints or 'pug' marks made in wet soil by trampling animals

Reintroduction: the deliberate release of a species in an area which is part of its natural historical range but in which it no longer occurs

Sedimentation: the process by which soil particles (sand, clay, silt, pebbles and organic materials) suspended in water are deposited or settle to the bottom of a water column

Threatening process: a process that threatens, or may threaten, the survival, abundance or evolutionary development of a native species or ecological community

Turbid: the cloudy appearance of water due to suspended material

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column

Personal communications

Name	Date	Position	Organisation
Bill Bardsley	18/06/2010	Senior Biosecurity Officer	Department of Fisheries, Western Australia
Cara Francis	23/07/2009	Technical Officer	Department of Environment and Conservation, Western Australia

Dr Craig Lawrence	04/2010	Principal Research Scientist; Adjunct Associate Professor	Department of Fisheries, Western Australia; The University of Western Australia
Mark Muir	27/07/2010	Chairman	Lake Muir Denbarker Community Feral Pig Eradication Group
Dr Stephen Beatty	08/05/2012	Research Fellow	Murdoch University

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A guide to managing and restoring wetlands in Western Australia

Livestock

In Chapter 3: **Managing wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Livestock' topic

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Contents

Case studies

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'. In particular, note that grazing constitutes clearing under the provisions of the Environmental Protection (Clearing of Native Vegetation) Regulations 2004 and you may require a permit to graze livestock. For additional detail, see the section of this topic entitled 'Legal considerations'.

Livestock: for the purposes of this topic, the term livestock refers to introduced domestic ungulate (or hoofed) animals. While the focus is on sheep, cattle and horses as these are commonly farmed at or near wetlands, general principles introduced in this topic will also apply to other introduced ungulates such as goats, donkeys, deer, llamas, alpacas and camels. Management of feral populations of these animals is discussed in the topic 'Introduced and nuisance animals' in Chapter 3.

Introduction

The **livestock** industry was one of the first to be established in WA, and it remains extremely important to the state's economy. Since pastoralism first expanded across the state, wetlands have been valued as watering points and areas of good grazing for livestock. As farms became established, many wetlands in agricultural areas were cleared for pasture.

Wetlands contain valuable resources for livestock, including water for drinking and cooling off, trees for shade and shelter and plants that are highly palatable. As a result, wetlands are often used more intensively by livestock than other areas of the landscape, especially when it is dry and during drought. Many factors influence the degree to which livestock may impact upon a wetland, but in many cases, livestock grazing has resulted in significant degradation of wetlands.

Fortunately, livestock management systems better suited to Western Australian conditions are now available and becoming more popular. With livestock grazing forming the main land use across more than 40 per cent of the state, livestock management practices have the potential to affect many of WA's wetlands (Figure1). Sound management of wetlands on grazing land can have benefits for landholders and their livestock, the local community and future generations, because well managed wetlands can provide a range of services valuable to society. Livestock owners can use the management and restoration practices outlined in this topic to minimise the impacts of livestock, improve the condition of their wetlands and, in many cases, improve the health of their animals.

Figure 1. (below) (a) A fenced well-managed wetland in good condition on a horse property near Serpentine. Photo – C Prideaux/DEC. (b) A wetland near Gingin degraded by continuous cattle access. Water is contaminated by sediment, nutrients and faeces, vegetation has been damaged and removed and soils are pugged and exposed. The landowner is currently undertaking fencing to exclude livestock. Photo – R Lynch/DEC.

(a)

(b)

Ten good reasons to keep livestock out of wetlands

Allowing livestock to access wetlands is not only damaging to wetlands, it can also compromise livestock health, reduce productivity and create management problems. Sound livestock management will have benefits for wetlands and positive effects on livestock health and productivity.

1. Livestock contaminate wetland water with urine and faeces, disease-causing organisms and sediments. The poor water quality may cause livestock to reduce their water consumption or refuse to drink from the wetland. Providing alternatives to direct watering from wetlands improves water quality and some studies have found it improves livestock health and productivity.[1]
2. When water levels are low, livestock with no alternative water sources may be forced to wade through mud to drink. Weak or sick animals can become trapped and die.
3. Nutrients from livestock urine and faeces can accumulate in wetland waters and cause excessive algal growth. Blue-green algal blooms caused by excess nutrients in the water can be toxic to livestock.
4. Midges and mosquitoes can be more abundant in wetlands and, in particular, wetlands with poor water quality can be predisposed to nuisance midge populations. Livestock, especially horses, can suffer irritation and allergic reactions to these insects. In some areas, livestock may also be at greater risk of mosquito-borne disease.
5. Livestock kept in waterlogged or muddy paddocks are prone to bacterial and fungal infections. Cattle can experience problems caused by wet mud-covered udders and hooves.[1] Horses can suffer from infections of the hooves and legs such as 'mud fever', 'greasy heel', thrush[2] and sheep from foot rot and fly strike.[3]
6. Parasites such as Barber's pole worm, a serious roundworm parasite of sheep and goats in coastal and high rainfall areas of WA, can survive where pasture remains green over summer.[4] Allowing uncontrolled livestock access to wetlands can exacerbate worm problems and counteract worm control programs.
7. While some wetlands contain palatable native plants, most native vegetation is of low to very low nutritional value. Livestock that spend substantial time grazing coastal wetlands may develop deficiencies in trace elements such as copper and cobalt and require supplementation (R Butler 2009, pers. comm.). Sheep, cattle and horses which graze on stringy and fibrous native vegetation may develop fibrous masses called 'phytobezoars' in various parts of their gut[5] (Figure 2). These can cause obstructions, peritonitis and, occasionally, death (R Butler 2009, pers. comm.).

Figure 2. Phytobezoars inside a sheep gut, formed after grazing on native vegetation. Photo – R Butler/ Department of Agriculture and Food.

8. Mustering and moving livestock can be more difficult when they have access to wooded wetlands, where they can hide.
9. Allowing livestock to access wetlands can spread weeds, which can reduce biodiversity, increase the threat of fire and result in the need for costly weed management.
10. A degraded wetland filled with green, foul-smelling water, blue-green algae which are toxic to humans and livestock, and clouds of nuisance insects, is a management problem, a hazard and an eyesore. In contrast, many people will find a well-managed wetland visually appealing, enjoy the fact that it provides recreational opportunities and attracts native animals such as birds and frogs (Figure 3). A wetland in good condition can be an asset which demonstrates good land management practices and may add value when selling a property or diversifying into farm-based tourism.

How do livestock affect wetlands?

Before European settlement, Western Australian wetlands were grazed by native animals such as kangaroos, wallabies, emus and waterbirds. Native plants have adapted to **grazing** by native animals at natural densities[6] and it is thought that this natural process may be important in maintaining species and structural diversity in some wetlands.[3] However, heavy grazing by any animal will damage native vegetation, regardless of whether it is domestic or commercial livestock, feral animals, native fauna, rabbits or insects.[6]

Livestock access can cause severe degradation of wetlands. Livestock activities can compact and erode the soil, increase runoff and levels of sediments, nutrients and contaminants in wetlands, change the vegetation and degrade the habitats of native animals (Figure 3). These changes can cause serious damage to wetland **ecosystems** (Figure 4). Impacts can be compounded by certain management activities such as clearing of native vegetation for pastures, leaching of farm chemicals, fertilisers and other treatments into water supplies. Other poorly planned activities like carcass burial and inappropriate placement of infrastructure can impact on wetland condition.[7] Well-placed stockyards, waste ponds, roads and storage facilities can improve efficiency and reduce environmental impacts.

Grazing: feeding on grasses and other low-growing herbaceous vegetation

Ecosystem: a community of interdependent organisms together with their non-living environment. Natural ecosystems provide a range of benefits and services to humans such as clean water, nutrient cycling, climate regulation, waste decomposition and crop pollination

Figure 3. Sheep have contaminated this seasonally inundated wetland with faeces and urine, pugged the soils and removed most of the vegetation. Photo – R Lynch/DEC.

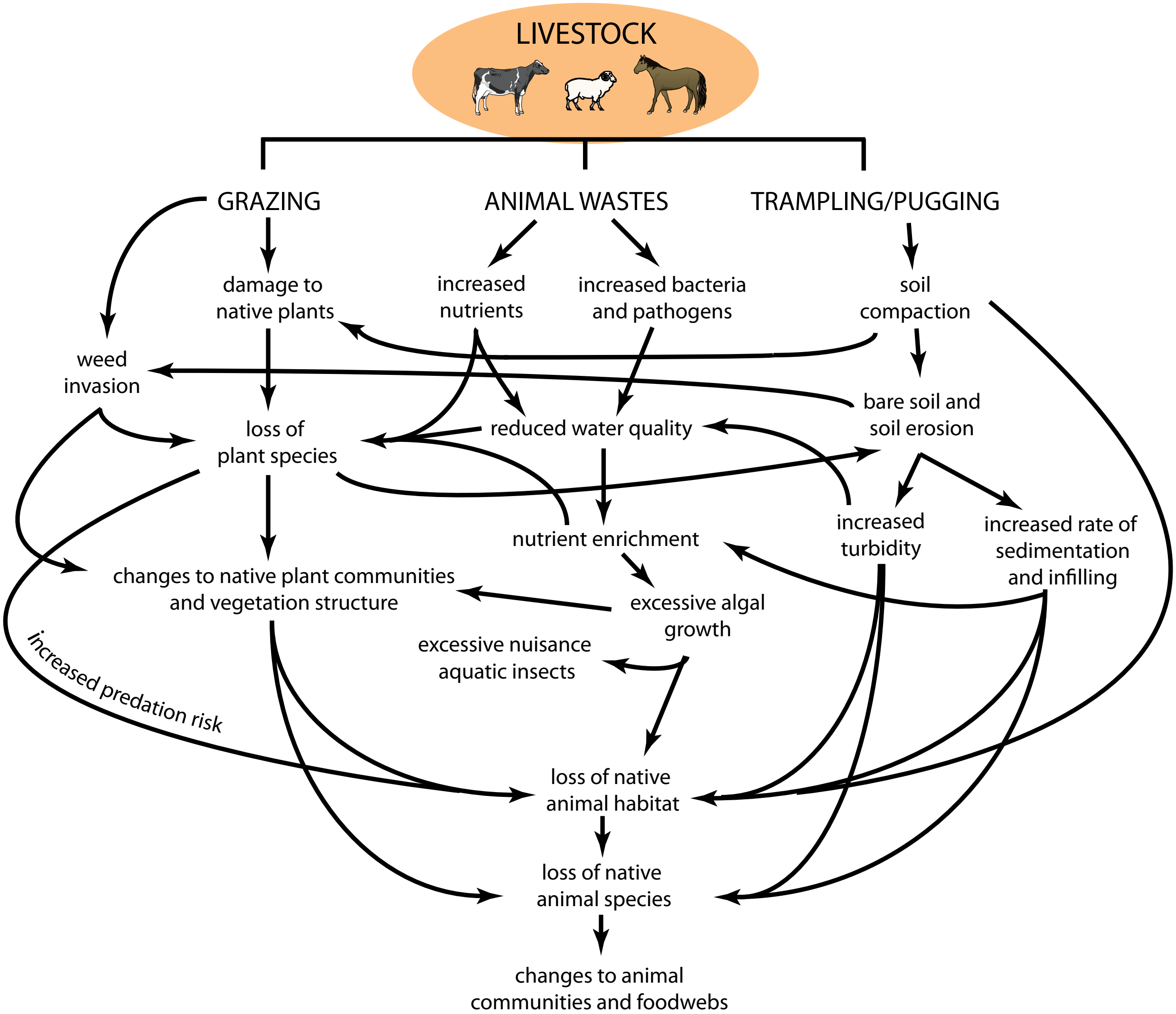


Figure 4. Some impacts of livestock on wetlands.

Effect of wetland type and season

Wetlands differ in attractiveness to livestock depending on the resources present and the time of year. Wetlands with permanent fresh water may be used for drinking by livestock all year round, especially if there are no alternative water sources. This can result in severe impacts on soils, vegetation and water quality (Figure 5). During hot, dry periods of the year and during drought, impacts may be intense as livestock will loiter in wetlands that are shady and cool even when alternative drinking water is available.

Figure 5. This permanent spring near Gingin has been severely degraded by continuous cattle access. Photo – C Mykytiuk/WWF Australia.

Wetlands that are dry at some times of the year may have less livestock activity when they are completely dry. However, this is not always the case, as these wetlands often support a wide variety of very palatable plants both when they are drying out and when dry, and they may be favoured by livestock for grazing at these times (Figure 6).

Figure 6. (below) Large areas of flat, (a) seasonally inundated and (b) seasonally waterlogged wetlands on the Swan Coastal Plain, like these near Dunsborough, were historically cleared for agriculture as they are highly productive. Photos – R Lynch/DEC.

(a)

(b)

Impacts on wetland vegetation

Livestock do not affect all species of plants in the same way, but the overall effect of uncontrolled livestock grazing is to degrade wetland vegetation. The impact of livestock on wetland vegetation depends on many factors. These include the plant species present, the age and size of individual plants, the type of livestock, the stocking rate, the timing of grazing and environmental conditions such as rainfall.

Unmanaged, livestock will reduce native plant diversity, reduce the structural complexity of vegetation and degrade wetland habitats. These impacts can be compounded by other impacts such as plant diseases, drought, weeds, fire and changes to the natural water regime.[3]

Browse: to feed on leaves, twigs or bark from non-herbaceous (woody) plants, such as trees and shrubs

Impacts of different types of livestock

Livestock affect native plants in different ways, due to their physical differences in height, their grazing preferences and the way in which they are able to use their lips and tongues[8] (Table 1). The behaviour of livestock also varies with factors such as herd size, breed and climatic conditions.[9]

Cattle are unable to graze as close to the soil as other species, so the survival of herbaceous species (herbs) is always higher with cattle grazing than sheep.[10] The mobile lips of sheep and the way they use their tongues allow them to feed very selectively. They can easily choose individual leaves over others on the same plant and graze plants very close to the ground.

Goats are similar to sheep in their ability to selectively graze, but prefer a wider range of plants in their diet. They are quite adaptable to different food types and **browse** by climbing high into vegetation to feed. Up to 80 per cent of their diet can be from small trees and shrubs.[8] Goats should always be excluded from wetlands as they cause enormous damage to wetland vegetation.[11]

Table 1. Feeding preferences of cattle, horses and sheep[12,8,3]

Cattle	Horses	Sheep
Are least selective	More selective than cattle	Most selective grazers
Cannot graze as close to the ground as sheep	Tend to be spot grazers, grazing one area close to the ground and leaving other areas for droppings	Can crop vegetation very close to the ground
Prefer plants 10–30 cm in height	Like short grasses and avoid grazing woody plants	Prefer drier vegetation and are more likely to graze on woody seedlings; prefer to graze plants in the following order: herbs, broadleaved grasses, fine-leaved grasses, sedges, and dwarf shrubs
Can reach higher to browse upper stems of shrubs and lower tree branches	Can kill paddock trees by defoliating and bark stripping	Cannot browse shrubs and trees as high as cattle
Will readily enter water to feed on emergent wetland vegetation and can remove whole stands	Will enter water	Do not like to enter water

Physical damage to plants

Livestock grazing damages plants and plants differ in their ability to withstand this impact.

Grazing livestock remove the leaves or foliage from plants (called defoliation) and sometimes uproot the whole plant. This removes nutrients which must then be re-acquired from the soil. Plants may not recover well when nutrient availability is low as defoliation can reduce a plant's ability to take up nutrients when they are in low supply.[13]

Plant species respond to livestock grazing in different ways[14] and differ widely in their ability to withstand the impact of defoliation.[10] For example, a study in which plants were clipped to simulate grazing found that the clipped plants responded in one of three ways. In some species, amount of plant material and reproduction increased, in some the amount and reproduction decreased, and in others the amount decreased while reproduction increased.[15] For some plant species, grazing at low intensity stimulates greater growth, but in general plant performance decreases as grazing intensity increases.[12]

Many wetland plants are sensitive to grazing when they are seedlings and when they are flowering or setting seed. Grazing may impair reproduction by reducing flowering and seed production which results in fewer new plants being produced.[9,10] **Annual** species are usually more tolerant of disturbance because they grow fast and produce lots of seed early. Palatable **perennial** species of **herbs**, shrubs and trees are more vulnerable, because they are comparatively slow-growing and usually require several years to reach reproductive maturity.[16] Seedlings can also be more vulnerable to grazing as their root systems are not fully established.

Livestock graze selectively, choosing the ground layer plants and seedlings they prefer first, along with **palatable** shrub and tree foliage within reach[6] (Figure 7). Grazing animals often prefer new plant growth and revisit grazed patches to feed on regrowth[12], so individual plants can be repeatedly defoliated. Over time, continuous grazing may reduce the capacity of plants to survive, grow and reproduce.

Annual: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) within a single growing season

Perennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) in two or more growing seasons

Herb: a small non-woody, seed-bearing plant in which all the above-ground parts die back at the end of each growing season

Palatable: pleasant-tasting

Figure 7. Cattle have grazed and trampled the understorey and created a 'browse line' by eating the low foliage from these paperbark trees in a wetland near Muchea. The cattle have not eaten the less palatable *Astartea* spp. shrubs (on the left).
Photo – C Mykytiuk/WWF Australia.

Livestock also damage plants by trampling, rubbing and ring-barking.Trampling and tracking–can damage and kill **understorey** plants (Figure 8). Rams, bulls and stags like to butt and rub against trees and shrubs, damaging branches and causing death by ringbarking. Horses, which are more active that other livestock, are also notorious for killing isolated paddock trees by stripping bark and foliage, often out of boredom[6] (Figure 9). Other types of livestock will also strip bark, for example, sheep will chew bark and ringbark trees, often in autumn when there is little fibre in paddock feed.[6]

Understorey: the layer of vegetation beneath the main canopy

(a)

(b)

Figure 8. Effects of livestock trampling on wetlands. (a) Cattle tracking has damaged a samphire (*Sarcocornia* spp.) wetland community in Capel. Photo – S Priddle/NGH Environmental. (b) Horses have trampled wetland vegetation along a fence line within a paddock near Australind. Photo – R Lynch/DEC.

(a)

(b)

Figure 9. Bark-stripping by livestock. (a) Horses have stripped the bark of a tree in a seasonally waterlogged wetland near Capel. Photo – K Wenziker/DEC. (b) Cattle have stripped bark from a paperbark (*Melaleuca* spp.) tree in a wetland on the Swan Coastal Plain. Photo – M Rogers/ DEC.

Some wetland plants and plant communities are more sensitive to livestock impacts than others. The following case study profiles the effect of livestock on samphires.

case study

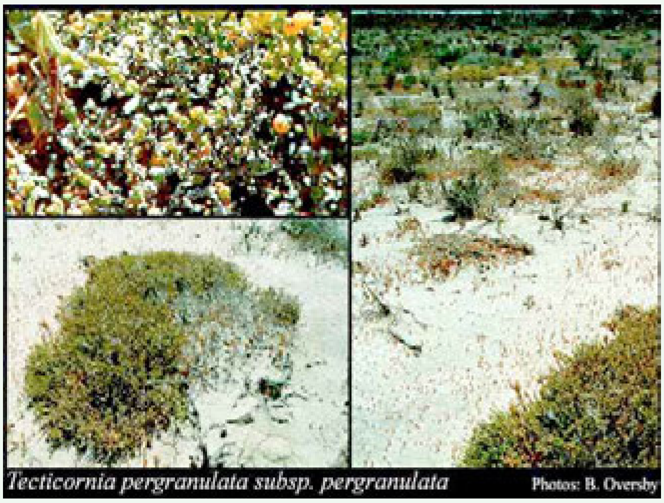
Samphires – grazing-sensitive wetland plants

The name samphire refers to a group of delicate perennial low succulent shrubs including *Sarcocornia, Halosarcia* and *Tecticornia* species. Many saline wetlands in Western Australia support samphires, such as salt lakes, salt pans, salt marshes, coastal flats and saline drainage lines. Many samphire species have evolved to grow in specific areas, under certain conditions in harsh environments and are quite fragile and susceptible to change.[17] Samphires grow actively only during wet periods. Samphires in general produce large quantities of seeds that are held in spongy or woody parts of the plant to be released when conditions are suitable for germination.[17] They germinate after rain when the soil is wet with relatively fresh water.

In general, samphires are high in salt and have low feed value for livestock[18], but sheep will eat samphires if there is fresh water for them to drink and access to supplementary dry food such as crop stubble[17] (Figure 10). Samphires are brittle plants and are particularly sensitive to trampling by hoofed animals. Where grazing and trampling is indiscriminate, samphire plants may be unable to regenerate or re-establish and they can die out.[19]

Where samphire areas are to be grazed, it is best to fence them and only allow sheep to graze for a short period when it is dry and other feed is exhausted. To maximise their recovery, they should be protected from livestock for the rest of the year.[17]

➤ For more information about samphires, see *Samphires in Western Australia.*[17]



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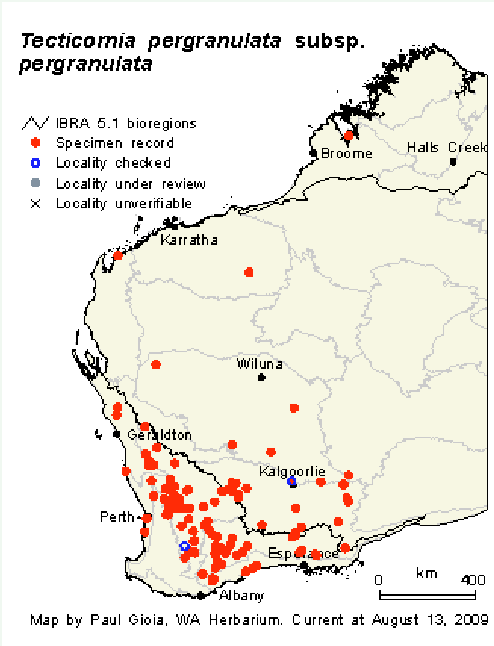


(b)

Figure 10. (a) Blackseed samphire (*Tecticornia pergranulata*) is commonly used as animal feed.[17] Photo – B Oversby; (b) Distribution of blackseed samphire in WA. Image – P Gioia/DEC. Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright.

case study

Mound springs in the WA rangelands – wetlands especially vulnerable to livestock grazing

Mound springs are an uncommon wetland type which occurs around permanent groundwater springs. Most of WA's mound spring types occur either in a restricted geographic area or there are a few isolated occurrences.

In the rangelands of WA, existing mound springs are known from the Kimberley region and in and on the edge of the Great Sandy Desert. They occur singularly or in clusters of up to around twenty separated by several metres to tens of kilometres.[20] These wetlands contain 'mounds' formed from peaty organic soil which can rise up to two metres above the surrounding landscape and be up to several hundred metres across.[20] Research at two mound springs in the Great Sandy Desert has shown that organic sediments have accumulated continuously over the past 6,000 years.[21] The mound is often surrounded by a moat of fresh or low salinity water.[20] Mound spring vegetation can range from sedgelands to paperbark (*Melaleuca*) forests to *Sesbania* woodlands to monsoon vine thickets.[20] The plant and invertebrate communities of mound springs are often diverse or unusual and sometimes contain rare plant species which were more widely distributed in the past when the climate was wetter.[20] As well as having significant ecological values, many mound springs have cultural values for local Aboriginal people.

The presence of permanent water, dense vegetation and sometimes shade can make mound spring communities particularly attractive to cattle as well as feral camels and pigs. Mound springs are particularly vulnerable to livestock activity as it damages the vegetation, causes erosion of the fragile peat soils, can promote weed invasion and contamination of the groundwater source. Several mound spring community types have been listed as threatened ecological communities (TECs).

Springs and mound springs can be best protected by fencing them to keep livestock out (Figure 11, see also Figure 31).

Figure 11. Two plant communities within Saunders Spring, an organic mound spring, in the Shire of Broome. Photos – G Daniel/DEC.

Loss of leaf litter

Livestock reduce leaf litter. **Leaf litter** performs several important ecological functions: it breaks down to return nutrients to the soil, it creates habitat for invertebrates and other small animals and it protects the soil surface from the sun. Loss of leaf litter can affect plants by changing the microclimate around them, allowing heat to damage their roots, increasing water loss and reducing their growth.[6] Grazing livestock remove much of the foliage that would become leaf litter and some livestock, such as sheep, even consume leaf litter when other food sources are in short supply.

Leaf litter: dead plant matter including leaves, flowers, nuts, sticks and bark which accumulates on the ground

Diversity: a measure of the number of species of a particular type and their abundance in a community, area or ecosystem. It can refer to a particular group of organisms, such as native plant diversity or frog diversity. The broader term **biodiversity** is used to encompass the whole variety of life forms–the different plants, animals, fungi and microorganisms–the genes they contain, and the ecosystems they form

Figure 12. Leaf litter around shrubs in a wetland. Photo – K Wenziker/DEC.

Weed invasion

Livestock can promote weed invasion of wetlands. There are many wetland weeds that pose serious threats to the condition of WA wetlands. Many weeds also greatly reduce the grazing value of wetlands. Weed seeds may be carried into wetlands in the coats, hooves or faeces of livestock as well as by wind and water.[22] Nutrients in livestock urine and faeces and bare patches of ground created by overgrazing or trampling increase opportunities for weeds to grow.[22]

Many weed species are well adapted to coping with grazing, as they originate from regions of the world where hoofed animals are part of the natural environment. Weeds tend to be good at either growing back quickly or withstanding damage from trampling and grazing. In general, weeds are fast growing and reach reproductive maturity more rapidly than native plants, so livestock grazing often doesn't disrupt reproduction to the degree that it does for native plants.

Weeds have a detrimental effect on native vegetation by competing with and inhibiting growth of established plants, inhibiting native plant regeneration, altering nutrient cycling and reducing native plant **diversity**.[6]

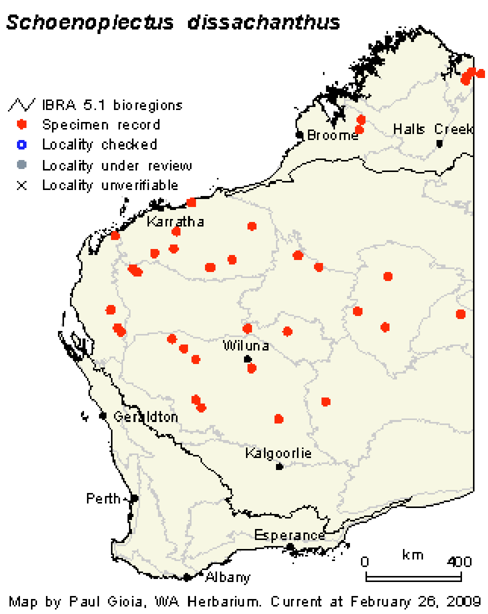
➤ For additional detail, see the topic 'Wetland weeds' in Chapter 3.

Reduction in plant diversity and complexity

Some plant species decline in numbers under continuous livestock grazing while other species increase. Over time this leads to loss of native plant diversity. Livestock activity can cause changes to the abundance and diversity of plant species in a wetland. There is often a decrease in the palatable, grazing-sensitive species (called 'decreasers') and an increase in the number and distribution of unpalatable and grazing-resistant species (or 'increasers').[10] For example, pale spikerush (*Eleocharis pallens*), a perennial sedge found in central Western Australian wetlands, and *Schoenoplectus dissachanthus* (Figure 13), an annual sedge found in central WA and Kimberley wetlands, both decrease under persistent grazing. Bluerod (*Stemodia florulenta*), an erect faintly scented perennial shrub, is a wetland 'increaser'.[18] Many weed species are 'increaser' species.

Figure 13. (below) (a) *Schoenoplectus dissachanthus*, a wetland decreaser. Photo – CP Campbell. (b) *Schoenoplectus dissachanthus* distribution in WA. Image – P Gioia/DEC. Images used with the permission of the Western Australian Herbarium, Department of Environment and Conservation http://florabase.dec.wa.gov.au/help/copyright.

(a)



(b)

Loss of 'decreaser' species and greater dominance of 'increaser' species results in plant communities with lower native plant diversity. Such changes in abundance of native plant species are often a sign of declining land condition.[18]

Over time, uncontrolled livestock activity reduces the vegetation structure of wetland plant communities. Livestock grazing on native shrub and tree seedlings can prevent them from reaching maturity and reproducing. As mature trees age and die naturally, they are not replaced and the **vegetation structure** may change from a wetland with trees to a more open community (Figure 14).

Vegetation structure: the three-dimensional distribution of plant material. It includes the horizontal spacing of plants and the vertical heights or layers

Figure 14. (below) (a) A wetland near Bunbury in good condition showing diversity of plant species and vegetation structure (layers). Photo – R Lynch/DEC. (b) A wetland in the Shire of Serpentine-Jarrahdale degraded by continuous heavy cattle grazing. Ground layer plants have been removed, the soil is compacted, mature trees have aged and died and there are no seedlings to replace them. The bare soil is more susceptible to erosion and colonisation by annual weeds. Photo – E Davies Ward/DEC.

(a)

(b)

Soil damage

Livestock trampling can damage the soil, increase erosion and reduce soil spaces, and decrease water infiltration, nutrient cycling, germination and plant growth. **Pugging** is a highly visible form of soil damage caused by livestock activity in and around wetlands (Figure 15). It occurs as their hooves sink into wet soil, leaving depressions and compacting and damaging the soil surface and microstructure, and leaving it more vulnerable to erosion.[23] Compacted soil contains fewer spaces, known as **macropores**, within the soil. Macropores are important for soil aeration and the activity of microbes and other soil fauna, which play an important role in cycling nutrients and maintaining the condition of the soil. When there are fewer spaces between soil particles, less water can soak into the soil. As a result less moisture reaches plant roots[24] reducing plant growth and vigour. Soil compaction may also damage native seeds stored in the soil, reduce their germination, and reduce the chance of germinating seeds reaching the soil surface. Small pools of water that form in the depressions left by pugging can increase the period of time that plants stay wet, causing poor performance or favouring other species more tolerant of the altered conditions. Soils are at greatest risk of compaction when they are wet and heavily grazed.[23]

Pugging: depressions, hoof prints or 'pug' marks made in wet soil by trampling animals

Macropores: spaces in the soil (usually less than 2 millimetres diameter) that include channels created by cracking, old plant roots and soil fauna (such as earthworms). Macropores indicate good soil structure

Wetland hydrology: the movement of water in and out of, and within, a wetland

(a)

(b)

Figure 15. (a) Soil pugging by cattle in a seasonally inundated wetland near Gingin. Photo – C Mykytiuk/WWF Australia. (b) Soil pugging by horses in a seasonally waterlogged wetland. Photo – M Rogers/DEC.

Changes to wetland hydrology

Livestock tracks and farm infrastructure can degrade wetland ecosystems by changing the natural pattern of water flow to and from wetlands. 'Critical control points' are natural landscape features that act as dams or levees, causing surface water flows to slow, spread and pool, creating wetlands. They range from rock bars across rivers to low ridges of sand which trap water in small intermittently inundated wetlands.[25] Trails made by livestock and tracks for farm vehicles can act as shallow channels which breach (cut through) critical control points. Instead of slowing and pooling in the wetland, water flow is faster and concentrates along these pathways of bare compacted soil. This increases soil erosion and creates problems such as gullies. Depending on the circumstances, these incisions may channel more water and contaminants into wetlands or divert water away from wetlands. In some cases, this process has caused the intrusion of salt water into freshwater wetlands.[26] Altering drainage patterns can affect **wetland hydrology**, which may have major implications for wetland plants and animals and physical and ecological processes.

➤ For additional detail, see the topic 'Wetland hydrology' in Chapter 2.

For example, in the Murchison River catchment and tropical floodplain grasslands of northern Australia, cattle trails to river pools often breach critical control points on grassy floodplains (seasonally inundated wetlands). The water that formerly spread out across the floodplain becomes channelled along the cattle trails, forming erosion gullies which cut back into the floodplain. The changed drainage pattern has negative impacts on ecology and production in the rangelands. Instead of capturing water which can soak into the soil, the floodplains are drained rapidly and less palatable dryland shrubs begin to replace the native grassland community.[26]

Erosion: the gradual wearing away and movement of land surface materials (especially rocks, sediments and soils) by the action of water, wind, or a glacier

➤ For an example of pastoralists working together to reverse the problem discussed above, see the case study about Wooleen Lake in the Murchison River catchment in *Pastoral management options for central Australian wetlands – Fat cows and happy greenies*[18] (p.61).

Why wetlands shouldn't be dug out

Many farmers dig out natural wetlands to increase the depth or permanency of water for livestock use or other reasons. There are several reasons why this should not be done.

- Using heavy machinery to excavate wetlands causes soil compaction and damage to the soil surface and vegetation.
- Disturbing wetland soils in acid sulphate risk areas can cause acidification of soils and water.
- Changing the topography (landscape shape) alters the wetland's hydrology and habitats. This may change the types of plants and animals that can occur there.

It is better to find alternative sources of water, leave these valuable habitats undisturbed and appreciate them for their natural values, such as the wildlife that occur there.

➤ For additional detail about the impact of acid sulphate soils in wetlands, see the topic 'Water quality' in Chapter 3. For additional detail about wetland hydrology, see the topic 'Managing hydrology' in Chapter 3.

Soil erosion, turbidity and sedimentation

Livestock activity can cause soil erosion which degrades wetland habitats. The movement or **erosion** of soil by rain and flooding is a natural process, but this process can be greatly accelerated by livestock. When soil becomes compacted by livestock trampling, less rainfall infiltrates into the soil and more flows over the soil surface. This is compounded by the loss of groundcover to slow the water down and by the presence of livestock trails which channel the water (Figure 16). When more water flows more rapidly across the soil surface, it can remove more topsoil and create fissures and gullies in the ground (Figure 17).

➤ For additional detail about the effects of erosion on wetland water quality, refer to the topic 'Water quality' in Chapter 3.

Turbid: the cloudy appearance of water due to suspended material

Figure 16. Livestock trails through the vegetation have created new pathways for the movement of surface water and contaminants into the wetland. Photo – C Mykytiuk/WWF Australia.

Figure 17. Erosion and gullying caused by cattle grazing. Photo – R George/Department of Agriculture and Food Western Australia.

Soil erosion in a wetland's catchment results in increased quantities of sediment entering the wetland during rain and floods. Fine particles may remain suspended in the water, causing **turbid** conditions. In this 'muddy' state, less light is available to water plants and algae for photosynthesis, which causes reduced plant growth or death. As sediments begin to settle, they smother animals living on the bottom by clogging their gills and causing problems for filter-feeders; coat organic deposits and algae upon which aquatic animals depend for food and cover; and fill in aquatic habitats.[27, 28] Over time, increased erosion and sedimentation can gradually fill in wetland basins.[27]

Groundcover: the percentage of ground covered by plant materials (alive or dead) and leaf litter

Erosion is a serious environmental problem, particularly in arid lands managed for pastoral production.[29] The most important factor in reducing erosion is managing total grazing pressure. **Total grazing pressure** describes the combined impact of all grazing animals—domestic, wild, native and feral—on the vegetation, soil and water resources of a particular area.[30] When too many animals are grazing an area, **groundcover** will be reduced by grazing and trampling and the soil will become exposed and vulnerable to erosion.

Erosion is influenced by other factors including the body weight and type of grazing animal, slope steepness and the ability of the soil type to withstand trampling under wet conditions.[23] Livestock access to steep slopes, particularly by cattle (which are heavier than other species), can result in substantial damage such as collapse or slumping of banks and gullying.[9,14] Some types of livestock, although lighter in body weight, can cause extensive soil damage and promote erosion when allowed access to wetlands, because of their specific behaviours. For example, red deer deliberately create muddy wallows during the mating season, cake mud onto their hides to assist in scratching off their winter coats, and use mud to protect themselves from biting insects at other times of the year.[23] Pigs rapidly damage areas of wetland because they dig, turn over the soil and uproot vegetation while foraging for roots, tubers and invertebrates.

Nutrient enrichment

Livestock faeces and urine entering wetlands can cause nutrient enrichment, algal blooms and nuisance insect problems. Livestock faeces and urine are highly concentrated sources of nutrients, particularly nitrogen and phosphorous. Most Western Australian soils have naturally low levels of nutrients and native plants are adapted to cope with this. Livestock faeces and urine can be detrimental to the survival of some native plants, such as banksias[6], which cannot tolerate high levels of phosphorus.

Livestock faeces and urine are deposited directly in wetlands when livestock are allowed to graze in them. Excess nutrients from livestock faeces and urine, fertilisers and eroded sediments also enter wetlands from surrounding pastures in surface water runoff or by leaching into groundwater that flows into the wetland. Increased nutrients in wetlands (especially nitrogen and phosphorous) can result in excessive growth of water plants and algal blooms (Figure 18). Algal blooms may include blue-green algae, some of which are toxic to humans, pets, livestock and wildlife. They can also can cause taste, odour and aesthetic problems (they look like a green paint-like scum on the water).[27]

Figure 18. An algal bloom in a nutrient-enriched wetland on a cattle property near Muchea. Photo – C Mykytiuk/WWF Australia.

Changes in plant growth can alter the type and quantity of food and habitat available to wetland organisms, affecting food web structure and function, as well as favouring some species over others. Algal blooms deplete the oxygen supply which can result in death of aquatic animals (such as fish kills).[27] Nuisance midge numbers are often higher in nutrient enriched wetlands.

➤ For additional detail, see the topic 'Water quality' in Chapter 3.

extra information

How much faeces and urine?

Horses and cattle produce large amounts of faeces and urine. A standard light horse (450 kilograms) produces approximately 5.5 tonnes of wet faeces and 5.5 kilolitres of urine each year. This volume of waste contains 62 kilograms of nitrogen (N) and 5.5 kilograms of phosphorus (P).[31] If poorly managed, livestock faeces and urine can contaminate both groundwater and surface water[31] (Figure 19).

Figure 19. Grazing horses have removed most of the native vegetation in this seasonally inundated wetland in Kenwick. Horse manure accumulating on the degraded pasture will be washed into the water during heavy rainfall as there is little vegetation to trap it. Photo – M Rogers/DEC.

Contamination by pathogens

Livestock faeces are a source of bacteria, viruses and parasites which can pose serious health risks to humans, livestock and wildlife. Bacteria, such as *Salmonella*, and other harmful disease-causing organisms can enter wetland waters from livestock faeces and urine. Infection can lead to scouring (diarrhoea) and death of livestock. Research has shown that young livestock (particularly foals and dairy calves) have higher rates of infection by the parasites *Cryptosporidium* and *Giardia* and excrete large amounts of infective oocytes or cysts[32,33] which can contaminate water supplies. Some strains cause diarrhoea, and sometimes death, in young or weakened humans, livestock and other animals.

Faecal contamination is likely to be higher when livestock are allowed free access to wetland waters; no alternative drinking water is provided; stocking rates are high; the livestock are deer or cattle (these species are more likely to defecate in the water); or there is no alternative shade available in hot weather.[23] Contamination can also occur when livestock become trapped and die in wetlands or groundwater sources become contaminated by buried carcasses.

Chemical contamination

Unless carefully managed, agricultural chemicals such as herbicides, veterinary chemicals, fuel, oil or solvents can leak or drain into surface water or leach into groundwater. The active ingredients of some worm drenches are toxic to invertebrates (of which many are beneficial to soil health); these toxic drenches can enter the water when they leach out of faeces and urine.[31] Unless carefully managed, spraying herbicides, pesticides or fertilisers onto pastures next to wetlands can cause death of native plants and animals and contaminate wetland waters through run-off and spray drift.

Impacts on native animals

Livestock can impact native animals by trampling them or their nests and degrading the habitats and resources they require. Wetlands in good condition provide a wide variety of habitats and resources such as food, shelter, roosts and breeding sites and are important to a wide range of native animals. When these resources are degraded, some species may not be able to survive or breed (Figure 20). In particular, animal species that breed, shelter or feed on the ground, under leaf litter or in low vegetation may be more affected by loss of food sources, at greater risk of injury or nest damage by livestock trampling or be more exposed to predation due to loss of protective vegetation cover.[3] For example, on floodplains in south-eastern Australia, frog and bird communities varied with livestock grazing intensity.[34] Frog diversity, the numbers of some species of tadpoles and frogs and the numbers of small insect-eating birds (which depend on insects found in understorey vegetation, fallen logs and leaf litter) were lower where grazing intensity was higher because of impacts of grazing on wetland vegetation.[34,35]

Figure 20. Cattle have damaged this wetland near Harvey and degraded the resources used by wetland animals. The soil is trampled and exposed. The water is muddy and contaminated with wastes. Most native understorey vegetation has been grazed and trampled, except the unpalatable species in the foreground. Photo – R Lynch/DEC.

Aestivating: being in a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Trampling also closes spaces and cracks in the ground, collapses burrows and may crush soil-dwelling invertebrates, frogs, tortoises and small mammals.[36] For many intermittently inundated wetlands in semi-arid and arid pastoral lands, the top layer of soil is extremely important when the wetlands are dry, as it contains the dormant stages of aquatic invertebrates, **aestivating** burrowing frogs, seeds and carbon stores until the next time the wetlands are inundated.[37] Trampling can compact and disturb this soil layer and its plant and animal life, and grazing removes the vegetation, exposing the soil to wind erosion.[37]

Grazing livestock also compete for food with native grazers. Livestock grazing may reduce the abundance of important food plants or seeds eaten by certain animals. Native animals often take refuge in wetlands during droughts. As introduced livestock and feral animals also use wetland areas more intensively at these times, native vegetation may become severely overgrazed.

case study

Endangered burrowing crayfish – wetland animals threatened by livestock

The Dunsborough burrowing crayfish (*Engaewa reducta*) is found in seasonally inundated freshwater wetlands between Dunsborough and Margaret River in the south-west of WA.[38,39] The crayfish are small (up to 5 centimetres in length) with large claws that are usually vivid purple or cobalt blue[38] (Figure 21a). They are found in a variety of wetland habitats with moist sandy or loamy soils, including vegetated seeps, swampy plains and swamp headwaters of streams. They construct a complex burrow system that can be several metres deep. At wetter times of the year burrows are marked by conspicuous chimneys of soil pellets (Figure 21b). Their burrows enhance the flow of oxygen, water and nutrients through wetland soils and provide shelter and retreats for other organisms, especially when their habitats dry.

The Dunsborough burrowing crayfish is listed as a critically endangered species under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. The main threats to the crayfish are land clearing, farm dam construction and cattle grazing.[39] Cattle activity leads to soil compaction and erosion, reduces the water-absorbing and water-holding capacity of soils and trampling of burrows. Farm dam construction alters surface and groundwater flows, increases sedimentation and leads to waterlogging or flooding of suitable habitats.

Two very similar species of *Engaewa* crayfish – the Margaret River burrowing crayfish (*E. pseudoreducta*) and the Walpole burrowing crayfish (*E. walpolea*) – are listed as threatened species under Western Australian legislation.[38] Protecting critical habitat with livestock-proof fencing is a key conservation measure for all of these species of crayfish.[38]

Figure 21. (below) (a) The endangered Dunsborough burrowing crayfish (*Engaewa reducta*). Photo – K Rogerson/DEC. (b) A 'chimney' of soil pellets at the entrance of a crayfish burrow. Photo – J Jackson/DEC.

(a)

(b)

Managing livestock in and around wetlands

Sustainable agriculture is defined as profitable agricultural systems that conserve the environment while contributing to the economic and social wellbeing of rural WA.[40] The challenge for landowners and managers is to manage livestock and properties to be both profitable and ecologically sustainable in the long term. In the past, society and markets have not valued wetlands, but this is now changing and landholders whom manage wetlands are expected to ensure they are in good condition. The good news is that sustainable land management has positive outcomes for landowners and their livestock and that there is assistance, such as technical and financial assistance, available to enable landowners to manage wetlands.

There are four main strategies for managing livestock in and around wetlands (Figure 22):

1. Permanently exclude livestock from the wetland – this is the best option for wetlands.
2. Keep the wetland in reserve for special or emergency use only – this is the best of the options for grazing wetlands.
3. Graze the wetland for a short time period as part of a controlled grazing system – a better option than continuous grazing but this needs to be carefully managed.
4. Continuous wetland grazing – this option has the most impact on wetlands.

Livestock properties are very diverse. They range from a single paddock with a few horses for recreational purposes to extensive sheep and cattle enterprises in the WA rangelands. In considering which strategy is most suitable at a site, many factors relating to the property, the landowner's aims, and the nature of the wetlands need to be taken into account. Note that these options refer to livestock grazing systems and not to intensive livestock-keeping such as feedlots.

Four strategies for managing livestock in and around wetlands

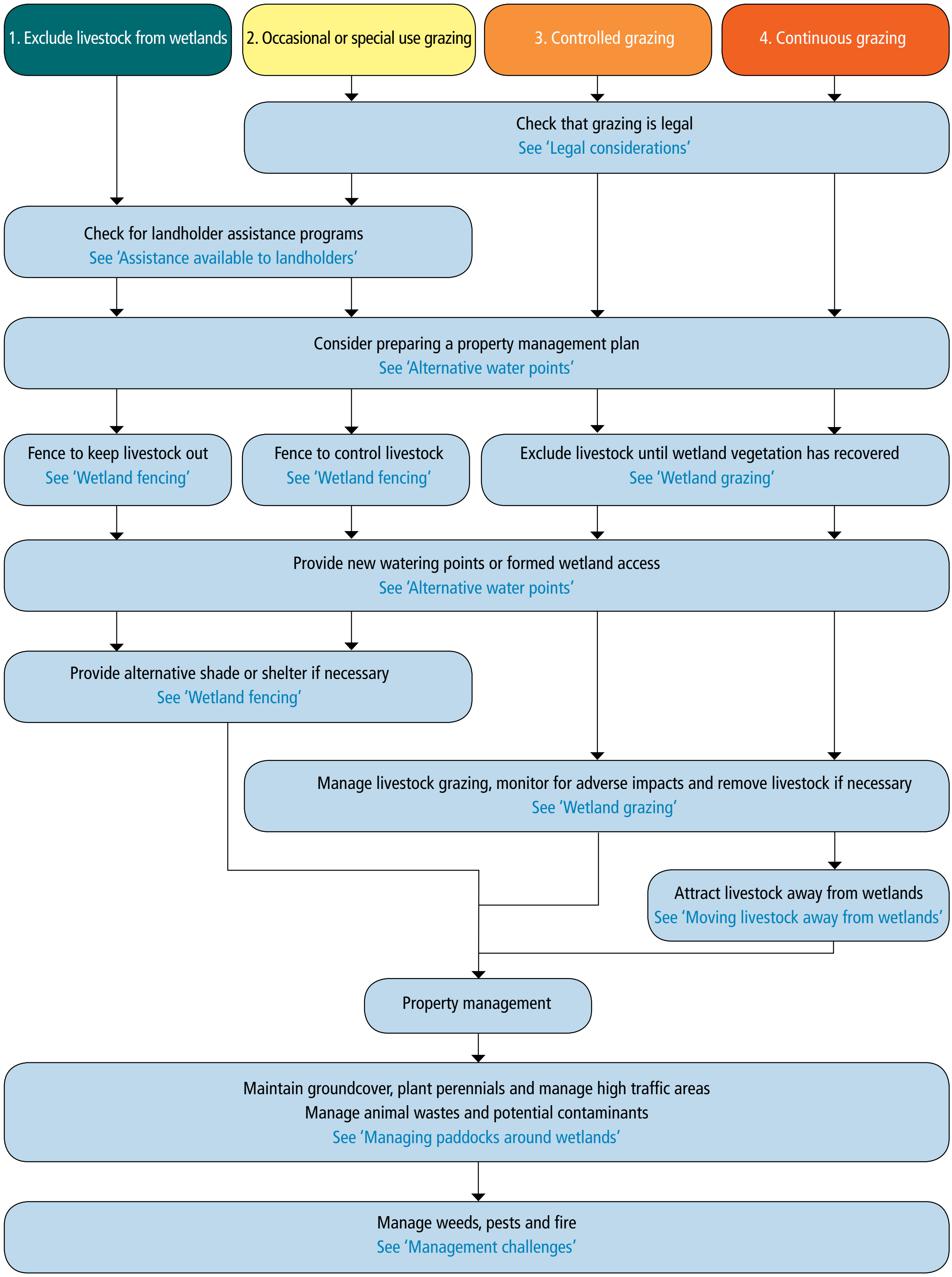


Figure 22. Four strategies for managing livestock in and around wetlands

Assistance available to landowners

Nature conservation assistance programs

There can be significant costs in effectively managing wetlands on livestock properties. Government and non-government organisations recognise that ecologically sound livestock management practices can contribute to the preservation of Western Australia's environment. As it benefits the wider community, a number of organisations have established programs to assist landowners to make positive changes.

➤ Wetland conservation assistance programs are listed in the topic, 'Funding, training and resources' in Chapter 1.

Tax deductions for landcare operations

Landholders or lessees may be able to claim a tax deduction in the year they incur capital expenditure on a 'landcare operation' for land in Australia. Landcare operations cover what were previously known as 'land degradation measures'. Landcare operations include the following activities: erecting fences to keep animals out of areas affected by land degradation, to prevent or limit further damage and help reclaim the areas; erecting fences to separate different land classes in accordance with an approved land management plan; eradicating, exterminating or destroying plant growth detrimental to the land; eradicating or exterminating animal pests from the land; and preventing or combating land degradation other than by the use of fences.

➤ For more information see *Landcare operations tax concessions*[42] from the Australian Taxation Office website (www.ato.gov.au).

Legal considerations

The *Environmental Protection Act 1986* (EP Act) contains provisions for the protection of native vegetation in WA while allowing for approved clearing activities. The native vegetation clearing provisions of the EP Act and the Environmental Protection (Clearing of Native Vegetation) Regulations 2004 came into effect on 8 July 2004 and are administered by DEC. These regulations govern all forms of land clearing. Livestock grazing is clearly identified as a type of clearing, because of its impact on native vegetation. Activities such as increasing the stocking rate on native pastures or grazing regenerated areas will require a permit if an exemption does not apply.

➤ The EP Act and the Environmental Protection (Clearing of Native Vegetation) Regulations 2004[43] can be viewed online at the State Law Publisher's website at www.slp.wa.gov.au. Fact sheets outlining the clearing provisions are available from DEC's website at www.dec.wa.gov.au/nvc.

Farming activities, such as land-use change or intensification, can have the potential to impact upon environmental assets including threatened species and ecological communities, migratory birds, wetlands of international importance, World Heritage properties and national heritage places. Activities which have the potential to impact on these assets need approval under the Australian Government *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The *Environmental Reporting Tool*[44] can provide an indication of whether a particular property is likely to contain any matters of national environmental significance under the EPBC Act.

➤ For more information see *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and *Farming and the national environment law: EPBC Act* fact sheets at www.environment.gov.au/epbc. Other fact sheets are available from the National Farmer's Federation (NFF) (www.nff.org.au/policy/nrm.html). Free advice on how the EPBC Act applies to particular properties is available from the Environment Liaison Officer at the NFF (email: environment@nff.org.au).

Property management planning

Livestock owners can employ a number of strategies to reduce the impacts of livestock on wetlands. A property management plan is a useful way to identify, plan and integrate new strategies into a farming operation. A **property management plan** or whole farm plan is a working plan for the design and management of a property based on its natural resources, the activities undertaken (such as horse breeding or beef production), the manager's goals and financial considerations.[45] A well thought-out and achievable plan can have many benefits including meeting personal and lifestyle goals; maximising the productivity, profitability and sustainability of a property by designing the most effective layout for paddocks, roads, watering points and other infrastructure; and managing and protecting natural resources such as wetlands. Many land managers have taken the steps involved in a property management plan but may not have recorded them in a plan or kept it up to date. A written property management plan is a valuable management tool that maintains a record of information and decisions and can also help with obtaining approvals, funding and tax concessions by demonstrating a duty of care to the environment and natural resources.[45]

➤ See *How to develop a property plan*, available at www.agric.wa.gov.au. HorsesLandWater *Management Guidelines*[45] also provide information about property management planning for horse-keepers. For assistance with property management planning, landholders with small properties (up to 100 hectares) can contact the Small Landholder Information Service (SLIS) at the Department of Agriculture and Food Western Australia or visit www.agric.wa.gov.au. In the rangelands, the Ecologically Sustainable Rangeland Management Program (ESRM) based within the Department of Agriculture and Food can help with property plans. For more information, see www.esrm.com.au.

Some land managers may wish to develop a more detailed plan of management for their wetland. A wetland management plan can also help with obtaining approvals, funding and tax concessions. Various organisations can assist with property planning and wetland management advice. For guidelines on wetland management planning see the topic 'Wetland management planning' in Chapter 1.

Figure 23. Pastoralists engaged in a property planning workshop as part of the Ecologically Sustainable Rangelands Program (ESRM). Photo – L Bayley/Department of Agriculture and Food.

Section 1: Wetland fencing

Fencing is the best tool for reducing the impact of livestock on wetlands. Keeping livestock out of wetlands can reduce erosion and promote livestock safety, protect or improve water quality, regeneration of native vegetation and habitats for native animals. Where it is not feasible to exclude livestock from wetlands, managers can use fencing to control livestock access.

As fencing is often a significant investment it is worth doing well the first time, by planning carefully, choosing good quality materials and using sound construction, as wetland fences often come under extra pressure compared to dryland fences. Issues to consider include the type of livestock, fence location, costs and maintenance requirements. Good access gates may be needed to carry out fire, weed and pest management, and for recreational use and livestock access, if grazing is to be permitted. Where livestock are excluded from wetlands, it is necessary to ensure that they have alternative sources of water, food and shelter.

Fence placement

To protect the whole of a wetland by fencing it involves identifying the whole area of the wetland. For example, a wetland that has surface water for all of the year will have one or more areas that are always under water, as well as areas that are only under water for part of the year. There will also be areas that are waterlogged after the wet season or after cyclonic rain but that eventually dry. As a rule of thumb for fencing purposes, the outer edge of the seasonally waterlogged area following successive wet seasons is the edge of the wetland.

➤ For additional detail on different types of wetlands and determining a wetland boundary, see the topic 'Wetlands in Western Australia' in Chapter 2.

It is best to position fences well above the highest known flood limits. Wetlands are very dynamic environments—that is, they vary over time—and during very wet years, they may cover a much larger area than in dry periods. Placing the fence too close to the edge of the open water can result in flood damage or loss of fences. If possible, locate fence lines where there is low erosion hazard to minimise damage from fence line tracking by livestock.[18]

➤ Determining a wetland boundary can be difficult. For advice about determining an appropriate place to put wetland fencing, contact your local regional DEC office, landcare organisation or NRM wetlands officer.

Fencing an area of dry land between the wetland and the adjacent paddocks helps to buffer wetlands from livestock impacts. Another way to maintain and improve biodiversity is to link wetlands with other areas of remnant vegetation on the property using corridors.

extra information

Wetland buffers and corridors

A buffer is an area of dryland around a wetland that can help to protect the wetland from the impacts of livestock and farm activities, such as chemical and fertiliser drift, wind erosion, nutrient enrichment and weed invasion.

Natural regeneration or replanting a wetland buffer can have other benefits, such as providing a windbreak or shade for livestock outside the fenced area, habitat for native animals and by using water, which may help protect the area from salinity caused by rising groundwater.

For some landholders, allowing for a wetland buffer will be a sacrifice of productive pasture on the wetland margin. However, wetland buffers can be used creatively to provide economic benefits as well as wetland protection. Maintaining or planting the buffer with local native bushland species could be a source of native seed for other local revegetation projects, provide timber, carbon or firewood. Examples which provide future economic benefits include native tree species for timber, carbon or firewood collection, sandalwood (with its host jam trees) or oil mallee for their specific products. It is best to choose species which do not require fertilising or irrigation as these activities will compromise the purpose of the buffer. In each of these cases, harvesting needs to be carefully planned and managed so that it doesn't reduce the function of the buffer or damage the wetland.

➤ For advice about determining an appropriate buffer width, contact your local regional DEC office. For more information about bushland buffers on farms, see the Department of Agriculture and Food publication *Vegetation buffer zones*[46] (www.agric.wa.gov.au).

Wildlife corridors (also known as ecological linkages) are a good way to maintain and improve biodiversity in rural landscapes. Doug and Eva Russell, cattle farmers in Manypeaks, have fenced wetlands and remnant vegetation on their farm (Figure 24). Seventy-three hectares of remnant vegetation and wetlands have been covenanted with the National Trust and their property is registered with DEC's *Land for Wildlife* program. The Russells have used fencing, direct seeding and planting to create vegetated corridors through the cleared farmland which now connect the wetlands and dryland remnants.

(a)

(b)

Figure 24. (a) Doug Russell at a lake on his Manypeaks farm which he has fenced off from cattle. Photo – B Schur/Green Skills Inc. (b) An aerial photo showing (in red) two corridors that have been revegetated to connect fenced wetlands and remnant vegetation. The corridor on the left is along a creek (that flows out of the lake in the foreground) and, in this photo, it had been recently planted. Photo – K Hopkinson/Green Skills Inc.

Fencing for flood-prone areas

When choosing fencing to use near wetlands, it is also important to consider the frequency and extent of flooding that occurs at the site. Fences in wet areas may deteriorate very quickly so putting in expensive fences may be a waste of resources. Instead, portable fencing that can be contracted or expanded to prevent damage to the fence and injury to livestock may be an option where frequent flooding occurs. In wetlands which flow during floods, prefabricated mesh fencing may trap debris like a net and collapse. Plain wire fencing with strainer assemblies either side of the floodway is one option to minimise damage. If it fails, only the section between the strainers will be lost (Tim Saggers 2009, pers. comm.). Lay-down fencing and drop-down fencing are other options for flood-prone areas.[47]

➤ For flood-proof fencing designs see the Department of Water's Water Notes 19 *Flood-proof fencing for waterways.*[47]

Types of fencing

There are many fence designs available to suit different situations. Table 2 compares the advantages and disadvantages of fences commonly used around wetlands. Fences around wetlands can come under extra pressure from livestock (Figure 25) when there is a feed shortage in their paddocks or where there is intensive grazing, so it is essential that they are well constructed. Local knowledge is usually a good guide to local best practice.[48]

➤ Good sources of information on fence types and costs are fencing manufacturers and suppliers (many have informative websites) and local fencing contractors.

Figure 25. Cattle from the paddock on the right have pushed their way through this barbed wire and star picket fence protecting Saunders Spring, a mound spring in the Kimberley, to access the regenerating pasture and wetland vegetation on the left. Photo – G Daniel/DEC.

Table 2. Advantages and disadvantages of common fence types used to exclude livestock from wetlands

Fence type	Advantages	Disadvantages
Plain wire high-tensile fencing High-tensile fencing consists of up to seven tensioned strands of wire usually supported by wooden posts or steel star pickets.	• lower construction costs compared to prefabricated mesh fences • suitable for covering long distances • strong • simple to maintain • longest lasting (up to thirty years) • plain wire (rather than barbed) is less prone to flood damage[49] • less damage to kangaroos (and the fence) compared to mesh fencing	• may deteriorate rapidly if inundated • plain wire is less effective in controlling livestock[49] • can be damaged by livestock and may require electrifying or use of barbed wire for two strands[50] • cheaper for straight sections, more expensive to follow contours[48,51] • plain wires have low visibility and horses in particular have been known to sustain leg injuries from entanglement. Plastic-coated 'sighter' top wires can be used to improve visibility.
Prefabricated mesh fencing These consist of strong 'ready-made' mesh such as Ringlock, Stocklock® and Griplock® suspended between droppers and end posts, often supplemented with one or two plain or barbed top wires. Mesh is manufactured in a range of horizontal wire spacings suited to different types of livestock.	• excellent control for cattle, sheep, lambs and vermin • requires fewer droppers, because the intermediate support is in-built • copes well with minor damage as snapped wires are supported by surrounding mesh	• more expensive than other types of fencing • can be damaged by flooding as it tends to collect more debris than plain wire • may create a barrier for native animals • difficult to repair where many wires have snapped • more damaging to livestock and native fauna (e.g. kangaroos) when they get legs tangled in the mesh
Electric fencing An electric fence consists of a power source/energiser, an earth/insulation system and a post/wire arrangement. Construction can be as simple as electrified tape on insulated poles which can be put in by hand. Alternatively, electric wires can be incorporated into traditional permanent wire fences or added as an outrigger to existing or deteriorated fences. The design of the fence and the shock the animals receive should be matched to the type of livestock and livestock need to be trained or educated to electric fences before they can be relied on.[52] Mains power is the most reliable and least expensive option but is not available in all areas. Solar powered battery energisers are another option.	• cheap to establish[52] • quick and easy to erect and move[52] • low risk of injury or damage to livestock • can follow the contours of the area to be protected, resulting in the need for fewer materials[52] • if inundation is a problem, electric wires can be removed and coiled for storage • cattle will generally require only one well-placed electrified wire	• sheep require three or more electric wires with close spacings between wires • regular inspection and maintenance is important as a short circuit can render a large section of a fence ineffective • native animals and feral goats can cause frequent shorting and high maintenance[51] • need to be kept clear of grass and weed growth, falling branches and debris • not suitable where overgrowth of vegetation is likely • poor earthing and lightning strikes are common problems • not a physical barrier and may not stop aggressive animals • electric fences and energisers can pose a danger to people, especially children, and if people can access the fence warning signs are mandatory • small native animals, such as echidnas and bandicoots, may be killed by electrified wires close to the ground[53]

Native animals and wetland fencing

Wetland fencing may unintentionally exclude or trap native animals. Mesh, barbed, plain and electric wire fences have caused injuries and deaths of bats, kangaroos, wallabies, small mammals, waterbirds (Figure 26), birds of prey and owls.[54] Wetland fences can pose a higher risk of entanglement or injury when they are new, where they cross animal flight paths and tracks into a wetland and where they are less visible at the boundary between low pasture and taller native vegetation.[54] The top and bottom wires are where animals most often come in contact with the fence, with small animals such as echidnas and snakes being killed by electrified wires close to the ground.[53]

Figure 26. Straw-necked ibis (*Threskiornis spinicollis*) are commonly seen in wetlands. This individual died after it became entangled in barbed wire fencing. Photo – A Johnson/Tolga Bat Hospital.

These problems can be minimised by choosing a fence type and location that increases fence visibility and by installing native animal access ways, such as gates. The use of four or five strands of plain wire fencing is considered safer for native animals than barbed wire or mesh and is usually effective for livestock control where stocking rates are not high. Barbed wire fencing can be modified to reduce wildlife injuries by replacing the top two wires with plain wire or covering barbs with tubing such as longitudinally split poly pipe. In areas where entanglement is a problem, fence visibility can be increased by attaching metal tags, old CDs, tin cans or aluminium pie dishes to the top two wires. Other options include solid high-tension nylon sighter wire which glows in the dark and is used mainly for horse fencing.

As well as being injured, kangaroos and emus can cause damage to fences (Figure 27). Allowing them to pass through safely reduces fence damage, repair costs and time spent locating escaped livestock. Kangaroos and wallabies generally cross fences by crawling through lower wires or by digging underneath; generally their least preferred option is to jump over. Prefabricated mesh fencing can be dangerous to kangaroos and wallabies, but even plain wires can cause entanglement if they attempt to jump over or through while being chased. Emus usually try to roll between the wires. Solutions can be relatively simple. A cattle producer in the Murchison found that stringing the bottom wire one foot above the ground let native animals move underneath and reduced damage by kangaroos and emus.[51] Placing the bottom wire 15–20 centimetres from the ground will allow kangaroos to go under, but it should be noted that lambs will also be able to get under (Tim Saggers 2009, pers. comm.). Owners of a cattle property in Queensland found positioning two end posts separated by a gap too narrow for cattle, allowed animals to move through the high-tensile fence without injury or causing damage.[53] Livestock-proof kangaroo access gates can be installed where kangaroos have dug under a fence along a well-used kangaroo track (Figure 28).

➤ For more information, see *Wildlife Friendly Fencing Guidelines*[53] at www.wildlifefriendlyfencing.com and DEC Fauna Note 32 *Fencing and gates to reduce kangaroo damage.*[55]

Figure 27. Kangaroos have damaged this mesh fence in order to access the wetland. Photo – E Davies Ward/DEC.

Figure 28. A livestock-proof kangaroo gate in a fence around Lake Mealup in the Shire of Murray. Photo – P Wilmot/Lake Mealup Preservation Society.

extra information

Barbed wire fences around wetlands – a problem for brolgas

Barbed wire fences around wetlands can be especially hazardous to large waterbirds.[56] For example, brolga (*Grus rubicunda*) which occur in northern WA, have large wingspans of 2 metres or more, require space for a 'run-up' to gain momentum for take-off and their long legs hang down for both landing and take-off. Fences, especially barbed wire, placed close to wetlands and in flight paths can entangle these and other large waterbirds such as black-necked storks (*Ephippiorhynchus asiaticus*).[56] Young birds and those not familiar with fences are the most vulnerable. Fencing around wetlands can also prevent young flightless brolgas from following their parents between pastures where they feed and roosting and breeding areas in wetlands.

➤ For more information about this issue and alternative fence designs, see the *Australian Crane Network*[56] at ozcranes.net.

Providing alternative shade or shelter

On some farms, wetland vegetation is important for livestock welfare, as it provides shade and shelter for livestock such as newly shorn sheep or ewes with lambs.[57] For this reason landholders can be reluctant to exclude livestock from wetland vegetation, or may choose to place fences very close to the vegetation, so that livestock can shelter.[57] However, in the long term, this approach can cause erosion and jeopardise wetland condition, because livestock will browse the wetland vegetation through the fence. Horses and sheep tend to 'track' along fence lines often causing excessive damage to vegetation and soil in these areas.[45] Alternative shade and shelter can reduce livestock dependency on wetland areas. Constructed shelters may fulfil the requirement for shelter in the short term, with strategically placed, fenced clumps of fast growing native shade trees or perennial shrubs providing a long-term alternative.

➤ Local Department of Agriculture and Food offices can provide advice on appropriate local plant species suitable for livestock shelter.

Natural regeneration or revegetation

If natural processes of the wetland are still functioning (that is, sources of native plant seed are present as soil seed banks or there is native vegetation nearby) and growing conditions are good, wetland plants will regenerate naturally (Figure 29). If the land has been cleared for a long time and native species and seed banks are depleted, revegetation may be a better option.

➤ For additional detail, see the topic 'Managing wetland vegetation' in Chapter 3.

Figure 29. Sandy Lyon, a cattle farmer with a property south of Stirling Range National Park, has fenced off flat-topped yate (*Eucalyptus occidentalis*) wetlands and associated remnant vegetation on his property. There has been prolific regeneration of flat-topped yate and paperbark (*Melaleuca* sp.) trees in some wetlands, rushes and sedges in others. Photo – B Schur/Green Skills Inc.

Section 2: Alternative watering points

When livestock are excluded from a wetland previously used for livestock watering, it will be necessary to provide alternative watering points. Even without the use of fencing, careful siting of alternative watering points can attract livestock away from wetlands, reducing grazing pressure in these sensitive areas and distributing grazing more evenly through dryland pastures. This needs to be planned carefully though as horses and cattle, in particular, like to cool off by standing in water or under trees during hot weather and may enter the wetland despite that fact that alternative water points are available.

Some benefits of providing an alternative watering system include:

- cleaner water, which can promote healthier livestock, less disease, increased growth rates and better wool, milk and meat production
- better capacity to match needs of livestock (for example pregnant or lactating) to the available pasture
- better control of grazing patterns and improved feed utilisation
- reduction in livestock losses due to floods or bogging
- reduced mustering times
- improved wetland condition.[51]

Providing a watering system for livestock can be relatively simple for small properties which have another readily available water source and few livestock. For extensive landholdings with large numbers of livestock that require a lot of water, installing a watering system can be expensive and time-consuming to establish and may involve ongoing maintenance and operating expenses, though the effort can be offset by the many advantages. Careful planning and consideration should be given to the best system for a given property, purpose and paddock layout.[51] The choice of watering system will depend on several factors including:

- the available water source/s
- the amount of water required
- the paddock layout
- the distance between the water supply and watering point and between watering points
- the height difference between the water supply and the watering point/s[51]
- the availability, type and quantity of feed.

➤ Case studies of watering systems used successfully by farmers in different parts of Australia are provided in *Stock and waterways: a manager's guide*.[51]

Water sources

In WA, the Department of Water regulates the use of water from many sources and a permit or licence may be required to take water from a natural surface water source, build a dam or weir, collect water in a dam or drill an artesian bore. Local government approvals may also be required.

➤ More information about farm water supply, licensing and permits can be obtained from regional Department of Water offices or from the Department of Water's Rural Water Planning Team. A range of Department of Water *Water Facts* publications are available at www.water.wa.gov.au.

Also, bear in mind that taking water from the environment, whether it is surface water or groundwater, may adversely affect the wetland you are trying to protect.

➤ For additional detail, see the topic 'Managing hydrology' in Chapter 3.

The quality of alternative water sources needs to be determined before establishing alternative watering points. The quality of the water required by livestock is determined mainly by the total soluble salts (the salinity) it contains. All livestock require access to clean, fairly fresh water, but different livestock have different tolerances to salt levels, and tolerance also varies with circumstances and conditions.[58]

➤ For more information, see the Department of Agriculture and Food's *Water quality for farm domestic and livestock use.*[58]

Water troughs are a common way to provide water to livestock and protect wetlands from trampling and fouling (Figure 30). Livestock prefer to drink from troughs rather than natural water bodies because they don't have to stretch their heads below their feet to drink, which they don't like to do due to their poor depth perception and behaviour adapted for predator avoidance.[59] Troughs need to be cleaned and checked regularly to ensure they provide a continuous supply of clean fresh water, especially in the dry season. Portable and permanent troughs may be manually or automatically filled by water pumped or piped from surface water, rainwater, groundwater or scheme water.

Figure 30. Water troughs provide clean drinking water for livestock excluded from fenced wetlands. Photo – P Maloney/Department of Agriculture and Food.

Surface water

Landholders with legal access to natural surface water may be able to pipe or pump it to other parts of their property (Figure 31). Taking water from or near wetlands needs to be managed carefully to minimise impacts associated with altering the natural water regime of the wetland.

➤ The importance of wetland water regime is discussed in the topic 'Wetland hydrology' in Chapter 2.

Figure 31. This dam has been constructed to reduce the impact of livestock on Saunders Spring, a mound spring wetland in the Shire of Broome. Cattle can access water which is gravity-fed to the dam from the continuously flowing spring, but the wetland (in the background) is protected by fencing. Photo – G Daniel/DEC.

Dams

On larger properties which contain a suitable site, a dam that captures surface run-off can be an effective and environmentally sound option for watering livestock. In general, the soil needs to contain more than 25 per cent clay and should not be strongly structured, friable or self-mulching for dam construction. Dams need to be carefully designed with adequate natural catchment and volume to supply the number of livestock to be watered.

The viability of dams as a water source will depend on factors such as the average annual rainfall, its reliability and the evaporation rate. Evaporation rates across much of WA are very high. For example, typical evaporative water losses from farm dams in the Wheatbelt range from 1 metre per annum in the south-west to 2.5 metres per annum in the north-east.[60] 'Roaded' catchments which direct water flow into dams can be used to increase collection.[61]

Unfenced dams may be subject to the same water quality issues as wetlands where livestock have direct access to the water, so fencing and piping or pumping to nearby troughs may be a good option.

➤ For more information, see *Farm dams in Western Australia.*[62] *Dam design for pastoral stock water supplies*[63] and *Dam construction and operation in rural areas.*[64] In arid areas, see the *WaterSmart pastoralism handbook.*[65]

Groundwater

Abstracting groundwater via a bore may provide a more reliable water source, though bores can be expensive to construct and equip. The availability and quality of groundwater varies from site to site. The cost of groundwater bores will vary according to soil type and the level of the water table.[51]

Domestic water supply

Water from household supplies, such as rainwater tanks or government-provided scheme water, may be an option for small properties with very few livestock.

➤ For more information on water supply issues affecting farms, please contact the Department of Water's Rural Water Planning Team or email ruralwater@water.wa.gov.au.

Water requirements

Water requirements should be determined according to the maximum number of livestock to be watered in each paddock. When planning water requirements, allow for losses by evaporation, and consumption by native and feral animals.[67] Water requirements of livestock vary depending on the type of livestock, environmental conditions (such as temperature and humidity levels), the type of feed they are eating, physiological condition (such as pregnancy or lactation) and the quality of the water. For example, while young cattle require 25–50 litres per head per day, lactating cows feeding on grassland or saltbush require 40–100 or 70–140 litres per head per day respectively. The quantities in Table 3 are a guide to the daily water requirements of some livestock.

➤ To calculate water requirements see *The Pastoral Stock Water Workbook*[66] at www.agric.wa.gov.au. The Department of Agriculture and Food can help landholders estimate costs of maintaining livestock water and make informed decisions about existing and proposed water points.

Table 3. Daily water requirements of livestock in summer[62,69]

Type of livestock	Sheep	Beef cattle	Dairy cows	Bulls	Horses
Litres/animal/day	7	30–45	50–70	Up to 90	45

Paddock layout and water point placement

The installation of a watering system is often a trigger to implement a more efficient paddock layout.[51] Property planning can assist in this process, since paddocks and fence locations can be altered to take advantage of existing water sources or landforms which provide elevation for water storages. In some cases, it may be more practical to establish a new water supply than to pump or pipe it over long distances.

If wetlands are not being fenced to restrict livestock access, water troughs are best installed well away from wetlands to encourage livestock to move away from these areas.[52] Allowing for additional water points at the time of installation will provide backups in the event of problems and builds flexibility into the watering system. Creating a system where watering points can be shut or closed off adds the potential to move livestock around to even up grazing or spell degraded areas by shutting down a particular water point.[51] As a general guide, permanent water points should be placed:

- no more than 3 kilometres apart for effective grazing and animal production, although healthy animals can travel further[51]
- at least 50 metres from waterways, wetlands and drainage channels which feed into them
- away from boggy, fragile or degraded areas, depressions and steep slopes to minimise erosion caused by livestock tracks
- along a fence line (for easy maintenance), rather than the interior of the paddock[52]
- in the shade, to keep algal growth to a minimum.[52]

Pumps and water delivery systems

The location of the water source relative to distribution points will determine the type of watering system that can be installed. Research has shown that the flow rate to a trough is a more important factor for effective livestock watering than the capacity of the trough[52], so this should be taken into account when designing a watering system.

Pumps can be selected based on the pressure and volume of water required. The operating requirements will determine the power required to drive the pump. The main types of pump power are electric, wind, diesel/petrol and solar. Solar pump systems are generally more expensive to install, but are reliable and require little maintenance.[65] They are gaining in popularity in the rangelands as they perform well in summer and are well-suited for water points at remote sites.

➤ A good overview of the different types of pumps and power sources including their applications, advantages and disadvantages is presented in The Kondinin Group's research report *Watering stock from natural sources*[67] and New South Wales Department of Primary Industries' publication *Farm Water.*[68] In the arid rangelands, see the *WaterSmart Pastoralism Handbook.*[65]

Telemetry is a technology that allows remote monitoring of infrastructure. Data is gathered, recorded and transmitted from measuring devices (such as a flow meter at a water point) using radio or cellular phone technology without a person having to be at the location. Telemetry systems are capable of switching pumps on or off, monitoring tank or dam levels, recording rainfall, starting and monitoring generators and medicating water. This allows monitoring when access is restricted (for example during the wet season) and offers substantial savings in terms of travel costs, time, labour and vehicle wear and tear.

➤ For more information, see *Telemetry systems for remote water monitoring control systems.*[69]

Formed wetland access for livestock watering and crossings

If access to the wetland area for livestock watering or crossing is unavoidable (and legal), strategically located formed access points can reduce the impacts of livestock. A fenced compacted rocky laneway that extends down into the water (to the low water mark) is a good method for allowing strategic access (Figure 32). The following guidelines should be considered:

- Choose an area that is relatively flat – this will reduce the risk of erosion as well as being easier and safer for livestock to access.
- The area provided should be the minimum required for the number of livestock that will be using the area.
- Ensure adequate fencing around the area so that livestock are not able to access other sections of the wetland.
- Reinforce the area's surface with gravel or a similar material to reduce the erosion risk. The use of coarse rocky material to create a rough variable surface (that is uncomfortable, but not dangerous, for livestock to walk on) will minimise the time they spend at the water's edge.[70]
- Avoid areas that are well sheltered as this is will increase the likelihood of livestock loitering in the area for longer than is necessary.

Restricted access points limit trampling and grazing of wetland vegetation and may reduce, but do not prevent, faeces and urine and the associated nutrients and contaminants from entering the water. Erosion can occur at the access point if care is not taken with its location, construction and maintenance.[70]

➤ For more information about constructing livestock crossings, see *Livestock management: construction of livestock crossings.*[71]

Figure 32. A fenced laneway with a compacted rocky ramp allows cattle to access and cross a waterway, but minimises damage at the site and protects the rest of the waterway. Photo – R Thorpe/Chittering Landcare Centre.

Section 3: Wetland grazing

General principles for wetland grazing

Allowing livestock access to wetlands is not recommended, because livestock degrade wetlands. Where grazing wetlands is proposed or is to continue, consider the following points.

Determine whether grazing is legally permitted in the wetland

A permit may be required to start or alter grazing practices in wetlands under the Government of Western Australia's Environmental Protection (Clearing of Native Vegetation) Regulations 2004. Be aware that there may be land use restrictions (including the exclusion of livestock grazing) which apply to wetland and bushland areas protected or restored with grants or funding for soil, water or biodiversity conservation. Local government legislation may also restrict livestock access to wetlands and regulate the type of livestock or stocking rate.

➤ For additional detail, see the previous section in this topic entitled 'Legal considerations'.

Exclude livestock until native vegetation has recovered

It may be important initially to 'spell' a wetland paddock. Spelling involves removing livestock for a period of time so that wetland and buffer vegetation can regenerate either naturally or through plantings. Some additional vegetation management, such as weed control or seeding, may be necessary to get good regeneration results. A good groundcover of native plants is desirable and livestock should be excluded until young trees have gained sufficient height to survive grazing when livestock are re-introduced.[72]

➤ For additional detail, see the topic 'Managing wetland vegetation' in Chapter 3.

Avoid grazing after flood, fire or drought

Grazing after flood events, fire or drought can result in pugging and accelerate erosion of exposed soils. At these times, wetland plant communities are stressed and at their most vulnerable. When rain returns after a drought, livestock should be excluded until plants have had the opportunity to recover. Floods and fires may also stimulate regeneration of native wetland plants and excluding grazing after these events is a great opportunity for native seedlings to establish.

If possible, choose livestock which will cause the least damage

Consider the type of livestock allowed access near wetlands, as some will impact less on wetlands than others. For instance, sheep don't tend to enter water but are more likely to graze low woody vegetation, so might have lower impact on water quality but higher impact on regenerating tree seedlings. Pigs and goats are highly destructive foragers and should never be given access to wetlands.[3]

Monitor the effects of grazing on wetlands

Check wetlands frequently once grazing is in progress, so that problems can be managed. It is important to manage grazing so that there is sufficient vegetation growth and post-grazing stubble to protect soils from erosion and act as a filter strip for sediment and nutrients when it rains. Look for evidence of:

- browsing on shrubs and trees rather than grasses
- bark stripping or other structural damage to trees
- uprooting of wetland plants
- increased water turbidity
- pugged soils
- damage to banks.

These are signs that livestock should be moved out of the area.

➤ For additional detail on monitoring the condition of wetlands, see the topic 'Monitoring wetlands' in Chapter 4.

Riparian: the habitats adjacent to waterways and estuaries

Build flexibility into the grazing management strategy

If possible, have a range of options available to move livestock to another paddock or de-stock, if it becomes necessary. Be willing to change the grazing strategy to achieve the best outcomes. A study of a range of riparian grazing strategies in the United States of America has shown that the commitment of the livestock manager was more important to achieving good land management than the grazing strategy they chose.[59]

Controlled grazing

Livestock exclusion is the best option for maintaining and improving a wetland's nature conservation values. However, if livestock grazing is to occur in and near wetlands, controlled grazing is more likely to minimise damage to these fragile areas than continuous grazing. Under controlled grazing systems, livestock managers may manipulate the paddock size, stocking rate, grazing time and livestock classes or species mix to achieve more even grazing, faster pasture recovery after grazing, persistence of more desirable plant species and maintain pasture productivity for longer.[8] The aim is to support more livestock and produce more meat, milk or wool per unit of land while effectively reducing the environmental impacts of grazing and increasing sustainability of pastures.

A range of controlled grazing strategies have been used successfully for riparian areas[59] which, like wetlands, are vulnerable to overgrazing. Management strategies will differ depending on whether they are being applied to a fenced wetland pasture or to a larger grazing unit which includes unfenced wetlands.

➤ For more information about grazing management options for wetlands in arid and semi-arid areas, see *Pastoral management options for Central Australian wetlands – Fat cows and happy greenies*.[18]

Special use grazing

One of the better options for grazing wetlands is to fence them and keep them as a 'special use' or reserve paddock to be used only for a short period at a particular time of year or for a special purpose such sheltering sheep during severe weather or lambing. In times of a feed shortage or drought, some farmers have opened their fenced wetlands to hungry livestock. It is important to be aware that this usually results in severe damage to wetland vegetation, which may take years to recover.

Rotational grazing

Rotational grazing is one type of controlled grazing system. It involves subdividing larger paddocks into several smaller pastures. Livestock graze a particular paddock for a certain period, and are moved to another paddock to spell the previous pasture.[8] A relatively high stocking rate relative to the size of the paddock forces livestock to be less selective in their grazing and to graze the paddock more evenly, but they are removed before they start to graze plant regrowth and this allows the vegetation to recover.[8] An example of a simple time-controlled rotational grazing strategy rotates livestock between four paddocks in a general program of two weeks grazing and six weeks rest.[73] More complex forms of rotational grazing, such as strip grazing and cell grazing, involve higher grazing intensities, many smaller paddocks and short rotation times (such as 1–3 days) based on the height of remaining plant cover.

When carefully planned, rotational grazing can benefit wetland vegetation by giving it a rest period during which it can regenerate. However, rotational grazing often involves higher stocking rates which can result in rapid degradation of wetlands (see the case study 'The Collards protect wetlands on their cattle property near Gingin' at the end of this topic). Rotational grazing can also benefit wetlands from which livestock are excluded, because it minimises erosion of paddocks adjoining wetlands by maintaining higher pasture cover and reducing the build-up of livestock wastes.

➤ Meat and Livestock Australia (www.mla.com.au) provide a range of fact sheets on rotational grazing.[73] See also *Towards a better understanding of rotational grazing* in Pastoral Memo: Southern Rangelands[74]

Dormancy: a state of temporary inactivity when plants are alive but not growing, i.e. they are **dormant**

When to graze wetlands

The following recommendations can be used to determine the time of year that controlled grazing will have the least negative impacts on wetlands. The recommendations may be contradictory, because grazing will have some impact on wetlands at any time of the year. While it may not be possible to satisfy all of the recommendations all of the time, by monitoring the effects, livestock owners can adapt and improve the controlled grazing strategy used for a wetland over successive grazing periods.

Keep livestock out when soils are wet or drying out

Grazing should be restricted during and after the period of maximum rainfall. This will help to maintain good groundcover during the period when the potential for water erosion and soil loss is greatest.[22] Also keep livestock out of wetlands when they are drying out as this is a time when damage by trampling can be severe.

Avoid grazing when native animals are breeding on the ground or in low vegetation

Disturbance to vulnerable animals such as waterbirds and migratory waders at key times may induce stress, reduce breeding success and cause breeding animals to relocate.

extra information

What are waders?

Wading birds, commonly called waders, are birds that feed on aquatic invertebrates found in shallow wetlands and tidal flats. Some species live in Australia all year round, but some species breed in the northern hemisphere and migrate to Australia for summer period from September to April. Some species are protected under international agreements and the Australian Government *Environment Protection and Biodiversity Conservation Act 1999*. For more information about waders, see the topic 'Wetland ecology' in Chapter 2.

➤ For information about local native wetland plants and animals, contact your regional NRM office, regional DEC office, *Land for Wildlife*, local landcare or bushcare group.

Avoid grazing when plants are germinating, actively growing, flowering and seeding

Grazing is likely to be most damaging to palatable native plants when they are actively growing, germinating, flowering and seeding.[14] Many wetland plants can reproduce from bulbs and tubers under the ground (called **vegetative reproduction**) without producing seed. These species are more vulnerable to grazing when they are actively growing.

Grazing is likely to be least damaging when most of the plants are **dormant**.[14] Different plant species move in and out of **dormancy** at different times and the period of dormancy also varies between regions and according to weather patterns.[14] For example, in south-west WA, the native perennial wetland grass swamp wallaby grass (*Amphibromus nervosus*) grows in winter and flowers from June to November, but matgrass (*Hemarthria uncinata*) grows actively in summer and flowers from December to April.[75]

Many wetland species germinate and seed in response to dry wetland soils being re-wetted. Livestock should be removed after wetting and not be re-introduced until these species have matured and re-seeded.[18]

As there are often many species of native plants within a wetland plant community, it may be difficult to determine the least damaging time to graze because a portion of the plant species in the wetland may be growing, flowering or seeding at all times. Reducing impacts may be a matter of controlling the grazing pressure, duration of grazing and grazing at different times or in different seasons in subsequent years.

➤ Seek advice about your wetland plant community from your regional NRM office, local landcare or bushcare groups to guide decisions about timing wetland grazing.

case study

Using controlled grazing to manage habitat – a trial at Lake McLarty in the Shire of Murray

In Eastern Australia, controlled livestock grazing has been used to achieve specific wetland management goals, such as weed control and fire management.[76] Livestock grazing in wetlands has also been used to maintain habitat suitable for migratory wading birds. Timing, duration and intensity of grazing have been manipulated to slow the spread of invasive aquatic emergent plants, maintain or create patchy vegetation or reduce emergent plant cover and maintain open water.[3]

Under the *Conservation and Land Management Act 1984* and Regulations, grazing is not usually permitted in nature reserves, as it is rarely compatible with nature conservation goals. However, restricted, regulated cattle grazing is planned at Lake McLarty Nature Reserve for the purpose of habitat management.[77] Lake McLarty, which lies south-west of Pinjarra, is a highly modified wetland that has been grazed by cattle since the 1880s, yet provides valuable habitat for many native species, including wading birds. Controlled grazing is to be reinstated on a trial basis, in order to control the growth of introduced pasture grasses and the invasive introduced bulrush (*Typha orientalis*) which threaten to colonise the open water and mudflat habitats favoured by the wading birds. Department of Environment and Conservation scientists will use this opportunity to closely monitor and assess the impacts and benefits of cattle grazing together with the impacts of other habitat management practices, such as regular slashing and use of herbicides.

Figure 33. Lake McLarty, showing introduced bulrush (*Typha orientalis*) growing along the lake edge. Photo – J Jackson/DEC.

Continuous grazing

The capability of any property to support grazing livestock without becoming degraded is determined by a range of factors such as soil type, slope, drainage and rainfall.[45,78] For example, steep land with clay soil that gets soft when wet is more vulnerable to erosion than flat, well-drained land. Land with different capabilities requires different management in relation to livestock.[49] Matching grazing management to land capability reduces the potential for land degradation. For example, creating paddocks on land with good capability and protecting land with low capability such as waterways, steep slopes and wetlands. Mapping land capability classes on a property is a one of the main steps in preparing a property management plan.

The main disadvantage of continuous grazing systems is that uneven animal distribution can lead to overgrazing in certain parts of even lightly stocked paddocks.[79] In paddocks with different land types, livestock will graze some areas in preference to others. To prevent land degradation, grazing management is then constrained by having to lower **stocking rates** to protect the most susceptible parts of a paddock.[79] Wetlands are usually the most susceptible part of a paddock with the lowest land capability, and may also be most favoured by livestock. Having unfenced wetlands in a paddock (i.e. a paddock with mixed land capabilities) can limit the stocking rate for the whole paddock, and will still risk degradation of the wetland and livestock safety. This is a good reason to separate wetlands from other land types using fencing.

extra information

Stocking rate

Stocking rate is the number of animals of a specified class per unit area of land, usually over a specified period of time. Stocking rates are expressed in units of 'dry sheep equivalent' (or DSE) which is the amount of feed required by a 2-year-old 45-kilogram Merino wether to maintain its weight. This is the standard used to express feed requirements of other classes of livestock (Table 4). For example, emus can be stocked at higher rates than sheep or cattle, but horses should be stocked at lower rates than cattle. If feral or native grazing animals are present, they may need to be accounted for in calculating suitable stocking rates. The recommended stocking rate (or **carrying capacity**) is the number of livestock that can consistently be kept on an area of pasture all year round with minor additional feed and without causing environmental degradation.[80]

Table 4. Livestock stocking rate comparisons expressed as Dry Sheep Equivalents (DSE)[81]

Animal to be stocked	DSE equivalent
One pony	8 DSE
One large horse	10 DSE
One breeding ewe	1.5 DSE
One large wether	1 DSE
One heifer	8 DSE
One alpaca (60–70 kg)	0.8 DSE
One large emu	0.7 DSE

It is unlikely that the condition of a wetland that has been degraded by livestock will improve under continuous stocking. To promote regeneration of wetland vegetation, the best strategy is to remove livestock for up to several years, then resume grazing at a lower stocking rate and use other methods discussed in other this topic to achieve a better distribution of livestock.

The capability of a land type will be influenced by its location within WA due to the affect of climatic conditions on plant productivity. As a guide, wetlands, whether inundated or waterlogged seasonally or intermittently, should be stocked at lower rates than the surrounding dryland. In many areas of the south-west, the recommended stocking rates for wetlands will be less than one animal per hectare when stocking animals other than sheep, and will limit the stocking rate for the whole paddock.[80] Meat and Livestock Australia advise not to 'set and forget'.[82] Varying a set stocking strategy between seasons can assist in managing grazing pressure effectively and improve pasture and animal production.

➤ The Department of Agriculture and Food has detailed information about local conditions across the state and can calculate the relevant permissible stocking rates on request. The Department of Agriculture and Food's Small Landholder Information Service provides advice tailored for small landholders. *The stocking rate guidelines for small rural holdings*[80] provides stocking rate guidelines for the Swan Coastal Plain and Darling Scarp areas.

Wetland management in the rangelands

Fencing wetlands

Pastoral enterprises in the rangelands typically graze low densities of sheep or cattle on native vegetation in extensive paddocks that incorporate many different land types. Often livestock are not actively managed beyond annual mustering. Native and feral animals frequently contribute considerably to the total grazing pressure which can lead to overgrazing and erosion.

➤ For more information see *Management of total grazing pressure: managing for biodiversity in the rangelands.*[83]

Managing grazing pressure at unfenced wetlands is rarely achievable. The most effective management for smaller discrete wetlands (such as springs) is to fence them to keep livestock (and other grazers out) and provide alternative water.

Over much of the rangelands the landscape has low relief, and extensive areas of floodplain (often associated with rivers) become intermittently inundated (Figure 34). These areas provide valuable grazing, but are often vulnerable land types. Fencing these land types to control grazing may be a costly improvement, but can improve livestock management, increase ground cover and vegetation condition, reduce erosion and improve water quality.

➤ For more information, read the case study *On the ground: What a difference a fence makes* by the Fitzroy Basin Association www.fba.org.au.

Figure 34. The inundated floodplain of the Lyndon River near Lake MacLeod in April 1998. Photo – L Bayley/Department of Agriculture and Food.

Trap yards

Trap yards, such as total grazing management (TGM) yards, are proving useful to livestock managers in the rangelands. These yards are self-mustering as livestock must enter them to access water points. They trap feral livestock (such as horses, donkeys and goats) and native grazers (kangaroos and emus) as well as livestock, allowing management of total grazing pressure.

➤ For more information, see *Total grazing management yards: A cornerstone for improved station profitability.*[84]

Conservative stocking

In the rangelands, it is common to stock more heavily during optimal weather conditions (such as the growing season following summer cyclonic rains), but these times are often followed by drought. Heavy stocking prior to drought or re-stocking soon after drought (before a pasture has recovered) can lead to degradation of both the vegetation and land.

More conservative stocking during optimal conditions can yield pasture that is better able to sustain grazing during times of drought when it is most needed. Monitoring the condition and productivity of paddocks and wetlands means that management actions can be taken before degradation occurs. If signs of degradation are evident, it is essential to move livestock to prevent further damage. It may be possible to agist livestock to locations outside of rangeland regions during times of drought and until vegetation has recovered.

➤ For more information about managing wetlands in the rangelands, see *Pastoral Management options for central Australian wetlands: Fat cows and happy greenies*[18] and HorsesLandWater's *Management Guidelines – Arid zone.*[85]

Figure 35. Wetlands in the rangelands can provide valuable grazing for livestock if they are fenced, livestock access is carefully timed, total grazing pressure is managed and livestock are removed at the first signs of degradation. Photo – L Bayley/Department of Agriculture and Food.

Section 4: Moving livestock away from unfenced wetlands

Alternative feed points

When given the opportunity, livestock tend to spend much of their time near water.[9] Fencing is the primary method of excluding or controlling livestock access to wetlands, but in some cases fencing is not a practical option. In these situations, it may be possible to attract livestock away from wetlands or discourage them from loitering there. In addition to locating watering points away from a wetland, supplementary hand-feeding or dietary supplements (such as mineral licks, low-moisture energy or protein blocks) can be sited away from wetlands to achieve better grazing distribution.[51] Locations should be chosen using the same guidelines for siting water points.

Behavioural methods of livestock management

Knowledge of livestock behaviour can be used to encourage use of dryland pasture areas.

Seasonal habitat preferences

Livestock have seasonal preferences for using wetland habitats. For example, cattle may move to dryland areas in spring when these have new plant growth, but favour wetlands from summer to autumn for better pasture, a cooler microclimate and shade. Wetlands may be avoided in winter if they are inundated, boggy or colder than the surrounds or may be favoured if they offer shelter from winter winds. Observing seasonal preferences and only permitting grazing in wetland pastures at times when animals are likely to prefer dryland areas can help to protect wetlands from over use.

Turn out locations

A **turn out location** is the site at which livestock are released into a fresh pasture. In large pastures that contain adequate water for livestock, choosing turn out locations well away from overused areas can influence the timing, duration and amount of use by livestock.[59] This technique has been used successfully to reduce pressure on riparian areas and therefore is considered likely to be useful for managing grazing pressure on wetlands. It may be beneficial to change turn out locations each year to vary behaviour patterns.

Low-stress herding

Low-stress livestock handling is a method of herding livestock with prompts rather than force. It involves trained livestock handlers using herding techniques that exploit the natural traits of livestock, encouraging them to stay together and bed down where they are placed.[59] Well-handled livestock prefer to stay together rather than scattering or hiding. This technique is gaining popularity in the United States of America as a tool to control livestock distribution in rangeland areas. Trials have demonstrated that a combination of low-stress herding techniques and strategically placed mineral supplements can be successful in reducing cattle use of riparian areas.[86] Low-stress herding techniques have been used to successfully train cattle to move from riparian areas to dryland areas after drinking.[59] These techniques also have economic and other benefits for livestock and producers.

➤ For more information about low-stress livestock handling in Australia, visit www.lss.net.au.

Section 5: Managing paddocks around wetlands

Manage paddocks to maintain permanent groundcover

Bare patches in paddocks are vulnerable to soil erosion by water or wind. Bare soil in paddocks can increase the risk of horses getting sand colic, and dust can cause respiratory tract infections.[85] Maintaining a healthy groundcover across paddocks all year round will retain topsoil, reduce dust and maintain wetland water quality. Meat and Livestock Australia's sustainable grazing program found that a minimum of 70 per cent groundcover is needed in late summer-early autumn to reduce erosion risk in the temperate high rainfall zones in south-western Australia.[87] The organisation HorsesLandWater recommend all grazing areas have plants at least 3 centimetres high with groundcover of 70 per cent (for soil susceptible to water erosion) or 50 per cent (for soil susceptible to wind erosion).[85]

➤ For information on how to calculate groundcover, see HorsesLandWater *Management Guidelines.*[85]

Perennial pastures

One way to maintain permanent groundcover is to improve pastures by planting deep-rooted perennial plant species. Perennial plants can prevent erosion and reduce nutrient run-off as well as provide a year-round food source for livestock. Perennial pasture grasses are best grazed in a rotation grazing system. They remain green later in spring than annual grasses, allowing longer grazing rotation times, and they are particularly useful in areas that experience medium to low rainfalls.

Introduced perennial pasture species should be selected with caution. Some species have caused seasonal toxicity problems in livestock. For example, signal and panic grasses that are growing rapidly or stressed can become toxic to young sheep.[88] Other perennial species, such as kikuyu (*Pennisetum clandestinum*) and tagasaste (*Chamaecytisus palmensis*), have the potential to become serious weeds in wetlands.

WA has many native species of grass that can be used as alternatives to introduced pasture fodders. Perennial species should be selected with professional advice and evaluated on a trial basis.

➤ For more information on perennial pasture species, contact the Department of Agriculture and Food. Good references include *Perennial pastures in Western Australia*[89] and *Evaluating perennial pastures – a case by case study of perennial pasture use in the south coast region of WA.*[90]

Figure 36. Pastures improved with a mix of perennial species on the margin of a fenced wetland near Gingin. Photo – K Angell/Small Farm Landcare Consultancy.

Figure 37. Kikuyu (*Pennisetum clandestinum*), a perennial pasture grass widely used on horse properties, can become a serious weed in wetlands. Here, kikuyu is spreading from a horse yard into a seasonally waterlogged wetland in Forrestdale. Photo – R Lynch/DEC.

Manage high traffic areas

Any area where livestock congregate, particularly around watering points, but also hand feeding areas, gateways, laneways, shelters and 'stock camps' can experience damage to pasture cover from intense trampling and be at risk of erosion.[45] Horses, which are more active that other types of livestock, tend to loiter at gates and walk along paddock fence lines (especially if they are left in a paddock on their own, but with other horses in the next paddock). Serious damage can be caused in a short time by a stressed horse left behind while companion horses are taken out for a ride.[45] Infrastructure which attracts livestock should be sited on stable ground, avoiding wetlands, paddock corners, clay and sand soils and steep areas.[45] High traffic areas can be permanently surfaced to make them more stable, or a moveable protective pad such as conveyor belt matting can be used to provide temporary surface protection.[45] Regularly moving portable troughs and feed locations is a good option for smaller properties. Temporary electric fencing can be erected to protect damaged groundcover while it recovers.

Manage potential contaminants

Animal faeces and urine

Restricting livestock access to wetlands will minimise direct inputs of animal wastes into wetlands. Well-vegetated dryland buffers between pastures and wetlands will also help by slowing run-off and reducing the volume of sediments, nutrients and faeces reaching wetlands. However, the accumulation of animal faeces and urine on other parts of a property can still cause wetland water quality problems.

While some well-distributed manure will act as a natural fertiliser for pasture plants, too much deposited in one area can enter wetlands through run-off or by leaching into groundwater. Faeces should be regularly collected from areas where it tends to accumulate, such as stables, animal sheds, yards and small paddocks.

Manure composting piles should be sited on hard stand containers, at least 200 metres from waterways and wetlands and well away from drainage lines.[45]

➤ For more information about manure management on horse properties, see *Horse poo – what to do?* at www.horsesa.asn.au.

Animal carcasses can also cause contamination. Livestock carcasses should be buried at least 100 metres from wetlands and not in places where the water table is less than 1.5 metres from the surface.[7] If possible, each carcass should be buried in separate pit and the pits distributed over a wide area.

Chemical contaminants

To avoid contamination of wetlands, agricultural chemicals (including fertilisers, herbicides, veterinary chemicals, fuel, oil and solvents) should be used, stored and handled in accordance with best practice guidelines and regulatory requirements and supplier's directions.

➤ The Department of Water produces Water Quality Protection Notes and guidelines for a range of activities that affect water resources. See *WQPN 35: Pastoral activities in rangelands*[7], *WQPN 33: Nutrient and irrigation management plans*, *WQPN 80: Stockyards* at www.water.wa.gov.au (search in 'Publications') for more information.

Some key points include:

- Livestock drenching and jetting should not be undertaken within 100 metres of a wetland or near waterways.
- Livestock should be kept away from wetlands for at least two days after worm drenching to minimise leaching of drench chemicals from animal faeces and urine.[31]
- Plunge or dipping pools for parasite control are not recommended, but if necessary this should not be undertaken within 200 metres of a wetland and any spills should be immediately contained and disposed of safely.[7]
- Herbicide, pesticide and fertiliser use near wetlands can contaminate them through overspray and spray drift. These chemicals should be used appropriately and with caution. Some herbicides that do not harm aquatic animals are approved for use over water, but may still harm native vegetation in the wetland and its buffer.

  ➤ For additional detail refer to the topic 'Wetland weeds' in Chapter 3.

- If possible, split fertiliser applications into several smaller applications. Using the smallest effective amount, applied at times of enhanced plant uptake, will reduce leaching.[49] Avoid applying fertilisers prior to storms and flooding or to soggy, waterlogged paddocks, as highly soluble forms of nitrogen and phosphorus are flushed by rain into wetlands and waterways.[49]

Section 6: Management challenges

Excluding or controlling livestock access to wetlands can result in significant improvements in wetland appearance and condition and provide benefits to property owners, especially over the long term. As with any change in management practice, it can also create new challenges. Management issues associated with excluding livestock from wetlands include weeds, pest animals and the potential fire risk from increased amounts of vegetation.[51] Accordingly, a variety of nature conservation programs offer financial, technical or labour assistance to eligible landholders.

➤ Refer to the topic 'Funding, training and resources' in Chapter 1 for more information.

Weeds

Many landowners express concern about excluding livestock from wetlands because grazing livestock will no longer keep weeds under control, allowing weeds to flourish and further degrade the wetland. In addition, a common concern is that increased weed and native vegetation regeneration can often make fenced areas difficult to access for spraying and slashing. These are valid concerns, and the exclusion of livestock from wetlands that contain invasive weeds requires planning and ongoing action. In the first few years following the exclusion of livestock, weed control will require a consistent effort. It is difficult for weeds to establish in areas where the native plant cover is intact, so as natural regeneration progresses, weed management is likely to be less time-consuming.[51]

➤ Methods of weed control suitable for use in wetlands are discussed in the topic 'Wetland weeds' in Chapter 3.

Grazing has been used to control highly invasive weeds in some wetlands, such as para grass (*Brachiaria mutica*) in Queensland.[91] If grazing is to be used to control weeds in a wetland, the targeted weed species must not only be palatable, but preferred by the livestock to the native vegetation. Ideally livestock should only be allowed access when soil moisture levels are low enough to avoid pugging. Allow livestock to graze weeds before they set seed, but aim for minimal damage to native vegetation and withdraw livestock as soon as the first signs of this occur. To reduce the spread of weed seeds in manure, livestock can be locked up for a day prior to grazing wetland areas.[51] They will excrete many of the seeds in their faeces while locked up, so fewer weeds are transported into wetlands. Excluding sheep until after shearing will also reduce the weeds transported in their fleece.

Fire hazard reduction

As wetland vegetation regenerates, fire hazard management may be necessary. The use of livestock grazing to reduce potential fire hazard is not recommended as it depends on livestock eating plants which create fuel loads, which is often not the case, and also requires heavy grazing, which is damaging to wetland habitats and vegetation.[3]

Pest animal control

As wetlands regenerate, understorey vegetation becomes denser and may be colonised by more native animals, such as bandicoots. This is a good sign that the wetland is providing good habitat for native animals. However, introduced animals may also use wetland habitats. These, and sometimes native animals, can become a problem if they destroy native vegetation, cause erosion, damage fences, spread diseases or kill livestock. Grazing by rabbits, goats, pigs, kangaroos and native wetland birds can destroy regenerating vegetation and hinder wetland restoration efforts by eating or uprooting plants. Cats and foxes using wetland vegetation as a refuge may also need to be controlled.

➤ Methods of controlling introduced and problem native animals are discussed in the topic 'Introduced and nuisance animals' in Chapter 3.

case study

The Collards manage wetlands on their cattle property near Gingin

In 1973, Ross and Tracy Collard bought a 400-hectare property near Gingin, which they named 'Caladenia Lake Estates', after one of the eight natural wetlands. They cleared much of the property for beef production, but retained areas of wetland vegetation (mainly low open paperbark woodland). They currently run more than 220 head of Red Angus breeder cattle between 'Caladenia' and their nearby property, 'Poverty Nook', which is 160 hectares and also has a wetland.

An intensive rotational grazing system

In 1998, Ross began using a rotational grazing strategy based on a registered system. He subdivided the four original paddocks at Caladenia into thirty-five smaller ones. Under this system, each paddock is intensively grazed by a mob of forty to fifty cattle for no longer than 3 days. The paddock is spelled until the pasture has regrown to a specific stage, which can take between 12 and 30 days, and then grazed again for up to 3 days. Ross found that this system worked well in terms of both livestock and pasture management – there was more feed, stronger plants and better groundcover.

Unintended impacts on the wetlands

Under the old four-paddock system, the margins of the wetlands had provided valuable grazing for the cattle. However, in the new rotational system, the cattle grazed more intensively and ate a wider variety of vegetation, including the wetland plants. It became clear to Ross that the wetlands were rapidly becoming degraded as a result. The cattle "were hammering the wetland … smashing up the tea trees … and the water was disgusting".

Ross was most concerned about the impact on the wetland vegetation and the water quality, as his cattle used the wetlands for drinking. The unfenced wetlands also provided hiding places for the cattle, which made moving them between paddocks more difficult.

Wetland fencing, funding and more fencing …

Ross began fencing some of the wetlands with his own resources, then applied for and received funding from the former Gingin Land Conservation District Committee for fencing to protect more wetlands from livestock. Cattle were excluded (with the exception of the occasional calf) by installing plain wire fences using substantial pine strainer posts with galvanised steel pickets at 10-metre intervals (to provide a visual barrier) and a single electric wire (an earth wire was not necessary).[92] At Poverty Nook, where fires are more frequent, Ross used steel strainer posts around the wetland.

To compensate for fencing the wetlands, Ross then put into practice a pasture improvement program based on a range of perennial species. This yielded a significant increase in the feed available to livestock. In 2007, the Collards applied to World Wide Fund for Nature (WWF) Australia's 'Balancing agricultural production and conservation – wetlands' program. They received wetland management advice as part of a whole farm plan and assessment and monitoring for wetlands and vegetation. With in-kind funding, Ross was able to fence more wetlands and a corridor of remnant vegetation, install a bore, water pump and solar panels, tank, trough and gates and sow 4 hectares of perennials in adjacent pastures.[93]

Figure 38. Red Angus cattle in perennial pastures on the edge of a fenced wetland at the Collard's 'Caladenia' property. The productivity of the perennials has compensated for fencing off wetland areas.
Photo – K Angell/Small Farm Landcare Consultancy.

case study

Next, Ross is planning to put in a new bore and upgrade the water pump for an existing bore at Poverty Nook, in order to provide his cattle with alternative water when he completes fencing off a spring-fed wetland. Ross also hopes that using alternative water sources will help to maintain the natural water regime in the wetlands; he is concerned that groundwater abstraction for other nearby land uses is causing the wetlands to dry out earlier than in previous years.

Few problems with weeds and same old pests

Many landowners have concerns that excluding livestock from wetlands will allow weeds to flourish, but this has not occurred at the wetlands at Caladenia. Ross has ongoing problems controlling rats, mice and foxes, but pest numbers did not increase after fencing the wetlands. Feral pigs occasionally move through the property, causing damage to the wetlands. Ross finds he needs to control kangaroos as they compete with his cattle by consuming a lot of vegetation and sometimes short out the electric fences.

Wetlands for the future

Since fencing the wetlands, the Collards have observed that the water is now clear, rather than clouded with sediment; there has been rapid natural regeneration of wetland trees, shrubs and rushes; growth in three different types of water plants; more frogs; and wild ducks.[92] The Collard family value the wetlands as scenic areas for quiet recreation and for their native plants and animals[92] which includes swans, pelicans, spoonbills, ducks, wading birds, bush birds, owls and frogs. Ross has always thought of their property as their 'grandchildren's farm' and is pleased to be protecting the beautiful wetlands so they can be enjoyed by future generations of his family. He says the wetlands "are just nice places to be".

Figure 39. South Ridge Swamp, a wetland on the Collard's property, is protected from livestock impacts by fencing and total cattle exclusion. Photo – K Angell/Small Farm Landcare Consultancy.

Topic summary

Letting livestock into wetlands can be harmful to livestock as well as destructive to wetlands. Livestock and associated farm activities can degrade wetlands by causing damage to soils, erosion, water contamination, damage to native vegetation, harm to native animals and loss of biodiversity.

Wetlands in good condition can provide valuable services for landowners, their livestock and the wider community. There are a range of incentives to help landholders protect wetlands.

Options for reducing livestock impacts on wetlands include:

- fencing wetlands to keep livestock out
- providing alternative watering points located away from the wetland
- creating formed water access points or livestock crossings
- keeping wetlands for occasional grazing, as 'special use' or reserve paddocks
- grazing wetlands for short periods as part of a controlled grazing system (for example rotational grazing)
- if allowing continuous grazing, spelling paddocks initially to allow vegetation regeneration, reduce stocking rates and de-stock, if necessary
- using other methods to reduce wetland grazing such as supplementary feed points, seasonal preferences, turnout locations and herding.

Management of surrounding paddocks can also reduce impacts on wetlands. Best practice is to:

- maintain permanent groundcover
- consider planting perennial pasture species
- manage high traffic areas
- manage animal wastes and other potential contaminants near wetlands.

It may be necessary to plan strategies to manage weeds, pests and fire.

Sources of more information on managing livestock in and around wetlands

Websites

Small Landholder Information Service (SLIS), Department of Agriculture and Food Western Australia
www.agric.wa.gov.au/content/FM/SMALL/PER_SUMM.HTM
A wide range of advice on managing landholdings up to 100 hectares

Ecologically Sustainable Rangelands Management Service (ESRM), Department of Agriculture and Food Western Australia
www.esrm.com.au
Land management and property planning advice for landholders in the WA rangelands

Horses Land Water community of practice
www.horseslandwater.com
Property management and other advice for horse owners including guidelines for horse-keeping in temperate, tropical and arid areas

Rural water planning program, Department of Water, Western Australia
www.water.wa.gov.au/ (click on 'Doing business with us' then 'Farm and pastoral assistance')
Offers technical advice and publications designed to assist with on-farm water supply issues

Other publications

Department of Agriculture and Food in partnership with Geographe Catchment Council and Western Dairy (2006) *DairyCatch – environmental best practice guidelines.*[94]

NSW Department of Environment and Conservation (2000) *Horse properties on the rural urban fringe: Best practice management guide for keeping horses.*[95]

Glossary

Aestivating: being in a state of dormancy that occurs in some animals to survive a period when conditions are hot and dry

Annual: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) within a single growing season

Biodiversity: the whole variety of life forms–the different plants, animals, fungi and microorganisms–the genes they contain, and the ecosystems they form

Browse: to feed on leaves, twigs or bark from non-herbaceous (woody) plants, such as trees and shrubs

Diversity: a measure of the number of species of a particular type and their abundance in a community, area or ecosystem. It can refer to a particular group of organisms, such as native plant diversity or frog diversity. The broader term biodiversity is used to encompass the whole variety of life forms–the different plants, animals and microorganisms–the genes they contain, and the ecosystems they form

Dormancy: a state of temporary inactivity when plants are alive but not growing, i.e. they are **dormant**

Ecosystem: a community of interdependent organisms together with their non-living environment. Natural ecosystems provide a range of benefits and services to humans such as clean water, nutrient cycling, climate regulation, waste decomposition and crop pollination

Erosion: the gradual wearing away and movement of land surface materials (especially rocks, sediments, and soils) by the action of water, wind, or a glacier

Grazing: feeding on grasses and other low-growing herbaceous vegetation

Groundcover: the percentage of ground covered by plant materials (alive or dead) and leaf litter

Herbs: plants with non-woody stems that are not grasses or sedges. Generally under half a metre tall. Most herbs monocots are herbs.

Land capability: the ability of land to be used for a particular purpose or managed in a particular way without becoming degraded

Leaf litter: dead plant matter including leaves, flowers, nuts, sticks and bark which accumulates on the ground

Livestock: introduced domestic ungulate (or hoofed) animals

Low-stress livestock handling: a method of herding livestock with prompts rather than force

Macropores: spaces in the soil (usually less than 2 millimetres in diameter) that include channels created by cracking, old plant roots and soil fauna (such as earthworms). Macropores indicate good soil structure.

Palatable: pleasant-tasting

Perennial: a plant that normally completes its life cycle (from germination to flowering, seed production and death of vegetative parts) in two or more growing seasons

Property management plan: also called a whole farm plan; a working plan for the design and management of a property based on its natural resources, the activities undertaken (such as horse breeding or beef production), the manager's goals and financial considerations

Pugging: depressions, hoof prints or 'pug' marks made in wet soil by trampling animals

Riparian: the habitats adjacent to waterways and estuaries

Rotational grazing: a type of controlled grazing system. Paddocks are usually subdivided into smaller pastures and grazed at higher intensities for shorter periods (to achieve more even grazing), then spelled (or rested).

Sedimentation: the process by which soil particles (sand, clay, silt, pebbles and organic materials) suspended in water, are deposited or settle to the bottom of a water column

Spelling: of a paddock or pasture, involves removing livestock grazing pressure for a period of time so that vegetation can regenerate

Stocking rate: the number of livestock that can consistently be kept on an area of pasture all year round with minor additional feed and without causing environmental degradation

Total grazing pressure: describes the combined impact of all grazing animals–domestic, wild, native and feral–on the vegetation, soil and water resources of a particular area

Turbid: the cloudy appearance of water due to suspended material

Turn out location: the site at which livestock are released into a fresh pasture

Understorey: the layer of vegetation beneath the main canopy

Vegetation structure: the three-dimensional distribution of plant material. It includes the horizontal spacing of plants and the vertical heights or layers

Vegetative reproduction: a type of asexual reproduction found in plants. Also called vegetative propagation or vegetative multiplication

Wetland hydrology: the movement of water in, out of, and within a wetland

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A guide to managing and restoring wetlands in Western Australia

Monitoring wetlands

In Chapter 4: **Monitoring wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Monitoring wetlands' topic

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Contents

Before you begin

Before embarking on management and restoration investigations and activities, you must consider and address the legal requirements, safety considerations, cultural issues and the complexity of the ecological processes which occur in wetlands to ensure that any proposed actions are legal, safe and appropriate. For more guidance, see the topic 'Introduction to the guide'.

Introduction

This topic is intended to assist people involved in wetland management and restoration to develop and implement monitoring programs. In particular, the requirements of land managers, landowners, community groups and technical officers in local and state government and non-government organisations have been considered. Consultants, planners and secondary and tertiary students may also find the information useful.

The topic aims to provide guidance on wetland monitoring in a simple and user-friendly manner. That said, some of the concepts presented are complex and readers may require expert assistance to apply them to their own monitoring.

There are many different ways to design a monitoring program and to measure **indicators** of wetland condition.

The method that is most appropriate will depend upon the objectives of the monitoring program, the characteristics of the site being studied and the available resources. As such, the information presented in this topic is not prescriptive; it does not provide a ready made monitoring program. Rather, this topic describes the principles of monitoring, some suitable techniques for monitoring commonly used indicators of wetland health and where to get additional help and information.

Monitoring defined

Monitoring is the systematic collection of data, over time, in order to test a **hypothesis**.

In the context of biodiversity conservation, the hypothesis will usually relate to the effect of management strategies on the **condition** of a natural area.

Put simply, monitoring determines whether management of an ecosystem is having the desired effect on its condition. Monitoring is an essential component of every wetland management program as it is the only way to ensure that management activities actually improve (or maintain) the condition of the ecosystem.

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site

Hypothesis: a concept that is not yet verified but that, if true, would explain certain facts or phenomena

Condition: the relative integrity of an ecosystem compared to a reference state. It includes being able to maintain key ecological and physical processes, ecosystem services, and communities of organisms. (Note: health is taken to have the same meaning as condition)

Strategies for managing biological diversity

There are six broad strategies for managing the biological diversity of a natural area[1]:

1. Take no positive management action
2. Ensure that current threats to biodiversity are not accelerated
3. Slow the rate at which biodiversity assets are lost from the landscape
4. Take positive steps to conserve specific elements of the biota
5. Take positive steps to conserve all natural populations in an area
6. Reconstruct landscapes and their natural biota

Monitoring may be undertaken to assess the effectiveness of any of these strategies. In the case of the first strategy, the hypothesis may be that the condition of the area is stable in the absence of management intervention and a monitoring program may be designed to assess this.

Replication: repeating an experiment several times and collating all the results. It allows the error margin of the measurements and natural variations in the subjects to be discounted from consideration

Control: a subject that is identical to the experimental subject in every way, except that the experimental subject receives the treatment and the control does not. This means that if a change is observed in the experimental subject after the treatment, but not observed in the control, that change could only have occurred due to the treatment

Treatment: subjection to some agent or action. In the case of a monitoring program, the treatment will be the management regime that is expected to cause some change in the condition of the site

The terms *monitoring* and *survey* are frequently confused and, because both are used in this topic, it is necessary to clearly define the difference between them. A survey is an exercise in which a set of observations are made about some components of an ecosystem. Monitoring is a series of surveys, repeated over time, that are designed to test a specific hypothesis. For example, a survey might involve counting the number of waterbirds at a wetland. This is not monitoring, unless the count is repeated over time in order to test a theory about the effect of management of the site on the bird population.

Monitoring outputs and outcomes

It is important to distinguish between monitoring *outputs* and monitoring *outcomes*. Outputs are activities undertaken, or products produced, by a particular project. An outcome, on the other hand, is a measurable consequence of the project's activities. For example, a project may *output* 20 kilometres of livestock exclusion fencing around a wetland. The *outcome* of this may be a 10 per cent increase in native vegetation biomass within the fenced area, due to reduced grazing pressure. Outputs are steps along the way to achieving the desired outcome. Although output monitoring is required in some situations, this topic discusses only outcomes monitoring in the context of wetlands biodiversity conservation.

➤ More information on output monitoring is available in the Australian Government's *Natural Resource Management Monitoring, Evaluation, Reporting and Improvement Framework.*[2] It is available from the Caring for Our Country website: www.nrm.gov.au.

Planning a monitoring program

A monitoring program is the series of actions that will be taken to gather the information required to test the monitoring hypothesis. Monitoring programs can vary greatly in complexity and rigour. At one extreme, anecdotal evidence and a simple 'mental tick' that things are progressing as expected. At the other, a research project involving pre and post management surveys, significant **replication** of both **control** and **treatment** plots and comprehensive statistical analyses.

There is no single correct approach to monitoring and no one program of actions that will suit all situations. A monitoring program must be developed to suit the requirements of each individual project. Regardless of the approach adopted, however, the following four questions must be answered when planning a monitoring program:

- What is the hypothesis to be tested?
- How much confidence is required in the answer?
- Which indicators will be measured?
- How will the collected data be analysed?

Depending on the nature of the work or project being undertaken, it may be necessary to formally document the answers to these questions in a monitoring plan.

➤ More information on writing a formal monitoring plan is available from the website of the Department of Environment and Conservation: www.dec.wa.gov.au.[3]

The monitoring hypothesis

Defining the hypothesis is probably the most important step in the design of a monitoring program. Without a meaningful question to answer, it will be difficult to know what to measure or how to measure it. Any data that are collected will lack context and may not inform management of the site.

Usually, the reason that a monitoring program has been proposed will guide the formulation of the hypothesis to test. Monitoring will have been proposed in response to a particular issue, such as a change to the way a wetland is managed or to the surrounding land use or because a water quality issue or some other impact is becoming apparent. The issue under consideration is expected to have some impact on the health of the wetland and the results of that impact are to be monitored. The monitoring hypothesis will clearly identify the issue being investigated, the change that is expected and the period of time over which it should be observed. In stipulating these factors, the hypothesis guides the design of the monitoring program.

Framing the hypothesis may require some background information to be gathered. Ideally, monitoring will seek to demonstrate some cause and effect relationship between the management of a wetland and changes in its condition. This will require an understanding of the components of the wetland ecosystem and the processes that connect them. It will also be important to understand the nature of the management regime that is affecting the site.

➤ Additional detail on the components and processes of wetland ecosystems can be found in Chapter 2 Understanding Wetlands.

The relationship between management and the monitoring hypothesis

Many Western Australian wetlands are degraded from the impacts of livestock grazing vegetation, disturbing soils and defecating in, or near, the water. The most common management response to this threat is to fence the wetland, excluding stock. A wetland manager might wish to assess the effectiveness of stock exclusion fencing at a particular wetland, before committing to fencing other sites on the property. In this example, assume the manager is particularly concerned with the status of native vegetation at the wetland. Monitoring is proposed to assess the effect that fencing the site has on the native grasses that grow there.

A suitable hypothesis to be tested by the monitoring program at the wetland might be:

That excluding stock from the wetland will result in a 20 per cent increase in the cover of native grass at the site by 2011, compared to 2009 cover.

This hypothesis states the management action that is being assessed, the expected change in the condition of the wetland component and the period of time over which the change should occur.

Characteristics of a monitoring program

Having formulated a hypothesis to be tested in a monitoring program, it is next necessary to decide how much certainty is required in the answer. Being certain of the answer to the hypothesis means being able to state, with confidence, whether a change occurred in the system being studied and, if it did, whether the change was caused by a specific management action. The degree of certainty required will determine what kind of monitoring program is undertaken and how it will be designed.

The most rigorous and robust monitoring programs will use replication of treatment and control sites to establish cause and effect relationships between wetland components, processes and threats. This is done to provide strong evidence that a particular management action caused an observed change in the wetland ecosystem, or resulted in no change to the system. The data that are collected will allow sophisticated statistical analyses of elements of the ecosystem. Documentation will be comprehensive, allowing critical appraisal of the techniques that were employed to collect and analyse data and the conclusions that are drawn from them.

At low levels of rigour, a monitoring program may suggest that a change is occurring at a site, but will provide little evidence of what the cause of the change is. It will not be possible to distinguish between 'natural' variation in the system and the effects of a particular management regime. The techniques that are used to measure indicators of wetland condition will often be relatively simple and prone to inaccuracy and imprecision. Methods may include opportunistic sampling and qualitative approaches and documentation of the program will be informal.

➤ For definitions of the terms inaccuracy, imprecision and qualitative, see the section 'Data Quality' in this topic.

These two examples are extremes on a continuum of approaches to monitoring. The less rigorous end of the spectrum is readily achieved by people with little previous experience in monitoring, but will probably not provide a full answer to the hypothesis. The most rigorous of programs will comprehensively address the monitoring hypothesis, but require significant experience, particularly in relation to the statistical design of the monitoring program. The advice provided in this topic aims to guide readers toward a middle path, with practicalities and logistical constraints balanced against the need to collect robust data.

➤ More information on data confidence is available in the *Queensland Community Waterway Monitoring Manual*.[4] www.qld.waterwatch.org.au.

Sources of errors in a dataset

There are a number of ways that errors may enter a monitoring program. Firstly, errors may relate to the design of the program. This results in the wrong indicators being measured, indicators being measured at the wrong time, too few measurements being taken or the use of instruments that are not suited to the task. A well planned survey may record poor data if members of the survey team are not adequately trained in the techniques being used, inconsistently apply methods, misread instruments, record or copy data incorrectly, contaminate samples or fail to properly calibrate equipment. The inconsistent application of methods is particularly likely when a number of different people collect data, but can result from a single person changing their approach over time. Such inconsistency can be minimised by implementing processes that ensure each person applies methods and interprets conditions in the same manner.

Finally, losing the collected data is an error. It may occur if recording sheets are misplaced or computer records incorrectly transcribed or corrupted. An 'institutional' data loss is when insufficient documentation of methods and procedures prevents data from being interpreted correctly.

There are a number of general principles that will help to avoid errors and achieve high quality data:

- Understand the system being studied, particularly sources of natural variation. This will allow spatial and **temporal** variation to be properly accounted.
- Ensure all participants in the monitoring program have the necessary training and competencies.
- Apply methods that are appropriate to the system being monitored and the objectives of the program.
- Comprehensively document the methods that are used.
- Use the correct equipment for a task and ensure that it is maintained and calibrated carefully.
- Treat samples with care to avoid contamination.
- Manage the data well.
- Analyse and report on data appropriately.

Temporal: of or pertaining to time. Temporal variations are changes that occur over time

Accuracy: closeness to the 'true' value of the parameter being measured

Precision: minimal variability between measurements

Data quality

High quality data are achieved by eliminating errors, so that the dataset truthfully represents the conditions at the study site. High data quality are required if a monitoring program is to show that a change in an indicator is significant and is not an anomaly of the data.

High quality data are accurate, precise, sensitive and representative. **Accuracy** and **precision** refer to the potential for error in each measurement taken. Accurate measurements are very close to the 'true' value of the parameter being measured. Precise measurements have minimal variability between measurements (Figure 1). Both accuracy and precision are achieved by the use of appropriate, well calibrated equipment and the careful implementation of suitable, consistent methods.

Sensitivity refers to the ability to distinguish between different values in the parameter being measured. Sensitivity is a product of the equipment used, data handling techniques and experimental design.

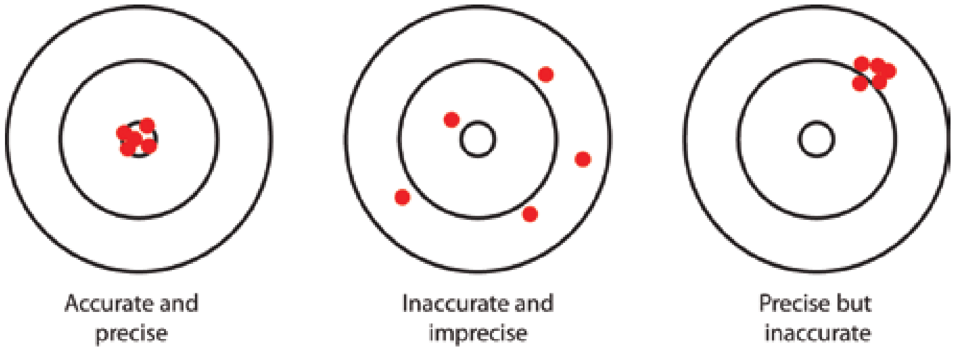

Figure 1. Accuracy and precision. Figure adapted from Department of Natural Resources and Water, 2007.[4]

Representativeness is how well a series of measurements reflect the full range of values in the system being measured. In order to be representative of conditions at the site, monitoring data must be comprehensive of spatial and temporal variation. For example, a salinity measurement taken at the point where a drain enters a wetland might not be representative of conditions at the site as a whole. That measurement may accurately reflect the salinity at the point it was taken, but it does not represent the range of salinity that is encountered across the water body. Similarly, a single salinity measurement taken at the wetland mid-summer will not be representative of the variation that occurs at the site throughout the year.

Qualitative data: descriptive data; they are collected using techniques such as estimation, categorisation, statements of type or condition, diagrams, photographs and maps

Causation

Showing causation, or lack of it, is a common requirement of monitoring programs. It means showing a relationship exists between two variables such that a change in one (the cause) causes a change in the other (the effect). To be sure of the relationship between cause and effect, it is also necessary to show that the effect will not occur if the cause does not. Demonstrating this requires the use of a control.

A control is a subject that is identical to the experimental subject in every way, except that the experimental subject receives a treatment and the control does not. If a change is observed in the experimental subject after the treatment, but not observed in the control, that change could only have occurred due to the treatment. It is also necessary to replicate the treatments and controls to ensure that the observed effect is not a chance occurrence.

Replication involves repeating an experiment several times and collating the results. It allows the error margin of the measurements and natural variations in the subjects to be discounted from consideration. In natural settings, replication is very difficult to achieve, because no two natural areas are identical. Showing causation in natural ecosystems, therefore, requires the use of specialised techniques. These are beyond the scope of this topic; more information is available from text books that deal with ecology or statistics in a biological context.

Quantitative and qualitative data

A monitoring program may collect quantitative or qualitative data, or a combination of both. **Qualitative data** are descriptive; they are collected using techniques such as estimation, categorisation, statements of type or condition, diagrams, photographs and maps. Quantitative data have been measured or counted in some way, for example, the number of plants in a plot or the pH of a water sample.

Collecting qualitative data usually requires less technical expertise and can be achieved more quickly than applying quantitative methods. The drawback of a qualitative approach is that it is subjective and so prone to inter-operator error. Also, if data are grouped into classes it is more difficult for other people to interpret.

Quantitative methods rely on the measurement of parameters. This means that, assuming methods are faithfully recorded, future workers can be sure they are obtaining comparable measurements. Recording the actual measurements, as opposed to grouping them into classes, also allows the data to be reanalysed at a later date. This may be important if, for example, a future project wishes to use the data differently or change the categorisation of a parameter. Quantitative measures are usually more time consuming and, in some instances, may require technical skills or training. Also, if the entire population is not measured, then some statistical analyses will be required to extrapolate from the data gathered from the sample.

Spatial and temporal scale

The spatial and temporal scale at which a monitoring program operates will influence the sensitivity of the data that are collected and the resources required to collect them. Operating at appropriate scales will ensure that meaningful data are collected in an efficient manner.

Spatial scale refers to the minimum size of an area about which data are collected. A program operating at a small spatial scale, for example, may conduct surveys in each micro-habitat within a wetland, while a larger scale program may survey only one location at each wetland.

When setting the spatial scale, consider whether it is important to detect variation within a wetland or if a single measure that is representative of the site will suffice. The first scenario will provide more data, but that may not translate to a better understanding of the system. It will, however, require more effort and so, entail higher costs.

Temporal scale refers to the timing of surveys, the frequency with which they are repeated and the period of time over which they are continued. Temporal scale needs to be tailored to suit the availability of resources, purposes of the monitoring program and attributes of the system being studied.

The various components and processes of a wetland ecosystem will respond to changes in the environment at different rates. The temporal scale of monitoring must be such that changes in the parameter of interest can be detected and monitored. For example, clearing in the catchment of a wetland might cause a relatively rapid change in extent and duration of inundation at the site. It might be several years before this is reflected in the extent and composition of plant communities. The monitoring program in this example, therefore, might measure the inundation of the site seasonally, but only assess the vegetation annually. More frequent monitoring will collect a greater quantity of data, and so use more resources, but this may not better address the monitoring hypothesis.

The timing of monitoring activities is also important. The elements of the system that are being observed must be 'active', measurable and interpretable at the time of survey. For instance, it is difficult to conduct a vegetation survey when plants are not flowering or to sample aquatic invertebrates when no water is present.

Another aspect of the timing of monitoring is determining how long to continue with a monitoring program that is not detecting the predicted changes in indicators. Some changes can be slow to occur, but this should not be a reason to continue an ineffective management regime or an insensitive monitoring program. The monitoring plan should stipulate within what period of time changes should be detected. If the identified milestones are not met, either the monitoring program or the management regime may need to be re-evaluated.

Sampling

The vernacular usage of the term 'sampling' is to take a measurement from a water body, collect a specimen or record a reading from an instrument. Sometimes its usage is even broader, being applied to describe the entire survey process. For the purposes of designing a monitoring program, however, it is important to be familiar with the strict definition of the term 'sampling'.

Sampling is the process of selecting a set of individuals that will be analysed to yield some information about the entire **population** from which they were drawn.

Population: in statistics, the term population refers to the entire aggregation of components that are the subject of a study. This may be all the individuals in a biological population, but it may equally relate to a non-biological entity such as quadrats.

For example, a sample of ten plants may be selected from the population of all of the plants at the wetland. The measurements taken of these ten plants will be extrapolated to make assumptions about all of the vegetation at the wetland. Similarly, measurements of groundwater salinity taken at ten bores within a catchment are a sample of the entire population of the aquifer.

Monitoring does not always require sampling. Sometimes it may be possible to count or measure every individual in a population. This is termed a census or inventory. More often, however, it will be necessary to select a sample that will represent the whole population.

Most ecological studies rely on random sampling, that is, randomly selecting a subset of the population to measure. Random sampling aims to avoid bias in the measurements. For example, say the condition of vegetation at a wetland is to be assessed by measuring the health of ten individual plants. Clearly, selecting ten dead plants, or the ten most vigorous plants, will bias the results. To be unbiased, it is necessary to select ten plants entirely at random.

There are situations in which measurements might be intentionally biased to a certain sample of the population. For instance, if investigating point source pollution of a water body, specimens will probably be taken from near water inlets rather than from random areas. If a biased sampling technique is applied, specialised types of analysis may be required to draw meaningful information from the data.

A thorough explanation of sampling and its effects on the interpretation of data is beyond the scope of this topic. The reader is advised to seek guidance from a dedicated textbook, statistician or ecologist when developing a monitoring program. A few basic principles are provided:

- Sample randomly unless there is good reason not to. If sampling is not random, be sure to document the approach that was taken and why it was adopted.
- A larger sample size usually makes the data more representative, although this must be balanced against logistical constraints.
- Be careful about extrapolating from small samples.
- Always present information about the sampling method and size of the sample with the results. This will allow users of the information to understand the data's statistical power, or reliability.

Quality assurance

Quality assurance is the process of documenting data quality and data confidence by describing how the dataset was collected, analysed and stored. Without proper documentation, other users cannot trust the data to be free from errors.

All datasets should have an accompanying quality assurance statement (also known as metadata) that tells other users about the group that collected them and the methods that were employed. In particular, it is important to record the following information:

Why monitoring was conducted

It is helpful for other users of the data to understand the background to the monitoring program. This is because the reasons that a monitoring program was conducted will have a bearing on the type of measurements that are taken and the methods that are used. For example, a program that monitors a population of rare plants may only record specimens of that rare species. If it is not clear that a specific taxon was targeted, it may seem that no other taxa were present at the site.

Who conducted the monitoring program

To help predict the potential for errors in the data, other users need to know the identity of the group that was responsible for designing and implementing the program. Although it is not necessary to identify the individuals involved, it is important to list their competencies, experience and training in relevant fields.

What equipment and methods were used

Every instrument, piece of equipment and method has a limit of sensitivity and an inherent margin of error. Other users of the data need to know what equipment and methods were used so that they can appreciate the potential errors in, and sensitivity of, the measurements. It is also important to record how the equipment was calibrated. The description of methods applies not just to field methods, but also to how samples were stored, transported and analysed in the laboratory.

What quality controls were in place

Quality control is the process of detecting errors and determining their magnitude. The quality assurance statement should describe what methods were used to control the quality of the data. There are specific quality control techniques for different methods, but some of the important general principles are:

Calibrating meters and performing a calibration check against a known standard

Calibration of electronic meters and equipment is necessary to ensure that their accuracy does not deteriorate over time. After calibration, the meter should be tested against a standard; a solution that is prepared in a laboratory and has precisely known properties (such as pH or salinity). Any deviation between the meter's reading and known properties of the standard should be recorded. If the deviation is significant, the meter may not be calibrated correctly.

Use of blanks to test for contamination

Blanks are solutions (usually deionised water) that have a value of zero for the parameter being assessed. The blank is treated the same way as a sample throughout the analysis process and then analysed. If they return a detectable measurement of the parameter being tested, some contamination has occurred which may also affect other samples.

Use of replicates to test precision

Taking multiple measurements of a parameter allows statistical analysis of the error margin inherent in the technique or equipment used. For more information on this, see the section 'Analysis of data' in this topic.

Referring subsamples to experts

A subsample of a biological sample, such as aquatic invertebrates, can be re-identified by a person with relevant expertise, to check the accuracy of the original identifications.

Data management procedures and custodianship arrangements

Errors can enter the dataset when field sheets are entered to an electronic database or due to corruption of that database. Any steps taken to reduce the error margin, such as having the data entry checked by a second operator, should be recorded. Also, the quality assurance statement should state which individual or organisation will be responsible for maintaining the dataset and ensuring it is kept current.

➤ More information about quality assurance information, including a template for a monitoring metadata statement can be found in *The Volunteer Monitor's Guide to Quality Assurance Project Plans*.[5] It is available from the website of the United States Environmental Protection Agency: www.epa.gov.

Selecting indicators to measure

Indicators are the specific characteristics of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site. Any component or process of an ecosystem may be used as an indicator, but they are broadly grouped into biotic and abiotic types. Biotic indicators that are commonly used in wetland monitoring include vegetation composition and vigour and the diversity and composition of invertebrate or waterbird communities. Abiotic indicators include characteristics of the water chemistry, soils and hydrology.

It will usually be necessary to select a suite of indicators to accurately gauge the effects of management on a site. However, an effective monitoring program will be able to take a relatively small number of indicators and draw conclusions about the condition of the entire system. The indicators that are selected for use in a monitoring program should be informative in the context of the wetland's ecology, address the monitoring hypothesis, be measurable with sufficient sensitivity and show changes at an appropriate temporal scale.

Selecting the most appropriate indicators to measure will require a good understanding of the system being managed. This will be facilitated by considering the broad 'type' of wetland being studied and by developing a conceptual model of its components and processes.

National indicators of wetland extent, distribution and condition.

The National Indicators of Wetland Extent, Distribution and Condition (National Indicators) project is an attempt to implement a consistent approach to monitoring and reporting on wetlands nation-wide. The National Indicators project proposed standard condition indicators that were derived from conceptual models of typical Australian wetland types. Benchmarks were recommended to allow each indicator to be assessed against a reference condition.

The indicators recommended by the National Indicators project are shown in Table 1. Compliance with these will ensure that monitoring projects measure and report on biologically relevant and nationally consistent variables. As such, it is recommended that these indicators be used in all wetland monitoring programs. Unfortunately, standard measures of some of the indicators have not yet been stipulated. More information is available from the website of the National Land and Water Resources Audit: www.nlwra.gov.au.[6]

Table 1 – The national indicators of wetland extent and condition, as defined by the National Land and Water Audit.

Indicator	Measure
EXTENT AND DISTRIBUTION	
Extent and distribution of wetlands	Extent of wetlands in bioregion
Extent and distribution of significant wetlands	Extent of significant wetlands in bioregion
CONDITION	
Catchment Disturbance	Land use category
	Infrastructure
	Land cover change
PHYSICAL FORM AND PROCESSES	
Area of wetland	Percentage change in wetland area
	Loss in area of original wetland
Wetland topography	Percentage of wetland where activities have resulted in a change in bathymetry
	Degree of sedimentation / erosion
	Percentage change in bathymetry
Soil Disturbance	Percentage and severity of wetland soil disturbance
	Substrate disturbance
HYDROLOGICAL DISTURBANCE	
Local physical modifications to hydrology inflow, drainage and extraction	Severity of activities that change the water regime
	Impact of man made structures
Changes to water regime	Not yet developed
WATER AND SOIL QUALITY	
Turbidity regime	Not yet developed
Salinity regime	
Change in pH	
Soil properties – change in salinity, acidity	
FRINGING ZONE	
Change in fringing zone (measured by change in vegetation condition)	Percentage of fringing vegetation that is intact
	Percentage of natural and exotic vegetation
BIOTA	
Change in wetland vegetation	Not yet developed
Change in invertebrate diversity and community composition	
Change in wetland dependant vertebrates presence, breeding and abundance	
Change in introduced species presence and abundance	
Change in algae	

Wetland type

Every wetland is the result of a unique combination of hydrological, morphological, chemical and biological factors. Predicting how a wetland will respond to management intervention, and therefore selecting appropriate indicators to measure, will require an understanding of these various components.

A good starting point for understanding a wetland is to consider it as a representative of a broad wetland 'type'. An effective **wetland typology** will allow a relatively small number of readily discernable characteristics to be used to categorise a site.

Many different methods have been developed to divide wetlands into types. In WA, the 'geomorphic classification system' is used to identify wetland types for the purpose of wetland mapping. A national system is being introduced to enable consistent reporting nationally. This is the Australian national aquatic ecosystem (ANAE) classification framework. If these approaches are outside the scope of a monitoring project, a vernacular description can be applied to sites. This description should draw on the elements of the system that are most important to its character and ecological functioning. Examples of vernacular descriptors are *naturally saline lake* and *intermittently filled freshwater swamp*. Even such broad descriptors will help to communicate the nature of the site and guide decisions about which benchmarks and indicators should be used in the monitoring program.

➤ More information on wetland typologies is available at www.dec.wa.gov.au/wetlands.

Conceptual models

A wetland conceptual model is a simplified diagram that expresses ideas about components and processes that are important to the ecosystem. A model assists in the development of a monitoring program by demonstrating the relationships between elements of the ecosystem and the points at which the effects of a disturbance will become evident. Understanding these relationships will assist in developing a hypothesis by highlighting the points that a monitoring program should target.

Formal wetland studies should include conceptual models as part of the definition of the ecological character of the site. For instance, the Ramsar Convention recommends that a conceptual model of a wetland be developed prior to implementing management and monitoring.[8] Less formal studies, such as landholder monitoring, don't require conceptual models. It will still be necessary, however, to think about the relationships between elements of the wetland ecosystem when developing a monitoring program. Constructing a basic, generic conceptual model for the wetland type may help to identify important elements to monitor.

➤ The Queensland Department of Environment and Resource Management currently leads the nation in the use of wetland conceptual models. Their *WetlandInfo* website is an excellent resource: www.epa.qld.gov.au.[7]

Wetland typology: the process of classifying wetlands according to characteristics of their hydrological, morphological, chemical and biological factors

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region [4,9]

Wetland components: include the physical, chemical and biological parts of a wetland (from large scale to very small scale, e.g. habitat, species and genes)[10]

Wetland processes: the forces within a wetland and include those processes that occur between organisms and within and between populations and communities including interactions with the non-living environment and include sedimentation, nutrient cycling and reproduction[10]

Monitoring wetlands of international significance

When a wetland is nominated under the Ramsar Convention, the nominating party is required to complete an **ecological character** description of the site.[8]

The characteristics of the site at the time of nomination then become the benchmark against which any change in condition is measured.

In particular, the primary determinants of ecological character must be monitored. These are the features of the wetland that make it special or unique. In the case of a Ramsar listed site, these will be the **wetland components** and **wetland processes** that support the relevant nomination criteria.

For example, if a site is internationally significant because it supports large numbers of waterbirds, it is important to protect these birds and the habitat that they utilise. This may include maintaining the water level and the water quality to ensure that the birds' food source persists, as well as maintaining vegetation that is used for nesting.

At a minimum, monitoring must determine if the site continues to meet the Ramsar criteria under which it was nominated. Ideally, a monitoring program will include elements of the ecosystem that will provide early warning of any pending deterioration in ecological character.

Surrogate measures

There are times when it is not practical to measure a required indicator. This may be because the indicator is cryptic, slow to respond to environmental change, expensive to assess or poorly understood. In such cases a surrogate measure may be used. This is another component of the system that shows a correlated response to the management issue being evaluated. An example of a surrogate measure is the use of aquatic invertebrate community composition to draw conclusions about water quality. Some taxa of invertebrates persist only within a narrow range of environmental conditions (particularly salinity and pH). The presence of such taxa may be used as a surrogate for the direct measurement of water quality.

A surrogate measure must show a strong correlation with the response of the original indicator. Even so, a problem inherent in the use of surrogates is a loss of specificity. Although surrogate measures may alert us to trends in the condition of the indicator, they are unlikely to provide quantifiable data about the indicator. Also, surrogates may be affected by factors that do not relate to the original indicator.

Assessing condition

A common aim of monitoring is to assess changes in the overall 'condition' of a wetland. Although this can be a valid endeavour, it does require a very careful definition of condition.

In general terms, condition refers to the capacity of an entity to fulfil a particular function. It is a nebulous concept because of the requirement to link condition to a specific purpose. In the context of wetlands conservation, a wetland could simultaneously be in excellent condition for supporting salt tolerant invertebrates, but in very poor condition for the persistence of fish. It can be useful to compare the integrity of a wetland to a reference state. This may be the known or inferrred natural state of the wetland prior to alteration.

There have been many attempts to develop a broadly applicable method for categorising overall wetland condition. These have usually involved combining weighted measures of indicators of wetland function to provide a score or ranking. There is no universally accepted method for achieving this and most proposed methods stir controversy in some way. It is generally agreed, however, that a condition assessment scheme should include considerations of hydrology, geomorphology, water chemistry and biology and that both components and processes are important.

A project that aims to monitor wetland condition should develop a project-specific definition of condition. This should be guided by the type of wetland being studied and should incorporate a conceptual model to demonstrate the importance of the selected indicators. The weighting applied to different indicators will need to be carefully considered to ensure they accurately represent the way in which the ecosystem functions.

Of course, providing an overall score of condition is not necessary. It is often sufficient, and may be more accurate, to measure indicators without attempting to combine or scale them. Such an approach is more flexible as it allows more scope for the interpretation of data.

Implementing a monitoring program

This section provides information about practical elements of monitoring programs, including the methods recommended to measure commonly used indicators of condition. There are many different ways to measure most indicators and to combine them to build a picture of wetland health and function. Those presented here are examples that have been tested and found to be appropriate in the Western Australian environment.

Most of the recommended methods are within the capabilities of a private landholder or community group and, if executed properly, will provide high quality data. Some, however, do require specialised equipment and will require expert assistance.

Positioning monitoring actions

The correct positioning of the activities of a monitoring program is crucial to its success. There are three scales of positioning to consider:

- Study site: the wetland that is being monitored.
- Survey location: the area of the wetland where a survey is completed.
- Sampling point: the precise place at which a sample is taken.

When choosing where to undertake monitoring, the factors outlined below should be considered:

Available resources

More sites, locations and points mean more time and money are required to collect data. It may also mean that data can be collected less frequently or that hurried collection causes data quality to deteriorate. It is important to strike the right balance between developing a comprehensive dataset and having the time required to collect complete information in each survey. This balance will depend on the resources available to complete the program.

Objectives and design of the monitoring program

In some circumstances, it is appropriate to deliberately bias the positioning of monitoring activities. However, if the program relies on random sampling, consider using a random siting technique. One way to achieve this is to assign numbers to all potential sites, locations or points and then use a random number generator to select the final list.

Spatial scale of the project

A monitoring program should set the minimum size of a reporting unit at the outset. Detail that is collected at a finer scale than the reporting unit will be lost if values are averaged or combined. This may mean it is inefficient to collect fine scale data, unless greater statistical power is required.

Spatial heterogeneity of the indicator

Some indicators are only likely to vary significantly over fairly large distances, while others will be much more changeable. For example, air temperature and rainfall are likely to be quite stable across a wetland suite, while pH and salinity may be different in each wetland and vegetation composition may change several times at a single site. Likely sources of heterogeneity include variation in the type of habitat, soils, geology, aspect, hydrology and elevation. A monitoring program may need to account for any spatial heterogeneity in the parameter being measured in order to gather a representative sample.

External interference

Many monitoring programs will require a monitoring location to be representative of an entire wetland. A location may not be representative if it is subject to an obvious external influence. For instance, causeways are a popular place to take water quality measurements due to ease of access. However, causeways often disrupt the hydrology of the system and roads may be a source of pollutants. This means that the measurements taken at a causeway might not be representative of the wetland as a whole.

Constraints on access

Sampling points must be accessible at times that are appropriate and convenient. There is little point in planning to place a point in an area that is inaccessible due to tenure, hygiene or topography.

Recording the site location

It is very important that the positions of monitoring locations are accurately recorded. The best monitoring data are long term data so researchers might want to return to the exact position of the monitoring location in years to come. Here are some guidelines for accurately, and lastingly, recording the position of monitoring locations:

Assign a site name and code

Each site and location requires a unique identifier. Using a short alphanumeric code will help when storing monitoring data in a database or recording information on a sample bottle. It's also a good idea to include a project identifier in the site code. For instance the Department of Environment and Conservation's Resource Condition Monitoring Project study sites were coded RCM001 to RCM044. This identifies both the site and the project to associated personnel.

Site and location names are optional, but can be very helpful when discussing the monitoring program. People usually remember names better than numbers. Wherever possible, use an existing geographic identifier. If multiple locations are located within a single site, use cardinal points or topographic features.

Mark the location

A marker should be left in position to allow future workers to confirm the location. If the situation allows, leave a permanent marker, such as a star picket or fence dropper, in place. If the soil or water is saline, a plastic star picket should be used, as metal pickets will corrode. Attach an aluminium tag to the picket, by means of a sturdy piece of wire, with the project name and site code embossed on it. A cap on the picket or dropper will protect people and animals from sharp edges. It may also be helpful to attach a length of flagging tape or paint the top of the picket a bright colour. This will make it more visible, particularly if vegetation grows up around the marker.

If a star picket or dropper is not appropriate, usually because of concerns about potential impacts on people or domestic animals, a marker may be attached to a tree. Select a sturdy, long-lived species and drive a nail into the trunk. Hang the site identification tag from the nail by a short length of wire.

If no trees are available and a star picket is not appropriate, it may not be possible to permanently mark the monitoring location. This will increase the importance of recording very accurate positional information.

Recording the location using a geographical positioning system

A GPS is essential for accurately recording the position of a monitoring location or a sampling point. Modern GPS units are very reliable and even basic units are usually accurate to within a few metres. That said, if the wrong settings are used, or the full details of the readout not recorded, the position information will be useless. The important points when using a GPS are:

Use the correct datum

A datum is an established point on the globe that is used as the reference from which other locations are calculated. Australia uses the Geographic Datum of Australia 1994 (GDA94). If the GPS being used does not support that datum, then WGS84 is almost equivalent and will suffice for most purposes. The datum that was used must be recorded on the data sheet to allow other users to plot it accurately.

Record the zone

The entire planet is divided into zones to maximise the accuracy of GPS measurements. Western Australia lies across zones 48 to 52 south. The zone that a measurement is taken in will appear next to the location display on the GPS and it must be recorded on the data sheet. Without the zone number, the point cannot be mapped.

Record the error margin

GPS units are usually accurate to within a few metres. On occasions, however, poor reception or deliberate signal interference could result in much lower precision. Recording the error margin that is displayed on the GPS screen allows future users of the information to see its spatial accuracy.

Check that the reading makes sense

Quick consultation of a topographic map will show if the GPS reading is nonsensical. This will be a warning that the datum, or some other variable, is set incorrectly or that the unit is faulty.

Access details

Future site visits will be facilitated by recording information such as the name and contact details of the land manager and any specific instructions on gaining access to the monitoring location. A mud map of the access route and sampling points may also be helpful. Annotating an aerial photo is also a good way to record access details. Remember that the person who conducts the next site visit may not be familiar with the area. In particular, any potential hazards should be clearly identified.

Site and location overview

It is always useful to provide some contextual information about the site at the time that the survey was conducted. This is not monitoring data in the strictest sense, but will help others to interpret the survey findings. Here are some examples of contextual information that should be recorded during a site visit:

Time and date

Some indicators show variation throughout a day, for instance, pH varies in a diurnal cycle and waterbirds are most active at dawn and dusk. Recording the time that a measurement was taken will be important when the data are interpreted later. Recording the date is essential to allow the data to be included as part of a time series or compared to surveys at other sites.

Weather and climate

Weather conditions at the time of the visit, and in the time leading up to it, can be important. Weather at the time of the visit can directly influence measurements or increase the margin of error. For example, rain or fog will make it much more difficult to see waterbirds and a bird count done under such conditions is likely to underestimate their numbers. Weather patterns in the lead up to a survey may also affect measurements. For instance, rainfall may alter water chemistry by diluting salts in a waterbody or introducing pollutants to it.

Evidence of recent disturbance

Disturbance to a site may be a result of natural phenomena, land management practices, an accidental spill or illegal activities. A monitoring program should capture information about any evidence of disturbance at sites, including the source of the impact, extent of the area affected and severity of the impact. This will allow temporally discrete impacts to be accounted for in the monitoring dataset.

Table 2 shows the most common threats to wetland ecosystems. For some of these, it is possible to quantify the extent and severity of the impact. For example, it is possible to measure the area of the fringing vegetation that is infested with weeds and to calculate the percentage of the total cover contributed by weed species. Other categories of threat may require a more qualitative approach, because the area affected is difficult to assess, an area statement is irrelevant or the severity of the impact cannot be quantified. Whichever approach is adopted, it is important to take notes and photographs that will allow future surveyors to determine if the extent or severity of any impacts have changed. Notes should also indicate if the impact will affect the measurements taken of any indicators, for example a recent fire reducing the vegetation cover at a site.

Substrate: a generic term denoting the material forming the floor of a wetland and its surrounds. It is used here because the term 'soil' is not inclusive of organic substrates.

Table 2. Threats that may have a detrimental impact in wetland ecosystems.

Threat Category	Threat
Altered biogeochemical processes	Waterlogging and salinisation
	Eutrophication
	Erosion and sedimentation
	Drainage into / from site
	Groundwater abstraction
Introduced plants and animals	Weeds
	Feral animals
	Livestock grazing and wallowing
Problem native species	Usually overgrazing
Impacts of disease	
Detrimental regimes of physical disturbance and climate change	Fire
	Drought
	Flood
	Storm damage
Impacts of pollution	Herbicide, pesticide, fertilisers
	Spills
	Runoff
Competing land uses	Urban and industrial development
	Recreation
	Agriculture
	Consumptive and productive use
	Mines and quarries
	Illegal activities

Substrate composition

The **substrate** of a wetland is an important contributor to biological and chemical processes, such as nutrient cycling and the occurrence of vegetation.

Although an important part of the ecosystem, the substrate at a study site is unlikely to change, except over very long periods of time. As such, monitoring programs will not usually include repeated assessment of substrate composition. It is, however, very useful to record the characteristics of the substrate at the commencement of monitoring.

Many wetland substrates show classic soil structure, with a combination of mineral particles and organic matter. Some wetlands, however, lack true soils, and instead are underlain by deep deposits of organic matter. Little analysis is required of organic substrates, except to record their presence. The following information, therefore, relates to wetlands with a true soil profile.

The uppermost layer of a wetland soil is the P (peat) horizon, composed of organic materials in varying states of decomposition. This layer is termed the O (organic) horizon if it forms under dry conditions. Beneath the peat or organic horizon is the uppermost layer of mineral soil, known as the A horizon. The A horizon will often contain some organic material that has been incorporated from the O or P layers but will be predominantly mineral.

Various other layers of soil occur between the A horizon and the underlying bedrock. Unless soil composition is a particular focus of the project, however, it will probably only be necessary to record the nature of the O/P and A horizons. The documentation of deeper soil horizons will require a soil pit to be dug or soil cores to be taken.

Soil depth

The depth of the O / P horizon can be an important indicator of ecosystem health as organic material plays a role in nutrient cycling and habitat provision. The depth of the A horizon may also be a useful measure, as it is indicative of the suitability of the area for different types of vegetation.

Soil colour

The colour of soil reflects the minerals that compose it and the processes that are occurring within it. As such, it is indicative of the physical and chemical conditions in the soil. The colour of the O/P horizon is not usually important as decomposing organic matter is usually grey or black in colour. The colour of the A horizon of the soil profile may be a useful parameter to collect.

Soil colour is measured by comparing a soil sample to colour swatches in a Munsell Soil Colour Chart until a match is found. Colour is expressed as alphanumeric code that represents **hue**, **value** and **chroma** (Figure 2).

Hue: the property of colours by which they can be perceived as ranging from red through yellow, green, and blue, as determined by the dominant wavelength of the light

Value: the property of a colour by which it is distinguished as bright or dark; also known as luminosity

Chroma: the purity of a colour, or its freedom from white or grey

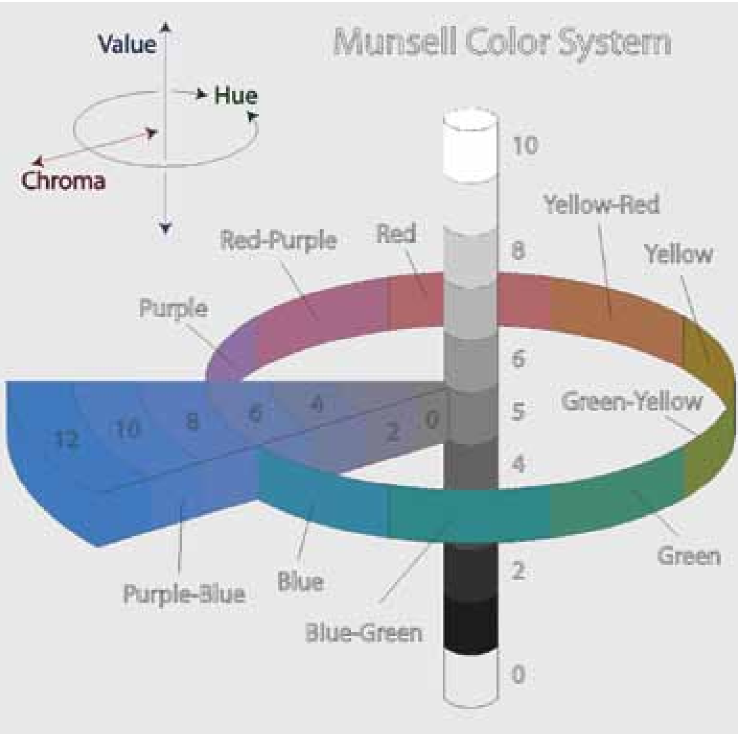

Figure 2. A diagrammatic representation of the combination of hue, value and chroma to give a unique colour identifier in the Munsell Colour System. From en.wikipedia.org.[11]

Colour is usually recorded when the soil is damp, but dry colour can be used. Annotate the recorded colour with ‘M’ for a moist recording or ‘D’ for a dry one.

If a Munsell chart is not available an attempt may be made to provide a vernacular descriptor of the soil. Most soils will be some mixture of grey, yellow, red and brown.

Soil texture

Texture refers to the distribution of grain sizes of the mineral particles in a soil. Soil texture strongly influences the physical and chemical properties of soil.

Soil particles are grouped into classes of clay, silt and sand according to size (Table 3). The texture of a soil is defined by the relative abundance of particles of these different sizes. A texture category is assigned by plotting, on a texture triangle diagram (Figure 3), the percentage of a soil sample that is in these different size classes.

Table 3. Soil size fractions. Adapted from McDonald (1998)[12]

Soil Particle Group	Maximum Particle Size (mm)
Clay	0.002
Silt	0.02
Fine sand	0.2
Coarse sand	2.0
Fine gravel	6.0

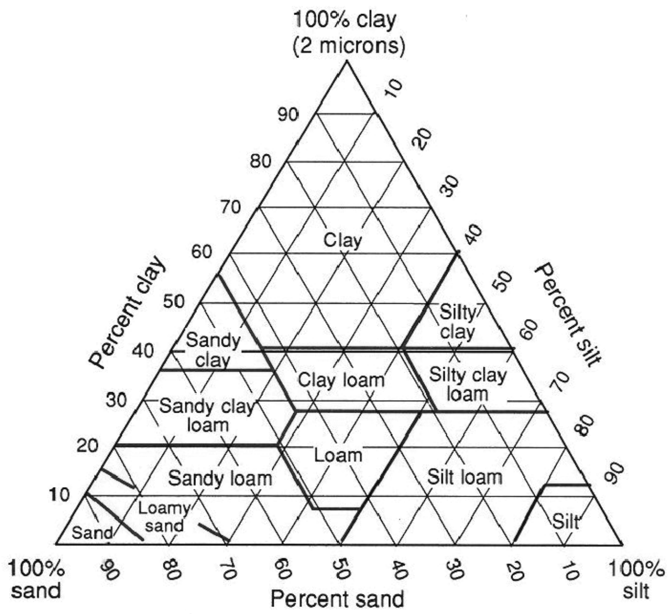

Figure 3. Triangular soil texture diagram. Texture is determined by plotting the percentage of particles in a soil sample that are in the size category of clay (<0.002 mm), silt (<0.02 mm) and sand (<2 mm). From Wikipedia en.wikipedia.org.[13]

Soil texture can be accurately measured by passing a dried soil sample through a set of nested sieves. The weight of soil collected by 0.002 millimetre, 0.02 millimetre and 2.0 millimetre sieves is weighed and converted to a percentage of the total soil weight. However, texture is more commonly assessed in the field using a ribbon test.

To assess soil texture in the field, begin by moistening a small handful of the soil while kneading and rolling it in the hand. Continue slowly adding water until the soil ball (or bolus) just fails to stick to the fingers. Once this point is reached, squeeze the bolus between the thumb and forefinger such that a ribbon of soil is squeezed away from the hand. Continue squeezing the ribbon until it breaks under its own weight. The behaviour of the bolus during its formation, and the length of the ribbon that can be formed from it, provide a good indication of soil texture (Table 4).

Table 4. Guidelines for the assessment of soil texture in the field. From the website of the New South Wales Department of Planning and Infrastructure www.dpi.nsw.gov.au.[14]

Field Texture Group	Texture Grade	Coherence	Feel	Ribbon Length (mm)	% Clay
Sands	Sand	Nil	Sandy	Nil	<5
Loamy sand	Slight	Sandy	5	5	
Clayey sand	Slight	Sticky	5–15	5–15	
Sandy loams	Sandy loam	Just coherent	Sandy	15–25	10–25
Fine sandy loam	Just coherent	Sandy	15–25	10–25	
Loams	Loam	Coherent	Spongy greasy	25	25
Silt loam	Coherent	Smooth	25	25	
Clay loams	Sandy clay loam	Strong	Sandy	25–40	20–30
Fine sandy clay loam	Coherent	Smooth, sandy	40–50	20–30	
Clay loam	Strong	Smooth	40–50	30–35	
Silty clay loam	Coherent	Smooth	40–50	30–40	
Light clays	Sandy clay	Coherent	Plastic	50–75	30–40
Silty clay	Coherent	Plastic	50–75	35–40	
Light clay	Coherent	Plastic	50–75	35–40	
Clays	Medium clay	Coherent	Plastic	75+	45–55
Heavy clay	Coherent	Plastic	75+	50+	

Soil pH

The pH of soil is an important determinant of the ecological character of a wetland. It will influence the chemical properties of the water body and the biology of the system. Soil pH may undergo rapid changes if environmental conditions are altered, and so, is one element of the sediment that may be measured regularly in a monitoring program. It is measured using a soil pH test kit, available from nurseries, or with a pH probe.

Hydrology

There are two components of hydrology that are of interest to wetland managers: water budget and water regime. The water budget of a wetland is the balance of all of the inflows and outflows of water. The water regime of a wetland is the specific pattern of when, where and to what extent water is present in a wetland.

➤ For additional detail on wetland hydrology, see the topic 'Wetland hydrology' in Chapter 2.

Water budget

The water budget of a wetland is calculated by summing all of the inputs of water to the system and subtracting all of the outputs. The main inputs of water to a wetland are from direct rainfall, surface water inflow via channels and overland flow and groundwater inflow. The main outputs of water from a wetland are evaporation, evapotranspiration, surface water outflows and groundwater outflows.

Determining and monitoring the water budget of a wetland is one of the most difficult monitoring activities to attempt. Establishing a water budget monitoring program is likely to require expert assistance and professional equipment. However, recording some basic information, such as rainfall and channel flows at the site, may be useful even if a full water budget is not calculated.

Rainfall

Precipitation falling directly on the wetland is the easiest component of the water budget to measure. The quantity of rain received at the site is measured in a rain gauge. A gauge should be sited so that it is no closer to any obstruction than three times the height of that obstruction. For example, a gauge should be no closer than 30 metres from a tree that is 10 metres in height. A gauge should also be about 1.5 metres above the ground, as this helps to standardise the influence of wind on rainfall measurements.

The following formula will convert the rain gauge reading to a volume of water entering a wetland via direct rainfall:

$$V_W = V_G A_W / A_G$$

Where

V_W = Volume of rainfall on wetland
V_G = Volume of water in gauge
A_W = Area of wetland
A_G = Area of gauge opening

If the volume and area measurements are expressed in cubic metres and metres respectively, the output of the equation will be in cubic metres of water. This can be converted to litres by multiplying by 1000.

Channel inflow and outflow

Channel flows are ideally measured using a V-notch weir or similar in-stream device. A V-notch weir is a channel engineered to known proportions such that the volume of water passing through can be calculated. These require quite precise engineering to install and, because of the need to modify the channel, will not be appropriate in some settings.

➤ More information on V-notch weirs is available from this website: www.lmnoeng.com.[15]

An alternative to establishing a weir is to use measurements from the extensive network of water gauging stations maintained by the Western Australian Department of Water (DoW). If one of these is located in near the study site, it may be able to provide the flow rates required to calculate the water budget.

➤ The location of, and data produced by, these stations are available from the DoW website: www.water.wa.gov.au.[16]

If a permanent monitoring station is not available, a handheld flow metre may be used to measure the flow velocity. The metre should be used mid-stream, where the velocity is highest. The flow volume can then be estimated by multiplying the flow velocity (in metres per second) by the channel cross sectional area (in square metres).

The cross sectional area of the channel is calculated by taking water depth measurements at regular intervals across the width of the waterway. Minimising the distance between measurements will improve the accuracy of the calculation.

These measurements can then be graphed to construct a channel cross section. On a sheet of graph paper, draw horizontal and vertical axes that are appropriate to contain the cross section of the waterway being assessed. Mark a dot on the graph to represent the depth of water at the point where the measurement was taken. Repeat this for all the points at which depth measurements are taken. Finally, connect the dots to form a diagram of the channel's cross-section. The area can then be calculated by counting the graph squares that are within the waterway. The area of any incomplete squares should be estimated (Figure 4).

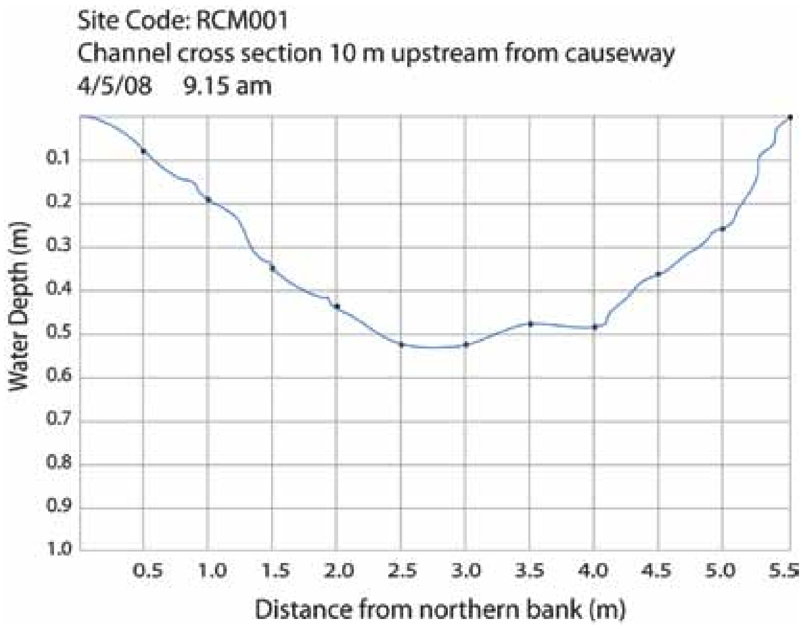

Figure 4. An example of a channel cross-section diagram. Depth measurements were taken every 0.5 metres across the channel width and plotted onto graph paper. The area of the channel can now be calculated by counting the number of squares within the depth profile. In this example, each square has an area of 0.05 square metres.

Overland flow

Overland inflow occurs when surface water runoff enters wetlands after heavy or persistent rainfall exceeds the infiltration capacity of soils in the catchment. Water may exit a wetland via overland flows if water tops the banks and floods surrounding land.

Overland flow is very difficult to measure in the field. If it is important that overland inflow is included in a water balance equation, it will be necessary to use modelling software to calculate the runoff from surrounding land. This will be affected by many factors including rainfall duration, quantity and intensity, topography, soils and geology, land use in the catchment and the nature of surrounding vegetation. Such modelling will require assistance from a professional hydrologist.

Measuring flood outflows will not be necessary for most monitoring programs, as it will be possible to calculate the quantity of water remaining in the system after a flood event. At the cessation of flooding, the wetland will be at maximum capacity.

➤ For additional detail on calculating the capacity of a wetland, see the 'Water regime' section of this topic.

Groundwater inflow and outflow

Groundwater is an important element of the water balance of most wetlands. Measuring groundwater fluxes is, however, a difficult task that requires both expertise and specialised equipment. In brief, piezometers (monitoring bores) are sunk into the groundwater across the landscape. Regular measurement of the height of groundwater in these bores allows a hydrogeologist to calculate the position of the water table and its direction and rate of flow.

Once a network of piezometers is established, the depth to groundwater is measured by lowering a weighted string, known as a 'plopper', down the bore. When the weight can be heard to hit the water, a reading of the depth below surface is taken from the string. Although this aspect of the operation is straightforward, establishing a suitable piezometer network and analysing the data require specialised knowledge. A hydrogeologist must be employed to assist if groundwater monitoring is required by a project.

Evaporation

The loss of water via evaporation is a major factor in the water balance of Western Australian wetlands. Evaporation rate is influenced by the amount of solar radiation received, ambient temperature, wind speed, atmospheric humidity and water chemistry. It is measured using a class A evaporation pan.

An evaporation pan is a water tight, circular pan, 121 centimetres in diameter and 25 centimetres deep, made of 20 gauge galvanized iron. It is mounted on an open wooden platform and protected with a wire bird-guard to prevent animals drinking the water (Figure 5). The pan is filled to a fixed mark 19 centimetres above the base. Twenty-four hours later, the volume of water required to refill the pan to that mark is measured. Every 1.14 litres of water required to refill the pan represents 1 millimetre of evaporation. Any rainfall that has occurred during the 24 hour period must be deducted from the evaporation measurement.

Figure 5. Class A evaporation pan. Image from Pickering (2007).[17]

Water will evaporate more rapidly from an evaporation pan than from a wetland. This is mainly due to a layer of water vapour that sits above large water bodies and insulates them against further evaporation. The chemical composition of the water and the extent to which a wetland is shielded from the wind are also important factors.
A correction factor is required to determine lake evaporation from pan evaporation:

Evaporation = Lake Factor x Salinity Factor x (Pan Evaporation – Rainfall)

Evaporation, Pan Evaporation and Rainfall have the same units and are normally expressed in millimetres per day.

Lake Factor is normally assumed to be 0.7, although it may be lower in the case of sunken wetlands or sites that are otherwise shielded from the wind. If the site is highly shielded from the wind, use a lake factor of 0.65.

Salinity Factor is 0.7 for saturated brines. The following formula allows the salinity factor to be calculated for other solutions.

Salinity Factor = 1-salinity (%) x 0.00086[18]

Evapotranspiration

Vegetation within and around a wetland will influence the water balance by transpiring water. Measuring the rate at which plants transpire requires specialised equipment, and is very difficult to achieve in a natural setting. This is because the rate of evapotranspiration will be different for each plant and will also be affected by the type of soil, the availability of water and the ambient climatic conditions.

The number of variables affecting evapotranspiration rate makes it impractical to measure in a wetland monitoring program. Two alternatives approaches are mathematical modelling and remote sensing. Both of these approaches are beyond the scope of the current document and will require expert assistance if they are to be applied.

Water regime

The water regime of a wetland is the timing, duration, frequency, extent, depth and variability of water presence at the site. The water regimes of Western Australian wetlands typically show a high degree of variability. For example, it is common in arid parts of the state, for wetlands to be dry for long periods of time before rapidly filling in the aftermath of a storm. The variability of wetland water regimes means that relatively long term data (probably in the order of decades) will be required in order to identify trends amidst natural variation.

Australian Height Datum (AHD): is a fixed survey point from which the elevation of any point in Australia may be measured

Documenting the water regime of a wetland will require a surveyed depth gauge and some knowledge of the bathymetry of the system. A depth gauge should be positioned at the deepest point of a wetland and should be surveyed to **Australian Height Datum** (AHD) or a suitable local height datum.

The water level on the depth gauge is recorded regularly to monitor seasonal changes. A bathymetric survey of the wetland will allow a correlation between the depth of water measured on the gauge and the total volume in the basin.

Bathymetric survey involves constructing a three dimensional model of a wetland's floor by taking depth measurements along a number of transects. The measurements must be calibrated to AHD or a suitable local height datum, so that they are relative to a fixed datum, rather than to water level at the time of survey.

The extent of a wetland is best delineated by determining the maximum area that is waterlogged over several wetting / drying cycles. This may be problematic, however, at sites that are only 'wet' occasionally and at sites that flood over broad areas.

Water conditions

Water in natural settings is never pure; it always contains dissolved ions and molecules that give it particular chemical properties. These properties of the water body are very important to a wetland's condition as they dramatically affect many of the components and processes in the system.

Some of the chemical properties of the water column may be measured in-situ, while others will require water samples to be analysed in a laboratory (Table 5). Techniques are provided here for taking in-situ measurements and for collecting water samples for laboratory analysis. The actual methods required to complete laboratory analyses are not included as they are beyond the scope of this document. If such analyses are required, it is recommended that a commercial laboratory be contracted to provide them.

Table 5. A summary of standard equipment and where measurements may be conducted for various water quality parameters.

Parameter	Equipment Required	In-situ Measurement	Laboratory Measurement
Conductivity	Meter with probe	✔	
pH	Meter with probe	✔	
Transparency	Secchi disc	✔	
Turbidity	Meter with probe or water sample for lab	✔	✔
Dissolved Oxygen	Meter with probe	✔	
Total dissolved solids	Meter with probe or water sample for lab	✔	✔
Ionic composition	Water sample for lab		✔
Nutrients	Filtered water sample for lab		✔
Colour	Water sample for lab		✔
Chlorophyll a	Frozen filter paper for lab		✔

Water chemistry is monitored to confirm that the parameters of interest remain within an appropriate range to maintain ecosystem health. This requires predetermination of the range of values that are acceptable for each water chemistry parameter. It is difficult to generalise about these values because the many different types of wetland ecosystems across Western Australia each give rise to unique environmental conditions.

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC guidelines)[19] describes 'trigger values' for various water quality parameters (Table 6). These describe the acceptable range of measurements in different types of wetlands in various parts of Australia. Although it provides some context for water quality measurements, the ANZECC guidelines do not fully reflect the potential range of 'natural' wetland conditions in WA.

Rather than relying on a prescribed acceptable range, monitoring programs should set trigger values or limits of acceptable change for the study site. This will require an understanding of the natural variability of the system. Such understanding may be developed from a review of relevant literature, but is best achieved through surveillance of the site through several wetting and drying cycles.

➤ More advice on developing site specific trigger values is available in Chapter 2 of the ANZECC guidelines [20] and the topic of the guide 'Conditions in wetland waters'.

Table 6. Default trigger values for chemical stressors for slightly disturbed ecosystems in Western Australia.[19]

Water Quality Parameter	Trigger Value Northern Australia	Trigger Value Southwest Australia
Chlorophyll a (µgL-1)	10	30
Total Phosphorous (µgL-1)	50	60
Filterable Reactive Phosphate (µgL-1)	25	30
Total Nitrogen (µgL-1)	1200	1500
Oxides of Nitrogen (NOx µgL-1)	10	100
Ammonium (NH4+ µgL-1)	10	40
Dissolved Oxygen (% saturation)	<90 and >120	<90 and >110
pH	<6.0 and >8.0	<7.0 and >8.5

➤ More information on measuring water quality parameters is available in Module 4 of the *Waterwatch Australia National Technical Manual*: www.waterwatch.org.au.[21]

In-situ measurement of electrical conductivity

Pure water is a poor conductor of electricity, as it contains few of the free ions required to transfer an electrical charge. The electrical conductivity of a water body is, therefore, determined by the concentration of dissolved ions in the water. Because of this, electrical conductivity (EC) can be measured as a surrogate for the total dissolved solids (TDS) in a water body. The greatest contribution to the solids dissolved in a wetland will be the ions of various salts, unless the water is very turbid, in which case the suspended particles can make up more of TDS than the salts. In turbid wetlands, TDS is not a good indicator of salinity; a more accurate measure is the summed concentration of the major ions.

EC is measured in preference to TDS because the former is easily measured in the field using an inexpensive handheld meter. However, EC only provides an approximation of TDS. There are many factors that affect the conversion of EC to TDS, including the type of salt dissolved and the pH and temperature of the water. For most purposes, it will be sufficient to simply multiply the EC reading in millisiemens per metre (mS/m) by 5.5 to get an approximation of the milligrams of salt per litre of water (note that relatively fresh water may return a value measured in microsiemens per centimetre (µS/cm); this must be divided by 10 to convert it mS/m). If a precise measurement of TDS is required, it is necessary to use the laboratory method provided later in this section.

The natural concentration of salts in wetlands varies markedly, both through time and between wetlands. The geology, hydrology and soils of a wetland play an important role in determining the salinity regime and many WA wetlands are naturally saline.

Also, even in relatively fresh wetlands, salt concentration is directly related to the volume of water in the system. Salts will be diluted when water levels are high and become more concentrated as wetlands dry. This is part of the natural cycle of a wetland. Although freshwater generally supports a greater richness and diversity of biota, naturally saline sites also provide valuable habitat for flora and fauna that are adapted to such conditions. It is not possible, therefore, to provide any range of EC values that are acceptable or ideal in wetlands. Rather, monitoring should aim to detect any unnatural change in the pattern of EC measurements at a site. To provide some context, the maximum EC of water that is fit for human consumption is approximately 250 millisiemens per metre, while adult sheep may tolerate up to 2200 millisiemens per metre. Seawater has an EC of approximately 60 000 millisiemens per metre.

When monitoring EC, it will be necessary to take measurements regularly (at least seasonally) through a number of wetting and drying cycles. This will allow the natural variation in the system to be documented, and so, any unnatural trend in conditions to be identified. It is also important to record the volume of water in the wetland when each EC measurement is taken. This will allow the total salt load in the system to be monitored rather than the concentration of salt in the water, which will vary through a wetland's seasonal cycle.

Before using a handheld EC meter, it must be calibrated according to the manufacturers instructions. This will involve placing the probes into solutions of a known concentration of salts. It is also necessary to clean the probes after use, as per the manufacturers instructions, to ensure their longevity.

Conductivity meters have a maximum detection threshold, and so, cannot measure highly saline solutions. If the detection threshold of the meter is exceeded, it is possible to dilute a sample with fresh water of known conductivity, in order to obtain a reading. If this approach is used, the volume of the water sample and the volume of fresh water added must be measured very accurately. Alternatively, a water sample could be taken for laboratory analysis.

In-situ measurement of pH

pH is a measure of the concentration of hydrogen ions in a solution; dissolved hydrogen ions being responsible for giving a solution the properties of an acid. The pH of a solution will influence the solubility of compounds and the behaviour of ions in it. This makes pH a strong determinant of the biota that can persist in a wetland.

pH is measured on a logarithmic scale typically ranging between 1 and 14. Lower pH values denote a greater concentration of hydrogen ions, making the solution acidic. Many wetlands have near-neutral pH (approximately 7), but considerable variation in either direction occurs naturally. Very low pH in wetlands is a cause for concern, as it may cause the mobilisation of toxic metals or other contaminants.

pH is measured in the field using a handheld meter. The meter should be calibrated prior to use, according to the manufacturers instructions. Calibration will involve immersing the probe into solutions of known pH.

pH varies in a diurnal cycle, so measurements in a monitoring program should ideally be taken at the same time every day. If this is not possible, ensure the time of day that the reading was taken is recorded. A water temperature measurement should be recorded at the same time that a pH measurement is taken, as temperature also affects pH.

In-situ measurement of transparency

Transparency is a measure of the degree to which light is able to penetrate the water column. Light penetration is important to the survival of the aquatic plants and algae which are at the base of the wetland food chain. The transparency of wetlands varies according to a number of factors including the nature of the sediments in the wetland and in the catchment, water chemistry, rainfall and wind. Transparency is reduced by high concentrations of dissolved and suspended material in the water column, such as clay, algae or tannins. It can naturally be very low, such as in turbid claypans. Any significant, ongoing reduction in transparency should be investigated as it may be indicative of increased algal activity, erosion in the catchment or changed chemical conditions in the water.

A secchi disc is used for measuring water transparency. This is a 15–20 centimetre diameter, round, metal plate that is divided into quadrants that are alternately painted black and white (Figure 6).

The secchi depth of a water body is found by lowering the disc into the water until the black and white quadrants are no longer discernable. The depth at which this occurs is the secchi depth and the transparency of the water column is double the secchi depth.

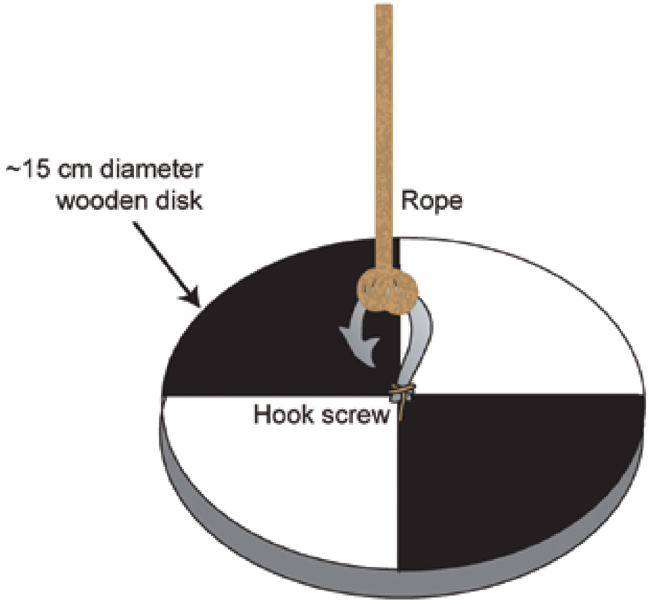

Figure 6. Recommended width, colouration and weighting of a secchi disc. Images taken from website www.globe.gov.[22]

In-situ measurement of turbidity

Turbidity is, essentially, the inverse of transparency. It is the extent to which light is scattered and reflected by particles suspended or dissolved in the water column (turbid water appears cloudy due to suspended material). It is measured with a handheld, electronic probe. If turbidity is to be measured, it must be done before the substrate is disturbed by other monitoring activities. Turbidity can also be measured in the laboratory using a water sample from the wetland.

In-situ measurement of dissolved oxygen

Oxygen in the water column is essential to many of the natural chemical processes that occur in a wetland and to the persistence of aquatic fauna. The concentration of oxygen dissolved in the water of a wetland reflects equilibrium between atmospheric exchange, oxygen-producing processes, such as photosynthesis, and oxygen-consuming processes, such as respiration and chemical oxidation.

Dissolved oxygen (DO) concentration is measured using a handheld, electronic meter. It is important to follow manufacturers instructions to calibrate the unit prior to use. This will involve placing the probe into an oxygen-saturated solution, followed by a solution from which all oxygen has been chemically removed. It is also necessary to clean the probe after use, to ensure its longevity.

DO will show diurnal variation caused by photosynthetic activity during daylight. It is good practice, therefore, to take measurements at dawn and midday to track this natural variation. At a minimum, a monitoring program must take DO measurements at the same time of day in every round of surveys.

The solubility of oxygen in water is influenced by atmospheric pressure, water temperature and the concentration of dissolved salts in the water column. To take these factors into account, it is usual to express DO as a percentage of the saturation value. Most meters will complete this calculation automatically. It is good practice, however, to also record the actual concentration of oxygen, in milligrams of oxygen per litre of water (mg/L).

DO meters are most accurate when oxygen levels are moderate or high. At low oxygen concentrations, meters may be slow to register a reading and the reading may change continually. In such cases, it will be necessary to estimate a mean value over a period of up to two minutes. Note also, that oxygen levels can exceed 100 per cent saturation, particularly on hot sunny days or when algal growth is prolific.

Collecting water samples

Water samples are collected for laboratory analysis of water chemistry attributes that cannot be measured in the field with sufficient accuracy or precision. It is very important to avoid contamination of water samples, as the equipment that will be used to analyse samples is very sensitive and will detect trace amounts of contaminants.

Water samples should be collected and stored in high density polyethylene or polypropylene bottles. These bottles should be washed with a phosphorous free, laboratory grade detergent prior to use and handled with care to avoid any potential for contamination.

When taking a water sample, gloves should be worn to avoid contamination of the water body with oils from the sampler's hands. Whenever possible, a sampling pole should be used to avoid the need to enter the water body. This is a 1 to 2 metre long polycarbonate pole with acrylic jaws that hold a bottle. If it is necessary to enter the water, disturbance of the substrate should be minimised and a sampling pole used to ensure that the sample is taken some distance from the disturbed area. If the water is flowing, samples should be taken upstream from any people that are in the water, with the bottle mouth upstream of the collector's hands and the body of the bottle.

The cap of the sample bottle should not be removed until immediately prior to collecting the sample and the inside of the bottle or cap should never be touched. Before collecting the sample, rinse the bottle and lid several times in the water body to remove any rinse-water left over from washing the container. The sample bottle should be filled by holding it near the base and plunging it below the water surface with the opening downward. The bottle should be held about 20 centimetres below the water surface, or mid-way between the water surface and bottom if the water is shallow, until it is full. Once full, the bottle is recapped without the sampler having any contact with the inside of the bottle or the cap. Table 7 shows the volume of water required for laboratory analysis of various chemical parameters.

The details of the sample are recorded on the datasheet form and the sample bottle labelled with the same details. Standard details to record are the site and location codes, date, water quality parameter, type and quantity of any preservative used and any hazard warnings.

Water samples that will be used for measuring chlorophyll and nutrients must be passed through filter papers and the filter papers frozen until they are analysed. This requires samples to be transported in an insulated carrier box (esky) with ice or in a portable refrigerator. Note that carrier boxes can be a source of sample contamination and must be cleaned thoroughly before use.

Table 7. The volume of water required for laboratory analysis of various parameters.

Parameter	mL required	Notes
Total filterable phosphorus and nitrogen	100	Filtered through 0.45 micron filter paper that is then frozen until analysis
Acidity, Colour, Conductivity, pH, Turbidity, Total dissolved solids, Suspended solids	250	
Calcium, Magnesium, Sulphate, Potassium, Chloride, Sodium, Hardness, Alkalinity, Bicarbonate, Carbonate	500	Hardness and Alkalinity are calculated from these ions
Total Nitrogen, Total Kjeldahl Nitrogen, Total Phosphorus, nitrate and nitrite	250	Store frozen until analysis
Chlorophylls*	1000	Container is used to collect a sample for filtration. Filter paper is analysed. Filtered water can be used for further filtering the dissolved nutrient fractions.

Laboratory analysis of total dissolved solids

The total dissolved solids (TDS) in a wetland are all the molecules, ions and microgranules present in the water column. It also includes suspended material that is smaller than 2 microns in diameter. TDS is the most accurate measure of the salts that are present in a water sample, although organic chemicals and other pollutants may contribute to the TDS. TDS is determined by passing water through a 2 micron filter and then evaporating a known mass of the filtered water. The weight of the remaining residue is expressed as a weight per volume of the water sample.

Laboratory analysis of ionic composition

The complete chemical composition of a water sample is determined in the laboratory by ion chromatography. This is a process that allows the separation of ions and polar molecules based on the charge properties of the molecules. It provides a complete analysis of the concentration of every ion in a sample. The sum of the concentrations of these ions is the most accurate measure of salinity but is also the most expensive.

Laboratory analysis of nutrients

Nitrogen and phosphorous are the two most important elements for the growth of plants and algae. These elements are also common pollutants, with elevated concentrations leading to dangerous and/or cyanbacterial algal blooms.

Both nitrogen and phosphorous can exist in several forms within a wetland ecosystem; categorised as dissolved and organic components. The dissolved component; consisting of nitrate, nitrite, ammonia and orthophosphate; can be readily used by plants.
The organic component is bound to carbon, for instance within bacteria or algae, and is not available for use by plants. A measure of total nutrients includes both the dissolved and organic components. A more useful measure is total dissolved nutrients or measures of the individual 'species' of each element.

Water samples taken for the purpose of determining dissolved nutrients should be passed through a filter paper of pore size 0.45 micron (μm) and frozen in the field. The exception is highly turbid samples, which should be frozen unfiltered and centrifuged prior to analysis.

Laboratory analysis of turbidity

When analysed in the laboratory, turbidity is measured with a nephelometer. A beam of light is passed through the sample and onto the nephelometer's detector. The detector registers the scattering of the light beam by particles in the sample. The units of turbidity from a calibrated nephelometer are called Nephelometric Turbidity Units (NTU).

Laboratory analysis of colour

Colour can be precisely measured in the laboratory using a spectrophotometer. The absorbance of light of particular wavelengths by the water sample provides its colour in True Colour Units (TCU).

Highly coloured water will limit light penetration, and so, can mitigate the effect of elevated nutrient concentrations on plant and algal productivity. This means that damaging algal blooms are less likely to occur in highly coloured water.

Collecting and analysing a sample for chlorophyll a

Chlorophyll a is the pigment required for photosynthesis in plants and algae. Its concentration in a water sample is the best indicator of the algal biomass in the water column. Very high chlorophyll a levels may indicate an algal bloom due to nutrient enrichment of the wetland.

To measure chlorophyll a concentration, a water sample is first passed through a glass fibre filter paper. The quantity of water required is somewhat dependant on the nature of the water, as highly turbid samples will rapidly block the filter pores. In general, aim to filter at least 500 millilitres (mL) of water. The filter paper is then removed and frozen for transportation to the laboratory. The content of chlorophyll a in the water is determined by using a spectrophotometer.

Wetland vegetation

Vegetation is an integral part of a wetland ecosystem and, as such, will usually be included when monitoring a site. There are many different ways to monitor vegetation, but most aim to collect a similar set of data: the **composition** of the **plant communities** that are present, their **structure**, condition and extent.

Note that no distinction is drawn here between vegetation that grows on the floor of a wetland, including aquatic plants, and that which fringes it. This is because the recommended survey methods are suitable for both.

Community composition: the plant taxa that occur in a given community

Plant community: a discernable grouping of plant populations within a shared habitat. A community develops due to a unique combination of geologic, topographic and climatic factors and will be recognisable where those factors co-occur

Community structure: the three-dimensional distribution (height and width of foliage) and abundance of plant taxa and growth forms within a community

Plant community survey for the community

The method of vegetation assessment recommended here is designed to provide a high level of data confidence. It requires some botanical knowledge and can be relatively time consuming to implement. Monitoring programs that do not require this level of rigour may prefer a more rapid assessment. The book *Bushland plant survey: a guide to plant community survey for the community*[23] is a well respected publication that provides such a method.

To accurately assess these factors, a monitoring program will require a detailed assessment of vegetation based on quantitative measures. The assessment will define the composition and structure of each plant community and measure its extent. It will also measure the percentage **crown cover** for each stratum in each community.

The method that is recommended here relies on the collection of quantitative data using standardised techniques. This approach will minimise inter-operator errors and make the resultant information more robust. It will also require some botanical expertise and may be more time consuming than qualitative methods.

Data should also be collected on the impacts of threats to vegetation. At lower levels of data confidence, this may require assessors to broadly categorise evidence of the impacts of threatening processes. If more confidence is required, it may be desirable to record additional information about the health of individual plants and the reproductive success of the community. This detail will show if changes are occurring within communities and if communities are likely to persist in their current form.

Canopy cover: the proportion of ground surface covered by the leaves and branches of plants when projected vertically downwards

Crown cover: the vertical projection of the outer extent of the crown of a plant. A line around the outer edge defines the limits of an individual canopy, and all the area within is treated as 'canopy' irrespective of gaps and overlaps

Stratum: (plural strata) a visibly conspicuous layer of photosynthetic tissue within a plant community

NVIS - the National Vegetation Information System

The National Vegetation Information System (NVIS) was developed to resolve differences in the way that vegetation data are interpreted and managed across Australia. This includes a method for writing a standardised description of a plant community. NVIS was produced by the National Land and Water Resources Audit (NLWRA) as part of a nation-wide assessment of vegetation extent.

The guidelines for capturing, interpreting and managing vegetation survey data for NVIS are provided in *The Australian Vegetation Attributes Manual*.[24] The manual describes the attributes that should be measured in the field and how these are used to build a description of the vegetation. It also stipulates the requirements for metadata and the process of collating vegetation information into a relational database.

An NVIS community description concisely communicates a great deal of information about the vegetation at a survey location. There are six levels of detail in NVIS; higher levels require more data to be collected and give a more detailed description of the vegetation (Table 8). At the higher levels of detail, the community description states the **strata** that are present, their height, canopy cover and growth form and the plants that are dominant in each.

A complete NVIS level VI vegetation description may look like the example in Figure 7 (note that colouration has been added to assist the reader in distinguishing between parts of the description):

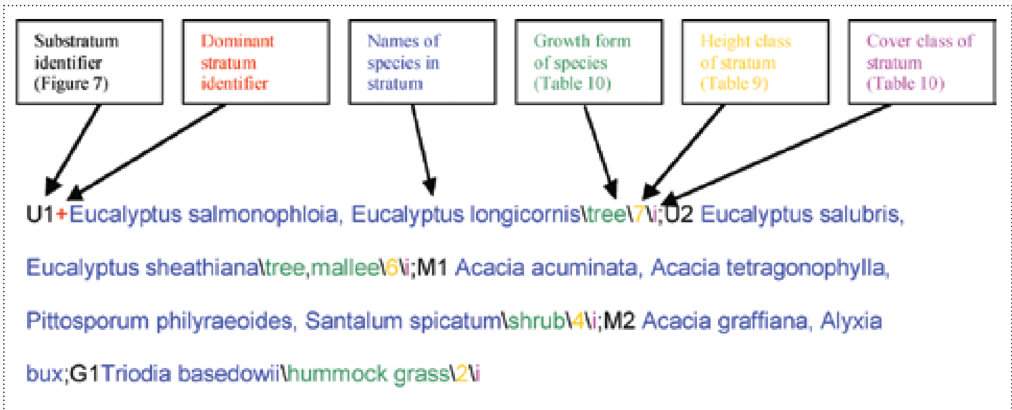

Figure 7. An example of an NVIS vegetation association description.

NVIS is required to be flexible to allow for regional environmental differences. As such, it does not require the application of a particular vegetation survey technique. However, the manual recommends the approaches described by Hnatiuk et al. (2008).[25] The point intercept and zig-zag methods described in this section are based on the methods of Hnatiuk et al. with some minor adjustments deemed necessary to ensure suitability for application in a wetland setting.

Describing a plant community

This section explains the process of developing an NVIS association (Level 5) or sub-association (Level 6) vegetation description (see Table 8 for an explanation of these terms). The same basic approach can also be used to describe vegetation at lower NVIS levels. Data should be collected that allows a community description to be developed that is appropriate to the purposes of the monitoring program. It is recommended, however, that monitoring programs describe vegetation to at least association level.

There are a number of reasons why it will be useful to define the plant communities that occur at a wetland. Firstly, community names are an effective way to communicate the nature of the vegetation. Also, vegetation will naturally undergo continuous minor changes in composition and structure. A monitoring program will need to decide if these changes are significant, and one measure of this will be if they cause a change in the definition of the community. Finally, defining communities will allow them to be mapped, and the position of community boundaries to be used as an indicator of changes in conditions at the site.

The minimum data required to describe a community are the height, dominant species and percentage cover of each stratum in the plant community. These parameters are recorded along a transect established within the community being described. The transect should be 50 metres in length, run in a straight line and remain within a single vegetation community. The requirement to remain within the selected vegetation community will mean that, at wetland sites, the transect will run approximately parallel to the shoreline. If it is not possible to fulfil the requirements above, a shorter transect may be established, but this should be noted on the data sheet.

Photographs should be taken every 10 metres along the transect. They should be aligned in such a way that they show the nature and condition of the vegetation that is present. These photos will provide photo monitoring data, assisting in the detection of changes in site conditions over time. Take care not to trample understorey vegetation when moving along the transect, as doing so may affect the results of the survey.

Table 8. Description of the information used to develop vegetation descriptions at NVIS levels I – VI. Italicised text denotes the new information added at each successive level.

NVIS Level	Name of Level	Data Required	Example
I	Class	Growth form of the dominant stratum.	Mallee.
II	Structural formation	Growth form, height class and cover class of the dominant stratum.	Sparse mallee shrubland.
III	Broad floristic	Growth form, height class, cover class and dominant genus of the dominant stratum.	Eucalyptus sparse mallee shrubland.
IV	Sub-formation	Growth form, height class, cover class and dominant genus of the three traditional strata (upper, middle, lower).	Eucalyptus sparse mallee shrubland / Acacia sparse shrubland / Triodia sparse hummock grassland.
V	Association	Growth form, height class, cover class and 3 dominant species of the three traditional strata (upper, middle, lower).	U^Eucalyptus oleosa, Eucalyptus transcontinentalis, Eucalyptus platycorys\mallee\6\r etc.*
VI	Sub-association	Growth form, height class, cover class and 5 dominant species of all strata.	U1+Eucalyptus oleosa, Eucalyptus transcontinentalis, Eucalyptus platycorys, Eucalyptus sp. aff. concinna, Eucalyptus sp. aff. comitae-vallis\mallee\6\r etc.*

* Note that, for brevity, the examples given for NVIS levels V and VI provide only a description of the uppermost sub-stratum. Other sub-stratum would follow with a similar format. Species should be listed in order of dominance.

Strata in the community

A stratum is a measurable, visibly conspicuous layer of photosynthetic tissue in a plant community (Figure 8). The plants in the community being surveyed should be separated into strata (and sub-strata if appropriate) based on the height of their canopy or foliage.

There are no defined height brackets for upper, mid or lower strata; they are named in relation to the height of other plants in the community. The approximate mean height of the top and bottom of each stratum must be recorded to allow future workers to replicate the strata descriptors that are used. At most locations, there will be plants that intergrade between strata. A decision should be made as to which stratum these really belong to (i.e. is it an unusually tall example of the mid-storey or is it a juvenile member of the upper storey). If there is no identifiable, discrete break in the range of canopy heights, all plants may belong to a single stratum.

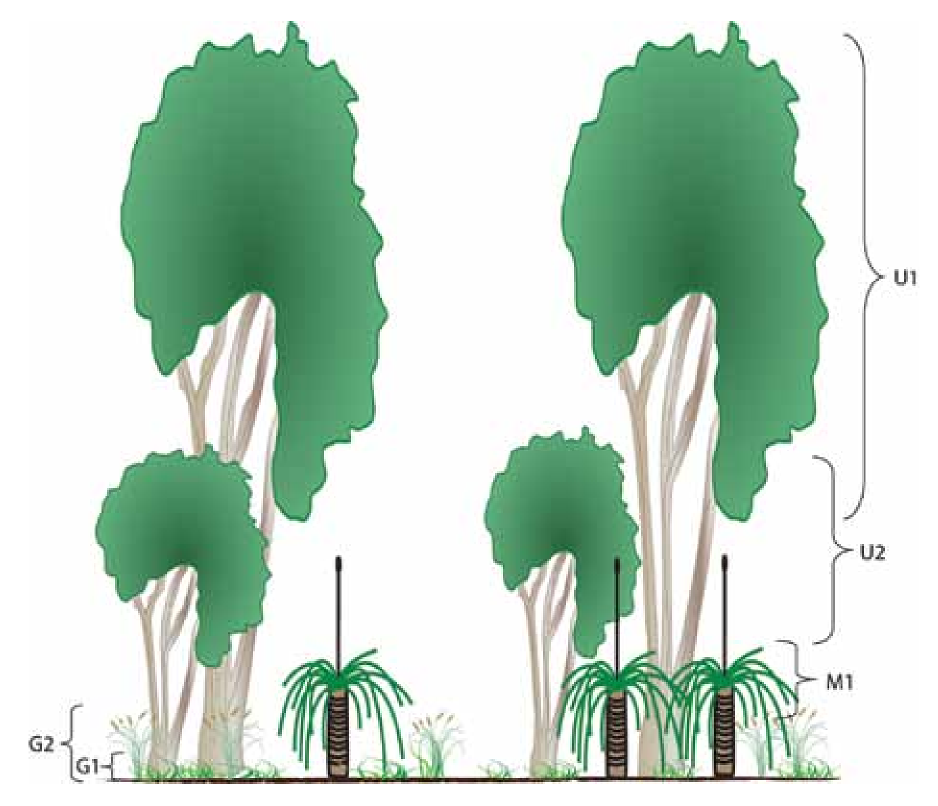

Figure 8. Identification of sub-strata in the upper strata (U1 and U2) and ground cover (G1 and G2).

In an NVIS description, the letter 'U' is used to denote the upper storey, 'M' the mid storey and 'G' the under storey (ground cover). These letters can be followed by numerals to denote substrata. For example, U1 is the tallest substrata of the upper storey, U2 the next tallest etc. (Figure 8).

Dominants and emergents

An NVIS community description names the dominant strata and dominant taxa in each strata. Dominance is conferred on the strata and taxa that have the greatest biomass (note that this is not necessarily the tallest stratum or taxon). Dominants will usually be identifiable with the naked eye, however, in some instances, measurements of canopy cover may assist the decision.

The dominant stratum or substratum in a vegetation association or sub-association is indicated with a '+' symbol e.g. U1+Eucalyptus oleosa, indicates that U1 is the dominant substrata in the vegetation unit and that it is composed of *E. oleosa*.

The dominant taxa in a vegetation description are preceded by the symbol '^', described as a 'hat'. A 'hat' preceding one species name will identify it as the dominant; 'hats' preceding two species names indicates co-dominance. A 'double hat' (^^) indicates that more than two species are co-dominant and the broad floristic will be described as 'mixed'. e.g U^Corymbia calophylla,^Eucalyptus rudis, Melaleuca preissiana\tree\7\i; indicates that *Corymbia calophylla* and *Eucalyptus rudis* are co-dominant species in the upper stratum.

Emergents are individuals that are taller than the highest stratum, but are not present in sufficient numbers to form a stratum in their own right. Emergents may be ecologically important, even if they are widely dispersed, and their presence should be recorded. Emergents are not identified in the community description.

Growth form and height classes

In an NVIS description, strata are given a height descriptor, based on the median height of the top of the canopy of that stratum. Table 9 shows the range of actual heights that comprise each height class and which growth forms may occur in each height class. The growth form and height class code are given for each stratum and substratum at the end of the species list e.g. U1+Eucalyptus oleosa \mallee\6 indicates that the U1 substrata is dominated by low (less than 10 metres high) mallees.

Table 9. **NVIS height class bracket descriptors for different growth forms. Empty boxes represent an unacceptable combination of growth form and height. Table from ESCAVI (2003)[24].**

Height		Growth Form				
Height Class	Height Range (m)	Tree, vine, single stemmed palm	Shrub. Heath shrub, chenopod shrub, fern. Samphire shrub, cycad, tree fern. Grass tree, multi-stemmed palm	Tree mallee. Mallee. Shrub	Tussock grass, hummock grass, other grass, sedge, rush, forb, vine	Bryophyte, lichen, seagrass, aquatic
8	>30	Tall				
7	10-30	Mid		Tall		
6	<10	Low		Mid		
5	<3			Low		
4	>2		Tall		Tall	
3	1-2		Mid		Tall	
2	0.5-1		Low		Mid	Tall
1	<0.5		Low		Low	Low

Species in the community

A list of plant species occurring at the survey location should be compiled, along with the relative abundance of each taxon. Although the community description only uses the most dominant species, it may be prudent to record all of the species at the survey location.

A plant specimen should be collected for submission to the WA herbarium if there is any doubt over its identity, it is considered to be rare, unique or unusual or it has not previously been collected from the general area. The specimen should include as many features of the plant as possible (roots, bark, leaves, flowers, buds, fruit etc.) and be kept in a sealed plastic bag until it is pressed. More information about collecting voucher specimens can be found in Bean (2006).[26]

Remember that a permit is required from the Department of Environment and Conservation to collect native flora. A flora collecting permit does not authorise the holder to collect rare or endangered flora. It is important to be familiar with any rare flora that might occur at a survey location to prevent accidental collections.

Each specimen should be labelled with a unique identifier that matches it to a field collecting sheet. The collecting sheet will record where the sample was collected, when and by whom, as well as characteristics of the plant, soil and topography. Without this sheet, the collection cannot be submitted to the herbarium. The information captured on the field data sheet can also be very important for successful identification of unknown specimens.

Estimating canopy cover

The degree to which the canopy forms a continuous layer determines the penetration of light to the ground, and so influences the habitat available to flora and fauna. As such, canopy cover is an important element of a community description. Monitoring canopy cover can also provide early indication of changes in the vegetation, particularly of deteriorating plant health.

The easiest way to assess canopy cover is to estimate its continuity at several points at the monitoring location. The objective is to estimate how much of the sky is obscured by the canopy. This can also be thought of as the proportion of the ground that would be shaded if the sun was directly overhead. The number of points at which estimates should be taken will depend on the size of the area being assessed, the degree of heterogeneity of the vegetation and the available time and resources.

Estimations of canopy cover may be made more accurate by referring to a visual aid. While the exact appearance of various cover densities will be influenced by the type and height of vegetation, photographs of known canopy cover classes will provide some guidance.

Estimates of canopy cover are prone to a high degree of inter-operator error. They can also be affected by light conditions and wind. Although estimation is an efficient technique, the results should be treated with caution as they may be inaccurate.

Measuring crown cover

The purpose of measuring cover is to quantify the relative contribution made by different species or structural components to the biomass at a location. There are many different ways of expressing the cover characteristics of a plant community; two of these are recommended here.

Foliage cover should be measured when assessing ground cover and plants up to around 50 centimetres in height. The point intercept method is recommended to calculate foliage cover. For taller plants, the per cent crown cover should be calculated using the zigzag method.

The point intercept and zigzag methods require transects to be established within the plant community being studied. The point intercept method requires a 30 metre transect, while the zigzag method requires a 50 metre transect. Transects should be positioned in areas that appear representative of the plant community.

The accuracy of these cover measurements can be improved by surveying multiple transects within a community. More transects will decrease the potential error margin in the dataset, but will also be more labour intensive. Establishing three transects in any one community should be adequate to ensure high quality data.

The point intercept method and percentage foliage cover

Foliage cover is a measure of the direct projection of foliage on a tape measure on the ground. Looking down on the tape measure, record the length of tape that is covered by any part of a plant (Figure 9). Also record the total length of the transect.

Foliage cover is the percentage of the total length of the tape that is covered by plants (cover / total length x 100). Usually, around 30 metres of the transect will be sufficient to get a good measure of cover, although this may vary depending on the density of vegetation at the site.

One issue that commonly arises is a difficulty in determining the cover of thin leafed grasses on the transect. The suggested approach here is to gently bunch the grass and take a measurement of the total area the bunch covers. This is more accurate than trying to measure the width of several very thin leaves.

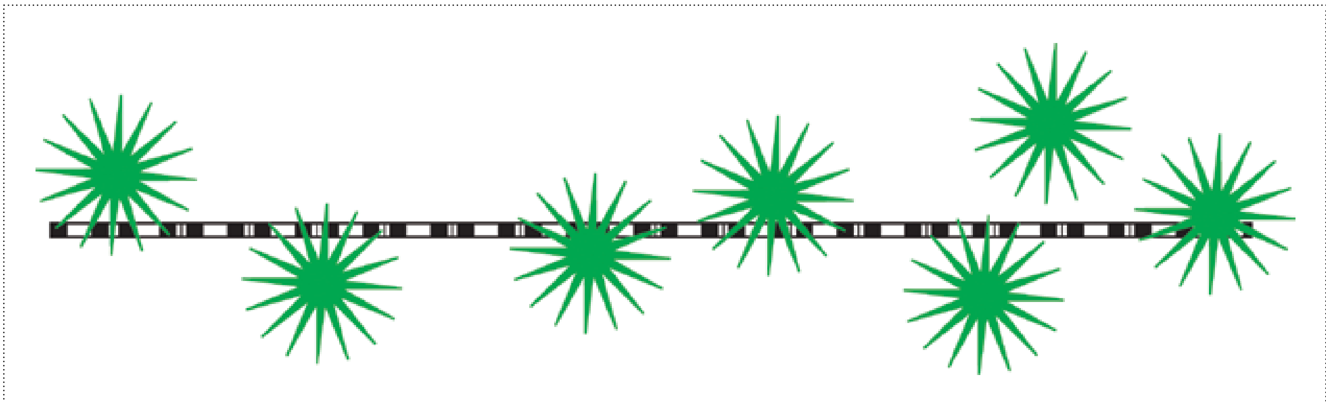

Figure 9. The point intercept method for measuring percentage foliage cover of understorey vegetation. The measurement taken is the length of the tape (dashed line) that is covered by vegetation (green shapes). Only tape that is directly beneath the foliage of the vegetation is measured as an intercept. Figure adapted from Hnatiuk (2008)[27].

The zigzag method and crown cover percentage

In order to calculate percentage crown cover, it is first necessary to determine the crown separation ratio. This is the simple ratio of the mean distance between the crowns of plants along the transect relative to the mean size of those crowns. It is measured in the field using the 'zigzag method' (Figure 10). Crown separation ratio can then be converted to crown cover percentage, using a simple formula. The following steps refer to Figure 10 and describe the process for calculating crown cover. A template for recording the required measurements is provided in the 'Data collection' section, later in this topic.

1. Measure and record the distance from the beginning of the transect (P) to the nearest crown (A).
2. Measure the width of crown A (perpendicular to transect) and the length (parallel to transect). Record the arithmetic mean of these measurements.
3. Measure and record the shortest distance between crown A and the nearest crown that is towards or across the transect and closer to the end of the transect (crown 1). If the two crowns are overlapping, measure the width of the overlap as a negative gap. If the crowns are touching, record a gap of zero.
4. Repeat steps 2 and 3 until the end of the transect is reached (point Q).
5. Calculate the crown separation ratio (C) by dividing the mean gap between crowns along the transect by the mean width of crowns along the transect.
   C = mean gap / mean width
6. Calculate the percentage crown cover
   Crown cover % = 80.6 / (1+C)2

The most common issue encountered when applying this method is determining which plants to include as part of the transect and which to exclude. Firstly, as this method is designed to give a mean measure of cover over the length of the transect, the selection of plants used is not critically important. Apply the general rule of moving to the next plant that is further along the transect and either towards or across the transect line. Also, the important feature of the plant is the crown. A tree with a stem near the transect that leans such that its crown is several metres from the transect probably should not be included. Conversely, a stem several metres from the transect with a crown over the transect should be included. Finally, if the crown of a plant is in two or more distinct and separated clumps, it may be appropriate to treat those clumps as separate crowns.

Table 10 shows how increasing canopy 'connectedness' alters the description of a vegetation unit. The 'cover code' attribute is provided in a written NVIS description to identify the vegetation structure e.g. U1+Eucalyptus oleosa\mallee\6\r indicates that the U1 stratum has less than 10 per cent foliage cover and is, therefore, an open mallee woodland.

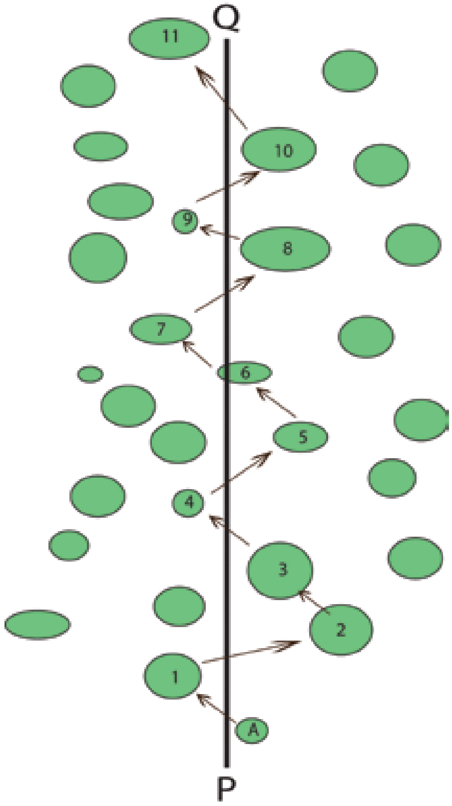

Figure 10. The 'zigzag' method for measuring crown separation ratio. (Figure on the left from Hnatiuk, 2008[27]).

Table 10. Selected structural formation classes defined by crown cover and growth form under National Vegetation Information System.[24] The full table can be found in ESCAVI (2003).

Crown Cover	>80	50-80	20-50	0.25-20	<0.25
Cover Code	d	c	i	r	bc
Growth Form	Structural Formation Class				
Tree	closed forest	open forest	woodland	open woodland	isolated trees
Mallee	closed mallee forest	open mallee forest	mallee woodland	open mallee woodland	isolated mallee trees
Shrub	closed shrubland	shrubland	open shrubland	sparse shrubland	isolated shrubs
Grass	closed grassland	grassland	open grassland	sparse grassland	isolated grasses
Sedge	closed sedgeland	sedgeland	open sedgeland	sparse sedgeland	isolated sedges
Rush	closed rushland	rushland	open rushland	sparse rushland	isolated rushes
Forb	closed forbland	forbland	open forbland	sparse forbland	isolated forbs
Aquatic	closed aquatic bed	aquatic bed	open aquatic bed	sparse aquatic bed	isolated aquatics

Measuring the extent of native vegetation

The native vegetation surrounding a wetland acts as a buffer between the wetland and many threatening processes that are occurring in the catchment. It also provides habitat for fauna, assists in groundwater regulation, prevents erosion and sedimentation and provides a multitude of other roles. The greater the extent of vegetation, the more effectively it will fulfil these functions. The total extent of dryland vegetation surrounding a wetland can, therefore, be an important variable to monitor. Note that monitoring total vegetation extent is only required when a wetland is situated within remnant vegetation in a cleared landscape. If the wetland is within extensive unmodified vegetation, it may be desirable to monitor the extent of the wetland vegetation, but monitoring total vegetation extent will probably not be required.

The extent of vegetation surrounding a wetland is best measured and recorded on a current aerial photograph or satellite image. Regularly updated imagery will be required to determine if changes in vegetation extent are occurring. Often, the density of vegetation will gradually decrease as the remnant transitions to agricultural or urban land. It will be necessary to decide what density of native plants constitutes 'remnant vegetation' as opposed to, for example, a paddock with scattered trees. This decision will depend on the nature of the landscape, the objectives of the monitoring program and the spatial scale of the mapping.

Determining the extent of the vegetation that is 'wetland dependant' is more difficult to achieve. The delineation between wetland and terrestrial vegetation is complex, and no standardised method has been published.

One approach to defining the extent of wetland vegetation is to undertake on-ground surveys to define the plant communities, determine which of these are more commonly associated with wetland areas and then map the extent of each. Communities may be mapped by walking their boundaries with a GPS unit. It is common for plant communities to transition gradually, so some interpretation will be required to decide where a community boundary lies. The precision with which boundaries should be defined will be influenced by the required scale of the resultant map. For this reason, the working scale should be defined before commencing mapping.

Monitoring the condition of vegetation

The condition of vegetation at a wetland is an important indicator of the health of the ecosystem. Wetland plants are adapted to flourish in relatively narrow environmental niches. Any deterioration in vegetation condition may, therefore, be indicative of some significant change in the system. This makes the ability to quantitatively assess and compare the condition of vegetation an essential component of a wetland monitoring program.

The condition of a plant community is determined by comparing its composition, structure and regenerative capacity to those of a reference site. The reference site, known as a benchmark, is an example of the same plant community that is pristine, or free from evidence of degradation. Good condition sites will have very similar composition, structure and regenerative capacity to the reference site.

Benchmarks may be actual areas of vegetation or they may be theoretical, constructed from historical data and expert opinion. Benchmarks are difficult to define because plant communities change in structure and composition through time. Communities can develop in different ways, and exist in different states, depending on the prevailing conditions and the time elapsed since the last significant disturbance. This means it can be difficult to judge what the 'ideal' nature of the community is.

An example of a vegetation condition assessment process is the Vegetation Assets States and Transitions model (VAST), proposed by Thackway and Leslie.[28] In the VAST model, vegetation communities are assigned to a condition category dependant upon consideration of regenerative capacity, composition and structure. The diagnostic criteria are defined for each class but it is left to the surveyor to determine the appropriate method to evaluate those criteria at the monitoring site.

VAST recognises that vegetation communities can exist in different states and can make transitions between states. A shortcoming of the VAST approach is the very broad nature of the condition categories. There are only three categories of native vegetation condition: residual, modified and transformed. VAST does, however, guide the user toward a rapid and defensible appraisal of vegetation condition at monitoring sites.

Methods for quantifying vegetation composition and structure have been recommended in the previous section. The application of the VAST framework, therefore, requires only a method for determining the regenerative capacity of the community.

Regenerative capacity

The regenerative capacity of a plant community is the ability of its constituent taxa to successfully produce new generations of plants. It is a critical consideration of community condition because it determines whether the community will remain viable in the long term. Successful recruitment is also an indicator of ecosystem health as it shows that processes such as pollination have not been disrupted, that soil conditions are suitable for vulnerable juvenile plants and that grazing pressure is within acceptable limits.

The regenerative capacity of a vegetation unit is difficult to assess because many Australian taxa reproduce only in response to disturbance. If an appropriate disturbance, such as a fire, has not occurred, no recruitment will occur. There are some approaches that will assist an assessment of regenerative capacity, but the data obtained will usually be qualitative for all but annual taxa.

The first step is an appraisal of evidence of historical recruitment. Examine the vegetation for evidence of different age classes within taxa. The presence of plants of different ages shows that successful recruitment has occurred in the past. Look also for any recent recruitment or evidence that a disturbance (such as a fire) has occurred without stimulating recruitment. Make note of any taxa that have recruited or that have not, despite apparently conducive conditions.

If a recruitment event has occurred, it may be desirable to quantify its magnitude. Doing so will allow comparison of future recruitment events and may also allow an assessment of the survival rate of germinants.

Due to the small size of newly recruited plants, a **quadrat** is a more appropriate sampling technique than a transect. A quadrat is a square plot that is marked, either temporarily or permanently, to facilitate counts of plants in a given area. The most appropriate size for a quadrat will depend on the density of the vegetation and germinants. A larger quadrat will obtain a more representative sample, but will be more labour intensive to analyse.

Once a quadrat is marked, count the number of germinants within it. If the taxa being counted are perennial, it may also be useful to record the height and/or width or each individual. Note that this quadrat technique may also be applied to monitor weed populations.

It is also good practice to record any evidence of stress or ill health affecting individual plants at a study site. Doing so will assist in the interpretation of changes that occur over time. Due to the difficulty in assessing the condition of plants, this measure will tend to be qualitative. Simply estimate the percentage of plants in the surveyed area that are showing evidence of stress. It is also helpful to note any likely causes of that stress, such as disease, grazing, salinity, waterlogging, fire, agricultural chemical impacts and drought.

Table 11. The Vegetation Assets States and Transitions (VAST) model

		NATIVE VEGETATION COVER **Dominant structuring plant species indigenous to the locality and spontaneous in occurrence**				**NON-NATIVE VEGETATION COVER** **Dominant structuring plant species alien to the locality or indigenous to the locality but cultivated.**		
Vegetation cover classes		Type 0: RESIDUAL BARE Areas where native vegetation does not naturally persist	Type 1: RESIDUAL Community structure, composition and regenerative capacity intact with no significant perturbation from land management practices.	Type 2: MODIFIED Community structure, composition and regenerative capacity intact but perturbed by land management practices.	Type 3: TRANSFORMED Community structure, composition and regenerative capacity significantly altered by land management practices.	Type 4: REPLACED ADVENTIVE Native vegetation replaced by species alien to the locality and spontaneous in occurrence	Type 5: REPLACED MANAGED Native vegetation replaced with cultivated vegetation	Type 6: REMOVED Native vegetation removed
Diagnostic criteria	Regenerative capacity	Unmodified – ephemerals and lower plants	Unmodified	Enduring under past and / or current land management practices	Limited and at risk. Rehabilitation possible with changes to land management	Suppressed by ongoing disturbance with limited potential for restoration	Lost or suppressed by intensive land management with limited potential for restoration	Nil or minimal
	Vegetative structure	Nil or minimal	Very high	Altered but intact e.g. a stratum, growth form or age class is missing in places	Dominant structuring species significantly altered e.g. strata removed	Dominant structuring species removed or extremely degraded	Dominant structuring species removed	Vegetation absent or ornamental
	Vegetative composition	Nil or minimal	Very high	Altered but intact e.g. particular taxa reduced in abundance	Species dominance relationships significantly altered	All dominant species removed.	All dominant species removed.	Vegetation absent or ornamental
Examples		Bare mud, rock, river and beach sand, salt and freshwater lakes	Old growth forest, with a natural fire regime native grasslands that are not grazed	Vegetation under sustainable grazing systems, forests with altered fire regime	Heavily grazed grassland, weedy native remnants, degraded road reserves	Isolated native tress within severely weed infested area	Improved pastures with isolated trees, plantations, tree cropping	Urban and industrial landscapes, salt scalded areas

Macroinvertebrate: invertebrate taxa that, when fully grown, are visible with the naked eye. It usually includes all of the insects, worms, molluscs, water mites and larger crustacea such as shrimps and crayfish

Microinvertebrate: invertebrate taxa that are too small to see with the naked eye, also referred to as plankton, specifically ostracods, copepods, cladocerans, rotifers and protozoans

Monitoring the impacts of threatening processes

Some studies may opt to avoid the difficulty of defining condition by recording the impacts of threatening processes instead. This is an easier approach, as it requires less knowledge of the vegetation being assessed. The assessor records, usually qualitatively, the extent and severity of disturbance caused by events such as: waterlogging and salinisation, erosion, drainage, groundwater abstraction, weeds, feral animals, stock, problem native animals, disease, fire, drought, flood, storm damage, spray drift, recreational usage of the site, consumptive and productive uses of the site, mines and illegal activities. Monitoring then consists of regular re-assessment of the extent and severity of these impacts. Establishing photo points might assist in this. A proforma for recording the impacts of threatening processes is provided in the 'Data analysis' section of this topic.

Algae

Algae is an important component of wetland ecosystems, and so, a valuable indicator of wetland condition. Although some algae is required as a food source for wetland fauna, excessive algal biomass is detrimental to wetland function. Such 'blooms' occur as a result of artificial nutrient inputs. Blooms can reduce light penetration of the water column, be toxic to fauna and, when they break down, dramatically reduce the dissolved oxygen content of the water column. All of these effects are detrimental to the ecosystem.

The biomass of algae in the water column is commonly determined by recording the chlorophyll a concentration in the water. More information on this can be found in the section 'Collecting and analysing a sample for chlorophyll a' of this topic titled. Identifying the species of algae present may require the assistance of an experienced algologist.

➤ A user-friendly guide to the algae and aquatic plants found in WA water bodies is provided in *Scum book: a guide to common algae and aquatic plants in wetlands and estuaries of south western Australia.*[29]

Aquatic invertebrates

Aquatic invertebrates are a popular target for wetland monitoring programs because they are found in almost all wetlands, are sedentary for at least part of their lifecycle and are relatively easy to survey. Also, they can be an effective indicator of environmental conditions because many invertebrate taxa have quite specific ecological requirements.

A survey of aquatic invertebrates has three stages: collecting a sample, picking specimens and identifying specimens. The first two stages can be undertaken by inexperienced workers with some basic training. The identification of specimens, however, requires considerable expertise. Lay-people can roughly group specimens to broad morphological types, which may suffice for some purposes. More rigorous monitoring programs, however, will require at least family level identification. This will not usually be achievable without expert assistance.

Collecting a sample of the aquatic invertebrate community

A sample of the aquatic invertebrate community is collected from a wetland by sweeping a mesh net through the water column. A monitoring program may choose to collect only **macroinvertebrates**, but more rigorous programs will also collect **microinvertebrates**.

A sample is collected using a D—frame pondnet constructed with 250 micron mesh for macroinvertebrates or 50 micron mesh for microinvertebrates. Figure 11 shows the recommended dimensions for a net. The net should be checked for holes prior to each survey. It should be washed thoroughly after surveying each habitat to remove any animals remaining from the previous location and to avoid potential transfer of contaminants between locations.

Figure 11. D-framed pondnet. The net opening is approximately 35 cm wide and 25 cm deep. The attached net is approximately 75 cm long.
Photo - A Nowicki/DEC.

Timing of sample collection

Most wetlands experience constant change in the composition of the aquatic invertebrate community. This means the suite of species collected will be influenced by the timing of the survey in relation to the season and water regime of the site. The best time to survey aquatic invertebrates will usually be several weeks after the main wet period at the study site. This allows time for flood flows to recede, habitat conditions to stabilise and invertebrate communities to mature after hatching or colonizing. In wetlands that have strongly seasonal water regimes, conditions usually become less conducive to invertebrates as the wetland dries.

Surveying too soon after a wetland fills will increase the likelihood of collecting immature specimens that will lack identifying features. It may also mean that taxa that have not yet hatched in response to the change in conditions are not collected. Surveying too far into the site's drying phase will mean that little water is present and habitat availability is reduced. Water quality is also usually poorer during the drying phase of a wetland, due to the concentration of nutrients and salts in the remaining water. These factors are likely to reduce the richness and diversity of invertebrates present as the wetland dries. There is also a risk that taxa that develop into aerial forms will have left the wetland.

In the south-west of Western Australia, mid spring (around October) is normally the best time for an aquatic invertebrate survey, although this depends on the timing of rainfall. In the Pilbara and Kimberley, the seasonality of surveys is less important than the water regime of the site. Surveys may be timed to coincide with consistent water levels rather than the being conducted at the same time each year. Surveying weeks to months after summer rainfall is ideal. In arid regions, sampling is usually opportunistic, ideally within two to three weeks of rain. If a site is not inundated during the life of a monitoring program, it may be necessary to collect sediments and incubate invertebrates in the laboratory (see 'Collecting a sample of invertebrates from a dry wetland' later in this section for more information). This will usually only capture a small proportion of the species that are present when the site is inundated.

Selecting sampling points

A survey of aquatic invertebrates should collect samples from all potential habitats at the survey location. If this is not possible, a monitoring program should, at a minimum, collect a sample from the same **habitat type** in each survey event.

Habitat type: 'habitat' is a species specific term, with every taxon having its own environmental requirements. 'Habitat type' is used here to refer to areas where environmental conditions are appreciably different from their surroundings. These differences increase the likelihood that the area may support a distinctive flora or fauna assemblage

Some aquatic invertebrates will be present in the water column, but many seek shelter within the sediments, or on and under plants, rocks, leaf litter, logs, sticks and any other materials that are in the water. These materials must be agitated and moved in order to flush invertebrates into the water, where they can be collected in a net. The diversity of available habitat is usually greater near the edge of the water body and the greatest sampling effort will probably be required there.

Sampling method

To collect a sample of macroinvertebrates the surveyor should move through the area being sampled, disturbing the substrate with their feet or the net. Care should be taken not to agitate the substrate too violently, as doing so may crush animals. Also, if using the net to disturb the substrate, do not allow the net to fill with sediment and organic material. After allowing a few seconds for the larger sediments to settle, the net is swept vigorously through the water column. This will capture invertebrates that were disturbed from the substrate, as well as those that were in the water column.

The net should also be swept through any plants that are present, and large plants agitated to shake invertebrates loose. Large rocks and twigs should be washed in the net to dislodge animals from them. In flowing water, rocks should be disturbed upstream of the surveyor to dislodge animals.

If the net becomes too full of litter and sediment, it will be difficult to handle. In this event, empty the contents of the net into a bucket and resume sampling. The two subsamples are combined at the conclusion of all the required sweeps. As a general rule, the net should not be allowed to become more than one third full.

If using a 50 micron net, aim to collect a very clean sample by sweeping only through open water and very gently against some of the submerged plants. Do not agitate the sediment as this will cause suspended material to clog the net. If both net sizes are to be used, sample with the fine mesh net before agitating the environment and collecting a sample with the coarser mesh net.

Samples should be collected over the same distance in every survey of the monitoring program. A sample collected over 50 metres of variable habitat (not necessarily contiguously) should capture approximately 60 to 75 per cent of taxa at a site. Sampling over this distance is excessive for single habitat sampling, where a sample taken over 10 to 20 metres will suffice (Halse, et al. 2000 and Pinder et al. unpublished data)

In some circumstances, it may be desirable to separate the fauna of each habitat type. If this is the case, a sweep should be conducted of the water column prior to disturbing the substrate, another after the substrate is agitated and individual sweeps conducted through any other habitat types that are present, such as vegetated areas. The net should be emptied and washed after each sweep and each sample stored separately.

Sorting invertebrate specimens from the sample

In most instances, too many invertebrates will be collected for it to be practical to identify all individuals. A sub-set of the sample is identified instead. The term 'sorting' refers to picking individual organisms from the sample to form a sub-sample. Sorting may be undertaken in the field, immediately after sampling, or the sample may be returned to the laboratory for sorting.

Laboratory sorting should be undertaken when accurate determination of species diversity is required, such as when conducting a biodiversity audit. The time required for laboratory work is dependant on the nature of the sample and the skill of the taxonomist, but is usually greater than that required for field sorting.

Sorting in the field will save time but accurate identification of specimens will be more difficult and some taxa may be overlooked altogether. If applied consistently, field sorting can be used to compare relative diversity across sites and over time. However, it is an imprecise method and is not suitable for a detailed audit of biodiversity. Field sorting is only appropriate for macroinvertebrate taxa, as a microscope will be required to see microinvertebrates.

The sorter should always be familiar with the taxa that might be expected to occur in the wetland before beginning sorting. This will help them to 'get their eye in' as well as alerting them to remain vigilant for cryptic taxa.

➤ Information about the invertebrates found in wetlands of south west WA can be found in *A guide to wetland invertebrates of south west WA.*[30] This includes taxonomic keys that will aid in specimen identification.

Sorting in the field

Field sorting is the rapid selection of a subsample of invertebrates at the conclusion of sampling at a survey location. The subsample might also be identified in the field, but is often returned to the laboratory for more detailed study. Samples collected with a 50 micron plankton net cannot be identified in the field as it will include microscopic zooplankton.

Box-subsampler: watertight box that is divided into a number of cells. A box-subsampler is used when sorting aquatic invertebrates to eliminate observer bias. Dividing the sample into a number of cells which are sorted individually, and in their entirety, reduces the likelihood of preferential selection of larger or more conspicuous taxa

Begin by emptying the sample from the net into a large bucket that contains several litres of water. Swirl the bucket to dislodge invertebrates that are clinging to detritus and decant the sample back through the net into a second bucket. Aim to leave heavy inorganic matter in the original bucket while the lighter organic matter is caught in the net. Check the inorganic matter for heavy animals such as molluscs, or small animals that may be clinging to rocks, then discard it. Repeat this process until all conspicuous inorganic matter has been removed from the sample.

Empty the organic matter from the net into a bucket containing clean water. Wash any vegetation, leaf litter or sticks in the water, check for animals that are within, or on, it and then discard. Be particularly alert for any pieces of detritus that move in the water, as they may contain caddisflies. What remains should be a bucket of relatively clean water, containing the aquatic invertebrate sample.

Figure 12. A box subsampler, shown with the lid removed. This one is constructed from perspex and measures 355 by 355 by 160 millimetres high. It contains 8 by 8 compartments, each 40 by 40 millimetres.[31]

Separate the sample into three size fractions by pouring the contents of the bucket through a 2 millimetres and then a 250 micron sieve, catching in another bucket the material that passes through the finest sieve. The three fractions are sorted separately because it is easier to look for animals within a limited size range. If a sieve size contains very little material, the whole fraction can be placed into the sorting tray without subsampling. Otherwise, separate the sieves and place the contents of one into a box-subsampler.

Securely close the subsampler before agitating and rotating it. Transfer the contents of one randomly selected cell into a white sorting tray using a hand vacuum pump and conical flask.

An alternative randomised subsampling method is to stir each sieve size in a bucket of clean water and remove subsamples using a cup. This is especially useful if the available water is limited and the box-subsampler cannot be washed between samples.

Remove animals from the sorting tray using a pipette and/or tweezers and preserve in a small vial of 100 per cent ethanol (this assumes that identification will be performed in the laboratory). Start by picking out common, abundant taxa while avoiding a bias toward large or highly conspicuous taxa. The most effort, however, should be directed at finding less common and inconspicuous taxa. Particular care should be taken to search for the groups that are easily missed when sorting such as larvae, Oligochaeta, Empididae, Hydroptilidae, and Ceratopogonidae. A sample will normally contain many species that look superficially similar. Look for different sizes, colours and movement patterns (swimming, crawling, squirming etc.) to separate superficially similar taxa.

Count the number of animals removed using a hand-held counter. The rule of diminishing returns applies to sample sorting: as the number of individuals picked increases, the likelihood of finding new taxa decreases. A subsample of 200 individuals has been shown to adequately represent family richness and diversity in most wetlands.[32]

Approximately 50 of the 200 individuals should come from the largest fraction, 100 from the medium fraction and 50 from the fine fraction. If insufficient individuals have been found after the finest sieve size has been picked, return to the coarsest sieve size and start again. In some cases, a second sample may be required to obtain the 200 animals.

In order to maintain consistency, it is essential that the same number of individuals are picked at each site, although the proportion taken from each sieve size may vary according to site characteristics.

Some texts recommend that sorting continues for a set period of time, rather than until a certain number of individuals are subsampled. This 'fixed time' approach is highly susceptible to inter-operator errors as more experienced workers will tend to find many more individuals within the time limit. Other variables, such as light conditions and water colour can also affect results. For these reasons, the fixed time approach is not recommended.

Sorting in the laboratory

Laboratory sorting and specimen identification requires considerable expertise and should be only be undertaken by suitable experienced workers. If it is to be undertaken, wash and sieve the sample as per the field sorting method then preserve it in 100 per cent ethanol for transportation to the laboratory.

In the laboratory, the sample will be examined under a dissecting microscope with 10–50x magnification. Animals are picked out, placed into groups and identified using a taxonomic key and comparison to reference material.

Collecting a sample of invertebrates from a dry wetland

Most wetlands in arid and semi-arid areas of Western Australia only contain free water intermittently. This can make it difficult to survey these sites during their wet phase. An alternative approach is to collect dry sediments, containing resting eggs of invertebrates from the bed of the wetland, incubate them in the laboratory and identify the taxa upon maturation. Although this approach will provide some indication of the diversity of invertebrates that occupy the site, it will never allow determination of the full suite of invertebrate taxa.

Begin by marking a series of 1 metre by 1 metre quadrats across the floor of the dry wetland, from which surface sediments will be collected. The distribution of quadrats should be such that they capture the diversity of habitat types that would be present when the wetland is inundated and as it dries. A greater density of quadrats may be required near the maximum extent of inundation as eggs will tend to be concentrated there by wind and wave action. Taxa dependant on fresh water conditions will deposit eggs near the high water mark, when the system is fresh after filling. Species tolerant of more saline conditions will usually deposit eggs nearer the centre of the wetland, as the water recedes and becomes more saline through evapoconcentration.

Eggs are collected by using a piece of PVC pipe, split lengthways, to scrape and gather the upper layer of sediment from the quadrat. Approximately 3 centimetres of the sediment profile should be collected, although this may prove difficult if the substrate is very hard. A total of approximately one kilogram of sediment should be collected and stored in a calico bag (B Timms 2009, pers. comm.).

In the laboratory, oven dry the sediment sample for 2–3 days at 50 degrees celcius. After drying, mix the sample thoroughly to distribute eggs evenly through it. Spread a thin layer of sediment across the bottom of several rectangular plastic containers (takeaway food containers are ideal). To each container add 200 millilitres of deionised, distilled water or rain water. Tap water is not suitable as the chemicals in it will prevent eggs from hatching.

Place the containers where they will receive natural light from a north facing window. They can also be incubated in a growth cabinet that provides at least 8 hours of light per day. Ensure the containers receive constant air flow and are at room temperature.

If no hatching occurs after 14 days, dry the sediment, then rewet 4 weeks later. This wetting and drying cycle may need to be repeated several times before the eggs are induced to hatch. After hatching, allow at least two weeks for individuals to reach maturity, then proceed with sorting as per the laboratory sorting method.

Identifying specimens

The identification of aquatic invertebrates should be completed by a person with relevant expertise. The taxonomic level to which specimens are identified depends on the aims of the project and time and funds available. A substantial proportion of the state's aquatic invertebrate fauna is undescribed, so formal scientific names cannot always be applied.

Fish

Fish are not present in all WA wetlands but, where they are, can be a good indicator of wetland condition. Fishes' survival depends on good quality water that is oxygenated and disease free; food, which has its own habitat requirements; shelter from currents and predators and, in some cases, shade. Finally, water regime is important to fish survival as particular types of flows are required for different lifecycle stages. If these factors are all adequate to support healthy populations of native fish, it is likely that the wetland ecosystem is not significantly degraded.

The methods available to survey fish populations are: electrofishing, netting and visual survey. All but the last of these carry some risk of harming the fish, require permits and must be undertaken in a manner consistent with animal ethics policies. Limited information is presented here about these methods, as it is not recommended that fish monitoring be undertaken without the assistance of a suitably qualified and experienced researcher.

Fish should not be taken from a wetland without approval from the Department of Fisheries and the relevant animal ethics committee. Contact your local Fisheries office for more information.

Electrofishing

Electrofishing is a technique in which an electric current is applied to the water. Fish, like many aquatic animals, will become motionless if their body exceeds a certain voltage. If the current is carefully controlled, this effect will be temporary. Fish will initially be involuntarily attracted to the electrode before going into a state of narcosis. The stunned fish can be collected and identified before being returned to the water to recover. Electrofishing is only effective in waters shallower than approximately 2.5 metres.

The voltages used when electrofishing are sufficient to cause serious injury or death to humans. As such, there are considerable health and safety risks for the operators. Under the *Australian Code of Electrofishing Practice*[33], electrofishing surveys must be supervised by an operator who has participated in at least twenty previous sessions, holds a current senior first aid certificate and has a current medical certificate stating freedom from major heart or respiratory complaint. All other team members must also hold a senior first aid certificate and current medical clearance.

The equipment required for electrofishing is highly specialised and not readily available to the public. It must be constructed for the purpose by a qualified electrical engineer. Electrofishing is only regularly undertaken by research organisations.

Netting

Netting is safer for the survey team, but carries significant risks for the fish that are caught. There are three main types of net that are used to conduct surveys: fyke nets, seine nets and gill nets. Fyke nets are large hoop nets that act as funnels to trap swimming fish. They are often placed together in an array that captures all fish using a waterway. A seine net is a large fishing net that hangs vertically in the water due to weights attached along the bottom edge and floats along the top. Seine nets are used like long fences to encircle fish and are then drawn closed to complete the trap. Gillnets are long rectangular panels of netting. They are held vertically in the water column by floats and anchored by weights. Fish swim into the net but are unable to fit through the mesh. They are entangled by the gills, fins and spines and so are unable to back out of the net.

All three approaches to netting carry a risk of harming the trapped fish. As such, netting should not be conducted unless fish abundance is a critical consideration in a monitoring program. If fish are netted, they must be freed from the net as soon as possible, handled as little as possible and returned to the water as soon as possible after capture. Nets should be checked and emptied regularly to minimise impacts on caught fish.

Visual survey

The most benign way to survey a fish population is by a visual assessment of the wetland. This can be achieved by using a glass bottomed boat or snorkelling or diving in the water body and counting fish numbers. This type of survey relies on good visibility in the target wetland.

A visual survey simply involves one or more people diving, snorkelling or traversing transects in a boat and recording the number and identity of any fish that are seen. Methods similar to those for bird surveys may be employed to ensure adequate coverage of the site and avoid double counting (see the section ‘Waterbirds’, later in this topic).

Frogs

Frogs are often used as condition indicators at wetlands because of their sensitivity to changes in the local ecosystem. Also, because frogs are amphibious, their presence provides information about both the aquatic and terrestrial environments. Frogs are particularly good indicators of changes to water chemistry because their skin is semi-permeable and their eggs lack a protective shell. Both of these factors make them highly susceptible to pollutants in the water and to changes in water chemistry.

The easiest way to conduct a frog survey is to listen for calling frogs. Each species has a distinctive call, used by breeding males to attract females. The calls that are heard can, therefore, be used to identify the species of frog that are present at a site and the intensity of calls can be used to estimate of the size of the population.

Frog surveys are best conducted at night, as this is when frogs are most active. The first couple of hours after sunset is a particularly good time to hear frogs calling. Surveys must also be timed to coincide with the breeding season of the frogs at the study site and may need to be repeated as not all species of frog breed at the same time. In arid regions, frogs breed whenever water becomes available. In the south west of the state, many frogs breed in spring, when water is plentiful and the weather becomes warmer. A comprehensive frog audit, however, may require several surveys throughout the year to include the breeding season of all species that might be present.

When planning a frog survey, it will be necessary to determine what species are likely to be present at the site and what time of year they breed. Surveys are best done following rain, as calling activity is greatest in wet conditions.

➤ The website of the Frogs Australia Network frogsaustralia.net.au[34] is a valuable resource for anyone wishing to monitor frogs. The site includes lists of the species that are known to occur in various regions of Australia. It also provides a host of information about these taxa, including the breeding period of each and a recording of the breeding call.

➤ A CD of frog species calls is also available from the WA Museum, see their website for more information: frogwatch.museum.wa.gov.au.[35]

Frog surveys should not be conducted in windy conditions or when it is raining heavily as both of these conditions will affect the ability to hear frogs calling. A good rule of thumb is that a frog survey should not be attempted if the wind strength exceeds 3 on the Beaufort scale (Table 12) or if precipitation is heavier than a light drizzle. Background noise, such as passing traffic, can also reduce the effectiveness of a survey, but this is more difficult to avoid.

Table 12. The first five divisions of the Beaufort wind scale.

Beaufort Wind Scale	Wind Speed (km/h)	Description	
0	<2	Calm	smoke rises vertically
1	2–5	Light air	rising smoke drifts, weather vane inactive
2	6–11	Light breeze	leaves rustle, can feel wind on face
3	12–19	Gentle breeze	leaves and twigs in constant motion, small flags extend
4	20–28	Moderate breeze	small branches begin to move, dust and loose paper raised (too windy to monitor)
5	29–38	Fresh breeze	small trees begin to sway (far too windy to monitor)

Begin a frog survey by becoming familiar with the calls of frogs that are expected to be present at the study site. This can be achieved by visiting the website of The Australian Frog Network.

Next, select the 'observation' locations that will be used in the survey. This is best done during daylight hours. A small wetland may be surveyed from a single location, while larger sites may require multiple observation locations.

The observation locations should be accessible without causing disturbance to vegetation or frog habitat. This is particularly important if monitoring is to extend over several nights or several seasons. If not managed carefully, the cumulative impact of surveys can cause degradation of the site. It may be appropriate to lay out a temporary elevated boardwalk if the vegetation or substrate is particularly fragile.

After nightfall, the surveyor should establish themselves at the observation point. It is important that the surveyor remains still and quiet throughout the observation period, as disturbance may discourage frogs from calling. On a data sheet, record the prevailing weather conditions, including air temperature and any recent rainfall. Also, record any other factors that may affect the results, such as background traffic noise. After spending several minutes quietly at the location, begin recording the identity of any frogs that are heard calling. Also record the intensity of calls (Table 13), as this is indicative of the size of the population. It may also be helpful to record frog calls on a portable tape recorder. This will allow them to be checked against reference material at a later time.

Continue identifying frog calls for a set period of time. The time over which calls are recorded must be the same at every observation point to ensure that data are comparable. Fifteen minutes of listening should be sufficient to hear all calling frogs at a location.[36] If disturbed, for example by an aeroplane passing overhead, begin the listening period again.

Table 13. Call intensity rating system used during frog surveys.

Rating	Call Intensity Definition
0	No frogs can be heard calling.
1	Individual calls can be counted; there is space between calls.
2	Some calls are overlapping; but individuals are still distinguishable.
3	Chorus is constant, continuous and overlapping; impossible to count individuals.
4	A species was seen but not heard during the survey.

If a more comprehensive census of frogs is required than what is achievable using the calling intensity scale, it is necessary to capture and mark each calling frog. This ensures that individuals are not double counted. A licence from the Department of Environment and Conservation is required if native fauna is to be caught. A catch and release survey should not be undertaken without instruction from that department.

An alternative survey method is to record the number of tadpoles that are present in the wetland. Tadpoles may be caught in the same manner as aquatic invertebrates (see the preceding section: Aquatic invertebrates) or in a tadpole trap. The advantage of surveying tadpoles is that they demonstrate that successful breeding has occurred. They do, however, require some expertise for species identification (A Storey 2009, pers. comm.)

Waterbirds and shorebirds

Waterbirds and **shorebirds** are common targets for wetland monitoring programs because they are highly visible, they are relatively easy to survey and many people feel an affinity for them.

There is also a school of thought that birds can be used as indicator species because their position near the top of the food chain means that impacts on taxa lower in the food chain will be reflected in bird populations.

The accuracy of birds as an indicator of condition at wetlands, however, is subject to a number of limitations. Firstly, birds' mobility means there is often a large degree of variability in species occurrence and population sizes at individual sites. The movements of birds are influenced by climatic conditions, seasonality, diurnal cycles and population size is also subject to natural fluctuations in breeding success. Populations of migratory birds may also be affected by factors far removed from the wetland being monitored. Finally, birds may be slow to respond to deterioration in environmental conditions. For example, the collapse of a bird population due to a shortage of their aquatic invertebrate food source may not occur until some time after the environmental change that triggered the shortage. A further time lag will then occur before the change in bird numbers can be confirmed. These limitations aside, birds are an important component of wetland ecosystems and their abundance and diversity is likely to be of interest when monitoring a site.

There are two main methods for conducting a bird count; aerial survey and ground survey. Aerial surveys, undertaken from light aircraft, are usually required at very large or isolated sites. The techniques for aerial bird counts are not covered in this topic as they are highly specialised and will require expert assistance.

Waterbirds: birds that have specialised beaks and feet that allow them to swim, dive and feed in water. Examples include egrets, crakes, herons, ducks, swans and grebes

Shorebirds: those birds commonly found wading near the shores of wetlands, beaches, mudflats and lagoons in search of food. They include plovers, sandpipers, stone-curlews, snipes, pratincoles, oystercatchers, stilts and avocets

A ground survey is an inexpensive, non-intrusive and relatively easy alternative. It involves observing a wetland over a period of time and recording any birds that are present at the site. Ground survey is the most appropriate method for conducting counts at small wetlands and is required to detect cryptic species and to count shorebirds.

extra information

Shorebirds 2020

Shorebirds 2020 is a program designed to reinvigorate and coordinate national shorebird monitoring in Australia. It is a collaborative enterprise between Birds Australia, The Australasian Wader Studies Group, the WWF-Australia and the Australian Government's Natural Heritage Trust.

The primary objective of the program is to collect data on long and short-term trends in shorebird populations, and to explore what may be causing any changes. The project also seeks to understand the effect of habitat quality and threats on the distribution and abundance of shorebirds.

Shorebirds 2020 maintains a website that contains many resources to assist with conducting bird counts. These include data sheets that may be used in the field and information about shorebird conservation. The website address is www.shorebirds.org.au.[37]

Observation point

The observation point, from which the count will be conducted, should be situated where the observer can see the entire wetland. If this is not possible, the wetland should be divided into sectors and counters situated at an observation point in each sector, such that the entire wetland is covered. The delineation of sectors will be determined by the topography of the site, the number of counters available, considerations of access and safety and the number of birds present. All sectors should be counted concurrently, with observers recording the birds within their assigned sector only. Observers should identify any flocks that enter, leave or pass over the sector and the time at which this occurs. This will prevent mobile birds being counted in multiple sectors. On the data sheet, record if the site was divided into sectors and, if so, how this was done. It is important that surveys are standardised, with the same area of the wetland being counted on each occasion.

Number of observers

A minimum of two observers at each observation point is recommended, in order for species identification and flock counts to be confirmed. The number of observers involved in the count, and the experience of each, should be recorded on the data sheet, to allow future users of the data to evaluate its probable accuracy.

Seasonality of survey

A survey during summer is essential for recording migratory birds, as these species usually spend October to March in Australia. In the south of the state, January and early February is the ideal time to conduct surveys for migratory birds. In northern Australia, surveys should be conducted before the beginning of the wet season. After this, migratory birds are likely to disperse in response to rainfall and access to sites will become difficult. Resident waterbirds are ideally surveyed in late spring in the southern part of the state. In the north of the state, resident birds concentrate at water sources during the dry season, providing the best opportunity for counting their numbers.

It may be necessary to conduct several surveys over the course of the year to develop a comprehensive species list. Although the spring / summer surveys described above are required as a minimum, additional surveys throughout the year will provide more comprehensive data. The size and composition of the bird population at a site will vary throughout the year in response to many external variables. Any additional surveys through the year will help provide information about these natural variations.

On the field data sheet, record the date on which the count was conducted, as well as the water regime of the wetland at that time. If possible, record the actual depth or extent of inundation, or if this is not known, use a general description, such as 'filling' or 'full'.

Time of survey

Bird surveys are best conducted in the morning as a heat haze that may occur later in the day will affect visibility. If possible, conduct counts with the sun behind the observer as this improves visibility by avoiding glare. In areas with a tidal influence, the ideal time for conducting bird surveys is at high tide. The inundation of the inter-tidal habitat zone tends to force birds to congregate along the shoreline, making them easier to observe.

If regional populations are being assessed, sites that are near to one another should be surveyed on the same day. This will minimise the opportunity for birds to move between sites, thereby avoiding duplicate counting. The time of day that the count was conducted should be recorded on the data sheet.

Weather

Bird surveys should not be conducted during significant rainfall events or in windy conditions. These may cause birds to seek shelter or take flight, thus affecting the count. Rain may also affect visibility, obscuring birds from the sight of observers. Very hot days should also be avoided, as the heat haze that forms over water bodies can distort viewing and make counting and identification difficult. On the data sheet, record details of the weather on the day of the survey, including temperature, wind speed and wind direction.

Counting techniques

The appropriate counting technique is determined by the size of the waterbird population at a site. Small populations may simply be tallied, while larger populations will require a component count to be undertaken.

Total count

Small bird populations can be surveyed with a total count. The survey team should begin by quietly watching from the observation point and tallying the number of birds of each species that are seen. Once they are confident that the majority of birds have been sighted, they should walk the shoreline (or parts of the shoreline at larger wetlands) looking for small wader species. The number of birds of each species should be recorded on a datasheet, audio recorder or notebook.

Birds will fly and swim around the site during the survey, potentially confusing the count. It is important to remain aware of bird movements and avoid double counting individuals or flocks.

Component count

Counting individual birds is impractical when very large flocks are encountered. A component count may be used to estimate and record the number of individuals in large flocks. Pairs of workers conducted the count, with one person acting as the observer and the other as the scribe.

The observer estimates bird numbers by grouping individuals into sets of approximately ten or 100 birds, depending on the size of the flock. The ability to do this accurately is crucial and will only be developed through practice. Some experience in counting birds is, therefore, essential for the observers in the component count team.

The scribe uses a form of shorthand annotation to record the data called out by the observer. A letter code is assigned to each flock of birds at the site and that letter precedes the number of individuals counted in the flock. For example, if flock A has 100 red-necked stints and flock B has fifty, the population of stints will be recorded as: A100 / B50. An X follows any count that was estimated or counted in multiples.

As with total counts, it is important to make note of any birds that move during the count. Birds that fly through a sector are annotated with an 'f' suffix and the time and direction of movement are recorded. If any disturbances cause birds to take flight during the count, a note of this should be made on the field data sheet. It may also be helpful to use abbreviations for species names. The complete list of shorthand annotation is provided in Table 14.

Table 14. Summary of standard shorthand annotation used in bird counts.

Code	Position	Meaning
X	suffix	birds counted in multiples or estimated.
(f)	suffix	birds flying through sector but not landing (include time of transit and direction of flight)
(b)	suffix	breeding
A, B, C etc.	prefix	flock identifier (note capitalisation to distinguish from codes for breeding etc.)
/	separator	separates flocks in a species tally.

An example of a component bird count:

The following is recorded on a field data sheet:

Red-necked stint 11 / 35 / A444 X / 325 / B77 / 10

Bar-tailed godwit 40 / A 12,000 X / 781 (f) / B 848 / 7 / 39

Curlew sandpiper A 57 / 5 / 2 / 5,000 X / 99 / 878

This shows that the site had:

- Approximately 902 red-necked separated into 6 flocks.
- Approximately 13 715 bar-tailed godwits separated into 6 flocks, one of which flew over the site.
- Approximately 6041 curlew sandpipers separated into 6 flocks.
- 444 red-necked stint, 12,000 bar-tailed godwit, and 57 curlew sandpiper in flock A and that the number of red-necked stint and bar-tailed godwits in that flock were estimated.
- 77 red-necked stint and 848 bar-tailed godwit in flock B.

Finalising counts

The participation of multiple observers in a survey creates the potential for duplication in counts. All observers should, therefore, come together to collate their data at the conclusion of survey. Each observer will have recorded the time that flocks of birds entered or left their sector and the direction they came from, or departed to. This will allow a moving flock to be tracked, and any duplicate counts of it to be discounted from consideration.

Data analysis

Measuring indicators in a series of surveys will not provide an answer to the monitoring hypothesis, unless the collected data are analysed appropriately. Data analysis is the process of extracting information from the data collected in the field in order to address the monitoring hypothesis.

The data, information, knowledge, wisdom pyramid is an anecdote that is commonly used to explain the progression from data collection to understanding an ecosystem (Figure 13). The pyramid has a broad base of *data*; unorganized and unprocessed facts that, in this case, have been collected about a wetland by a monitoring program. Those data are aggregated and analysed to provide a lesser quantity of information, which means it is now useful to the decision making process. In the current context, this will mean that it indicates to the land manager whether the land management regime is having the desired effect on the health of the wetland ecosystem. Once the land manager has complete information, they may claim to have *knowledge* of the system, meaning understanding of a subject matter that has been acquired through proper study and experience. The pyramid anecdote shows that a large quantity of information is required to develop a relatively small store of knowledge. Finally, if this knowledge leads to good decisions about land management practices, the land manager may claim *wisdom*. Climbing the steps of the pyramid will require that data are well collected, stored, analysed and reported on.

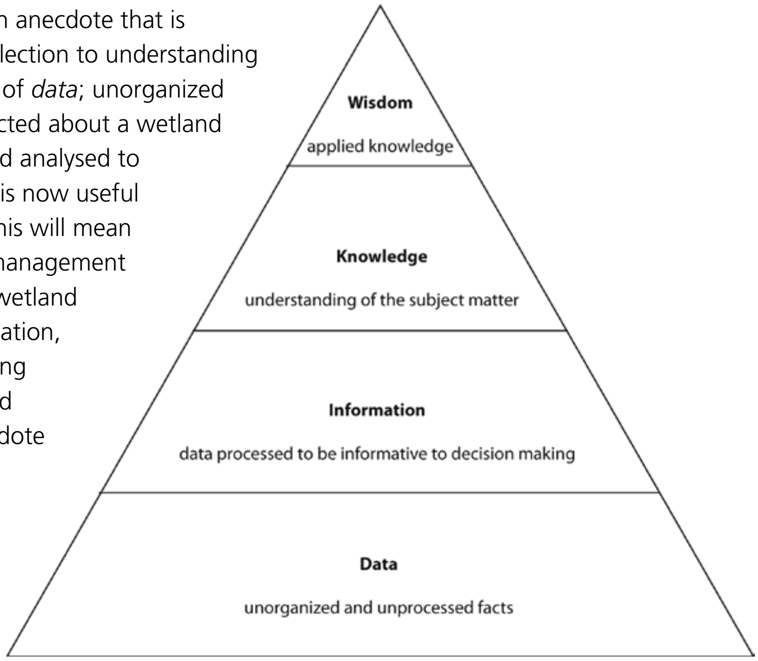

Figure 13. The data, information, knowledge, wisdom pyramid.

Data collection

The use of a standard template is essential to collecting good data. A template, such as a field data sheet, acts as a checklist of the parameters to be measured and assists in the standardisation of units and methods.

An example of a data recording sheet is provided in Appendix A. It was developed by the Department of Environment and Conservation's Inland Aquatic Integrity Resource Condition Monitoring project. A monitoring program will need to develop its own field data sheets with spaces to record all of the required parameters. The provided example may be tailored to suit the requirements of a monitoring program.

The provided data sheet is divided into four sections. The first section is for recording general information about the monitoring site and survey locations. This includes a map of the site showing where any survey locations and monitoring points are situated and how to access them; site scale notes on the hydrology, geomorphology and vegetation of the system; the number of photos that were taken and any other general information that helps to provide context. The second section of the data sheet is used for recording water chemistry readings, waterbird counts and information about the aquatic invertebrate survey. The third section relates specifically to the vegetation of the survey locations.

It provides space to record the data required to develop an NVIS community description and also some more qualitative fields. The final section of the sheet is used for recording the nature and magnitude of, and area affected by, various threatening processes.

Data storage

It is important to retain raw data, as well as any intermediate datasets produced during the process of analysis and reporting. Doing so will allow the source of any errors to be identified. Retaining raw data also allows reanalysis of the dataset if new information about a site comes to light. Hard copies of the field data sheets should, therefore, be filed for future reference.

Usually, data sheets will also be entered into an electronic database. Data entry is a common source of errors and the entered data should be checked by a second person to ensure it accurately reflects the field sheets.

The database should be stored in a place and format where it will remain safe, accessible and understandable for future users. It should be accompanied by metadata that explains how the database was created, by whom and when. Metadata should also provide an explanation of all headings or classes that are used in the database.

Analysis of data

Having collected good data, the next step is to use them to test the monitoring hypothesis. The way this is achieved will depend on the nature of the monitoring program and the type of data collected. Probably the most readily applied technique is data visualisation, which can be used to display trends in the measurements taken at a site. This is a basic form of statistical analysis, but can be quite powerful if it is used appropriately and its limitations respected.

More sophisticated monitoring programs may employ statistical tests to show that a significant change has, or has not, occurred in the system and to allow cause and effect relationships to be explored. If the demonstration of statistically significant cause and effect is required, it is advisable to seek the advice of a statistician before developing a monitoring program. A statistician will be able to assist in the program design to ensure that sufficient and suitable data are collected during surveys.

Summary statistics

There are several statistical measures that are commonly used to provide a summary of a dataset (summary statistics). These measures aim to express the central tendency and variability of the data. In biological monitoring programs, the most useful measure of central tendency is usually the mean, but median and mode measurements may also be used in some circumstances. Measures of variability include the range of values obtained, the standard deviation of the dataset and the percentile distribution (Table 15).

Table 15. Overview of statistical summary techniques.

Summary Statistic	Definition	Calculation Method
Mean	Representative of the values being summarised due to being intermediate between the extremes of the dataset.	Divide the sum of the values by the number of values. $\mu = \sum xi / N$ μ is the mean xI is each of the values in the set N is the population size
Median	The value for which one-half (50%) of the observations (when ranked) will lie above that value and one-half will lie below that value.	List all values in ascending order and select the middle point of the list. If the dataset has an even number of values, sum the two middle values and divide by 2.
Mode	The most commonly occurring value in a dataset.	Count the frequency with which each value occurs in the dataset.
Range	The difference between the maximum and minimum value in a dataset.	Subtract the smallest value from the largest value in the dataset.
Standard deviation	A measure of how closely the values in a dataset are clustered around the mean.	$= [\sum (x_i - \mu)^2 / N]^{1/2}$ where is the standard deviation xI is each of the values in the set μ is the population mean. N is the population size.
Standard error	A measure of how close the sample mean is likely to be to the population mean.	$s = (/ N)^{0.5}$ where s is the standard error is the standard deviation n is the sample size
Percentile	The value below which a given percentage of the data values lie. The pth percentile is the value in the dataset which p% of values is less than. The 25th, 50th and 75th percentile are called quartiles. The 50th percentile is the median.	List all values in ascending order and select the value that is ranked p% of the way through the list.

Data visualisation

Data visualisation is the technique of summarising a dataset graphically. It is an approach with limited statistical power, but it is a highly effective way to communicate results. Some of the most commonly used methods are bar graphs, line graphs, box and whisker plots and scatter plots. All of these can be easily prepared with a spreadsheet application such as Microsoft Excel.

When creating a graph, remember that the primary purpose is to assist the reader to understand the dataset. To achieve this, the graph must be clear – do not try to convey too much information on a single chart. To avoid skewing data, graph axes must be scaled and labelled appropriately, including a statement of the unit of measurement that has been used. Using inappropriate units or scale can dramatically change the readers interpretation of the data that are presented. A legend may also be important, in order to differentiate between classes or attributes. Finally, a graph must have a caption that explains what information is being presented and any analyses that have been undertaken prior to graphing the data. If the graph shows error bars (see the following subsection), the caption must state whether a standard error or a standard deviation is shown. A good caption should allow a reader to understand the figure without referring to the main body of the report.

Error bars

It is always a good idea to add error bars to graphs, as these allow the reader to judge the reliability of the data displayed. Large error bars indicate that the data have a high degree of variability, while small error bars show that the data are tightly clustered around the mean.

Excel provides several options for the type of error bar to be displayed. Two of these are most useful for monitoring applications, an error bar of:

- a set number of standard deviations or
- one standard error.

Standard deviation error bars should be used if the graph is intended to show the extent to which individual measurements deviate from the population mean. For example, when determining if a management action has caused an indicator to move away from its long term mean value. If the error bar overlaps the data point, any perceived difference between the value and the mean may be due to chance. If the error bar and the data bar do not overlap, there is a likelihood that the measurement is truly different from the population mean. Using an error bar that is two standard deviations in length will provide 95% confidence that non-overlapping bars represent truly different values.

An error bar of one standard error should be used when a graph is comparing the means of two samples or sites. This is the case when determining, for example, if two wetlands have different salinity levels. In this example, it will be necessary to measure salinity at the two sites on a number of occasions. These measurements can then be graphed in pairs, according to the day they were taken and a standard error bar for each wetland added (Figure 15). If the error bars for the two sites overlap, it is likely that no statistically significant difference exists between the two measures on that day. Non-overlapping error bars, such as in the provided example, do not guarantee that the difference is statistically significant, but do make it much more likely.

Bar graphs

A bar graph is a simple, two dimensional chart that shows the magnitude of a measurement, or the frequency with which it was recorded as a bar or column (Figure 14). It allows a rapid comparison between sites or between survey events. Usually, bar graphs will only be used when there are a small number of measures to be displayed, as displaying too much information will make the chart messy and difficult to interpret.

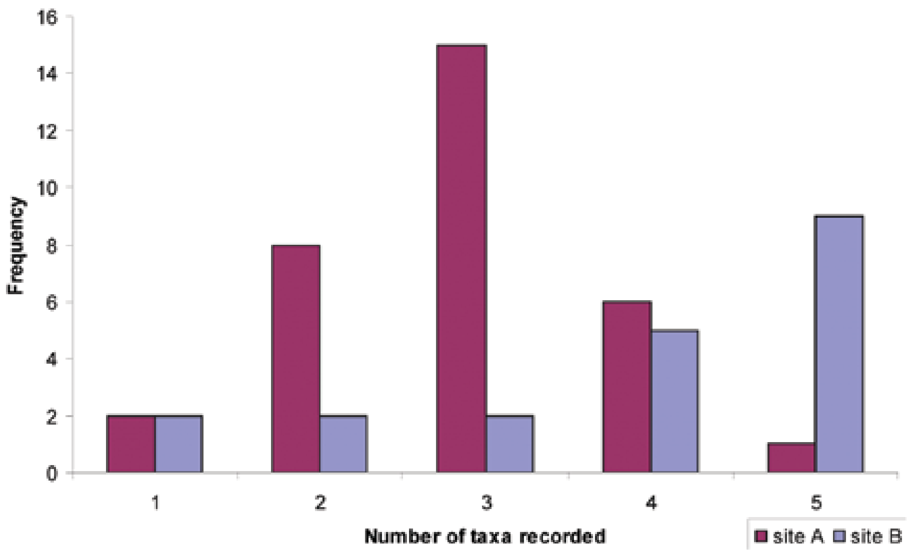

Figure 14. An example of a bar graph showing the frequency with which a given number of taxa were collected at two different sites in a long term monitoring program.

Line graphs

Line graphs are commonly used to show time series data. They are similar to a bar graph, except that the measurement value is displayed as a point and adjacent points are connected. Figure 15 shows the water salinity measured at two sites over four days, presented as a line graph.

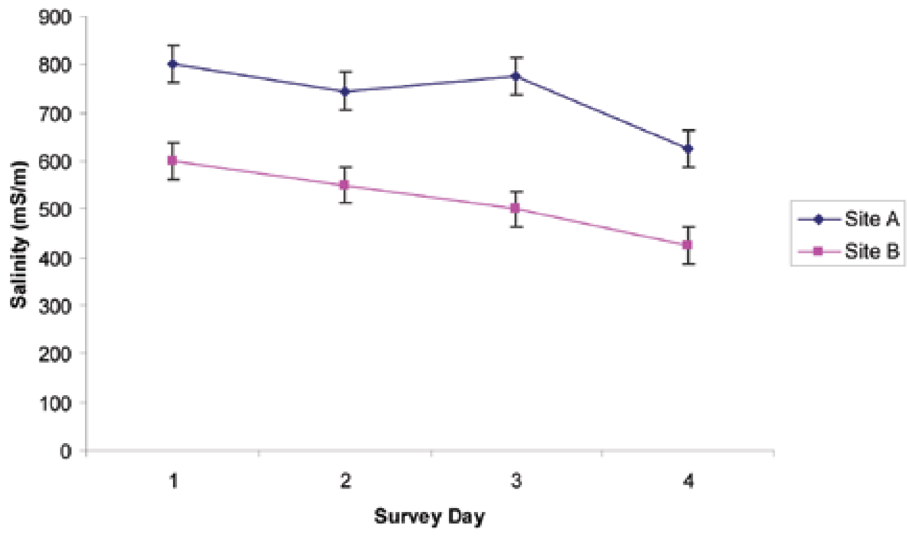

Figure 15. A line graph showing changes in salinity over four survey days at a hypothetical wetlands. Standard error bars are shown for each data point.

Scatter plots

A scatter plot is used when looking for a relationship between two variables. It allows a lot of data to be displayed and trends to be readily identified. Figure 16 is an example of a scatter plot in which the salinity of a hypothetical wetland has been plotted against the total rainfall for the month. A table showing all of these data would be large and difficult to interpret, but a scatter plot allows the reader to see a strong trend. Trends may be further highlighted by adding a trend line. Error bars may also be added to the data points to illustrate the variability of the data, although this is already indicated by the distribution of dots.

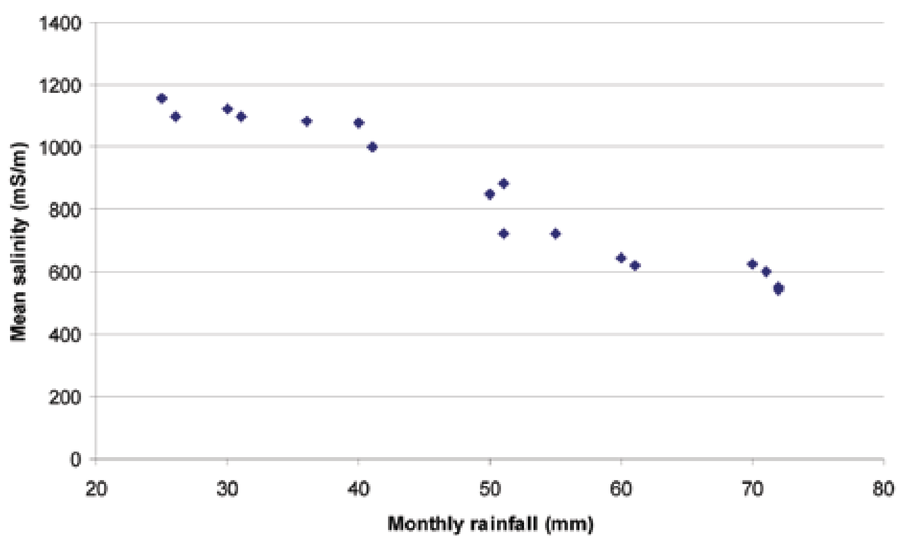

Figure 16. A scatter plot showing the relationship between rainfall and salinity in a hypothetical wetland.

Box and whisker plot

A box and whisker plot is a good way to graphically display the most important summary statistics. The 'box' is bounded by the 25th percentile and the 75th percentile with a horizontal line through it at the median. The 'whiskers' extend from either end of the box to the last data point that is within 1.5x the interquartile range (Figure 17).

Interquartile range: the distance between the 25th and 75th percentile

Values greater than the whiskers (outliers) may be plotted to show the full range of variability in the dataset. Sometimes, a format is used whereby the whiskers extend to the maximum and minimum values in the dataset.

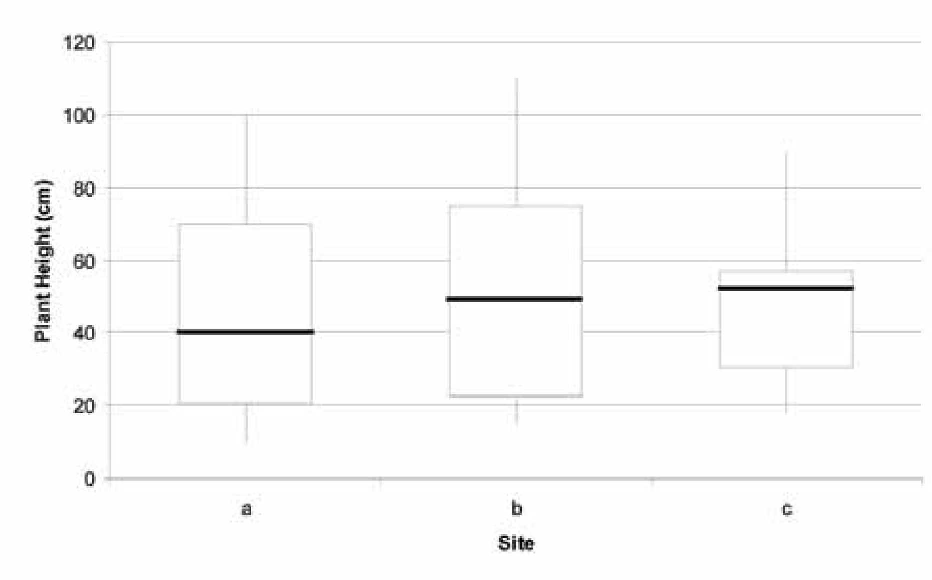

Figure 17. An example of a box and whisker plot. In this example, the height of all plants in three different quadrats have been measured. The 25th and 75th percentile heights are denoted by the ends of the box, while the heavy mark within the box is the median height. The whiskers extend to the last data point that is within a height of 1.5x the interquartile range.

Box and whisker is not a standard chart type in Microsoft Excel, but it is possible to construct them by modifying a stock chart. See support.microsoft.com for details.[38]

Statistical analysis

The objective of undertaking a statistical analysis of a dataset is to determine if a trend, or an observed difference, is statistically significant. In a monitoring context this means determining if any observed difference between the treatment and control site occurred by chance, or because those sites really are different. If a monitoring program is required to demonstrate statistical significance, it is recommended that a statistician be consulted before commencing the design of the program. Tests of statistical significance are beyond the scope the current document.

Appendix A: Example field data sheet

Section 1a: Site Information

Project:				Assessor name:
Site name:				Site code: / Date:
Hydro regime at time of survey (circle):	Filling / Full	Drying / Dry	Recent rainfall:	Photographs (number, location, facing):
Location and access description:				Site map:
Site description (wetland type, size, habitats sampled etc.):				
Site scale notes on vegetation, fauna, condition, land use etc.:				

Section 1b: Monitoring Location Information

Code or name	Zone	Easting	Northing	Reason for Location

Notes on monitoring locations:

Page ____ / ____

Section 2a: Water Chemistry and Aquatic Invertebrates

Site name or code:	Assessor name:	
Location name:	Location code:	Time:

Sample checklist (record #):				Habitats sampled for invertebrates:	Description
125 mL filtered water		Chlorophyll			
125 mL unfiltered water		Volume filtered			
250 mL unfiltered water		# filter papers			
500 mL unfiltered water					
Substrate samples					

Water property measured	Habitats sampled				Notes on measures
Conductivity below surface					
Conductivity above sediment					
pH below surface					
pH above sediment					
Temperature below surface					
Temperature above sediment					
Turbidity below surface					
Turbidity above sediment					
Maximum flow					
Minimum flow					

Section 2b: Waterbirds

Species	Count	Notes		
			Observer names:	
			Area surveyed:	
			Weather obs:	
			Method used:	
				Page ____ / ____

Time:

Section 3a: Vegetation Monitoring Location

Site name or code:		Assessor name:	
Location name:		Location code:	Date:

Transect or quadrat location		
Datum	Easting	Bearing
Zone	Northing	Length or size
Reason for transect location	Transect photos	

Substrate composition						Soil %
Bare%	Rock%	Crypto%	Litter%	Trash%	Logs%	Dry
A horizon						Wet
depth:						
colour:						
texture:						Inundated
pH:						

Section 3b: Qualitative Vegetation Assessment

Growth form	Trees			Shrubs		
	>30m	10-30m	<10m	>2m	1-2m	<1m
Cover %						
Dominant Species						
Recruitment						
Stress						

Growth form	Grasses	Herbs	Sedges	Other
Cover %				
Dominant Species				
Recruitment				
Stress				

Overall Vegetation Condition		
Pristine		see Keighery, B. 1994. *Bushland Plant Survey*. Wildflower Society of WA. Perth.
Excellent		
Very good		
Good		
Degraded		
Notes:		

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Section 3c: Quantitative Vegetation Assessment

Site ID:	Assessor name:
Location ID:	Transect ID:
Dominant Stratum:	Emergents:

Stratum	% cover	Height		Stratum	% cover	Height	
Species (in order of dominance)		Form	Voucher #	Species (in order of dominance)		Form	Voucher #
1				1			
2				2			
3				3			
4				4			
5				5			
6				6			

Stratum	% cover	Height		Stratum	% cover	Height	
Species (in order of dominance)		Form	Voucher #	Species (in order of dominance)		Form	Voucher #
1				1			
2				2			
3				3			
4				4			
5				5			
6				6			

Stratum	% cover	Height		Stratum	% cover	Height	
Species (in order of dominance)		Form	Voucher #	Species (in order of dominance)		Form	Voucher #
1				1			
2				2			
3				3			
4				4			
5				5			
6				6			

Page ____ / ____

Section 3c: Quantitative Vegetation Assessment

Site ID:	Assessor name:
Location ID:	Transect ID:

Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						
Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						
Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						
Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						
Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						
Stratum													
Crown gaps or tape intercepts							Crown widths or tape intercepts						

Page ____ / ____

Section 4: Impacts of threatening processes

Site ID:	Assessor name:
Location ID:	Transect ID:

Threat Category	Threat	% area affected	Severity of impact	Notes
Altered biogeochemical processes	waterlogging and salinisation			
	eutrophication (aquatic only)			
	erosion			
	drainage into site			
	groundwater abstraction			
Introduced plants and animals	weeds			
	feral animals			
	stock grazing			
Problem native species (list)				
Disease (list)				
Detrimental regimes of physical disturbance	fire			
	drought			
	flood			
	storm damage			
Impacts of pollution	spray use			
	spills			
	runoff			
Competing land uses	recreation			
	agriculture (other than above)			
	consumptive, productive use			
	mines and quarries			
	illegal activities			

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Topic summary

- Monitoring is the systematic collection of data, over time, in order to determine the effect of a management regime on the condition of a wetland.
- Planning a monitoring program requires four questions to be addressed:
  1. What is the hypothesis to be tested?
  2. How much confidence is required in the answer?
  3. Which indicators will be measured?
  4. How will the collected data be analysed?
- The hypothesis should state which elements of the ecosystem are expected to change, the magnitude and direction of the change and what period of time changes are expected to occur over.
- Data confidence is achieved by using replication and controls to be sure that a significant change has occurred in an ecosystem and to be able to state what the cause of the change was.
- The indicators to be measured in a monitoring program should address the monitoring hypothesis, be informative in the context of the wetland's ecology, show changes at an appropriate temporal scale and be measurable within the budget and technical expertise available to the program.
- The methods used to analyse the data should be determined when planning the program to ensure that appropriate data are collected.

Sources of more information on monitoring wetlands

Aquatic biodiversity assessment and mapping method – AquaBAMM
www.epa.qld.gov.au
A decision support tool that utilises existing information and expert input to assess conservation value in aquatic ecosystems in Queensland.

Index of Wetland Condition Methods Manual
www.dse.vic.gov.au
Provides a methodology used by Victoria's Department of Sustainability and the Environment to assess the condition of wetland ecosystems.

Matter For Target Inland Aquatic Ecosystem Integrity – Wetlands
nlwra.gov.au
Describes the national indicators for wetland extent, distribution and condition and progress toward developing nationally consistent measures for them.

Natural Resource Management Monitoring, Evaluation, Reporting and Improvement Framework
www.nrm.gov.au
Information about output monitoring for NRM projects funded by the Australian Government.

The Volunteer Monitor's Guide to Quality Assurance Project Plans
www.epa.gov
The website of the United States Environmental Protection Agency provides information about quality assurance, including a template for a monitoring metadata statement

Queensland Community Waterwatch Monitoring Manual
www.qld.waterwatch.org.au
Promotes a strategic approach to community waterway monitoring that supports local and regional natural resource management, and improved understanding and awareness of waterway and catchment issues.

Water Quality Monitoring Program Design
water.wa.gov.au
Assists agencies and groups involved in surface water quality monitoring to develop programs that use standard operating procedures for sample collection and analysis.

Waterwatch Australia National Technical Manual
www.waterwatch.org.au
Provides information to help Waterwatch coordinators, environmental staff, teachers and experienced Waterwatchers to understand the health of Australia's waterways and the tools to monitor their condition.

WetlandInfo
www.epa.qld.gov.au.
The Queensland Department of Environment and Resource Management's wetlands website. It includes information about wetland typology and conceptual models.

Glossary

Accuracy: closeness to the 'true' value of the parameter being measured

Australian Height Datum: a fixed survey point from which the elevation of any point in Australia may be measured.

Blank: a solution (usually deionised water) that has a value of zero for the parameter being assessed. Used to calibrate meters.

Box-subsampler: watertight box that is divided into a number of cells. A box-subsampler is used when sorting aquatic invertebrates to eliminate observer bias. Dividing the sample into a number of cells which are sorted individually, and in their entirety, reduces the likelihood of preferential selection of larger or more conspicuous taxa.

Canopy cover: the proportion of ground surface covered by the leaves and branches of plants when projected vertically downwards.

Causation: showing a relationship exists between two variables such that a change in one (the cause) causes a change in the other (the effect). To be sure of the relationship between cause and effect, it is also necessary to show that the effect will not occur if the cause does not.

Chroma: the purity of a colour, or its freedom from white or grey.

Community composition: the plant taxa that occur in a given community.

Community structure: the three-dimensional distribution (height and width of foliage) and abundance of plant taxa and growth forms within a community.

Control: a subject that is identical to the experimental subject in every way, except that the experimental subject receives the treatment and the control does not. This means that if a change is observed in the experimental subject after the treatment, but not observed in the control, that change could only have occurred due to the treatment.

Crown cover: the vertical projection of the outer extent of the crown of a plant. A line around the outer edge defines the limits of an individual canopy, and all the area within is treated as 'canopy' irrespective of gaps and overlaps.

Data confidence: the degree of certainty with which it is possible to state that a change has (or has not) occurred in a system and what the cause of the change is.

Data quality: the degree to which the data set truthfully represents conditions at the monitoring site. High quality data are achieved by eliminating errors from the dataset.

Data visualisation: the technique of summarising a dataset graphically

Datum: an established point on the globe that is used as the reference from which other locations are calculated. Australia uses the Geographic Datum of Australia 1994 (GDA94).

Ecological character: the sum of a wetland's biotic and abiotic components, functions, drivers and processes, as well as the threatening processes occurring in the wetland, catchment and region.

Electrofishing: a technique in which an electric current is applied to the water in order to temporarily stun fish.

Habitat type: 'habitat' is a species specific term, with every taxon having its own environmental requirements. 'Habitat type' is used here to refer to areas where environmental conditions are appreciably different from their surroundings. These differences increase the likelihood that the area may support a distinctive flora or fauna assemblage.

Hue: the property of colours by which they can be perceived as ranging from red through yellow, green, and blue, as determined by the dominant wavelength of the light.

Hypothesis: a concept that is not yet verified but that, if true, would explain certain facts or phenomena.

Indicators: the specific components and processes of a wetland that are measured in a monitoring program in order to assess changes in the conditions at a site.

Interquartile range: the distance between the 25th and 75th percentile.

Macroinvertebrate: invertebrate taxa that, when fully grown, are visible with the naked eye. It usually includes all of the insects, worms, molluscs, water mites and larger crustacea such as shrimps and crayfish.

Mean: representative of the values being summarised due to being intermediate between the extremes of the dataset.

Median: the value for which one-half (50%) of the observations (when ranked) will lie above that value and one-half will lie below that value.

Microinvertebrate: invertebrate taxa that are too small to see with the naked eye, also referred to as plankton, specifically ostracods, copepods, cladocerans, rotifers and protozoans.

Mode: the most commonly occurring value in a dataset.

Monitoring: the systematic collection of data, over time, in order to test a hypothesis.

Outcome: a measurable consequence of the project's activities.

Outputs: activities undertaken, or products produced, by a particular project.

Percentile: the value below which a given percentage of the data values lie. The pth percentile is the value in the dataset which p% of values is less than. The 25th, 50th and 75th percentile are called quartiles. The 50th percentile is the median

pH: a measure of the concentration of hydrogen ions in a solution; dissolved hydrogen ions being responsible for giving a solution the properties of an acid.

Plant community: a discernable grouping of plant populations within a shared habitat. A community develops due to a unique combination of geologic, topographic and climatic factors and will be recognisable where those factors co-occur.

Population: in statistics, the term population refers to the entire aggregation of components that are the subject of a study. This may be all the individuals in a biological population, but it may equally relate to a non-biological entity such as quadrats.

Precision: minimal variability between measurements

Qualitative data: descriptive data; they are collected using techniques such as estimation, categorisation, statements of type or condition, diagrams, photographs and maps.

Quality assurance: the process of documenting data quality and data confidence by describing how the dataset was collected, analysed and stored.

Quality control: the process of detecting errors and determining their magnitude.

Quantitative data: data that are measured or counted in some way, for example, the number of plants in a plot or the pH of a water sample.

Range: the difference between the maximum and minimum value in a dataset.

Replication: repeating an experiment several times and collating all the results. It allows the error margin of the measurements and natural variations in the subjects to be discounted from consideration.

Representativeness: how well a series of measurements reflect the full range of values in the system being measured.

Sampling: the process of selecting a set of individuals that will be analysed to yield some information about the entire population from which they were drawn.

Sampling point: the precise place at which a sample is taken.

Sensitivity: the ability to distinguish between different values in the parameter being measured.

Shorebirds: those birds commonly found wading near the shores of wetlands, beaches, mudflats and lagoons in search of food. They include plovers, sandpipers, stone-curlews, snipes, pratincoles, oystercatchers, stilts and avocets.

Soil texture: the distribution of grain sizes of the mineral particles in a soil.

Sorting (aquatic invertebrates): picking individual organisms from a sample to form a sub-sample.

Spatial scale: the minimum size of an area about which data are collected.

Standard deviation: a measure of how closely the values in a dataset are clustered around the mean.

Standard error: a measure of how close the sample mean is likely to be to the population mean.

Stratum: (plural strata) a visibly conspicuous layer of photosynthetic tissue within a plant community.

Study site: the wetland that is being monitored.

Substrate: a generic term denoting the material forming the floor of a wetland and its surrounds. It is used here because the term 'soil' is not inclusive of organic substrates.

Summary statistics: measures that express the central tendency and variability of a dataset; most commonly mean, median, mode, range, standard deviation, standard error and percentile.

Surrogate measure: another component of the system that shows a correlated response to the management issue being evaluated.

Survey: an exercise in which a set of observations are made about some components of an ecosystem

Survey location: the area of the wetland where a survey is completed.

Temporal: of or pertaining to time. Temporal variations are changes that occur over time.

Transparency: a measure of the degree to which light is able to penetrate the water column.

Treatment: subjection to some agent or action. In the case of a monitoring program, the treatment will be the management regime that is expected to cause some change in the condition of the site.

Turbid: the cloudy appearance of water due to suspended material.

Turbidity: the extent to which light is scattered and reflected by particles suspended or dissolved in the water column.

Value: the property of a colour by which it is distinguished as bright or dark; also known as luminosity.

Waterbirds: birds that have specialised beaks and feet that allow them to swim, dive and feed in water. Examples include egrets, crakes, herons, ducks, swans and grebes.

Wetland components: include the physical, chemical and biological parts of a wetland (from large scale to very small scale, e.g. habitat, species and genes).

Wetland conceptual model: a simplified diagram that expresses ideas about components and processes that are important to the ecosystem.

Wetland processes: the forces within a wetland and include those processes that occur between organisms and within and between populations and communities including interactions with the non-living environment and include sedimentation, nutrient cycling and reproduction.

Wetland typology: the process of classifying wetlands according to characteristics of their hydrological, morphological, chemical and biological factors.

Personal communications

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A guide to managing and restoring wetlands in Western Australia

Roles and responsibilities

In Chapter 5: **Protecting wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Roles and responsibilities' topic

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Contents

Case studies

INTRODUCTION

Wetland conservation and management is the collective responsibility of individuals, education and research institutions, businesses, non-government organisations and local, state, and national government. The roles of these stakeholders can be complex and often overlapping. This topic provides an overview of the roles of these stakeholders in wetland conservation and management, with the aim of unravelling the confusion surrounding 'who is responsible for what?'

Table 1 broadly summarises the roles and responsibilities of stakeholders in wetland management and conservation. Much more detailed information is provided in subsequent sections, grouped into three parts: community stakeholders, organisations, and government.

THE ROLE OF COMMUNITY

Both as individuals and a collective, the community has an important role in, and contributes significantly to, wetland conservation in Western Australia. The community can take on-ground action to manage privately owned wetlands, assist in the management of wetlands on public land, and significantly influence the policy and decision-making of organisations and government.

Community values and expectations influence both the private and the non-government conservation sector. In the private sector, the influence of community and increasing requirement for corporations to be accountable has led to corporations integrating the principles of corporate social responsibility into business models and day-to-day operations.

Non-government conservation groups are also influenced by the community, as community concern for particular environmental issues can draw attention to them and place them on an organisation's agenda. Many conservation programs are driven and reliant upon community involvement and those which have greater community support are deemed more likely to succeed.

Community wetland conservation efforts can be greatly assisted by understanding the role of other stakeholders and the processes within which they operate. This enables the community to direct efforts to the most appropriate agency or organisation, through the best process and at a stage in the process that will have the greatest possible influence on wetland conservation outcomes.

Table 1. A summary of stakeholder roles and responsibilities in wetland management and conservation

Key

Level of responsibility			
No role	Low	Moderate	Significant
N/A	✓ (Low)	✓ (Moderate)	✓ (Significant)

	Conservation on private land	Conservation on public lands	Conservation estate/Bush Forever/ Riverpark	Planning and policy development	Development assessment	Research	Formal advice	Water allocation licensing	Licensing of industry
Community	✓ (Significant)	✓ (Moderate)	✓ (Low)	✓ (Moderate)	✓ (Low)	✓ (Low)	N/A	✓ (Low)	N/A
Regional NRM organisations	✓ (Moderate)	✓ (Low)	N/A	✓ (Moderate)	N/A	✓ (Low)	N/A	✓ (Low)	N/A
Local governments	✓ (Moderate)	✓ (Significant)	✓ (Moderate)	✓ (Moderate)	✓ (Moderate)	✓ (Low)	✓ (Significant)	✓ (Low)	N/A
Department of Environment and Conservation (DEC)	✓ (Moderate)	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Low)	✓ (Significant)
Office of the Environmental Protection Authority (OEPA)	✓ (Low)	✓ (Low)	✓ (Moderate)	✓ (Significant)	✓ (Significant)	N/A	✓ (Significant)	N/A	N/A
Department of Water (DoW)	✓ (Low)	✓ (Low)	✓ (Low)	✓ (Moderate)	✓ (Moderate)	✓ (Moderate)	✓ (Moderate)	✓ (Significant)	N/A
Department of Planning (DoP)	✓ (Low)	✓ (Low)	✓ (Significant)	✓ (Significant)	✓ (Moderate)	N/A	✓ (Moderate)	N/A	N/A
Department of Agriculture and Food (DAFWA)	✓ (Low)	✓ (Significant)	N/A	✓ (Moderate)	✓ (Moderate)	✓ (Low)	✓ (Low)	N/A	N/A
Swan River Trust (SRT)	N/A	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Moderate)	✓ (Significant)	✓ (Significant)	✓ (Moderate)	N/A
Wetlands Coordinating Committee (WCC)	N/A	N/A	N/A	✓ (Moderate)	N/A	N/A	✓ (Moderate)	N/A	N/A
Environmental Protection Authority (EPA)	✓ (Low)	✓ (Moderate)	✓ (Moderate)	✓ (Significant)	✓ (Significant)	N/A	✓ (Significant)	N/A	N/A
Western Australian Planning Commission (WAPC)	✓ (Low)	✓ (Moderate)	✓ (Significant)	✓ (Significant)	✓ (Significant)	N/A	✓ (Significant)	N/A	N/A
Conservation Commission of WA (CCWA)	N/A	✓ (Significant)	✓ (Significant)	✓ (Significant)	N/A	N/A	✓ (Significant)	N/A	N/A
Department of Sustainability, Environment, Water, Population and Communities (DSEWCaP) (Aust. Govt)	✓ (Moderate)	N/A	N/A	✓ (Significant)	✓ (Significant)	✓ (Significant)	✓ (Significant)	N/A	N/A
Aquatic Ecosystems Task Group (AETG) (national)	N/A	N/A	N/A	✓ (Moderate)	N/A	N/A	✓ (Moderate)	N/A	N/A
Wetlands and Waterbirds Taskforce (WWTF) (national)	N/A	N/A	N/A	✓ (Moderate)	N/A	N/A	✓ (Moderate)	N/A	N/A

Individual or group action?

Members of the community, whether as individuals or a group member, can take action to benefit wetlands.

Landowners can take direct action to manage wetlands on their property. Assistance is available to individuals wishing to manage wetlands on their property for conservation purposes. This includes funding, training and access to other resources. For example, Doug and Eva Russell, cattle farmers in Manypeaks on the South Coast, have fenced off a wetland and remnant vegetation on their farm from cattle (Figure 1). They have created ecological corridors to connect their wetland with dryland remnant vegetation by fencing, direct seeding and planting. They have received funding and technical assistance from the National Trust and DEC's Land for Wildlife program.

(a)

(b)

Figure 1. Landowners are in a unique position of being able to manage wetlands on their property. (a) The Russells have fenced off their wetland in Manypeaks, South Coast. Photo – B Schur/Green Skills Inc. (b) They have also revegetated ecological corridors (shown in red), connecting the wetland with nearby bush. Photo – K Hopkinson/ Green Skills Inc.

➤ For listings of various programs that provide assistance to individuals to manage wetlands, see the topic 'Funding, training and resources' in Chapter 1.

Individuals can also help protect and manage WA's wetlands by participating in citizen science. This is the name given to research or monitoring conducted by individuals or communities in the public interest. Citizen science is how ordinary citizens help scientific research and in doing so help society. The contribution of individuals with an interest in a particular species, site or type of ecosystem can be invaluable. Many organisations have citizen science programs that individuals can participate in.

For example, the ClimateWatch program encourages citizens to record sightings of wetland species including a number of WA frogs: www.climatewatch.org.au/species/frogs and the oblong turtle: www.climatewatch.org.au/species/reptiles/oblong-turtle.

➤ There are many ways to get involved in protecting and managing wetlands using citizen science, the following are just examples:

www.ala.org.au/get-involved/citizen-science/

www.climatewatch.org.au/

www.citizensciencealliance.org

For complex issues or large wetlands, taking action as an individual can sometimes be a daunting task and so it may be preferable to join or form a community group, or to seek the assistance of a regional or sub-regional natural resource management organisation (outlined in the section 'Regional natural resource management organisations'). Local community groups have demonstrated excellence in protecting and conserving the WA environment, being heavily represented at the annual Western Australian Environment Awards. Local community groups are often integral to the conservation of a site, as shown in the case study in this topic entitled 'Working collaboratively to manage and restore Lake Mealup'.

➤ There are many local community groups interested in wetlands in specific areas of WA. Some groups are listed in the 'Environment conservation and heritage' directory on Our Community Pty Ltd: www.ourcommunity.com.au. Other sources of information on local community groups include local governments, regional and sub-regional NRM organisations and local DEC offices.

➤ Information on forming a community group can be accessed from various sources, including:

- Urban Bushland Council's notes: www.bushlandperth.org.au/images/stories/PDF/Resources/forming_a_friends_group_resource_notes.pdf
- the Shire of Kalamunda's hints: http://nrpg.org.au/page/Intro-to-Friends-Groups.aspx
- the Shire of Mundaring's notes: www.bushlandperth.org.au/images/stories/PDF/Resources/shire_of_mundaring_friends_group_manual.pdf

Visual surveillance of reserves is another important community function. Reporting activities that impact on a wetland, such as dumping of waste, damaging vegetation or lighting fires, can assist responsible authorities to avert environmental harm.

➤ Report illegal dumping to the illegal dumping hotline: 1300 766 541 or phone your local council. For more information see www.kabc.wa.gov.au/illegal-dumping.html

➤ Report pollution on the pollution hotline: 1300 784 782 (24 hours) or email pollutionwatch@dec.wa.gov.au; in the event of a hazardous materials release or life-threatening incident, call 000 and ask for Fire and Rescue.

➤ Report known or suspected arson (including suspicious behaviour) to Crimestoppers: 1800 333 000, or if it is an emergency, dial 000. See www.bushfirearson.gov.au/Pages/default.aspx for more information.

Community – helping to get things done at wetlands

The community can have a significant influence on wetland protection and management outcomes through participation in on-ground and wetland management planning activities.

Community assistance and guidance is often necessary for government to achieve successful, long-term implementation of programs. Public agencies responsible for management of public lands have recognised this and in particular the importance of community involvement in planning and undertaking wetland management.

In recognising that genuine engagement with the community is critical for environmental protection and natural resource management in Western Australia, DEC has embedded this ethos in its mission statement. It has developed a number of formal policies to encourage, support and guide volunteer involvement in management activities and to ensure that volunteers are covered by insurance when participating in these activities.[1]

Individuals can participate in working bees organised by land managers or community groups working in association with land managers. There are often a variety of on-ground management actions people can become involved in, including activities such as planting seedlings, weeding, fencing, conducting plant and animal surveys, water quality monitoring, and numerous other activities. Most restoration and management activities are restricted by the number of people available to assist and so every pair of hands helps. As the number of volunteer hours recorded for specific projects are a reflection of community engagement and concern for an area, this information is often used by government agencies to determine future allocation of funding and future projects to be implemented. Organised events will often be advertised in the local paper and local government websites.

There are a number of organisations that have valuable volunteer programs to help manage wetlands and other natural areas. DEC has a number of short-term and ongoing projects involving volunteers.

A program that provides help and assistance to community groups managing urban natural areas is DEC's Urban Nature program. Urban Nature provides technical advice and on-ground support for land managers and supporting groups working to protect, manage and restore bushlands and wetlands in the Perth metropolitan area and beyond, with a primary focus on regionally significant areas. For more information, see the Urban Nature webpage on the DEC website: www.dec.wa.gov.au/content/category/45/879/2024/.

Many community groups are eligible to apply for funding to do on-ground works at wetlands. Community groups often actively facilitate and broker relationships with community members, agencies and research organisations to improve wetland management (see the case study 'Working collaboratively to manage Lake Mealup' at the end of this topic for a great example of this).

➤ For listings of various programs that provide assistance to community groups to manage wetlands, see the topic 'Funding, training and resources' in Chapter 1.

➤ Details of DEC projects involving volunteers are provided on the volunteer webpage on the DEC website: www.dec.wa.gov.au/content/view/196/534/

➤ Local governments can also be contacted for information about upcoming events at wetlands managed by the local government.

➤ Information on volunteering is available from Volunteering WA: www.volunteeringwa.org.au.

A community voice in government policy development

The community has an important role in setting political agendas and raising government awareness of wetland conservation issues. While specific government agencies are assigned responsibilities for wetland conservation by the state government, government agendas and programs are frequently influenced by community concerns and opinions (Figure 2).

For example, the community was vocal in seeking the banning of recreational duck shooting in WA wetlands. Many groups and individuals formed the Coalition Against Duck Shooting. As a result of community opposition, recreational duck shooting was banned in 1992 in WA (the first state or territory to do so) by changes to legislation. Recreational shooting is still allowed in some other Australian states and territories.

Government agencies and committees prepare broad policy statements, strategies and/or position statements in regard to environmental issues. These policies provide the community and the private sector with a greater understanding of the government's likely position on any proposal or plan that affects that issue.

Some government committees include community representatives to facilitate greater consideration of community opinions when developing policy and making decisions. For example, the Wetlands Coordinating Committee (described later) and a number of its sub-committees include representatives of the voluntary conservation movement and wetland scientists from universities and the private sector.

Most policies, strategies, and position statements developed by government agencies or committees are released in draft form for public comment. Submissions made during this time are usually considered through a formal process and a response is made to each substantive point raised. Submissions with well defined and explained points make it easier for the agency or committee to respond. Most agencies publish guidelines for preparing submissions. The response to submissions is sometimes published.

Some agencies or committees will invite community input before a draft is prepared, in the form of a workshop or survey. Invitations may be extended on a random basis or to known representative community members. For example, in development of Network City, the strategic framework used to create sustainable development of the Perth and Peel areas, the (then) Minister for Planning and Infrastructure ensured the process provided for extensive community involvement from the very beginning of the framework's development. The consultation process included a resident survey, publication of issues papers, a television program, interactive website, school competition, radio coverage, a large interactive forum and publication of a draft for public comment.[2]

Broad policy development can also be initiated by government in response to an issue raised by the community through individual or group lobbying to the responsible Cabinet Minister. The community response to a specific plan or proposal can also contribute to broader policy development on an issue. For example, the development of the *State Planning Policy 2.6 (State Coastal Planning)* formalised planning requirements for coastal setbacks in new developments, following community reaction to the initial proposal for redevelopment of Leighton Beach in Perth.[3]

➤ A list of policies that influence wetland management and protection, and descriptions of these policies, is available in the topic 'Legislation and policy' in Chapter 5.

➤ DEC recognises the right of members of the public to have a meaningful role in protecting and conserving Western Australia's natural environment and advertises documents for comment online at www.dec.wa.gov.au/community-and-education/have-your-say.html

A community voice in government decision-making

Decision-making processes often have a public consultation phase built-in. Community input during these phases can be a very effective way to influence a decision-making authority's determination of a proposal (a decision-making authority, or DMA, is a public authority empowered by legislation to make a decision in respect of a proposal). Raising issues early in the planning process is most effective, as it provides the proponent with more opportunity to address an issue or modify a proposal during the earlier stages of planning.

Planning development and new infrastructure can require considerable investment and the later in the process an issue is raised, the less likely it will be that the proponent will

Figure 2. A community group speaking with media in the Kimberley region, WA. Photo – M Coote/DEC.

want to, or be able to afford to change the proposal.

More formally, the environmental impact assessment (EIA) process grants members of the community specific rights to have concerns and views regarding proposals taken into consideration.

These rights are generally applicable where a proposal is formally assessed, however, the EPA may request targeted public input into proposals that are assessed informally and that do not have to undergo a full EIA assessment.

The types of submissions and appeals an individual may make include:

(i) a submission to the EPA during the public submission period of a project proposal undergoing environmental impact assessment

(ii) an appeal against decisions, recommendations and orders issued in respect to the EIA process and applications to clear native vegetation to the Minister for Environment.

Appeal rights include the right to appeal:

- the decision of the EPA not to assess a proposal
- the content or recommendations of an EPA report.

The following appeals are only available to the proponent of the proposal:

- conditions imposed on a proposal by the Minister

- an order imposed on a proponent by the Minister following a breach of conditions.

Applications to clear native vegetation in WA are regulated through Part V of the *Environmental Protection Act 1986*. The process grants members of the community specific rights to have comments regarding proposals taken into consideration.

Table 2 provides some examples of statutory decision-making processes relevant to wetland conservation that involve an advertised public comment or appeal period.

Table 2. Examples of statutory decision-making processes in WA with public comment or appeal periods.

Decision	Decision-making authority	Public consultation process	Appeals process	Legislation
Local planning scheme amendment	Department of Planning	Submission	State Administrative Tribunal	*Planning and Development Act 2005*
Local planning scheme amendment (assessed)	Environmental Protection Authority	Submission	Appeals Convenor	*Environment Protection Act 1986*
Development or subdivision proposal (assessed)	Environmental Protection Authority	Submission	Appeals Convenor	*Environment Protection Act 1986*
Clearing application	Department of Environment and Conservation	Public comment	Appeals Convenor	*Environment Protection Act 1986*
Groundwater allocation (regional/ area) plans	Department of Water	Submission	State Administrative Tribunal	*Rights in Water and Irrigation Act 1914*

Community can also raise concerns or highlight opportunities for wetland conservation outcomes through a general enquiry to the relevant government agency or committee or local member of Parliament.

➤ For additional details on relevant legislation that provides for public consultation during decision-making processes, see the topic 'Legislation and policy' in Chapter 5.

➤ The Environmental Defender's Office of WA also provides a range of useful fact sheets on this matter: www.edowa.org.au

➤ For further information on current EIA proposals open for public submissions or to make a submission, see the EPA website at www.epa.wa.gov.au/public-comment

➤ DEC publishes applications received for Part V licences, works approvals and clearing permits online at www.dec.wa.gov.au/news/advertisements.html and in the Public Notices section of *The West Australian* newspaper each Monday.

➤ For further information on the appeals process or to make an appeal, see the Appeals Convenor website at www.appealsconvenor.wa.gov.au and the State Administrative Tribunal website at www.sat.justice.wa.gov.au.

THE ROLE OF ORGANISATIONS

For the purposes of this guide, the term 'organisation' is used to collectively refer to businesses, not-for-profit organisations such as environment groups and public institutions such as universities, education centres and schools.

Organisations have varying roles in wetland conservation, depending on their structure and purpose. In particular, whether it operates for profit, is a not-for-profit organisation or a research institution.

For-profit organisations

Corporate social responsibility (or corporate citizenship) enables companies to embrace responsibility for the social and environmental impact of their business over and above what is legally required, and promote the public interest by encouraging community development and sustainability and voluntarily eliminating practices that harm the public realm.

For example, corporations can demonstrate corporate social responsibility by voluntarily lowering environmental emissions and waste, consulting with local communities prior to planning of projects, contributing funding and facilities to the community and enabling employees to participate in local environmental projects and events, such as planting days.

Corporations and environmental or community groups can form partnerships to facilitate positive environmental or social outcomes. The Coles Group Ltd (formerly Coles Myer) began a partnership with Landcare Australia in 2001 and has achieved a number of positive outcomes for the environment. These include reducing plastic bag usage by 45 per cent between 2004–2005, raising funds for Coastcare through a reusable bag initiative and contributing funds to the Junior Landcare Program aimed at reducing the impact of salinity and other environmental issues on communities.[4]

The growing number of businesses now competing in the annual Western Australian Environment Awards is an indication that the private sector is becoming increasingly aware of the value that corporate environmental responsibility can provide to their business.

➤ The Western Australian Environment Awards' *Winners* book, available at www.dec.wa.gov.au, provides inspiring examples of corporate participation and innovation in conservation and sustainability.

➤ *Working together: involving community and stakeholders in decision-making*[5] is a guide by the Government of WA.

Land developers have a specific role in wetland management during the course of, and in the years following, the subdivision and development of an area of land. If a wetland is located within the parcel of land, it may be required to be ceded to the Crown free of cost as 'public open space' (often abbreviated to POS). For wetlands retained in areas of public open space within a residential development, it is common for developers to be assigned responsibility for the management of the wetland for a period of up to three years following the completion of a development. They are generally required to manage the wetland and associated wetland buffer in accordance with a wetland management plan that has been prepared in liaison with and approved by relevant authorities (for example, DEC and/or the local government). After this period, if the developer has satisfied the requirements and implemented all management actions outlined in the approved wetland management plan, transfer of the open space and therefore responsibility for the management of the wetland passes to the nominated vesting body, typically the local government. Community can have an important role in the scoping of the wetland's management, and should be consulted by the land developer as a matter of course during the development of the plan. For more information on public open space in residential areas, see *Liveable Neighbourhoods*[6] (Element 4, R11, page 7).

Corporatised and privatised service providers

Corporatised and privatised service providers of water, gas, electricity, and communication services are now largely commercial organisations which operate for profit or under strict regulatory control. These include Water Corporation, Western Power and Alinta Gas. Their association with state government varies between organisations, however, they are all regulated under legislation and policy and are required to meet government objectives.

While they do not have a lead role in wetland conservation, service providers have the potential to impact wetlands through infrastructure development and maintenance. As such, providers are required to conduct their business within the constraints of legislation and policies. This may include planning of infrastructure corridors to avoid impact on intact natural areas including wetlands, obtaining clearing permits prior to vegetation clearing for infrastructure corridors and conducting threatened flora and fauna surveys in environmentally sensitive areas prior to maintenance of infrastructure corridors.

Some service providers have developed internal policies to ensure business activities adhere to legislation and policy, ultimately reducing impacts on wetlands and other natural areas.

For example, Western Power has standards and instructions in place to restrict the movement of soil and plant life during construction and maintenance activities, which minimises the risk of spreading the pathogen *Phytophthora cinnamomi*, which causes Phytophthora dieback. Western Power has also supported the research efforts of the Centre for Phytophthora Science and Management with funding over four years.

extra information

Working with utility providers in and near wetlands

Utility providers may often need to access infrastructure in or near a wetland. Overhead or underground services may be located within a wetland area, often in formal drainage reserves or easements.

An easement is a right held by one person to make specific, limited use of land owned by another person. An easement is granted by the owner of the property for the convenience, or ease, of the person using the property. Common easements include the right to pass across the property, the right to construct and maintain a roadway across the property, the right to construct a pipeline under the land, or a power line over the land. Care should be taken to identify the location of these easements and ensure that the organisations that have access rights to the reserve are aware of the wetland management requirements. It is important to understand how their works and maintenance requirements may be made compatible with the values of the reserve.

For example, where an overhead power line enters a natural area, care should be taken by any vehicle that is entering the site in order to undertake pruning or other line maintenance work. Western Power now places signage on each power pole within conservation reserves that advise workers of the site's environmental sensitivity, and the need to take appropriate care. In addition

extra information

to these signs, sites are registered in databases and geographic information systems. Prior to undertaking any work near these areas, appropriate procedures are determined and field personnel are issued with work instructions that must be adhered to.

Whilst the *Utility Providers Code of Practice for Western Australia*[7] has been designed for works in road reserves, it provides a starting point when consulting with any of these organisations (for example, Alinta Gas, Western Power, Horizon Power, or any one of the number of telecommunications carriers). It is available from the Main Roads WA website: www.mainroads.wa.gov.au.

Key principles when encouraging responsible action by utility providers include:

- ensure that the utility is advised of environmental values and sensitivities of the wetland and surrounding natural area, preferably both in writing and in liaison for on-site staff
- both parties should establish an agreement in writing, making clear the responsibilities of the utility provider, its contractors, the local government and/or community groups
- utilities should avoid locating new services in natural areas
- utilities and their contractors should adopt a 'do not disturb' approach to native vegetation when working in the natural area
- utilities and their contractors should follow Phytophthora dieback hygiene protocols when working in the natural area
- utilities and their contractors should follow weed and pest hygiene protocols when working in the natural area.

Privatised water service providers

Water Corporation

The main role of the privatised water suppliers such as Water Corporation is to supply water of a high quality to residential and commercial properties throughout the state. The Water Corporation is also responsible for the main drain network and the conveyance, treatment and disposal of wastewater via its reticulated wastewater system. The Water Corporation is a corporatised organisation with a business agenda, owned solely by a single shareholder, the state government. Any profits from the Water Corporation business are returned to the state as a dividend to contribute to future development of water supply. It has a board of directors who report to the Minister for Water.

➤ For more information, see the Water Corporation website: www.watercorporation.com.au

The enactment of the Water Services Act 2012 and the *Water Services Legislation Amendment and Repeal Act 2012* will facilitate, amongst other matters, easier entry of new water service providers to the market. For the first time, all water service providers will operate under the same set of powers and obligations. The changes will also allow some of the state's water service providers to offer new services such as bulk water supplies, drainage, recycled water and sewerage services. It allows for the development of codes of practice for water service providers.[8]

extra information

Working with drainage service providers at individual wetlands

Relationships between local community groups and service providers can sometimes make or break wetland management efforts. In the case of Lightning Swamp located in Noranda, metropolitan Perth, a healthy working relationship has formed between the Friends of Lightning Swamp Bushland, City of Bayswater and the Water Corporation.

Management of the main drain that lead into, through and out of the wetlands in the reserve was a key issue identified through a management planning process. Routine mechanical removal of the introduced bulrush, *Typha orientalis*, from the drain by Water Corporation contractors was causing the loss of mature paperbarks and other native vegetation fringing the drain. The local community was understandably concerned.

Figure 3. The infestation of *Typha orientalis* that was present in the Water Corporation drain at Lightning Swamp. Photo – Friends of Lightning Swamp Bushland.

Representatives of the group met with Water Corporation staff responsible for the planning of drainage management. Through a process of negotiation, the Water Corporation agreed to keep all machinery out of the reserve on the basis that the group would take responsibility for the management of weeds in the drains. The group has successfully controlled the introduced bulrush and there has been no need to use heavy machinery to clear the drains.

Lightning Swamp case study acknowledgements: prepared by A. Del Marco, Ironbark Environmental with input from John Williams, Chairperson, Friends of Lightning Swamp Bushland and Jeremy Maher, Environmental Officer, City of Bayswater.

Harvey Water and Ord Irrigation Co-operative

Privatised water organisations such as Harvey Water and the Ord Irrigation Co-operative also have a role in water management in the state. These organisations are licensed by the Department of Water to deliver water sourced from catchment dams to regional irrigators through piping and channels for use in agriculture. Membership of these agencies is by means of shares that entitle irrigators (shareholders) to a relative allocation of water based on the amount of shares they own. The redistribution of water across the landscape by these organisations has the potential to impact wetland condition through altering wetland water regimes.

Public institutions

Public institutions are those organisations established for the public good and to undertake research, facilitate and deliver training and education to the public. They include institutions such as universities, schools, technical and educational centres. These organisations are often partially funded by government and partially funded privately through grants and partnerships with government, industry and other private sources.

Public institutions play a pivotal role in wetland conservation by conducting research and delivering education and training that enhances knowledge of wetland ecology and associated fields and develops the skills and knowledge necessary for management and conservation of wetlands. Wetland research conducted by university academics and research fellows facilitates development of innovative and more effective wetland management and conservation methods. Academics also play a valuable advisory role on many committees and collaborative projects. Education in primary and high schools is important to foster appreciation, understanding and respect in children for wetlands.

Not-for-profit organisations

Not-for-profit organisations (NPOs) are non-government organisations that are comprised of people with a common interest in addressing specific issues in support of the public good, through delivery of programs and services on a local, national or international level. These organisations do not exist to earn surplus funds (profits) to distribute to owners or shareholders, but instead use profits to help the organisation pursue its goals.[9]

As non-government organisations, NPOs are entities which remain independent of government, regardless of whether they receive complete or partial funding from government.

The goals and programs of NPOs, their membership base and available funding determine the role each NPO has on wetland conservation and protection. The role of some organisations may change over time, with some organisations only operating for a limited period while a cause is urgent.

Environment centres

WA's environmental education centres are very important and greatly increase community awareness and the capacity of individuals to make decisions and implement positive management actions for wetlands on their property, or the public properties they are involved in managing through Friends of groups or other associations.

Cockburn Wetlands Education Centre holds an annual conference on World Wetlands Day, 2 February. This highly successful conference, which has been held annually since 2005, brings together people involved in protecting and managing wetlands from across WA. For more information, see: www.cockburnwetlandscentre.wordpress.com

➤ Education centres that incorporate nearby wetlands into their activities include:

- Canning River Eco Education Centre: www.canning.wa.gov.au
- Cockburn Wetlands Education Centre: www.cockburnwetlandscentre.wordpress.com
- Henderson Environment Centre: www.stirling.wa.gov.au
- Herdsman Lake Wildlife Centre (WA Gould League Inc): www.wagouldleague.com.au
- Kings Park Education Centre and Rio Tinto Naturescape: www.bgpa.wa.gov.au/education
- Naragebup Rockingham Environment Centre: www.naragebup.org.au
- Piney Lakes Environmental Education Centre: www.melvillecity.com.au
- South West Environment Centre: www.swecwa.org

Non-government conservation organisations

Non-government, voluntary conservation organisations may be organised on a local, regional, national or international level to address issues which may impact on environmental values or promote conservation.

Non-government organisations (NGOs) can play a pivotal role in delivering on-ground management advice, funding, and assistance to private landowners who have high conservation value wetlands on their property. WWF Australia is one such conservation NGO operating within WA that has provided such a service, through its 'Wetland Watch' program (not currently running).

Conservation NGOs are very important in bringing community concerns regarding the implementation of policy and programs to the attention of government and the wider community. These NGOs serve as environmental watchdogs, by reviewing proposals and draft policies and helping to identify where environmental values are at risk and not being managed appropriately. For example, the Wetlands Conservation Society (http://cockburncommunity.asn.au/WetlandsConservationSociety) formed in 1985 to campaign for the protection of wetlands throughout the state. It has been based at the Cockburn Wetlands Education Centre since 1993. The Wetlands Conservation Society is involved in a wide range of activities aimed at conserving WA wetlands including submissions, education, wetland revegetation and excursions to wetlands. The Wildflower Society (http://members.ozemail.com.au/~wildflowers/conservation.html) has also been active for many years in considering conservation issues as they pertain to WA's native flora. It makes submissions and meets with government as well as interested parties as and when it can.

Some of WA's conservation NGOs exist as 'umbrella' community groups that represent the views of many affiliated groups and individuals and advocate upon their behalf. Examples include the Urban Bushland Council, the Conservation Council of WA and the Environmental Defenders Office.

Other organisations such as Green Skills Inc. deliver sustainability programs on-ground and deliver training and employment opportunities across a wide range of industries. Green Skills Inc. has worked with landholders on the South Coast to deliver wetland management plans.

The following is a brief overview of each organisation:

- Conservation Council of WA: the main objective of the Council is to promote conservation of the natural environment and environmental protection in WA. It is an umbrella group for approximately one hundred affiliated groups. CCWA seeks to facilitate advocacy and action through policy development and legislative change, consultation, campaigning, submission writing, and environmental education. Website: www.ccwa.org.au

- Environmental Defenders Office (EDO): endeavours to provide protection of WA's environment by providing community groups and individuals with environmental legal services including advice, education, representation, and opportunity to participate in reform of laws affecting the environment. The EDO provides free legal advice over the phone to members of the community in public interest environmental law matters. It also provides fact sheets on a wide range of matters, including wetlands. Call on (08) 9221 3030 or Freecall 1800 175 542 (for WA callers outside the Perth Metropolitan Region). Website: www.edowa.org.au

- Urban Bushland Council (UBC): the peak community organisation for the recognition and protection of urban bushland in Western Australia. It comprises approximately sixty community conservation groups concerned about urban bushland (including wetland). The UBC is involved in local action and networking, policy development, lobbying and raising public awareness of issues regarding urban bushland. Website: www.bushlandperth.org.au

- Green Skills Inc.: operates a diverse range of environmental sustainability programs in metropolitan and regional areas to address local, regional and national priorities. In addition to wetland conservation activities, such as planning and implementing wetland restoration on private land, Green Skills' work integrates project management, training and employment programs across a wide range of industries, including sustainable living, energy and water efficiency, waste management, landcare and farm forestry. Website: www.greenskills.org.au

A number of NGOs work nationally to implement programs on an Australia-wide scale to effectively address national environmental issues such as water management and climate change. Some of the national NGOs involved in wetland conservation and protection in Western Australia include WWF Australia, Greening Australia, The Wilderness Society, and the Australian Conservation Foundation. One of the national programs which demonstrates the benefits of a national approach to conservation planning is The Wilderness Society's 'WildCountry' program which involves protection of high value remnants of Australia's natural environment, and restoration of important areas to maintain and/or restore ecological connections across the continent.

Many national and international organisations work in partnership with other NGOs, industry, scientific experts, government and the community to develop both scientific and rational economic solutions which help to influence governmental policy and practice and generally allow for better management of Australia's environmental values.

Regional natural resource management organisations

There are six community-based regional natural resource management (NRM) organisations in WA, which are a part of a national network of fifty-six regions. Working in partnership with stakeholders, the regional and sub-regional NRM organisations play a key role in the regional delivery of natural resource management programs in their regions: Northern Agricultural, Perth, Rangelands, South Coast, South West, and Wheatbelt as detailed in Table 3.

Table 3. Regional NRM organisation and sub-regions[12]

NRM regional organisation	NRM sub-regions
Northern Agricultural Catchments Council www.nacc.com.au	Greenough Moore River West Midlands Yarra Yarra
Perth Region NRM www.perthregionnrm.com	North North-East East South Coastal
Rangelands NRM WA www.rangelandswa.com.au	Kimberley Pilbara Gascoyne Murchison Goldfields Nullarbor Desert Rangelands
South Coast Natural Resource Management Inc. www.southcoastnrm.com.au	Albany Hinterland Esperance Mallee Esperance Sandplain Fitzgerald Biosphere Kent Frankland North Stirlings Pallinup
South West Catchments Council www.swccnrm.org.au	Blackwood Cape to Cape Geographe Leschenault Peel-Harvey Warren
Wheatbelt NRM www.wheatbeltnrm.org.au	Avon Lockhart Yilgarn

In addition to the regional NRM organisations, many organisations are active in sub-regions. They include catchment groups, landcare groups and regional councils. For example, in the Perth Region NRM area, the Ellen Brockman Integrated Catchment Group, the Eastern Metropolitan Regional Council and the South East Regional Catchment Urban Landcare WA carry out NRM functions.

NRM regional organisations are eligible for funding via the Australian Government's Caring for our Country funding program and the Government of Western Australia's State NRM program (in previous years initiatives such as the National Action Plan for Salinity and Water Quality (NAP) and the Natural Heritage Trust (NHT) were the primary funding programs).

With community input, each regional NRM organisation and many sub-regional NRM organisations have prepared a regional strategy outlining their evaluation of the natural assets (including wetlands) in their region and their condition; threats to those assets; goals and targets to improve their condition; actions to achieve those goals; and targets and a framework for implementing those actions. Investment plans have also been prepared to allocate funding to projects towards achieving the goals and targets outlined in the regional strategies.

Through the regional strategies, a number of the regional NRM organisations identified that their region's wetlands were poorly documented, and they applied for funding to carry out wetland mapping, monitoring and research programs to improve knowledge of the wetlands and their values. This process has resulted in much better knowledge of wetlands in the Rangelands, Northern Agricultural, South West and Wheatbelt regions. For example, in the Wheatbelt catchment, wetland mapping was carried out to identify the location of wetlands and characterise them into wetland types. Methodologies for evaluating their values at a broad scale (1:100,000) and a much finer scale (1:25,000) were also developed, and the broad scale methodology was applied to a range of wetlands across the area. As a result of this identification and evaluation of wetlands across the Wheatbelt, there is now a much better understanding of where wetlands are and their values, providing individuals, organisations and government with a better understanding of wetland protection and management priorities in the region. Rangelands NRM WA established a project that brought together a wide range of stakeholders to discuss Kimberley region wetlands, culminating in the report, *Establishing priorities for wetland conservation and management in the Kimberley Region*.[10]

➤ DEC undertakes wetland mapping projects as funding permits and is the lead agency for wetland inventory standards and endorsement of wetland mapping across the state.

NRM regional organisations often significantly contribute to a range of on-ground activities at wetlands and in their catchments. Planting, weeding, fencing and control of feral animals and cattle are just a few of the wide range of on-ground activities that NRM regional organisations participate in.

NRM regional organisations can also play a leading role in water management. For example, the Peel-Harvey Catchment Council, within the South West Catchments Council region, has partnered in an agreement with the City of Mandurah and the Shire of Murray to implement seven new stormwater retrofit projects by 2013 in the Peel-Harvey.[11] Activities of this nature can have significant water quantity and water quality benefits in wetlands.

➤ For more information on the role of regional NRM organisations in wetland conservation, see the State NRM Office website: www.nrm.wa.gov.au.

➤ For more information on the Wheatbelt and other wetland mapping around the state, see the DEC wetlands webpage: www.dec.wa.gov.au/wetlands then selecting the 'Wetland mapping' tab.

Western Australian Local Government Association

The Western Australian Local Government Association (WALGA) is a non-government organisation that lobbies and negotiates on behalf of the 142 local governments of WA.[12] As such, it is referred to as 'the voice of local government'. WALGA aims to enhance the capacity of local governments by negotiating service agreements and providing other economic, social, and environmentally sustainable services and infrastructure to meet the needs of the community.

The operations of WALGA are funded by membership subscriptions, businesses and grants.[13]

WALGA has undertaken or facilitated a number of projects that contribute significantly to wetland conservation outcomes including programs such as:

- Perth Biodiversity Project: supports local governments to use their functions and powers effectively to protect and manage local natural areas; see http://pbp.walga.asn.au

- South West Biodiversity Project: (now ceased but still provides resources) supports local governments to use their functions and powers effectively to protect and manage local natural areas; see www.walga.asn.au/AboutWALGA/Policy/SouthWestBiodiversityProject.aspx

➤ More information on these programs is available from the WALGA website: www.walga.asn.au.

COLLABORATIONS: NON-GOVERNMENT AND GOVERNMENT WORKING TOGETHER

An emerging trend in conservation is consortiums who collaborate to achieve conservation outcomes. Two examples of consortiums whose work affects WA wetlands are:

- The New WAter Ways aim is to build the water sensitive urban design capacity of Government and industry to improve the delivery of urban water management and water sensitive cities through partnerships, collaboration and consultation. It is a partnership of the Department of Water, Department of Planning, Western Australian Local Government Association, Water Corporation, Urban Development Institute of Australia (WA) and Swan River Trust. Website: www.newwaterways.org.au

- The Southwest Australia Ecoregion Initiative (SWAEI), a consortium of partner organisations and government agencies. It is a multi-stakeholder, non-sectoral group and authority is not vested in any one government agency or non-government organisation. It is jointly co-chaired by WWF-Australia and the Department of Environment and Conservation. Website: http://swaecoregion.org/

THE ROLE OF GOVERNMENT

The role of government is discussed below under the three tiers: local, state and national. The role of each tier of government is defined by legislation.

Government agencies have the ability to influence policy and actions of other government agencies in wetland conservation in a similar manner to community members or groups, as described above. For example, a state government agency may provide a response to a local government on an advertised policy or proposal.

The profile of each agency or committee has been provided in the tables below to allow quick identification of information of interest.

When seeking government action on a matter, it is important to understand who has lead responsibility for that matter within government. It is also important to understand which agencies or individuals are *advice giving* agencies on any particular matter, and which are a *decision-making authority* for a matter. A decision-making authority, or DMA, is a public authority empowered to make a decision in respect of a proposal. It is important to note that the legislative authority for many decisions is a Minister of government, not a government agency.

Local government

Local government is the tier of government responsible for managing the development and operation of individual local government areas, development and maintenance of assets, and provision of local services.

There are 142 local governments (also called shires or councils) in the state. These are each responsible for a specific geographic area varying in size from 1.5 square kilometres (Shire of Peppermint Grove) to 379,000 square kilometres (Shire of East Pilbara).[13]

Each local government has the power to make local polices under the *Local Government Act 1995* on a range of matters including wetland protection, subdivision and development, lot sizes, stormwater management and housing densities. Local governments are responsible for the detailed planning of the use of land via the development of 'local planning schemes' which set out rules for subdivision and development of land. As such, local governments have significant potential to positively influence wetland protection and conservation by:

- ensuring local planning schemes, subdivisions and developments protect wetlands, buffers and ecological corridors, wetland water regimes and water quality, and ensure their long-term management;
- managing stormwater via local drainage networks to reduce environmental impacts; and
- ensuring land use activities within the area are in accordance with the approved land use plans.

Local governments have the power to reserve land through their local planning schemes to protect places of special heritage significance or of significance to the community. They may also include other land into a 'scheme' reserve such as local parks and primary school sites.[14]

Through the planning process, local governments may also have wetlands vested with them. As a result, they are often managers of wetlands and therefore play an important ongoing management role. If a wetland is located within the parcel of land proposed for development, it may be required to be ceded by the land owner to the Crown free of cost as 'public open space' (POS). For wetlands retained in areas of open space within a residential or industrial development, it is common for developers to be assigned responsibility for the management of the wetland for a period of up to three years following the completion of a development. They are generally required to manage the wetland and associated wetland buffer in accordance with a wetland management plan that has been prepared in liaison with and approved by relevant authorities (for example, DEC and/or the local government). After this period, if the developer has satisfied the requirements and implemented all management actions outlined in the approved wetland management plan, transfer of the open space and therefore responsibility for the management of the wetland passes to the nominated vesting body, typically the local government. For more information on public open space in residential areas, see *Liveable Neighbourhoods*[6] (Element 4, R11, page 7).

Local governments also have significant networks of local drains. The management of existing drains and the creation of new drains can both have significant impacts on wetlands. A number of local governments are now taking the proactive step of retrofitting existing stormwater drains to reduce their impacts on wetlands and other ecosystems via initiatives and resources such as the *Stormwater management manual for Western Australia*[15], the International Council for Local Environmental Initiatives' Water Campaign™ and the New WAter Ways program.

- ➤ WALGA has produced an excellent series of fact sheets about local government and natural resource management, available from the WALGA website at www.walga.asn.au.[12] These include 'Factsheet 2: Understanding Local Government roles and responsibilities' and 'Factsheet 3: Local Government processes and engagement tips'.
- ➤ WALGA has developed a range of tools that local governments can use to identify and prioritise their environmental assets, and plan for their management, such as local biodiversity strategies. See the Perth Biodiversity Project for more information: http://pbp.walga.asn.au

Case study

The City of Cockburn was awarded the 'Government leading by example' award at the 2011 WA Environment Awards. The city has undertaken a number of initiatives that will have a positive effect on wetlands in their area. These include:

- a published wetland conservation policy (policy SPD5)
- provisions within the City of Cockburn Town Planning Scheme No. 3 supporting the protection and management of wetlands and wetland buffers from development and adjacent land uses
- a new Conservation Zone in its Town Planning Scheme that ensures landowners who opt to retain areas of conservation value within a development protect, manage, preserve and enhance these areas
- publication of wetland management plans on its website
- a Landowner Biodiversity Conservation Grant Program that gives financial support of up to $3,000 to landowners to carry out on-ground works that directly relate to the conservation and improvement of privately-owned natural bushland and wetland areas on their property. Some examples of works include: fencing to exclude livestock, weed control, revegetation, erosion control, habitat creation, water quality enhancement and dieback treatment.
- support for WWF's now-finished Wetlands Watch program, which provided technical and financial assistance for private landowners to manage and rehabilitate high conservation value wetlands in Cockburn and surrounding LGAs.[16]
- advocating measures to minimise the need for spraying of wetlands, including encouraging residents to minimise midge and mosquito breeding conditions on their property and take steps to protect themselves from mosquitoes when outdoors
- converting drains to living streams
- participating since 2007 in the Water Campaign™ run by the International Council for Local Environmental Initiatives, and publishing a local water action plan committing to actions to improve its water management
- publishing a 'Parks, wetland and beach guide' online
- running the 'Better Tomorrow Sustainability Grants' to encourage and reward community participation in sustainability initiatives; and the 'Native plant subsidy scheme' to encourage the use of native plants in the city.

Local governments	**Role**
Website www.<LGAname>.wa.gov.au	Responsible for planning and management of the local area by administration of local planning schemes, policies, strategies in accordance with the local planning strategy[14]; reserve management and delivery of local amenities and services[12]
Processes or programs that contribute to wetland conservation • Management of local government reserves • Preparation and implementation of local planning schemes • Preparation and implementation of local planning strategies • Planning and development approvals • Development and implementation of planning policies	
Legislation relevant to wetland conservation *Local Government Act 1995*	
Relevant committees assisted Refer to each local government	**Minister** Minister for Local Government

extra information

Key considerations when working with local governments

- A. Del Marco, Ironbark Environmental

The management of wetlands vested with a local government largely depends on the resources and priorities of the individual local government and the interests of the local community. Many local governments are taking up the challenge of actively managing wetlands in their reserves and preparing management plans. However, because their roles are broad, the capacity of each local government to manage wetlands under their care is variable. Key points to consider when working with your local government are outlined below.

Capacity: gauge the local government's capacity to prepare a wetland management plan or undertake management of the wetland. This may involve speaking with relevant senior staff, and then following this up with a letter to the Chief Executive to build a more formal relationship. Where their capacity or willingness is low, initially consider simple joint activities that could be undertaken that raise Councillor and community awareness of the wetland. These include nature walks, rubbish pick-ups, or erection of a sign or fence. It may take one or two years before a small local government agrees to prepare a management plan or invest significant resources in a reserve.

Big picture approach: for local governments that manage numerous wetlands, or have numerous wetlands on local government and private lands, encourage them to undertake a broad-scale assessment of the municipality's wetlands. Better still, they could do this as part of a local biodiversity strategy.

Budget lead times: local governments have a long lead time between proposing and finalising an annual budget. The annual budget preparations for the following financial year generally commence by November of the previous financial year. Therefore it is necessary to submit proposals as early as possible in the preceding financial year. Better still, make comment on their forward five-year financial plan. These are called principal activity plans or future plans. This is where substantial projects and investments are planned by Council.

Legal responsibilities: remember that local governments have legal responsibility for lands vested in the Council, and will need to give approval for all works carried out in the reserve. This is best achieved through a management planning process, or where required, approval of a one or two year works program that is signed off by the Council.

extra information

Foster partnerships: help your local government work with another organisation to plan or undertake wetland management. There are many opportunities to develop co-operative projects and receive funding with regional Natural Resource Management organisations and local governments.

Develop partnerships: appreciate the skills and resources you and your group have to offer your local government. You may be able to provide expertise on an aspect of wetland management, or help the local government prepare a funding submission. You may be eligible for many grants that the local government is not eligible for.

Co-operate: keeping an eye on a reserve to ensure it is not being impacted by illegal activity (such as trail bike riding, dumping of garden refuse, and so on) is challenging for even the most well-resourced local governments. Local people enjoying and taking care of an area make for highly visible management and maximise passive surveillance to discourage illegal use of an area.

State government

Several state government authorities play very important roles in the protection and management of wetlands within Western Australia. The primary decision-making authorities are the Minister for Environment, the Minister for Water and the Minister for Planning.

Minister for Environment	**Role** Decision-making authority under environment legislation
Website www.premier.wa.gov.au	
Power *Environmental Protection Act 1986* *Conservation and Land Management Act 1984* *Wildlife Conservation Act 1950* *Swan and Canning Rivers Management Act 2006*	**Processes or programs relevant to wetland conservation** • Decision-making authority under EP Act - determines appeals lodged under the Act - sets environmental conditions on proposals after consultation with other relevant decision-making authorities • Reports to Parliament • Ensures EPA has resources and facilities to function • Issue requests to EPA for advice and policy development on environmental matters and special reporting and auditing requirements
Agency • Appeals Convenor • Department of Environment and Conservation • Environmental Protection Authority • Swan River Trust	

Minister for Water	**Role** Decision-making authority under water resources management legislation
Website www.premier.wa.gov.au	
Power *Water Agencies (Powers) Act 1984* *Rights in Water and Irrigation Act 1914* *Waterways Conservation Act 1976* *Water Services Act 2012* *Water Services Legislation Amendment and Repeal Act 2012*	**Processes or programs relevant to wetland conservation** • Decision-making authority under relevant acts - general function of conserving, protecting and managing water resources, assessing water resources and planning for the use of water resources under Section 9 of the *Water Agencies (Powers) Act 1984* - determines outcome of appeals regarding applications to take water - determines outcome of proposals in respect of bed and bank disturbance in consultation with relevant ministers • Reports to Parliament
Agency • Department of Water • Water Corporation	

Minister for Planning	**Role** Decision-making authority under planning legislation
Website www.premier.wa.gov.au	
Power *Planning and Development Act 2005* *Town Planning Regulations 1967* *Town Planning and Development (Subdivision) Regulations 2000* *Metropolitan Redevelopment Authority Act 2011*	**Processes or programs relevant to wetland conservation** • Decision-making authority under relevant acts - overseeing the administration of planning agencies - maintaining and reviewing planning legislation - directing statutory and strategic planning matters - approving regional planning schemes and local planning schemes -approving some planning policies. • Reports to Parliament
Agency • Department of Planning • Metropolitan Redevelopment Authority • LandCorp • Development assessment panels	

State government statutory offices, boards, tribunals, and committees

The following statutory offices, boards, tribunals and committees have been established under state government legislation and processes, and have significant roles and responsibilities in wetland protection and management:

- Environmental Protection Authority
- Appeals Convenor
- Western Australian Planning Commission
- Conservation Commission
- State Administrative Tribunal
- Wetlands Coordinating Committee

Environmental Protection Authority (EPA)	**Role** Board that provides independent advice to the state government on environmental matters[17]
Website www.epa.wa.gov.au	
Objective To protect the environment and to prevent, control and abate pollution and environmental harm[17]	
Power Statutory authority but not regulatory, provides advice to government via the Minister to assist decision making	**Processes or programs that contribute to wetland conservation** • Environmental impact assessment (EIA) resulting in recommendations on the environmental acceptability of proposals, schemes and their amendments • Publication of environmental protection bulletins (formerly position statements) and environmental assessment guidelines (formerly guidance statements) as indicators of the EPA's expectations in regards to specific issues • Formulation of environmental protection policies (EPPs) gazetted to protect specific parts of the environment • State of the Environment reporting indicating the status of major environmental issues in WA • Provision of strategic advice and on the formulation of regulations
Legislation relevant to wetland conservation *Environmental Protection Act 1986*	
Agency Office of the Environmental Protection Authority	**Minister** Minister for Environment
Membership Five members who are not public servants A full-time chairman, a part-time Deputy Chairman and three part-time members Appointed by the Governor of Western Australia on the recommendation of the Minister for Environment[17]	**Meeting frequency** Fortnightly **Sub-committees** None
Publications specific to wetlands Chapter B4 ('Wetlands') of *Guidance Statement 33: Environmental guidance for planning and development* *Position Statement 4: Environmental protection of wetlands* A number of other EPA policies are relevant to wetlands. See the 'Legislation and policy' topic for a full list.	

Appeals Convenor	**Role** Statutory office that investigates and provides advice to the Minister for Environment regarding appeals made under the *Environmental Protection Act 1986*
Website www.appealsconvenor.wa.gov.au	
Power *Environmental Protection Act 1986* (section 107A)	**Processes or programs relevant to wetland conservation** • Advice to the Minister for Environment on appeals made under the EP Act, in regard to environmental impact assessment, permits for clearing native vegetation and conditions applying to certain industrial and commercial premises. • Consult with DEC, EPA, appellant and others as required in consideration of appeals • Provide fair hearings • Resolve disagreements between parties • Provide reports to the Minister on conclusion of appeal investigations
Agency Office of Appeals Convenor (inclusive of a Deputy Appeals Convenor, a Registrar and four appeals assessors who are employed under the *Public Sector Management Act 1994*)	**Minister** Minister for Environment

Western Australian Planning Commission (WAPC)	**Role** Statutory authority responsible for urban, rural and regional land use planning and land development matters Responsible for the strategic planning of the state in response to the strategic direction of government
Website www.wapc.wa.gov.au	
Objective To formulate and coordinate land use strategies for Western Australia to facilitate its growth while continuously enhancing it's unique quality of life and environment[18]	
Power Statutory decision-making authority	**Processes or programs relevant to wetland conservation** • Strategic planning of land use, including regional parks, other parks and recreation reservation • Decisions on planning proposals, including all subdivision proposals • Administration of regional planning schemes • Recommendations to the Minister on local planning schemes[14] • Management of reserves e.g. Whiteman Park • Preparation and review of planning strategies, policies, standards and guidelines • Land acquisition • Implementation of Bush Forever[19]
Legislation relevant to wetland conservation *Planning and Development Act 2005* **Subsidiary legislation** Metropolitan Region Scheme Peel Region Scheme Greater Bunbury Region Scheme	
Agency Department of Planning	**Minister** Minister for Planning

Membership Up to 15 members, appointed by the Governor An independent chairman, individual Director Generals from the Department of Housing, Department of Planning, Department of Transport, Department of State Development, Department Environment and Conservation and Department of Water and representatives from economic, social and environmental areas and Local Government.[18]	**Meeting frequency** Monthly **Sub-committees** 23 committees with a range of expertise and local community knowledge. For example, Environment and Natural Resources Management Committee[18]

Publications relevant to wetlands

- *Better urban water management (2008)*
- *Liveable neighbourhoods: a Western Australian Government sustainable cities initiative (2009)*
- *Statement of Planning Policy 2.2 Gnangara groundwater protection (2005)*
- *Statement of Planning Policy 2.3 Jandakot groundwater protection (2003)*
- *State Planning Policy 2.8 Bushland policy for the Perth Metropolitan Region (2004)*
- *State Planning Policy 2.9 Water resources (2006)*

Conservation Commission of Western Australia **Website** www.wapc.wa.gov.au	**Role** Statutory authority that is the vesting body for all terrestrial lands under the *Conservation and Land Management Act 1984*, including national parks, conservation parks, nature reserves, state forests and timber reserves Advisory body to the Minister for Environment on management of native flora and fauna and ecologically sustainable forest management

Objective

To conserve the State's biological diversity and to ensure the land estate, for which it has responsibility, is managed in an ecologically sustainable manner

Power Statutory authority but not regulatory, provides advice to assist government decision making via the Minister. **Legislation relevant to wetland conservation** *Conservation and Land Management Act 1984* *Conservation and Land Management Amendment Act 2000*	**Processes or programs relevant to wetland conservation** • Vesting of terrestrial lands and their management, for conservation, including national parks, conservation parks, nature reserves, State forests and timber reserves (DEC manages land on the Commission's behalf). • Development of policies to protect the state's natural environment and for the appreciation and enjoyment of that environment by the community • Promotion and facilitation of community involvement • Guidelines for ecotourism
Agency Department of Environment and Conservation	**Minister** Minister for Environment
Membership Nine Commissioners Appointed by the Governor of Western Australia on the nomination of the Minister for Environment	**Meeting frequency** Monthly **Sub-committees** None

State Administrative Tribunal	**Role** Independent body that makes and reviews a range of administration decisions related to civil, commercial, and personal matters, made by government agencies, public officials and local governments
Website www.sat.justice.wa.gov.au	
Power *State Administrative Tribunal Act 2004* *State Administrative Tribunal (Conferral of Jurisdiction) Amendment and Repeal Act 2004* (Conferral Act)	**Processes or programs relevant to wetland conservation** • Efficient, effective resolution of questions, complaints or disputes • Responds to appeals made under water legislation and planning legislation (not the *Environmental Protection Act 1986* – this is the responsibility of the Appeals Convenor) • Encourages resolution of disputes through mediation • Reviews and/or make decisions regarding individual cases • Publishes and provides in writing to all parties all final decisions within ninety days
Agency No associated agency	**Minister** State Attorney General

Wetlands Coordinating Committee	**Role** Committee established by the Minister for the Environment to coordinate the implementation of the *Wetlands Conservation Policy for Western Australia*[20]
Website www.dec.wa.gov.au/wetlands/wetlands_coordinating_committee	
Objective Encourage the conservation and proper management of wetlands and to encourage development to be consistent with objectives of the *Wetlands Conservation Policy for Western Australia*[21]	
Power Non-statutory, that is not legally bound or prescribed by policy and or legislation **Legislation relevant to wetland conservation** Refer to member agencies	**Processes or programs relevant to wetland conservation** • Review of and report to the Minister on implementation of actions listed in the *Wetlands Conservation Policy for Western Australia* (1997) • Endorsement of wetland mapping, classification and evaluation methodologies and data • Review and endorsement of member policy documents affecting wetland conservation
Agency Department of Environment and Conservation	**Minister** Minister for Environment
Membership Positions appointed by Minister for Environment Chaired by DEC and includes representatives of DEC, Department of Planning, Department of Agriculture and Food, Department of Water, the West Australian Local Government Association, the voluntary conservation movement and non-government wetland scientists	**Meeting frequency** Annually **Sub-committees** Active working groups: Wetland Status Working Group (wetland inventory including mapping and loss), Wetland Buffer Guideline Working Group Others: Wetland Conservation Incentives Working Group, Drainage Evaluation Working Group.

State government agencies

State government agencies with responsibilities for aspects of wetland conservation and management in WA are:

- Office of Environmental Protection Authority
- Department of Environment and Conservation
- Department of Water
- Department of Planning
- Department of Agriculture and Food
- State Natural Resource Management Office
- Department of Fisheries

The Office of the Environmental Protection Authority

The Office of the Environmental Protection Authority (OEPA) is the state agency that supports the EPA in conducting environmental impact assessments and developing policies to protect the environment. The OEPA also monitors compliance with Ministerial conditions related to approvals. The OEPA is accountable to the Minister for Environment, as well as to the EPA.

Office of the Environmental Protection Authority (OEPA)	**Role** Supports the EPA in conducting environmental impact assessments and developing policies to protect the environment.
Website www.epa.wa.gov.au	
Objective To support the EPA to meet its stated objective to use its best endeavours – a) to protect the environment; and b) to prevent, control and abate pollution and environmental harm.	
Processes or programs relevant to wetland conservation • Management of the environmental impact assessment process for the Environmental Protection Authority • Implementation of Environmental Protection Authority policy	
Legislation relevant to wetland conservation • *Environmental Protection Act 1986*	
Relevant committees assisted/ supported Environmental Protection Authority	**Minister** Minister for Environment

The Department of Environment and Conservation

The state government agency with a lead role in the protection and management of wetlands is the Department of Environment and Conservation.[22] Specifically, it has responsibility for certain activities relating to wetlands except for waterways, their floodplains, estuaries and peripheral estuarine wetlands. These wetland types are the responsibility of the Department of Water unless these areas are, or are proposed to be, DEC managed estate.

Department of Environment and Conservation (DEC) **Website** www.dec.wa.gov.au	**Role** Lead responsibility for protecting and conserving the State's environment and for aspects of natural resource management in Western Australia

Objective

Working with the community, we will ensure that Western Australia's environment is valued, protected and conserved, for its intrinsic value, and for the appreciation and benefit of present and future generations[1]

Processes or programs relevant to wetland conservation

- Development and advocacy of wetland protection and management through DEC guidelines, standards, procedures and education initiatives; input into broader policies and initiatives e.g. national wetland policies
- Lead role in wetland mapping; coordination of wetland mapping, survey and monitoring programs and standards, custodian of various wetland datasets
- Advice on the conservation significance of wetlands
- Lead role in implementing and achieving the objectives of the *Wetlands Conservation Policy for Western Australia* (Govt of WA 1997)
- Provision of technical wetland advice to the Environmental Protection Authority in environmental impact assessment and broader policy development processes
- Provision of expertise and advice to planning authorities to ensure that the appropriate level of protection is given to wetlands in the land planning process
- Advocacy for wetland protection via land use planning processes
- Advocacy for wetland protection via water planning processes
- Management of national parks, conservation parks, state forests, and timber reserves and nature reserves, which include many of WA's nationally and internationally significant wetlands
- Support for conservation activities at privately owned wetlands through community engagement and capacity building programs through programs such as Healthy Wetland Habitats and Land for Wildlife
- Research into wetland species and processes
- Research into climate change and biodiversity
- Regulation of clearing of native vegetation
- Implementation of international migratory bird treaties
- Identification, protection, monitoring and recovery of rare and threatened species and communities
- Regulation of industry, contaminated sites and development and draining of acid sulfate soils
- Identification of internationally and nationally significant wetlands and proposal for inclusion under the Ramsar Convention and *Directory of Important Wetlands of Australia*

Legislation relevant to wetland conservation

- *Environmental Protection Act 1986*
- *Conservation and Land Management Act 1984*
- *Wildlife Conservation Act 1950*
- Environmental Protection (Clearing of Native Vegetation) Regulations 2004
- Environmental Protection Regulations 1987

Publications relevant to wetlands

- *A guide to managing and restoring wetlands in Western Australia* (2012)
- *A guide to the assessment of applications to clear native vegetation under Part V of the Environmental Protection Act 1986* (2009)
- *Guidelines checklist for preparing a wetland management plan* (2008)
- *Draft framework for mapping, classification and evaluation of wetlands in Western Australia* (2007)
- *Protecting our wetlands in Western Australia* (2006)
- Wetland inventory series – wetland mapping and evaluation reports for areas of WA
- *Guideline for the determination of wetland buffer requirements* (DoP and DEC in preparation)

Relevant committees assisted/ supported	**Minister**
Environmental Protection Authority Conservation Commission of WA Wetlands Coordinating Committee	Minister for Environment

The Department of Water

The Department of Water (DoW) is the state agency whose core business is to manage the state's ground and surface water resources to support sustainable use and development to meet the needs of current and future users, while protecting water dependent ecosystems and environments.

It does this by measuring and allocating the state's water resources, licensing and setting rules for the abstraction of water, integrating land and water planning and protecting the state's waterways and catchments.[23] The Department is the lead agency for the management of waterways (such as rivers, creeks, streams and brooks) including their floodplains, estuaries, inlets and reservoirs unless these are in DEC estate. Where a waterway or floodplain is listed under the Ramsar Convention but is not within DEC managed estate, DoW works in consultation with DEC.

Department of Water (DoW)	**Role**
Website www.water.wa.gov.au	Leads the management and protection of the state's water resources including waterways and groundwater by informing the government and the community on the quantity, quality, use and availability of the state's water resources and encouraging water conservation and alternative water sources[24]

Objective

Support WA's growth and development by managing the availability and quality of water sustainably – now and for the future[24]

Processes or programs relevant to wetland conservation

- Provision of expertise and advice to planning authorities to ensure that the appropriate level of protection is given to water resources in the land planning process
- Water resource management legislation and reform
- Water allocation, including the establishment of environmental water provisions for wetlands
- Water management plans
- Water licensing and regulation, giving consideration to water requirements of high value ecosystems
- Water re-use, recycling and conservation programs
- Stormwater/drainage plans, programs and policies
- Waterway management plans
- Water quality improvement plans
- Authorising bed and bank disturbance
- Environmental water planning including ecological water requirements and ecological water provisions for wetlands
- Algal bloom management techniques
- Catchment monitoring programs
- Salinity management
- River restoration action plans, training and activities

Legislation relevant to wetland conservation
- *Water Agencies (Powers) Act 1984*
- *Rights in Water and Irrigation Act 1914*
- Rights in Water and Irrigation Regulations 2000
- *Waterways Conservation Act 1976*
- *Water Services Act 2012*
- *Water Services Legislation Amendment and Repeal Act 2012*

Publications relevant to wetlands
- *Better urban water management* (2008)
- *Stormwater management manual for Western Australia* (2004–2007)
- *Decision Process for Stormwater Management in WA* (2009)
- *State Water Plan* (Government of Western Australia 2007)
- *Environmental Water Provisions Policy for WA* (2000)
- *Operational policy: identifying and establishing waterways foreshore areas* (2012)
- *The State Waterways Initiative* (2008)

Relevant committees assisted/ supported	Minister
Rural Water Advisory Committee	Minister for Water

The Department of Planning

The Department of Planning (DoP) has the potential to influence wetland protection and management in WA, through provision of planning and policy advice to the Western Australian Planning Commission (WAPC).

Department of Planning (DoP)	Role
Website www.planning.wa.gov.au	Statewide responsibility for planning for future communities. Plan cities, towns and connecting transport routes.[25]

Objective

The department plays a vital role in improving the quality of life of all Western Australians. We plan the cities and towns in which we live and the transport routes that connect us to our jobs, friends and places of recreation. We generate thousands of direct and indirect jobs through the planning approval process.[25]

Processes or programs relevant to wetland conservation
- Advice to Western Australian Planning Commission on planning proposals and policies and implementation of the WAPC's decisions
- Delegated authority for decisions on subdivision and development applications, when they comply with WAPC policies and practices
- Bush Forever
- EnviroPlanning (in partnership with WALGA)

Legislation relevant to wetland conservation
- *Planning and Development Act 2005*
- *Town Planning Regulations 1967*
- Region schemes: Metropolitan Region Scheme; Peel Region Scheme[14]; Greater Bunbury Regional Scheme

Relevant committees assisted/ supported	Minister
Western Australian Planning Commission	Minister of Planning

The Department of Agriculture and Food

The Department of Agriculture and Food (DAFWA) assists WA's agriculture, food and fibre sectors to be sustainable and profitable. DAFWA has a number of investment priorities which support wetlands management. These include developing long-term management solutions to salinity, soil degradation and water quality to ensure sustainable management of land and water resources in a changing climate. DAFWA is the lead agency for managing biosecurity risks and invasive plants, animals and diseases in WA. It also has a significant role in the state's land and water resources condition assessment and planning. DAFWA supports the State NRM Office which facilitates funding and governance of coordinated community delivery of natural resource management in Western Australia (see State NRM Office, below, for more information).

Department of Agriculture and Food (DAFWA) **Website** www.agric.wa.gov.au	**Role** To work with our partners to develop the agriculture and food sector; and to effectively manage the risks to the natural and biological resources on which the sector relies.

Objective/mission

To foster a progressive, innovative and profitable agriculture and food sector that benefits Western Australia now and in the future.

Processes or programs relevant to wetland conservation

- Support the agricultural sector to minimise impacts by ensuring sustainable management of land and water resources in a changing climate
- Minimise the introduction of invasive plants, animals and diseases and management of them to exclude, eradicate, control or minimise their impact to agriculture and related natural resources
- Administers the *Soil and Land Conservation Act 1945* to regulate land degradation and proposals to drain sub-surface water to control salinity
- Coordination of state NRM policy and funding programs (see below)
- Contributes to state government policies including land and water resource allocations, biosecurity and climate change to support sustainable natural resource use for agriculture

Legislation relevant to wetland conservation

Biosecurity and Agricultural Management Act 2007 and regulations

Soil and Land Conservation Act 1945

Soil and Land Conservation Regulations 1992

Publications relevant to wetlands

Relevant publication topics include biosecurity, invasive species and climate.

Minister

Minister for Agriculture and Food

The State Natural Resource Management Office

The State Natural Resource Management Office (SNRMO) was formed by the state government in 2003 to facilitate improved coordination of NRM delivery in WA and to advocate NRM activity and engage resource managers on key NRM issues.

State Natural Resource Management Office (SNRMO) **Website** www.nrm.wa.gov.au	**Role** Coordinate natural resource management (NRM) across state government.

Processes or programs relevant to wetland conservation

- Develop and coordinate 'whole-of-government' state NRM policy
- Negotiate and interact with the Commonwealth on matters related to the Caring for Our Country program
- Provide strategic advice for regional project and investment plan development
- Administer Commonwealth and State NRM funding
- Communicate with stakeholders and the broader community on NRM matters
- Support NRM councils and committees

Relevant committees assisted/ supported WA NRM Ministerial Committee Council for Natural Resource Agency Chief Executives (CONRACE) NRM Senior Officers Group	**Minister** Minister for Agriculture and Food

The Department of Fisheries

The Department of Fisheries' primary responsibility is to conserve, develop and manage the fish and aquatic resources of Western Australia to ensure there are 'fish for the future'.

Department of Fisheries (DoF) **Website** www.fisheries.wa.gov.au	**Role** Conserve, develop and manage the fish and aquatic resources of WA to ensure there are fish for the future.

Processes or programs relevant to wetland conservation

- Maintain expert knowledge of WA's freshwater fish
- Control of the introduction and spread of introduced fish and crayfish, maintenance of the noxious fish list and operation of the FISHWATCH service
- Regulation of relocations, introductions and reintroductions of freshwater species of fish and crayfish

Legislation relevant to wetland conservation
Fish Resources Management Act 1994
Fish Resources Management Regulations 1995

Publications relevent to wetlands *Freshwater fish distribution in Western Australia database* http://freshwater.fish.wa.gov.au	**Minister** Minister for Fisheries

case study

Case study: organisations involved in urban water supply and stormwater management

There are a number of organisations involved in urban water services and management in WA, including the Water Corporation, Department of Water, local governments and Swan River Trust. Their roles can be complex and overlapping. Similarly, the legislation governing water management is spread across a large number of Acts, some of which are very old. The *Water Services Legislation Amendment and Repeal Act 2012* and the *Water Services Act 2012* will replace and streamline a number of these Acts.

Table 3 outlines the roles of key water management organisations.

Water supply and demand management

Organisations such as Water Corporation, Busselton Water Board and Aqwest (Bunbury Water Board) are authorised to supply water to households and businesses in the state. The Department of Water is responsible for development of the overarching policy and management of water resources (and use) in the state. It is the Department of Water that allocates and licences the amount of water an organisation such as the Water Corporation can use or extract. This is important way of stimulating better water demand management responses by water supply organisations, diversification of water supply sources (e.g. desalination of water) and water disposal options that make use of this precious resource.

The Department of Water is also responsible for licensing water extraction by smaller organisations, such as market gardens, and for developing and implementing policies in this regard. The Department uses allocation limits, licensing, efficiency programs and the recouping of unused entitlements to distribute abstraction to limit impacts on the environment and to reduce abstraction in areas where the reductions will benefit the conservation of wetlands. On the Gnangara Mound, where many wetlands are drying due to the drier climate and water and land uses, the Department of Water has stated that 'no long term licences for accessing the fresh groundwater resources of the Leederville or Yarragadee aquifers are to be granted for additional groundwater entitlements, other than for extenuating circumstances'.[26]

A proposal to use water that is likely to have a significant impact on the environment may be referred to the Environmental Protection Authority (EPA) for assessment under Part IV of the *Environmental Protection Act 1986*. The supply of groundwater from the Gnangara Mound for public water supply and private licensed use in Perth is one such case. As a result of the referral of a proposal to abstract groundwater from the Gnangara Mound in the 1990s, the EPA determined that the proposal should be assessed, and made recommendations to the Minister for Environment regarding appropriate conditions and commitments should the Minister approve the proposal. As a result, the Department of Water is required to undertake a range of actions to protect wetlands on the Gnangara Mound in accordance with Ministerial conditions of approval and commitments. For more information, see the report, *Review of Ministerial conditions on the groundwater resources of the Gnangara Mound*.[27]

Table 3. The role of organisations in water management in Western Australia

	Responsibility	**Water Corporation**	**Department of Water**	**Swan River Trust**	**Department of Environment & Conservation**	**Local Government**	**Harvey Water**	**Ord Irrigation**	**Department of Planning**
POLICY	Develops policy for wetland management in WA				✓				✓
	Develops policy for water resource management in WA		✓						✓
	Provides input into policy and regulation that affects wetlands		✓		✓	✓			✓

case study

	Responsibility	Water Corporation	Department of Water	Swan River Trust	Department of Environment & Conservation	Local Government	Harvey Water	Ord Irrigation	Department of Planning
LICENCES	Licences groundwater and surface water abstraction		✓						
SERVICE DELIVERY	Delivers clean drinking water	✓							
	Removes wastewater	✓							
	Maintains drinking water, drainage network and sewage pipelines from residential and commercial properties to main network	✓							
	Maintains local government drains					✓			
	Pipes irrigation water from local dams to shareholders in Collie, Harvey and Waroona for agricultural use						✓		
	Pipes irrigation water to shareholders from Lake Argyle to the Ord irrigation area in Kununurra for agricultural use							✓	
DEVELOPMENT / LAND USE PLANNING	Ensures future development and land use planning enhances ecological health and amenity of the Swan-Canning Rivers			✓					
	Provides advice on development and land use planning that has the potential to affect waterways, groundwater and catchments		✓		✓	✓			✓
	Provides advice on land use planning (structure plans, subdivisions, development etc) that has the potential to affect wetlands		✓		✓	✓			✓
	Decision-making authority for most development applications					✓			
PROTECTION/ RESTORATION	Protects waterways and catchments in WA		✓			✓			
	Protects wetlands in WA		✓		✓	✓			
	Manages wetlands within reserves				✓	✓			
	Protects and enhances the ecological health and community benefit of the Swan-Canning rivers			✓					
	Catchment management programs and activities e.g. conversion of stormwater drains to 'living streams'		✓	✓	✓	✓			
MONITORING	Monitors surface and groundwater (quality and water levels)		✓				✓	✓	
	Monitors drinking water quality	✓							
	Monitors water quality and water level of Swan-Canning rivers			✓					
	Monitors water quality, quantity and treatment in dams, storage facilities and Perth desalination plant	✓							

case study

Surface and groundwater (drainage) management

The Department of Water is responsible for overseeing surface and ground water management policy and planning in WA.

The urban drainage network is made up of drains that principally flow to wetlands, waterways or the ocean. Most urban drains are managed by local governments. In some parts of the Perth metropolitan area the Water Corporation manages 'main drains' that receive drainage water from the local government drainage network. Main Roads and the Public Transport Authority also manage drainage associated with their infrastructure.

The Water Corporation is required to manage stormwater in the landscape within declared drainage districts, under licence from the Economic Regulatory Authority. Properties within these districts pay an annual drainage service charge for this service. The pipes, roadside channels and open drains known as 'main drains' are all part of the Water Corporation's network. In metropolitan Perth, this is made up of 828 kilometres of drains, diverting water from more than 400,000 hectares of land and preventing the flooding and waterlogging of approximately 260,000 properties.[28]

Outside of the Perth metropolitan area the Water Corporation is responsible for maintaining rural drainage in defined rural drainage districts. Properties within rural drainage districts do not pay annual service charges. The rural drainage service was initially provided only to make land viable for agricultural. It provides a limited flood protection service, allowing adjacent land to be inundated following major storms.

Unlike the urban drainage of other Australian cities, Perth's main drains are designed to intercept and convey shallow groundwater in addition to surface overland flow.[29] Many main drains have been constructed to make land that was naturally waterlogged or inundated, that is, wetland areas, viable for agricultural or urban development. The draining of Perth's wetlands has affected all wetland types but in terms of area, it is particularly the extensive waterlogged wetlands that have been affected over decades, as historically they were not typically considered environmentally valuable.

Many main drains flow through significant wetlands in the Perth and Peel Regions. In fact whole chains of wetlands are influenced by the main drains. These drains, and their impacts on wetlands, are a legacy of historical urban and rural development.

Water regime and drainage

Wetland water regime is the specific pattern of when, where and to what extent water is present in a wetland.[30] Its components are the timing, frequency, duration, extent, depth and variability of water presence.[31] The protection of wetland water regime is fundamental to protecting a wetland's values. Inherent in drainage planning is the concept that water needs to be removed from the landscape, beyond its natural flows, to enable people to inhabit the land. There is a strong potential for drainage to significantly alter wetland water regime, and consequently, wetlands and their natural values. However, there has been significant reform of the urban water planning process over the last decade, resulting in a much more transparent, accountable and environmentally-based planning framework for drainage planning in urban areas (Figure 4). As a result, greater opportunity exists for individuals and groups to be involved to ensure that valuable wetlands are considered appropriately in the planning process. Although the issues involved may be complex, stakeholders can influence the process by supporting this principle and advocating for the protection of wetlands in the planning area. Development proponents are required to address arterial drainage planning issues when proposing land use changes. However, in large and complex catchments, the Department of Water may take lead responsibility in the development of plans, in conjunction with the Department of Planning and local governments.

case study

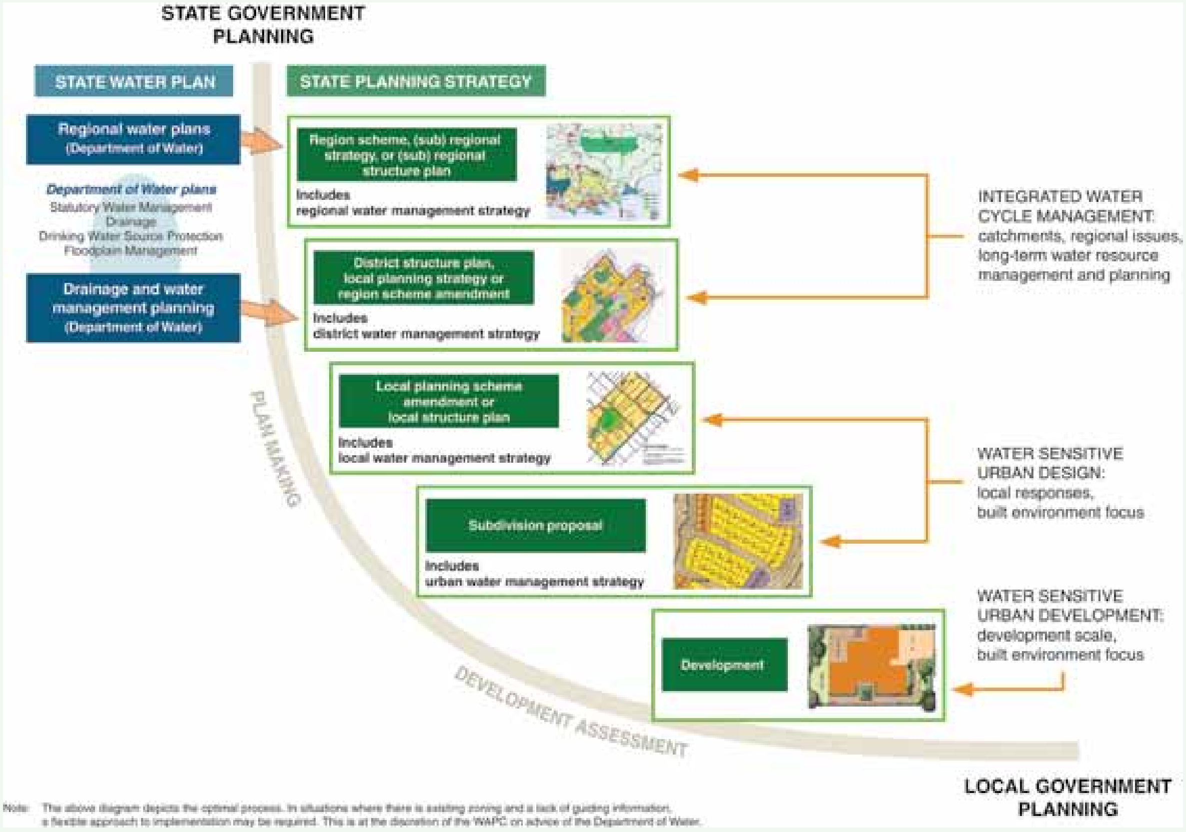

Figure 4. Urban water planning is now better integrated into the broader planning framework in WA. Image – *Better Urban Water Management*[32]

The Department of Water has identified the following objectives for stormwater management in WA:

- Water quality: to maintain or improve the surface and groundwater quality within the development areas relative to pre development conditions.
- Water quantity: to maintain the total water cycle balance within development areas relative to the pre development conditions.
- Water conservation: to maximise the reuse of stormwater.
- Ecosystem health: to retain natural drainage systems and protect ecosystem health.
- Economic viability: to implement stormwater management systems that are economically viable in the long term.
- Public health: to minimise the public risk, including risk of injury or loss of life, to the community.
- Protection of property: to protect the built environment from flooding and waterlogging.
- Social values: to ensure that social, aesthetic and cultural values are recognised and maintained when managing stormwater.
- Development: to ensure the delivery of best practice stormwater management through planning and development of high quality developed areas in accordance with sustainability and precautionary principles.[15]

case study

➤ For additional detail on the water regime of WA wetlands, see the topic 'Wetland hydrology' in Chapter 2.

➤ The Department of Water invites comments on drainage plans on its website: www.water.wa.gov.au. There is often a link from the front page of the website to plans currently open for comment.

➤ The document outlining how wetland water regimes are protected through urban water planning processes is *Better Urban Water Management*.[32] It describes how water resources, including wetlands, should be considered at each stage of the land planning process by identifying the various actions and investigations required to support the particular planning decision being made. It is available online at www.planning.wa.gov.au/dop_pub_pdf/Better_Urban_Water_Management.pdf.

➤ The *Stormwater management manual for Western Australia*[15] and the *Decision process for stormwater management in WA*[33] provide stormwater planners and managers with guidance on how to manage stormwater to protect wetlands.

Wetland water quality and drainage

The Department of Water is responsible for overseeing surface water and groundwater management policy in WA. It has spearheaded significant reform in urban water management through a variety of initiatives over the past decade. However, managing the water cycle and its quality in the urban environment requires the participation and compliance of a number of stakeholders, from individuals in the community to local and state government authorities.

Local governments are well placed to make significant improvements to the water quality of the estimated 3,000 kilometres of drains within their networks. In WA, there has been a significant uptake of water quality management initiatives by local governments. For example, more than forty local governments are participants of the Water Campaign™ run by the International Council for Local Environmental Initiatives. As participants, these councils have identified the changes that they will make to the management of water within the local government area. Ratepayers can encourage better wetland outcomes by supporting their local government's uptake of water initiatives such as the Water Campaign™. Resourcing is a constraint facing local governments; ratepayers can help influence the resourcing of such activities by providing their support. A holistic cost-benefit analysis of these activities will often demonstrate that the cost of managing drainage water quality, for example, will be offset by the reduction in costs of managing poor water quality in receiving wetlands and other environments they are responsible for managing.

➤ Individuals and community groups can find out if their local government is a participant, and what changes they have committed to, at the ICLEI website: http://iclei.org/index.php?id=2389te.

Any modifications to drains, or their management, require the approval of the managing authority. Key concerns of managing authorities will include whether changes to the capacity of the drain will increase the risk of flooding, or reduce the ease of management or public safety. Any proposed changes to the banks, cross-sectional area and levels of drains will require a professional hydrological assessment.

While the Water Corporation is responsible for providing and managing part of the urban and rural drainage networks, the Economic Regulatory Authority operating licence does not require the Water Corporation to control water quality within the main drains. The Water Corporation's stated responsibilities lie in design, construction, operation and maintenance of the drainage networks that convey drainage water to meet the flood protection requirements of the Economic Regulatory Authority operating licence.[29] However the Water Corporation has recently stated that it recognises a holistic and integrated catchment scale approach is required for the adequate management of water quality.[29] It has recently funded research into the water quality of its main drains[29] and undertaken a revegetation trial for a section of a branch drain with the objective of developing a more environmentally sustainable approach to urban drainage management and reducing maintenance by installing long term native vegetation that, once established, would significantly reduce maintenance cost.

➤ For more information on managing stormwater quality in WA, see the 'Stormwater' webpage of the Department of Water's website: www.water.wa.gov.au/Managing+water/Urban+water/Stormwater/default.aspx#

case study

Wastewater service providers are responsible for conveying, treating and disposing of wastewater. The Water Corporation is the main provider in WA, however, some local governments, land developers, mining companies, and other organisations are also wastewater service providers. Wastewater service providers are responsible for minimising environmental impacts associated with overflows from their wastewater systems into sensitive receiving environments, including wetlands. The overflow points in

Figure 5. A pumping station. Photo – C Mykytiuk/DEC

wastewater systems are typically located at pumping stations (Figure 5). These stations are generally located at low points in the landscape, and consequently they are often near wetlands. The overflow of wastewater into wetlands has the potential to impact wetland water quality.[34] Service providers are required to carry out actions to assess, contain and recover wastewater at overflow sites in accordance with the *Wastewater overflow response procedures*.[35]

Managing the catchment of the Swan and Canning Rivers

The Swan River Trust (SRT) is another state government agency involved with water management in Perth. Under the *Swan and Canning Rivers Management Act 2006* the SRT is responsible for protecting and enhancing the ecological health and long-term community benefit of the Swan-Canning River system. An important role undertaken by the SRT is to promote sound land use practices in the catchments of the Swan-Canning River system. The Swan-Canning river system includes the Ellen Brook, a westerly section of the Avon River, Helena River, Southern River and the Canning River. The SRT plays an important role in protecting wetlands by delivering a wide range of management programs and activities throughout the Swan Canning catchment to improve water quality in the Swan Canning Riverpark, which also improves water quality of wetlands in the catchment. These range from providing advice on development and land use changes to on-ground projects such as revegetation and fencing, re-engineering drains into living streams, restoring foreshores and improving the health of wetlands and floodplains along tributaries, and creating artificial wetlands in those drains that deliver large nutrient loads to the Swan and Canning Rivers.

➤ For additional detail on the Swan River Trust including current programs, see the website at www.swanrivertrust.wa.gov.au.

case study

Case study: regulating industry and environmental harm

Pollution control

DEC is responsible for regulating the emissions or discharge of a range of industrial activities that would otherwise pose a significant environmental risk. It has powers to investigate, enforce and to order pollution to be abated and remediated. DEC carries out these responsibilities in accordance with Part V of the *Environmental Protection Act 1986* (EP Act). In particular, DEC manages potential polluting activities of 'prescribed premises' through works approvals and licences.

However, a range of activities do not fall within this regulatory mechanism. Local government approval is required for a range of activities through land use planning, extractive industry and offensive trades approvals and local government by-laws. Department of Mines and Petroleum approvals apply to mine sites, petroleum industries and dangerous goods storage facilities.

Individuals, organisations and community groups such as 'Friends of' groups can play an important role in surveillance and education regarding pollution, and in proactive activities to improve compliance of industry and best practice management by the community in general. For example, the Light Industry Audit Project was delivered by Perth Region NRM between 2007 and 2012. The project aimed to educate and influence managers in regard to the discharge of nutrients and contaminant sources from small and medium sized enterprises by auditing the use, storage and disposal of all types of solid and liquid materials. The subsequent report identified that the main areas where businesses failed to minimise the risk of pollution were:

- inappropriate liquid storage and spill management infrastructure
- inappropriate disposal of wastewater
- wastewater containing detergents, degreasers or sediments not properly treated and/or being discharged to open ground, septic tank system or stormwater drainage
- no emergency spill kit
- no emergency spill management plan and/or staff training for managing spills
- Material Safety Data Sheets not held on site for all chemicals used.

DEC is also responsible for investigating potential environmental harm caused by pollution. Under the EP Act it is an offence to cause environmental harm to the environment. Under the EP Act, an 'alteration of the environment to its detriment or degradation or potential detriment or degradation' or an 'alteration of the environment to the detriment or potential detriment of an environmental value' is considered environmental harm.

➤ To report pollution, call the Pollution Watch Hotline, 1300 784 782 (24 hours) or email pollutionwatch@dec.wa.gov.au. In the event of a hazardous materials release or life-threatening incident, call 000 and ask for Fire and Rescue).

➤ DEC publishes details of granted and refused licences. These are available to view at the 'Licensing and regulation' webpage of the DEC website www.dec.wa.gov.au/pollution-prevention/licensing-and-regulation.html.

➤ Information on the Light Industry Audit Project is available on the Swan River Trust website: www.swanrivertrust.wa.gov.au/the-river-system/tackling-the-issues/addressing-contaminants/light-industry-program

Australian government

National wetland protection and management is coordinated by the Australian government and through two committees. It plays a role in wetland policy and management, particularly with regard to nationally and internationally significant wetlands in WA.

Australian government agencies

The Australian government agency with primary responsibility for wetland protection and management issues of national interest is the Department of Sustainability, Environment, Water, Population and Communities.

Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) **Website** www.environment.gov.au www.nrm.gov.au	**Role** Develops and implements national policy, programs and legislation to protect and conserve Australia's environment

Objective/mission
Advancing a sustainable Australia: our environment, water, heritage and communities

Processes or programs relevant to wetland conservation

- Administrative authority for the Ramsar Convention in Australia. Is the Australian representative; liaises with state and territory governments; designates sites for listing; provides guidance and advice; coordinates reporting on Ramsar sites. For more information see the 'Case study: roles and responsibilities for Ramsar wetlands' below.
- Participates in partnerships and implements agreements that seek to protect migratory species and their flyways as part of Australia's international commitments to the Convention on Migratory Species (Bonn Convention).
- Caring for Our Country investment program.
- Environmental biosecurity and invasive species policy.
- Implements the *Environment Protection and Biodiversity Conservation Act 1999* including regulating actions; maintaining the migratory species list; maintaining the list of threatened species, ecological communities and key threatening processes; development conservation advice and recovery plans for listed species and ecological communities; developing and implementing threat abatement plans.

Legislation relevant to wetland conservation
Environment Protection and Biodiversity Conservation Act 1999
Natural Heritage Trust of Australia Act 1997
Water Act 2007

Publications relevant to wetlands

- *The Wetlands Policy of the Commonwealth Government of Australia* (1997)
- EPBC Act Policy Statement *1.1: Matters of national environmental significance* (2009)
- National guidelines for Ramsar Wetlands (publication series)
- Fact sheets (publication series)
- *Aquatic ecosystems toolkit* (2012)
- *Discovering Wetlands in Australia* (2011) – a primary classroom resource
- *Issues Paper: The role of wetlands in the carbon cycle* (2012)

Relevant committees assisted/ supported	Minister
Standing Council on Environment and Water (SCEW) www.environment.gov.au/about/councils/scew/index.html SCEW Senior Officials Committee National Water Reform Thematic Oversight Group (Water TOG) Landscape and Ecosystems Scale Biodiversity Thematic Oversight Group (Bio TOG) Aquatic Ecosystems Task Group Wetlands and Waterbirds Taskforce	Minister for Sustainability, Environment, Water, Population and Communities Minister for Climate Change and Energy Efficiency Parliamentary Secretary for Sustainability and Urban Water

Australian government committees

Aquatic Ecosystems Task Group (AETG)	**Role**
Website Nil	Responsible for developing a national approach for the identification, classification and management of high ecological value aquatic ecosystems Responsible for ensuring other high ecological value aquatic ecosystem work undertaken is coordinated and consistent with the AETG objectives[36]
Objective Develop a national framework for the identification, classification and management of high ecological value aquatic ecosystems Provide a nationally coordinated approach to policy development for cross-jurisdictional issues within the aquatic ecosystems context	
Power Advice to National Water Reform Thematic Oversight Group (Water TOG) and Standing Council on Environment and Water (SCEW)	**Processes or programs relevant to wetland conservation** • Development of a common definition of high ecological value aquatic ecosystems • Development of a national framework and or methodology for the identification, delineation, classification and description of Australia's high ecological value aquatic ecosystems • Development of guiding principles for the management of high conservation value aquatic ecosystems[36]
Legislation relevant to wetland conservation *Environment Protection and Biodiversity Conservation Act 1999* *Water Act 2007* State and territory environmental legislation	
Agency A Council of Australian Governments (CoAG) committee chaired by the Department of Sustainability, Environment, Water, Population and Communities	**Minister** Minister for Minister for Sustainability, Environment, Water, Population and Communities
Membership Jurisdictional nominations from relevant agencies. In WA: Principal Coordinator, Wetlands Section, DEC.	**Meeting frequency** As required

Wetlands and Waterbirds Taskforce (WWTF)

Role
Responsible for advising the Standing Council on Environment and Water (SCEW) on the implementation of the Ramsar Convention

Objective
To promote a coordinated approach to the implementation of national obligations under the Ramsar Convention and international agreements on migratory waterbirds. To provide advice and undertake actions that facilitates such coordination[3]

Power
Advisory to the Landscape and Ecosystems Scale Biodiversity Thematic Oversight Group (Bio TOG) and Standing Council on Environment and Water (SCEW)

Legislation relevant to wetland conservation

Environment Protection and Biodiversity Conservation Act 1999

Water Act 2007

State and territory environmental legislation

Sub-committees
Wetlands and Waterbirds Advisory Group

Processes or programs relevant to wetland conservation

- Australia's National Ramsar Committee; National reporting for the Ramsar Convention Conference (of Contracting Parties) and biennial meetings of the bilateral migratory bird agreements between Australia and Japan, China and the Republic of Korea
- Provide advice on Australian and New Zealand obligations under the above international agreements and the Bonn convention
- Provide advice on Australian and New Zealand's contribution to ensure long term conservation of migratory waterbirds in the East Asian Australasian Flyway
- Provide advice on meeting the objectives for the conservation of wetland biodiversity as enunciated under the National Strategy for the Conservation of Australia's Biological Diversity[3]
- Develop and implement a practical three-year rolling plan for coordinated implementation for Ramsar sites

Agency
A Council of Australian Governments (CoAG) committee chaired by Department of Sustainability, Environment, Water, Population and Communities

Minister
Minister for Sustainability, Environment, Water, Population and Communities

Membership
Jurisdictional nominations from Australian state, territory and NZ agencies. In WA: Principal Coordinator, Wetlands Section, DEC.

Meeting frequency
Twice yearly

case study

Case study: roles and responsibilities for Ramsar wetlands

- M. Coote, DEC

Australia is one of 160 countries that are party to the Ramsar Convention on Wetlands, which was signed in Ramsar, Iran in 1971. This treaty, officially known as *The Convention on Wetlands of International Importance, especially as Waterfowl Habitat*, currently lists more than 1,906 wetlands worldwide covering some 186.5 million hectares. The Ramsar Convention is an international intergovernmental treaty, which aims to halt and, where possible, reverse, the worldwide loss of wetlands and to conserve those that remain through wise use and management.

Australia was the first to nominate a site—Cobourg Peninsula in the Northern Territory in 1974—and now has sixty-four wetlands listed under the Ramsar Convention. Twelve of these sites occur in Western Australia, covering a total area of 514,800 hectares.

Designation as a Ramsar site confers upon it the prestige of international recognition, it also raises the profile of the site; enhances opportunities for management assistance and improves long-term management of the wetland; and increases legislative protection through the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

Nomination of a Ramsar site

Ramsar site nominations can be initiated by the Australian, state and territory governments, non-government organisations (NGOs), community entities, trusts, Traditional Owners, individuals, private landowners or a company. Proposed nominations on state or private land require support from the relevant state government. In practice, most Ramsar site nominations are proposed and developed by the state or territory governments, which have priorities for new Ramsar sites and processes for reviewing and supporting Ramsar nominations.

The development of a Ramsar site nomination should be the result of a collaborative process between site managers/landowners and the Australian and state or territory governments. Consultation with the landowner(s) and key stakeholders is an important consideration in both the preparation of a Ramsar nomination and the negotiation of ongoing management arrangements for the site.

Roles and responsibilities for Ramsar in Australia

Australian government (via the lead agency, the Australian Department of Sustainability, Environment, Water, Population and Communities):

- designating Ramsar sites on account of international significance in terms of ecology, biology, zoology, limnology or hydrology
- working with state and territory governments to promote the conservation of Ramsar sites and wise use of all wetlands, and review Ramsar site condition
- reporting any changes to the ecological character of Australia's listed wetlands and responding to the Ramsar Secretariat's inquiries about reports from third parties
- using its best endeavours to ensure there are management plans for wetlands listed under the Ramsar Convention
- regulating actions that will have, or are likely to have, a significant impact on the ecological character of a Ramsar wetland. This includes relevant actions that occur outside the boundaries of a Ramsar wetland.
- providing advice on the Ramsar Convention and any agreed assistance to wetland managers
- reporting to the regular Conference of the Contracting Parties.

case study

State government (via the lead agency, DEC)

- leading the development of the nomination documentation for candidate nominations within the state including the consultation on these nominations
- liaising with the Australian Government about nominations within the jurisdiction
- coordinating and updating information on Ramsar sites within the state (for example, the Ramsar National Report).

Site managers/landowners:

- under the EPBC Act, seek approval prior to undertaking an action within or outside a declared Ramsar wetland if the action has, will have or is likely to have a significant impact on the ecological character of the Ramsar wetland. The action could be a project, a development, an undertaking, an activity or series of activities, or an alteration to any of these things.
- managing the Ramsar site(s) to maintain ecological character through applying the principles of wise use and sustainable resource management. This may be through the development and implementation of a management plan or system for the site.
- having procedures and monitoring in place to detect if any threatening processes are likely to, or have altered the site's ecological character. This will help to identify if there are any actual or likely changes to ecological character of the site.
- taking action to manage or remediate Ramsar sites that have undergone an actual or likely change in ecological character
- report any actual or likely changes in ecological character to the Australian Government
- undertake required site level updates and reporting as required (for example, Ramsar Information Sheet updates)
- seek guidance and assistance about managing and representing the needs of wetlands, if required
- inform the Australian and relevant state governments of any intention to transfer ownership or otherwise sell land on which the wetland is situated and
- notify future land managers of the property's Ramsar status, should the property be sold or otherwise change ownership.

For further information on the details of the roles and responsibilities for Ramsar Convention in Australia see the Australian Ramsar site nomination guidelines, *Module 4 of the National Guidelines for Ramsar Wetlands - Implementing the Ramsar Convention in Australia*.[37]

case study

Case study: working collaboratively to manage and restore Lake Mealup

Lake Mealup is a large freshwater wetland situated on coastal lowlands on Lake Mealup Rd, West Pinjarra, one kilometre east of the Peel-Harvey Estuary (Figure 6). It is located on the Pinjarra Plain, the most heavily cleared landform unit within the Swan Coastal Plain. Lake Mealup is an excellent representation of coastal lowland wetlands on the coastal plain and its vegetation, as well as surrounding dryland vegetation communities, is home to a number of threatened plant and animal species.

Figure 6. The location of Lake Mealup relative to Harvey Estuary and Peel Inlet, Mandurah. Image – L Duffy/DEC.

Lake Mealup is also one of a number of wetlands in the Peel-Yalgorup wetland system listed under the Convention on Wetlands of International Importance (Ramsar Convention). The Peel-Yalgorup system is known to be the most significant area in the south-west of Western Australia for waterbirds and waders.[38] Several migratory bird species such as the great egret (*Egretta alba*) and the sharp-tailed sandpiper (*Calidris acuminata*) have been known to visit the wetland[39] and are protected under the EPBC Act. The ecological character of the site is protected under the EPBC Act. Lake Mealup is also listed as a nationally important wetland in the *Directory of Important Wetlands* under the 'Lake McLarty System' listing; on the Register of the National Estate under the 'Peel-Harvey Estuarine System' listing; and identified under the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992*. The wetland is recognised as a Conservation management category wetland by DEC in the *Geomorphic Wetlands Swan Coastal Plain* dataset, a category assigned to wetlands of the highest conservation value.

➤ For additional detail regarding wetland policy, see the topic 'Legislation and policy' in Chapter 5.

In the 1990s, it became increasingly evident that declining water levels and drying of the lake beyond its natural variability was leading to increasingly acidic conditions, poor water quality, increasing weed coverage and declining waterbird habitat. The lower water levels have been attributed to a decline in rainfall, changes in drainage management in the catchment and groundwater abstraction.

case study

Collaborative action, initiated by the community

Many individuals and groups have been involved in the restoration of Lake Mealup. Community groups, landholders, Aboriginal groups and representatives, state government agencies, consultants and university staff have all contributed. However, a community group – the Lake Mealup Preservation Society (LMPS) – has been a driving force over a number of decades.

The LMPS formed in 1986 and by 1989 it had purchased three properties adjoining the Lake Mealup Reserve managed by DEC, with the aim of preserving the natural values of the wetland and adjoining bushland. During this time, DEC also purchased an additional lot to expand its existing reserve. The purchase of three properties by the LMPS consolidated the area of land managed for conservation. Historically, ownership of the wetland spanned several properties including Lake Mealup Reserve managed by DEC, and a number of small-scale farming properties including a piggery. The properties purchased by LMPS included Little Lake Mealup, a 10 hectare wetland to the west of Lake Mealup (Figure 7).

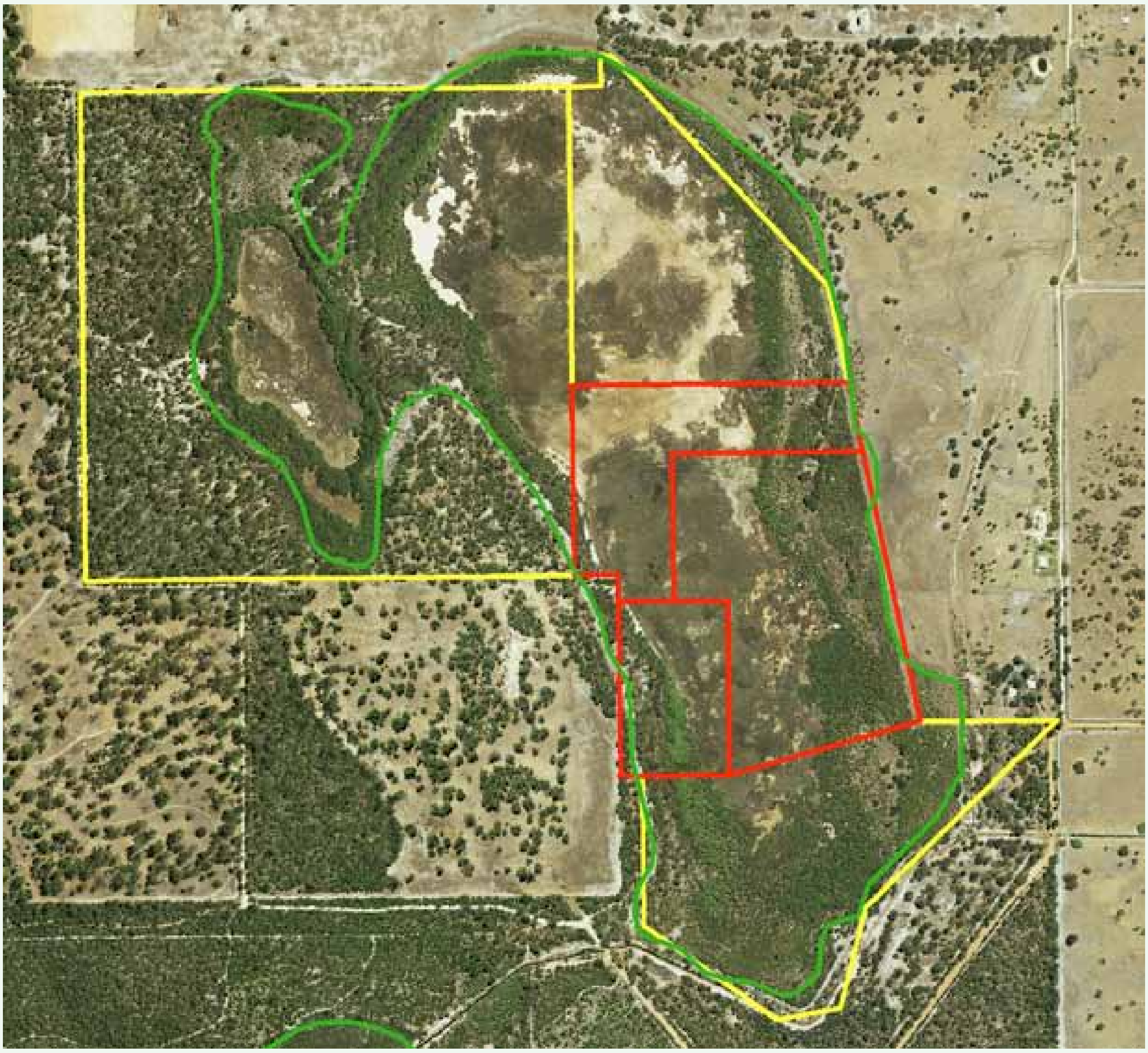

Figure 7. Lake Mealup, showing the wetland boundary (green), the Lake Mealup Preservation Society property boundaries (yellow) and DEC land (red). Image – A Fairs/DEC.

case study

The LMPS has taken a very active role in maintaining and managing the properties and has completed a range of management activities, many on a monthly or annual basis with funding from membership fees and grants. Some activities have occurred in collaboration with the Peel-Harvey Catchment Council (PHCC), consultant wetland scientists V & C Semeniuk Research Group (VCSRG) and DEC. Activities have included:

- hand weeding of introduced bulrush (*Typha orientalis*), dock (*Rumex* sp.), lupin (*Lupinus cosentinii*) and arum lily (*Zantedeschia aethiopica*)
- fencing to exclude livestock
- 1080 fox baiting
- flora, waterbird, macroinvertebrate, mammal and reptile surveys
- ongoing monitoring of an extensive piezometer (groundwater monitoring) bore network since 1996
- monitoring of surface water levels and water quality in the lake since 1987
- revegetation
- community awareness activities
- local seed collection
- annual fire break maintenance
- construction of a birdwalk and bird hide.

LMPS – achieving restoration by engaging other stakeholders

Lake Mealup Preservation Society has taken a very active role engaging relevant NRM and government organisations in Lake Mealup's management over many years. This active engagement has resulted in the group receiving support in the form of specialist skills, funding, equipment and increased exposure through stakeholder communication and some media coverage.

LMPS has been actively collaborating with DEC, PHCC, DoW, Natural Trust of Australia (WA) (NTWA) and VCSRG to address these degrading processes and protect the ecological condition and amenity value of the wetland.

LMPS joined DEC's Land for Wildlife program in 2002. This voluntary program is designed to encourage and assist landholders to provide habitats for wildlife on their property. Through the program, DEC conducted a bushland condition assessment, established a weed prioritisation and management schedule, and provided LMPS with information and books on bushland management and conservation covenants.

In 2003, LMPS registered an agreement with NTWA, placing their properties under a voluntary conservation covenant as a means to legally protect the natural values of the property in perpetuity[40]. Together, the NTWA and LMPS established a bushland management plan for the properties which established the management framework which is used to manage the lake.

In 2009, the LMPS entered a voluntary management agreement with DEC's Healthy Wetland Habitats program. This program provides funding and support to private landholders to manage high conservation value Swan Coastal Plain wetlands. The LMPS was provided $10,000 to undertake agreed management actions including water quality and hydrology investigations, fencing and weed control over five years (Figure 8).

Typha control and revegetation funding has been provided through the Australian Government's Caring for Our Country funding, via Peel-Harvey Catchment Council and the South West Catchments Council.

Funding and technical support needed to improve water levels in the lake have been provided by the State NRM program via the DoW. In-kind support from stakeholders has also been invaluable.

case study

Figure 8. Lake Mealup Preservation Society representative Peter Wilmot receiving a Healthy Wetland Habitats funding cheque from DEC's HWH Officer Amanda Fairs. DEC Lake Mealup Project Officer Heidi Bucktin, DoW officer Keiryn Kilminster and Peel-Harvey Catchment Council officer Amanda Willmott look on. Photo - L Duffy/DEC.

Progressing Lake Mealup's recovery

In 2007, LMPS compiled the document, *A proposal to improve the quality and quantity of water in Lake Mealup by changes in drainage management.*[41] This was the catalyst for a recovery program implemented over the course of the following five years. In response, DEC developed the *Lake Mealup Nature Reserve Recovery Program 2009*. DEC's Nature Conservation Project Officer coordinates and implements this program with assistance and in collaboration with LMPS.

The first stage of the recovery program, from 2009 to 2010, involved the collection and analysis of hydrological data (surface and groundwater level and quality, rainfall) to investigate whether managing water levels was feasible. This data was collected by LMPS, DEC and PHCC, under advice and assistance from VCSRG (groundwater) and advice and equipment offered by DoW. Analysis was carried out on surface water data collected by LMPS between 1987 and 2008, and groundwater data collected by LMPS under the direction of VCSRG from 1996 to present. Water quality data for the main drain collected by the Department of Water (DoW) intermittently between 1991 and 2004 was analysed. DoW assisted with surface water quality monitoring, providing technical advice and lending monitoring equipment.

In 2010 the Lake Mealup Technical Advisory Group convened for the first time and agreed upon the second stage of the recovery program based on the data collected during the first stage. The focus of the second stage was to reconnect the lake to the catchment and increase its water levels using an adjustable height weir (Figure 9) and drainage modifications. Targets and triggers were developed as part of an adaptive management plan. As the lake is part of a Ramsar site, the adaptive management plan was referred to the Australian Government Department of Sustainability, Environment, Water, Population and Communities. The Conservation Commission's approval was also sought, due to changes on conservation estate land vested in it. The Water Corporation, the authority with whom the drain is vested, approved proposed modifications to the Mealup Main Drain, to divert drainage flows back into the wetland.

case study

Figure 9. The adjustable height weir, receiving flows diverted from the Mealup Main Drain. Photo – H Bucktin/DEC.

Since the first drainage flows were diverted into the lake in May 2012, Lake Mealup is showing the first signs of recovery (Figure 10). Monitoring indicates that the pH of the lake is improving and animals once again inhabit the wetland. DEC and the LMPS will continue to monitor and manage the lake.

Figure 10. Lake Mealup, full in August 2012. Photo – R Rose.

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A guide to managing and restoring wetlands in Western Australia

Legislation and policy

In Chapter 5: **Protecting wetlands**

Version 1

Australian Government

Department of Environment and Conservation

Our environment, our future

Introduction to the guide

Western Australia's unique and diverse wetlands are rich in ecological and cultural values and form an integral part of the natural environment of the state. *A guide to managing and restoring wetlands in Western Australia* (the guide) provides information about the nature of WA's wetlands, and practical guidance on how to manage and restore them for nature conservation.

The focus of the guide is natural 'standing' wetlands that retain conservation value. Wetlands not addressed in this guide include waterways, estuaries, tidal and artificial wetlands.

The guide consists of multiple topics within five chapters. These topics are available in PDF format free of charge from the Western Australian Department of Environment and Conservation (DEC) website at www.dec.wa.gov.au/wetlandsguide.

The guide is a DEC initiative. Topics of the guide have predominantly been prepared by the department's Wetlands Section with input from reviewers and contributors from a wide range of fields and sectors. Through the guide and other initiatives, DEC seeks to assist individuals, groups and organisations to manage the state's wetlands for nature conservation.

The development of the guide has received funding from the Australian Government, the Government of Western Australia, DEC and the Department of Planning. It has received the support of the Western Australian Wetlands Coordinating Committee, the state's peak wetland conservation policy coordinating body.

For more information about the guide, including scope, purpose and target audience, please refer to the topic 'Introduction to the guide'.

DEC welcomes your feedback and suggestions on the guide. A publication feedback form is available from the DEC website at www.dec.wa.gov.au/wetlandsguide.

Contents of the guide

These topics are available in PDF format free of charge from the DEC website at www.dec.wa.gov.au/wetlandsguide.

'Legislation and policy' topic

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Contents

ACRONYMS

DEC	Department of Environment and Conservation
DIA	Department of Indigenous Affairs
DoF	Department of Fisheries
DoP	Department of Planning
DoW	Department of Water
EIA	Environmental impact assessment
EPA	Environmental Protection Authority
EPP	Environmental protection policy
SAT	State Administrative Tribunal
SPP	State Planning Policy
WAPC	Western Australian Planning Commission

Enacted: to make into law

Statute: a law enacted by State or Australian Parliament

Regulation: a law made under the authority of an Act of Parliament

Important note

This topic provides an overview of environmental legislation and policy that contributes to wetland conservation in Western Australia. It is for general information purposes only. Whilst all care has been taken to ensure the accuracy of the information presented in this guide, it is not intended to be comprehensive and should not be seen as a substitute for professional legal advice. Legal advice relating to specific circumstances can be sought from a solicitor or, where the matter is in the public interest, the Environmental Defender's Office WA (Inc.): www.edowa.org.au.

Introduction

Legislation and policy has an important role in protection and management of wetlands in Western Australia. A range of Acts and policies provide for specific aspects of wetland protection and management in Western Australia, the most important of which have been described in this topic.

A range of other Acts that have a bearing on specific aspects of wetland management are outlined in relevant topics of the guide (for example, use of pesticides is outlined in the topics 'Wetland weeds' and 'Introduced and nuisance animals').

'Legislation' refers to laws **enacted** by state or Australian Parliament. A law can also be called an Act of Parliament or **Statute**, and often referred to as a statutory mechanism.

Statute also refers to the schedules, policies, or **regulations** formed under an Act, such as local planning schemes, environmental regulations and environmental protection policies (EPPs). These contain details of how a statute applies and as they are also enacted they are legally binding. Specifically, regulations are more commonly referred to as subsidiary legislation, and should be read in the context of the over-riding Act under which they apply.

Subsidiary legislation is often required to provide greater detail for the implementation of an Act in relation to a particular matter, such as to address specific issues, different applications in geographic regions, or schedules (lists) to which the Act is to apply. Subsidiary legislation can be passed or enacted more quickly than Acts, and hence provide the ability to amend the manner in which an Act might be implemented in relation to changing knowledge and understanding of the matters to which the Act applies. The Acts discussed in this topic are shown in Table 1.

Administrative policies and guidelines are also used to protect wetlands and while these are not statutory instruments, they provide direction for how Statutes may be applied, such as whether future planning and development is likely to be environmentally acceptable. These include State Environmental Policies (SEPs), state planning policies (SPPs), and guidelines and position statements of the Environmental Protection Authority (EPA). The policies discussed in this topic are shown in Table 2. Note that only government policies are covered.

Some policies are statutory rather than administrative (that is, they have the power of law). For example, gazetted environmental protection policies prepared under the *Environmental Protection Act 1986* are statutory, not administrative. In this topic, statutory policies are discussed in both the 'legislation' and 'policy' sections.

Legislation and policies are a reflection of community expectations and aspirations. Legislation and policies can best achieve these expectations and aspirations when the community participates in their development and application. Community engagement in decision-making processes is built into much of the legislation and policies covered in this topic, giving all members of the community a say in how WA's wetlands are protected and conserved.

Roles of agencies and decision-making authorities

The topic 'Roles and responsibilities', in Chapter 5 describes the roles of individuals and a range of community and government organisations in relation to wetland conservation and management more broadly. It describes many of the government agencies and decision-making authorities listed in this topic.

Table 1. Key Acts for wetland management and protection.

Acts and Statutes	Legislative mechanisms relevant to wetland management and protection	Administering agency/ agencies	Minister
Environmental Protection Act 1986	• Function of the Environmental Protection Authority (Part II) • Development of policies for environmental protection (Part III) • Environmental impact assessment (Part IV) • Regulation of pollution, environmental harm and clearing (Part V)	Environmental Protection Authority (Parts I – IV) Department of Environment and Conservation (Part V)	Minister for Environment
Wildlife Conservation Act 1950	Protection of native flora and fauna	Department of Environment and Conservation	Minister for Environment
Conservation and Land Management Act 1984	Use, protection, and management of certain public land and waters	Department of Environment and Conservation Conservation Commission	Minister for Environment
Planning and Development Act 2005	• State planning policies • Region planning schemes • Local planning schemes • Subdivision and development control	Western Australian Planning Commission Department of Planning Local government	Minister for Planning
Aboriginal Heritage Act 1972	Conservation of and protection for places and objects of importance to Aboriginal people	Department of Indigenous Affairs	Minister for Indigenous Affairs
Fish Resources Management Act 1994	Protection of aquatic species and habitats	Department of Fisheries	Minister for Fisheries
Rights in Water and Irrigation Act 1914	Some protection of water resources in proclaimed areas. Assigns rights to take water from the environment.	Department of Water	Minister for Water
Soil and Land Conservation Act 1945	Protection of land degradation (erosion, salinity and flooding) which may impact wetland condition	Soil and Land Conservation Commissioner	Department of Agriculture and Food Minister for Agriculture and Food
Land Administration Act 1997	Management of pastoral lands	Pastoral Lands Board (through the Department of Regional Development and Lands)	Minister for Lands
Commonwealth Acts			
Environment Protection and Biodiversity Conservation Act 1999	• Protection and manage matters of national environmental significance • Regulations outlining the Australian Ramsar management principles	Department of Sustainability, Environment, Water, Population and Communities	Minister for Environment (C/wealth)

Table 2. Key policies for wetland management and protection

Policy	Publisher	Year
Wetlands Conservation Policy for Western Australia	Govt. of WA	1997
Draft Framework for mapping, classification and evaluation of wetlands in Western Australia	DEC	In prep
Draft Guideline for the Determination of Wetland Buffer Requirements	DEC	In prep
Guidelines checklist for preparing a wetland management plan	DEC	2008
WA Environmental Offsets Policy	Govt. of WA	2011
Environmental Protection (Swan Coastal Plain Lakes) Policy 1992	Govt. of WA	1992
Environmental Protection (South West Agricultural Zone Wetlands) Policy 1998	Govt. of WA	1998
Environmental Protection (Western Swamp Tortoise Habitat) Policy 2011	Govt. of WA	2011
EPA Position Statement No 4 *Environmental Protection of Wetlands*	EPA	2004
EPA Guidance Statement No 7 *Protection of the Western Swamp Tortoise Habitat, Upper Swan/Bullsbrook*	EPA	2006
EPA Position Statement No 9 *Environmental Offsets*	EPA	2006
EPA Guidance Statement No 10 *Levels of assessment for proposals*	EPA	2006
EPA Guidance Statement No 19 *Environmental offsets*	EPA	2008
EPA Guidance Statement No 28 *Protection of Lake Clifton catchment*	EPA	1998
EPA Guidance Statement No 33 *Environmental guidance for planning and development*	EPA	2008
EPA Guidance Statement No 40 *Management of mosquitoes by land developers*	EPA	2000
State Planning Policy 2 *Environment and natural resources policy*	WAPC	2003
State Planning Policy 2.1 *Peel-Harvey coastal plain catchment*	WAPC	1992
State Planning Policy 2.2 *Gnangara groundwater protection*	WAPC	2005
State Planning Policy 2.3 *Jandakot groundwater protection*	WAPC	1998
State Planning Policy 2.8 *Bushland Policy for the Perth Metropolitan Region*	WAPC	2005
State Planning Policy 2.9 *Water resources*	WAPC	2006
Planning Bulletin 64/2009: Acid sulfate soils	WAPC	2009
Acid sulfate soils planning guidelines	WAPC	2008
Policy framework for inland drainage	DoW	2012
Better Urban Water Management Strategy	WAPC	
State Water Plan	Govt. of WA	2007
Water allocation planning in Western Australia: a guide to our process	DoW	2011
Stormwater management manual for Western Australia	DoW	2004–2008
Decision process for stormwater management in WA	DoW	2009
Wetland Policy of the Commonwealth Government of Australia	Govt. of Australia	1997

LEGISLATION FOR WETLAND CONSERVATION

There is no single Act that provides for every aspect of wetland management and protection. This topic provides an overview of the main statutory mechanisms that can assist in the protection of wetlands in WA. Other Acts not covered in this topic will apply generally to wetland areas, as they do to any area in WA, and their exclusion does not suggest that they do not apply (for example, the *Land Administration Act 1997* and the *Mining Act 1978*).

➤ For copies of WA's individual legislative acts and regulations, see the State Law Publisher's website www.slp.wa.gov.au/legislation/statutes.nsf/default.html.

➤ For copies of the Government Gazette, see the State Law Publisher's website www.slp.wa.gov.au/gazette/gazette.nsf

➤ For copies of Australian government legislation, see ComLaw online www.comlaw.gov.au

➤ For a guide to legislation designed specifically for primary producers, see *Production and environmental legislation: a guide for primary producers*.[1]

Other relevant legislation that applies to wetland conservation and management activities are outlined in Table 3.

Table 3. Legislation relevant to specific wetland management activities, covered in other topics of this guide

Activity	Key legislation	For more information
Managing sites with declared weeds	*Agriculture and Related Resources Protection Act 1976*	'Wetland weeds' topic
Controlled burns, including local government permits	*Bush Fires Act 1954*	'Wetland weeds' topic
Using herbicides	*Pesticides Act 1999* *Health Act 1911* *Agricultural and Veterinary Chemicals Code Act 1994*	'Wetland weeds' topic
Managing non-native animals	*Pesticides Act 1999* *Agriculture and Related Resources Protection Act 1976* *Fish Resources Management Act 1994* *Animal Welfare Act 2002*	'Introduced and nuisance animals' topic
Managing activities with the potential to affect acid sulfate soils	*Contaminated Sites Act 2003*	'Water quality' topic

STATE LEGISLATION

The *Environmental Protection Act 1986*

The *Environmental Protection Act 1986* (the EP Act) provides for an Environmental Protection Authority; for the prevention, control and abatement of pollution and environmental harm; and for the conservation, preservation, protection, enhancement and management of the environment. The Environmental Protection Authority (EPA) and the Department of Environment and Conservation (DEC) are responsible for administering specific aspects of this Act.

The EP Act consists of nine parts:

Part I – Preliminary

Part II – Environmental Protection Authority

Part III – Environmental protection policies

Part IV – Environmental impact assessment

Part V – Environmental regulation

Part VI – Enforcement

Part VII – Appeals

Part VIII – General

Part IX – Transitional

Aspects of these parts relevant to wetland protection are discussed below.

Part I – Preliminary

Part I provides an explanation of the terms used in the EP Act. It also states that the Act binds the Crown (that is, government agencies). It also provides the objective of the EP Act, to protect the environment of Western Australia, having regard for the following principles:

- the precautionary principle
- the principal of intergenerational equity
- the principle of the conservation of biological diversity and ecological integrity
- principles relating to improved valuation, pricing and incentive mechanisms
- the principle of waste minimisation.

Part II – Environmental Protection Authority

Part II establishes the functions and powers of the Environmental Protection Authority (EPA). The EPA is the primary provider of independent environmental advice to government. It consists of five members, including a full-time chairman, each appointed by the Governor of Western Australia on the recommendation of the Minister for Environment. They meet fortnightly.

The objective of the EPA, as stated in Part II, is to protect the environment and to prevent, control and abate pollution and environmental harm. It assigns a range of functions and powers to the EPA to achieve these objectives and furthermore states that the EPA is independent and cannot be directed by the Minister. The composition and appointment of the board of the EPA is prescribed. The operation of the meetings and staffing of the EPA is provided for, as well as the provision of services by staff of the Office of the EPA to assist the EPA to perform its functions. It allows for the establishment of advisory groups, committees, councils and panels.

Functions under Part II include the provision of strategic advice to the Minister for Environment under section 16(e). The EPA has provided strategic advice on a range of matters that have significant bearing on wetland conservation. For example, the use of managed aquifer recharge using treated wastewater; and the future of the Dawesville to Binningup area (inclusive of the internationally significant Peel Yalgorup wetlands).

Environmental protection policies: statutory policies developed under Part III of the *Environmental Protection Act 1986*. They are whole-of-government policies that are ratified by Parliament and have the force of law as if part of the Act from the day they are published in the Western Australian Government Gazette.[2]

Part III – Environmental protection policies

Part III covers the full process of development of **environmental protection policies** (herein 'EPPs'). It describes the preparation, consultation, and publication of draft environmental protection policies by the EPA for consideration of the Minister for Environment.

EPPs are used by the state government to address environmental issues that could not otherwise be adequately addressed via other provisions of the Act. EPPs have been used to provide strong (legal) environmental policy positions and have been applied to a wide variety of environmental issues across various geographical scales.

An EPP may include:

- identification of the area of the environment to which it relates
- identification of the environmental values to be protected
- environmental quality objectives to be achieved by the EPP, a programme to achieve and maintain them and how they will be measured
- how the environmental area is to be protected from pollution and environmental harm and how any activities which might cause environmental harm could be prevented, controlled or abated
- creation of offences and provide penalties for any activities which cause undue environmental harm.

An approved EPP prevails over a town planning or region scheme unless the scheme was assessed by the EPA under Division 3 of Part IV (Assessment of schemes) of the EP Act. Approved EPPs are required to be reviewed within seven years of gazettal.

The EPA develops EPPs, however, it is DEC that has responsibility for investigating potential breaches. Penalties for breaches apply.

➤ Three EPPs directly relate to wetland protection:

  - the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992*
  - the *Environmental Protection (South West Agricultural Zone Wetlands) Policy 1998*
  - the *Environmental Protection (Western Swamp Tortoise Habitat) Policy 2011.*

These policies are described in this topic in the section 'Policies for wetland conservation'.

Part IV – Environmental impact assessment

Part IV of the EP Act establishes the requirement for **environmental impact assessment** (EIA) of proposals that are likely to have a significant effect on the environment.

The EPA's objectives for environmental impact assessment include:

(a) to ensure that proponents take primary responsibility for protection of the environment influenced by their proposals;

(b) to ensure that best practicable measures are taken to minimise adverse impacts on the environment, and that proposals meet relevant environmental objectives and standards to protect the environment, and implement the principles of sustainability;

(c) to provide opportunities for local community and public participation, as appropriate, during the assessment of proposals;

(d) to encourage proponents to implement continuous improvement in environmental performance and the application of best practice environmental management in implementing their proposal; and

(e) to ensure that independent, reliable advice is provided to the Government before decisions are made.[3]

The EPA provides advice, the Minister makes the decision

The EPA advises the Minister on the environmental acceptability of proposals and schemes. It is the government, through the Minister, who has responsibility for approving or refusing proposals and schemes under the EP Act. The EPA is not a regulatory agency and it does not issue approvals.

This part of the Act makes provisions for:

- the referral and assessment of proposals and schemes
- the preparation of a report by the EPA to the Minister on the outcome of its assessment
- conditions and procedures of implementation of proposals.

Section 122 of the Act also allows for the publication of specific administrative procedures to be followed during the environmental impact assessment process. These are the *Environmental Impact Assessment Administrative Procedures 2010*. These administrative procedures were published ('gazetted') in the **Government Gazette** No. 223.

Division 1 – Referral and assessment of proposals

Division 1 of Part IV of the EP Act outlines the process of referral and assessment of **significant** and **strategic proposals**.

The EP Act specifies who can refer significant and strategic proposals. In general, responsibility for referral of a proposal to the EPA rests with **decision-making authorities**.

Environmental impact assessment: an orderly and systematic process for evaluating a scheme or proposal, including its alternatives where relevant, and its effects on the environment, including the mitigation and management of those effects.[3]

Government Gazette: a government publication issued by the State Government which includes details of statutory matters, available from the State Law Publishers.

Significant proposal: a proposal likely, if implemented, to have a significant effect on the environment.

Strategic proposal: a future proposal that will be a significant proposal; or future proposals likely, if implemented in combination with each other, to have a significant effect on the environment.

Decision-making authority: a public authority empowered to make a decision in respect of a proposal. Often abbreviated to DMA.[3]

For example, subdivision and development applications are types of proposals that may require referral by planning agencies to the EPA. However, any person may refer a significant proposal, except if it comes under a scheme that has already been assessed. In this circumstance, only the **proponent** can refer the proposal. The EPA may also require a proponent or decision-making authority to refer a proposal if it considers it to be a significant proposal. If the referral is made by someone other than the proponent or the decision-making authority, it is known as a 'third party' referral.

Proponent: the person who is responsible for the proposal, or the public authority on which the responsibility for the proposal is imposed under another written law

Wetland triggers for referral to the EPA

The EPA has published an extensive list of wetlands that, for the purposes of environmental impact assessment, it considers to be of high conservation significance and to require a high level of protection. This list is available on page 4 of Chapter B4 of EPA Guidance Statement No. 33: *Environmental Guidance for Planning and Development*.[3] A proposal that is likely, if implemented, to have a significant impact on any of these wetlands is likely to require referral to the EPA for environmental impact assessment. Examples of significant impacts include: clearing of native vegetation, mining, filling, excavating, draining or disposal of waste, allowing emissions into the wetland, and activities located near the wetland without the provision of an appropriate setback or buffer, such as clearing or groundwater abstraction.

Figure 1. Developments with the potential to impact upon wetlands of conservation significance are one kind of activity that may trigger referral of a proposal to the Environmental Protection Authority for environmental impact assessment under the *Environmental Protection Act 1986*. Photo – J Davis.

Determinations about the use and management of water

How water is used and managed is critical to protecting and managing WA's wetlands. Water management is regulated by a range of Acts, many of which are old and overlapping. Section 3 of the EP Act defines a 'proposal' as a project, plan, programme, policy, operation, undertaking or development or change in land use, or amendment of any of the foregoing, but does not include scheme. On this basis, proposals regarding water use and management can be subject to either section 38 (significant proposals) or section 40B (strategic proposals) of the EP Act; or the EPA may prepared strategic advice to the Minister for Environment under section 16(e).

When a proposal that has previously been assessed as a strategic proposal (under section 40B) and granted approval is referred to the EPA, the proponent has the right to request the EPA declare this a **derived proposal.** The EPA does not assess derived proposals. With changes introduced in 2010, there are no longer appeal rights on the EPA's decision to declare a referred proposal a derived proposal.

Derived proposal: a proposal referred to the Environmental Protection Authority under section 38 of the *Environmental Protection Act 1986* that is declared by the EPA to have been identified in a strategic proposal that has been assessed and granted approval under Part IV of the Act[4]

The EPA may request additional information on a referred proposal and once the information provided is sufficient, it will publish the referral information on the EPA website: www.epa.wa.gov.au/EIA/referralofProp-schemes/Pages/Publiccommentonreferrals.aspx. The EPA will provide a seven day public comment period on each referred proposal before it proceeds to make a decision on whether or not to assess the proposal, and if so the level of assessment. Comments on the referral information must be made using the Referral Comment Form available on the EPA website (on the webpage listed above).

The EPA is required to decide whether or not to assess the referred proposal within twenty-eight days of receipt of all required information. The EPA publishes this decision on its website and in the public notices in *The West Australian* newspaper on Mondays.

Anyone can appeal an EPA decision not to assess a proposal, with the exception of those circumstances where the EPA has recommended that the proposal be managed under the native vegetation clearing provisions of the EP Act (these provisions are described below, see 'Part V' information).

The assessment of a proposal is usually carried out using a standard set of procedures. The nature of the proposal determines which of the following two procedures, or, 'levels of assessment' will be followed:

- assessment on proponent information (API), applied where the environmental acceptability or unacceptability of the proposal is apparent at the referral stage. A public review period is not considered necessary because either:
  - the proponent has appropriately and effectively consulted with the stakeholders during the preparation of the proposal, or
  - further consultation through a public review process is unlikely to identify additional stakeholders or raise additional significant environmental issues.
- public environmental review (PER), applied where:
  - the proposal is of regional and/or State-wide significance.
  - the proposal has several significant environmental issues or factors, some of which are considered to be complex or of a strategic nature.
  - substantial and detailed assessment of the proposal is required to determine whether, and if so how, the environmental issues could be managed.
  - the level of interest in the proposal warrants a public review period (generally 4–12 weeks).

The level of assessment determines what documentation and public review processes are required. With changes introduced in 2010, there are no longer appeal rights on the EPA's decision to assess a proposal or on the level of assessment.

➤ The procedures for each level of assessment, including public review processes, is shown in flow diagram format in Appendix 1 and 2.

Once the EPA has completed its assessment, it is required to prepare a report on the outcome of its assessment to the Minister which includes the key environmental factors identified and the EPA's recommendations as to whether or not the proposal may be implemented.

If it recommends that the proposal be allowed, any conditions and procedures that the proposal should be subject to will be detailed. An assessment is then required to be published and distributed to the proponent or referrer and to any other Minister or decision-making authorities to which the proposal relates.

The EPA and/or Minister also retain the right to inquire as to whether or not the implementation conditions relating to the proposal should be changed. Once the inquiry is complete, the EPA must report a recommendation to the Minister as to whether or not the implementation conditions should be changed.

extra information

How clearing of native vegetation is dealt with under Part IV

The regulation of clearing of native vegetation is primarily provided for under Part V of the *Environmental Protection Act 1986*. When a proposal that involves clearing is referred to the EPA under Part IV, the EPA will determine whether it will be assessed. Under Schedule 6 of the Act, if the proposal is assessed by the EPA, clearing of native vegetation that is done in accordance with an implementation agreement or decision is exempt from the requirement to obtain a clearing permit. The EPA can decide not to assess a proposal; if this occurs, the clearing of native vegetation may not be exempt and is subject to assessment under Part V of the Act.

Division 2 – Implementation of proposals

Once all appeals are decided upon, a Ministerial decision is made under section 45 of the Act. The Minister then serves copies of a statement setting out the implementation conditions and decision to the EPA, consulted decision-making authorities, the proponent and referrer (if this is not the proponent) and the statement is then published in the public notices of *The West Australian* newspaper and published on the Office of the Appeals Convenor website. If a decision is made that the proposal may not be implemented, the Minister shall notify relevant stakeholders and not issue a statement.

After a statement has been issued in relation to a proposal, the Minister may approve of the proponent changing the proposal without a revised proposal being referred to the EPA, where those changes to the proposal are not considered to have an effect on the environment different to the effect of the original proposal.

Once served a statement, the proponent is required to ensure that a proposal is implemented in accordance with implementation conditions; failure to do so is considered an offence.

➤ For more information, see the 'Environmental impact assessment' webpage of the EPA website www.epa.wa.gov.au.

➤ The Environmental Defender's Office of WA (Inc.) fact sheet *Environmental impact assessment in Western Australia*[5] outlines the laws relating to EIA in WA.

Division 3 – Assessment of schemes

Division 3 assigns responsibility to the EPA to decide whether or not to assess a **scheme** referred to it and the actions to be taken once this decision is made.

Scheme: a redevelopment scheme, a region planning scheme, a local planning scheme or a state planning policy to which section 32 of the *Planning and Development Act 2005* applies, or an amendment to any of these.

Schemes generally establish the appropriate land uses for large areas of land. They include a map showing the zonings applied over a geographic area and accompanying text outlining the details of what kinds of land uses are allowed to occur. Schemes include regional planning schemes such as Metropolitan Region Scheme, local planning schemes for each local government area, and redevelopment schemes such as the East Perth Redevelopment Scheme.

The legislative process for scheme assessments was introduced in 1996 in recognition that in many instances it is more appropriate to apply environmental assessment at the rezoning or scheme formulation stage than to leave it to the subdivision or development stage.[3] This principle is particularly relevant for wetlands. Providing for the protection of wetlands as part of broadscale planning processes is generally most effective. This is because wetland management and protection requires management of catchment scale processes, such as water management, and landscape scale processes such as ecological linkages and buffers.

➤ For a useful summary of the referral and assessment of schemes, see Chapter A3 'Environmental impact assessment of schemes' in EPA Guidance Statement No. 33, *Environmental Guidance for Planning and Development* (EPA 2008).

➤ A checklist of wetland issues to be considered during broadscale planning is available from Chapter B4 'Wetlands' in EPA Guidance Statement No. 33, *Environmental Guidance for Planning and Development.*[3]

The EPA is required to report to the Minister on the environmental factors relevant to the scheme and the conditions if any to which the scheme is to be subject.

This must occur within sixty days from the end of the public review period or thirty days after receiving a response to environmental issues raised in submissions or a period as the Minister allows. The Minister, after receiving the report and any recommendations made to him/her will publish the report and recommendations and provide copies to other Ministers concerned and to the responsible authority to which the scheme report relates. The Minister will then consult with the Minster of the responsible authority and if possible, agree with him/her on conditions, if any to which the scheme should be subject if implemented. If an agreement is reached, the Minister will provide copies of conditions to the Authority, the responsible Minister, the responsible authority and any relevant decision making authority and advise that there are no environmental reasons why the scheme should not be implemented.

A responsible authority may, after the publication of a statement of conditions and before the responsible Minister or the Governor grants final approval of the scheme, request the responsible Minister to initiate a review of the conditions set out in the statement. If the responsible Minister agrees to a request, the responsible Minister and the Minister shall consult each other and attempt to reach agreement on whether or not the relevant conditions should be altered and if so to what extent. If conditions are altered and an agreement is reached, copies of the new condition statement will be delivered to all the relevant stakeholders.

Division 4 – Implementation of schemes

Under Division 4, a responsible authority is required to monitor the implementation of its assessed schemes and those proposals under its assessed schemes, to ensure those assessed schemes and proposals subject to conditions are in compliance and conditions are being implemented. If the responsible authority finds a condition has not been complied with, it is required to report this to the Minister and to exercise the power it has available under law in regards to the non-compliance.

When a proposal under an assessed scheme appears likely to have a significant effect on the environment comes to the attention of the responsible authorities in respect to the assessed scheme, the responsible authority must determine whether or not environmental issues raised by the proposal were assessed under the scheme and whether the proposal complies with the scheme and any conditions which it is subject. If the proposal does comply and environmental issues raised were assessed the proposal does not need to be referred to the EPA.

Clearing of native vegetation that is done in the implementation of a proposal made under an assessed scheme in accordance with a subdivision approval, a development approval or a planning approval given by the responsible authority is exempt from the requirement to obtain a clearing permit under Part V.

Part V – Environmental regulation

Part V establishes environmental regulation for pollution and environmental harm offences and clearing of native vegetation (including the declaration of environmentally sensitive areas).

It also provides for the administration of clearing permits, licensing and registration of prescribed premises, works approvals and licences and the circumstances under which the EPA may administer notices, orders and directions.

DEC has responsibility under this part of the Act for the licensing and registration of prescribed premises, licensing of controlled waste transporters, and administration of a range of regulations. It also monitors and audits compliance with clearing permits, works approvals and licence conditions, takes enforcement actions as appropriate, and develops and implements departmental permitting, licensing and regulatory policy.

Division 1 – Pollution and environmental harm offences

Division 1 establishes the following offences:

- to cause pollution or allow pollution to be caused;
- to intentionally or with criminal negligence emit an unreasonable emission or cause an unreasonable emission to be emitted from any premises;
- to cause or allow waste to be placed in any position which is likely to cause pollution; and
- to cause or allow to be caused, serious or material environmental harm.

Regulations may require **authorisation** for conduct that might cause pollution or environmental harm.

Authorisation: a licence, permit, approval or exemption granted, issued or given under the Part V environmental regulations

What is environmental harm?

Environmental harm includes:

- the direct or indirect harm to the environment involving removal or destruction of, or damage to, native vegetation or the habitat of native vegetation or indigenous aquatic or terrestrial animals; or
- alteration of the environment to its detriment or degradation or to the detriment of an environmental value; or
- alteration of the environment of a prescribed kind.

The definition of environmental harm is provided in section 3A of the EP Act. It also defines 'material' and 'serious' environmental harm. The objective of the EP Act is not to outlaw day-to-day activities which cause some trivial harm to the environment. To be an offence under the Act, the harm must be more than trivial or negligible.

Figure 2. Officers of DEC's Pollution Response Unit. Photo – P Nicholas/DEC.

Clearing: any act that kills, destroys, removes or substantially damages native vegetation in an area. This includes severing or ringbarking of trunks or stems, draining or flooding of land, burning of vegetation and grazing of stock or any other act or activity that causes damage to some or all of the native vegetation in an area.

Native vegetation: native aquatic or terrestrial vegetation, and includes dead vegetation unless that dead vegetation is of a class declared by regulation to be excluded from this definition but does not include vegetation in a plantation or which was intentionally sown, planted or propagated unless that vegetation was sown, planted or propagated as required under law

Division 2 – Clearing of native vegetation

In July 2004, significant changes were made to the EP Act and the Environmental Protection (Clearing of Native Vegetation) Regulations 2004 ('the clearing regulations') were enacted to introduce provisions that protect native vegetation while allowing for permitted clearing activities.

This part of the Act establishes it to be an offence to cause or allow **clearing** of **native vegetation** unless it is done in accordance with a clearing permit, or is exempt. The Act applies to all land in WA, including private property, public and Crown land, pastoral leases and mining tenements. Commonwealth lands are the only land that may not be subject to the clearing regulations. The Act also applies to all waters in the state, including rivers, streams, wetlands, dams and all other natural and artificial watercourses and waterbodies. It also applies to coastal waters which include marine areas within 3 nautical miles (5.5 kilometres) of the low tide mark.

The exemptions specified in Schedule 6 of the EP Act generally relate to activities that are authorised under other law. For example:

- clearing that is caused by the grazing of livestock on land held under a pastoral lease, provided that the grazing is not in breach of the *Land Administration Act 1997*, the pastoral lease or any relevant condition set or determination made by the Pastoral Lands Board.
- clearing authorised under a licence ‘to take’ protected flora under the *Wildlife Conservation Act 1950* as issued by DEC.[6]

Regulation 5 of the Environmental Protection (Clearing of Native Vegetation) Regulations 2004 contains a further set of exemptions for day-to-day activities. Examples of the types of activities exempt under these regulations include clearing for firewood, clearing for vehicular tracks and clearing along fence lines. Some of these exemptions limit the amount of clearing for any purpose to a total of one hectare per property per financial year. Differing to the Schedule 6 exemptions contained in the Act, the exemptions under the regulations do not apply where the activity is proposed to be undertaken in an area declared to be an ‘environmentally sensitive area’ by the Minister for Environment.

What are environmentally sensitive areas?

There are a number of declared environmentally sensitive areas (ESAs) within Western Australia where the exemptions in the clearing regulations do not apply. Section 51B of the EP Act enables the Minister for Environment to declare by notice either a specified area of the state or a class of areas of the state to be an ESA. Declared ESAs are listed in the *Environmental Protection (Environmentally Sensitive Areas) Notice 2005*. These include ‘defined wetlands’ and the area within 50 metres of the defined wetland (Figure 3), and threatened ecological communities listed by the Minister for Environment, which include many wetland areas. The location of ESAs can be viewed on the ‘Native Vegetation Map Viewer’ on the Department of Environment and Conservation website: http://maps.dec.wa.gov.au/idelve/nv/index.jsp

Figure 3. Lake McLeod, in the Shire of Carnarvon, is one of many wetlands in the state that are declared environmentally sensitive areas in accordance with the *Environmental Protection (Environmentally Sensitive Areas) Notice 2005*.

➤ The document, *A guide to the exemptions and regulations for clearing native vegetation under Part V of the Environmental Protection Act 1986*[7], provides more details. It is available on DEC's website www.dec.wa.gov.au.

If an activity is not exempt under the clearing regulations or Schedule 6 of the EP Act then a person proposing to clear native vegetation must apply for a clearing permit.

DEC has primary responsibility for regulating the clearing of native vegetation in WA. Under section 20 of the EP Act, DEC has delegated certain provisions to the Department of Mines and Petroleum (DMP) for the administration, assessment and approval of clearing for mineral and petroleum activities.[8] Applications for a clearing permit should be made to DEC, unless the application relates to mineral or petroleum activities, in which case the application should be made to DMP.

There are a number of clearing principles which the relevant department must have regard to when deciding whether to grant a clearing permit. These include the level of biological diversity in the area to be cleared, the importance of the vegetation to maintain a significant fauna habitat, and the impact of clearing on the quality of the surface or groundwater. The assessing department must also take into consideration planning and other matters including schemes and strategies, policies or plans adopted under a scheme, state planning policies and local planning strategies, and the department must ensure that the clearing permit is consistent with any approved planning instruments.

extra information

How wetlands are considered under the clearing principles

Under section 51O of the EP Act, the CEO must have regard to ten clearing principles when deciding to grant, or refuse, a permit. The CEO must also have regard to planning instruments (such as town planning schemes) and other relevant matters.

The ten principles, as specified in Schedule 5 of the EP Act, are listed below (with those especially relevant to wetlands in italics, although wetlands may also be relevant to each of the other principles):

(a) Native vegetation should not be cleared if it comprises a high level of biological diversity.

(b) Native vegetation should not be cleared if it comprises the whole or a part of, or is necessary for the maintenance of, a significant habitat for fauna indigenous to Western Australia.

(c) Native vegetation should not be cleared if it includes, or is necessary for the continued existence of, rare flora.

(d) Native vegetation should not be cleared if it comprises the whole or a part of, or is necessary for the maintenance of a threatened ecological community.

(e) Native vegetation should not be cleared if it is significant as a remnant of native vegetation in an area that has been extensively cleared.

(f) Native vegetation should not be cleared if it is growing in, or in association with, an environment associated with a watercourse or wetland.

(g) Native vegetation should not be cleared if the clearing of the vegetation is likely to cause appreciable land degradation.

extra information

How wetlands are considered under the clearing principles

(cont'd)

(h) Native vegetation should not be cleared if the clearing of the vegetation is likely to have an impact on the environmental values of any adjacent or nearby conservation area.

(i) Native vegetation should not be cleared if the clearing of the vegetation is likely to cause deterioration in the quality of surface or underground water.

(j) Native vegetation should not be cleared the clearing of the vegetation is likely to cause, or exacerbate, the incidence or intensity of flooding.

More information is available from *A guide to the assessment of applications to clear native vegetation under Part V of the Environmental Protection Act 1986*.[7]

The relevant department must also invite comment from any public authority or person which/who has, in the opinion of the CEO, a direct interest in the subject matter of the application and the department must advertise the application (Monday's *The West Australian* newspaper and on online via the Clearing Permits Reporting System; see below), inviting the general public to comment. The department must then take any comments into consideration before deciding to grant or refuse a permit. Conditions may be attached to a clearing permit for the purposes of preventing, controlling, abating or mitigating environmental harm or offsetting the loss of the cleared vegetation. For instance, conditions can include permit holders to establish and maintain vegetation on other land, enter into a conservation covenant or agreement to reserve, monitor operations, investigate options for measures to prevent, control or avoid environmental harm and implement and adhere to an environmental management system and plans.

If an application is refused, the department is required to give the applicant written notice. The applicant has the right to appeal the decision to refuse to grant a clearing permit and the decision to refuse to grant all the clearing applied for. Anyone may appeal the condition of the clearing permit. Anyone, except the applicant, may appeal the decision to grant a clearing permit. Appeals must be made within twenty-one days of the decision. Once an appeal is lodged with the Minister, the Appeals Convenor will consult with the department and the person who lodged the appeal. The Appeals Convenor may consult with any other person they think necessary and make a report to the Minister. The Minister makes a decision about the appeal. Once the Minister has made a decision, there is no further appeal allowed. In the incidence that a permit is subject to an appeal, the permit holder cannot undertake any clearing until the appeal has been resolved.[6]

Publicly available information on native vegetation clearing permit applications

Information on clearing permits is available to the general public:

- Notices of clearing applications and decisions are advertised in *The West Australian* newspaper and available on the DEC website.
- The Clearing Permits Reporting System on the DEC website (https://secure.dec.wa.gov.au/cps_reports/index.cfm) states whether clearing has been authorised, and if so, what conditions apply.

There are two types of clearing permits—area permits and purpose permits.

Area permits are those granted for clearing a defined area and can only be granted to the owner of the land or someone acting on the owner's behalf. This permit is transferable upon change of ownership on request from the new owner. Area permits are generally valid for a maximum of two years and are granted for activities such as the clearing of bushland to expand an agricultural activity and the removal of seagrass from coastal waters.

Purpose permits are granted for clearing in various areas from time to time for a specified purpose (such as a program of works) and when the applicant is not the owner of the land they wish to clear but has authority under a written law or permission to access the land to undertake clearing. Purpose permits are generally valid for a maximum of five years. These permits allow the holder to undertake a series of works or activities that involve the clearing of vegetation, over a period without having to apply for a separate area permit on each occasion. Purpose permits are granted for activities such as clearing to construct a new road or highway, where there are a number of different locations to be cleared and the project may take a long time to complete; or progressive clearing of an area for mining over an extended period of time.[6,9]

The department assessing a clearing application must give precedence to decisions made by the Minister regarding related proposals. If a proposal is a component of an environmental impact assessment under Part IV of the Act, the department cannot grant or refuse an application to clear under Part V of the Act until the Minister for the Environment has made a decision on the proposal under Part IV of the EP Act. Only then can the department make a decision, which must be in accordance with the decision of the Minister.

Under the Act, a person who causes or allows clearing of native vegetation commits an offence unless that clearing is done in accordance with a clearing permit or is exempt. The holder of a clearing permit who contravenes conditions established on the permit also commits an offence under the EP Act. DEC's *Enforcement and Prosecution Policy 2008*[10] outlines the principles that are followed in seeking compliance with the legislation.

Prescribed premises: premises prescribed for the purposes of Part V of the *Environmental Protection Act 1986* as specified in Schedule 1 of the *Environmental Protection Regulations 1987*

Division 3 – Prescribed premises, works approvals and licenses

Division 3 establishes that it is an offence to carry out works which cause a premise to become a **prescribed premises** unless in accordance with a works approval.

Certain industries with a significant potential to pollute the environment are designated as prescribed premises under the EP Act and must hold a works approval (for construction) and a licence or registration (for operation).

DEC has responsibility under the EP Act for the licensing and registration of prescribed premises, licensing of controlled waste transporters, and administration of a range of regulations. DEC also monitors and audits compliance with works approvals, licence conditions and regulations, takes enforcement actions as appropriate, and develops and implements departmental licensing and industry regulation policy.

Division 4 – Notices, orders and directions

Division 4 of the Act provides the CEO of the relevant department with powers to issue an environmental protection notice to the owner and/or occupier of a premise if the CEO suspects that there is, or is likely to be, an emission from the premises that would not comply with a required standard or is likely to cause pollution, serious or material environmental harm.

An environmental protection notice may require an investigation, the preparation of a plan to prevent, control or abate the emission/pollution/environmental harm; measures to prevent, control or abate the emission/pollution/environmental harm; limit waste, noise, odour or electromagnetic radiation; monitor and report associated offences.

An environmental protection notice binds each owner or occupier to whom it is given and each successive owner or occupier of the land to which the EP notice relates.

The CEO of the relevant department may extend the period within which a requirement contained in the notice is to be complied with or may revoke or amend any requirement contained in the notice or the notice itself.

A person who does not comply with a requirement contained in the notice commits an offence and may be convicted of that offence.

Part VI – Enforcement

Part VI of the Act provides for the appointment of inspectors for the purposes of monitoring, inspecting, evaluating and analysing samples, records, monitoring and other equipment and installations approved for detecting the presence, level and other characteristics of noise, odour, waste and electromagnetic radiation, and for inspecting native vegetation.

The powers of inspectors are prescribed in the Act, generally entitling inspectors to enter at any time (i) any premises used as a factory or in which an industry, trade or process is being carried on (ii) any site classified as contaminated under the *Contaminated Sites Act 2003* and (iii) premises which the inspector has reasonable grounds to believe that an offence against the Act has been or is likely to be committed.

Part VII – Appeals

Part VII prescribes the process of lodging an appeal in respect to the level of assessment set, reports on proposals and conditions or procedures attached to a decision made by the EPA. The right of decision-making authorities, responsible authorities, proponents or other persons to appeal any decision made by the EPA is prescribed here.

Part VII, section 101 prescribes the process of lodging an appeal against native vegetation clearing permit decisions made by DEC's CEO.

Part VIII – General

Part VIII of the Act prescribes other offences, administrative procedures, codes of practice and regulations, dispute resolution between the EPA and any public authority and for review of the EP Act and operations of the EPA.

Part VIII provides for the production and publication of administrative procedures for the purpose of establishing principles and practices for environmental impact assessment. Codes of practice may also be issued in relation to activities that involve an emission or environmental harm.

The *Wildlife Conservation Act 1950*

The *Wildlife Conservation Act 1950* provides for the conservation and protection of wildlife. DEC is responsible for administering this Act.

It specifically provides protection for native flora and fauna, making it an offence 'to take' protected flora or fauna unless a license authorised by the Minister for Environment is first obtained from DEC.

Under section 6(1) of the WC Act, 'fauna' is legally defined as any animal indigenous to or which periodically migrates to and lives in any State or Territory of the Commonwealth or the territorial waters of the Commonwealth. An animal includes all parts of the animals' body and includes eggs, larvae, semen, carcass, skin, plumage or fur.

Threatened fauna: fauna that is rare or likely to become extinct and gazetted as such by the Minister for Environment

Red list criteria: developed by the International Union for the Conservation of Nature (IUCN) to allocate species of flora and fauna into threat categories of critically endangered, endangered and vulnerable, based on their likelihood of becoming extinct

Figure 4. 'Taking' of fauna, such as native turtles, is an offence unless a license authorised by the Minister for Environment is first obtained from DEC. Photo – A Matheson/DEC.

Also under section 6(1) of the Act, 'to take' in relation to fauna includes to kill or capture any fauna by any means or to disturb or molest any fauna by any means or to use any method whatsoever to hunt or kill any fauna whether this results in killing or capturing any fauna or not; and also includes every attempt to take fauna and every act of assistance to another person to take fauna.

Section 14 of WC Act provides for the listing of fauna which is likely to become extinct, or is rare, or otherwise in need of special protection as 'specially protected fauna'. Those fauna listed as likely to become extinct, or is rare, are referred to as **threatened fauna**. A range of wetland fauna species are identified as threatened fauna.

➤ For information on specific threatened wetland fauna species, see the topic 'Wetland ecology' in Chapter 2.

Threatened fauna are listed by the Minister in Schedule 1 (extant species) and Schedule 2 (extinct species) of a Wildlife Conservation (Specially Protected Fauna) Notice in the Government Gazette. This Notice is usually published each year following recommendations to the Minister from the Threatened Species Scientific Committee and DEC. Assessment of threatened fauna is based on **Red list criteria** developed by the International Union for the Conservation of Nature (IUCN).

The Notice (Schedule 3) also includes migratory bird species protected under the international agreements: the Japan-Australia Migratory Bird Agreement (JAMBA); the China-Australia Migratory Bird Agreement (CAMBA); and the Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA). Many of these bird species have specific relationship with wetlands.

Other specially protected fauna are included in the Notice in Schedule 4, and include fauna which have direct association with wetlands, for example, crocodile species and Burdekin duck (*Tadorna radjah*).

All fauna included on the Wildlife Conservation (Specially Protected Fauna) Notice, that is, in any Schedule to the Notice, have an increased penalty provision under the Act if not taken in accordance with the Act. The penalty is a fine of up to $10,000.

The Minister (or DEC, under delegated power) may grant a licence to take fauna, including threatened fauna. There are a limited number of licence types that may be granted, such as licences for the taking of fauna causing damage to property, and licences to take and mark fauna for research purposes. People who carry out fauna surveys for scientific purposes are required to hold a Regulation 17 Licence to Take Fauna for Scientific Purposes. As a condition of the licence, the licensee is required to submit a return detailing the species and numbers that were captured or sighted.

Threatened flora: flora that has been assessed as being at risk of extinction or is rare or otherwise in need of special protection and gazetted as such by the Minister for Environment. These species are commonly referred to as declared rare flora

Provisions are made under the Act to allow individuals to care for sick, injured or orphaned wildlife until such a time as it can be returned to the wild. A licence is not required unless the animal cannot be returned back to the wild through illness, disability or environmental issues. The decision then to grant a licence or send the animal to another facility or euthanase it will be made by DEC.

➤ For more information on fauna licensing, refer to the DEC fauna licensing webpage.[11]

Under the Act 'flora' is legally defined as any plant which is native to Western Australia or which is published in the Government Gazette as flora for the purposes of the Act (including any wildflower, palm, shrub, tree, fern creeper or vine). A plant includes any part of flora and all seed and spores thereof.

'Protected flora' are those types of flora that are declared (in the Government Gazette) to be protected flora for the purposes of the Act, and hence to which the provisions of the Act apply. Classes of flora that are currently protected are the Spermatophyta (flowering plants, conifers and cycads), Pteridophyta (ferns and fern allies), Bryophyta (mosses and liverworts) and Thallophyta (algae, fungi and lichens).

Under Section 23F of the Act, where the Minister is of the opinion that any protected flora is likely to become extinct or is rare or otherwise in need of special protection, the Minister may declare that flora to be 'rare' throughout the State. Such specially protected flora is termed 'declared rare flora', or commonly referred to as **threatened flora**. Threatened flora are listed by the Minister in Schedule 1 (extant species) and Schedule 2 (extinct species) of a Wildlife Conservation (Rare Flora) Notice in the Government Gazette. As with the specially protected fauna, this Notice is usually published each year following recommendations to the Minister from the Threatened Species Scientific Committee and DEC. Assessment of threatened flora is based on Red list criteria developed by the International Union for the Conservation of Nature (IUCN).

➤ For information on specific threatened wetland flora species, see the topic 'Wetland vegetation and flora' in Chapter 2.

'To take' as referred to in section 6(1) of the Act in relation to flora includes to gather, pluck, cut, pull up, destroy, dig up, remove or injure the flora. Therefore taking of flora includes everything from direct impact by removal or destruction by human hand or machine to indirect activities such as grazing livestock on flora, introducing pathogens that attack it, altering soil moisture, inundation of the flora or allowing air pollutants such as pesticides to harm foliage etc (K Atkins pers. comm.).

In general, the Act regulates the taking of part or all of a WA native plant (protected flora) through the issuing of licences. DEC does not issue such licences where the taking of the flora has been authorised through another legislative process. In this regard, the clearing of native vegetation is regulated under the *Environmental Protection Act 1986* and requires a clearing permit to be obtained from DEC unless exempt. Where a clearing permit has been issued, the further issue of a Wildlife Conservation Act licence is not required by DEC. For more information please refer to the information on Part V of the *Environmental Protection Act 1986* in this topic.

Under Section 23C, people who wish 'to take' flora on lands other than on private property (i.e. Crown land) for scientific study, education, hobby, propagation, or other non-commercial purposes must hold a Scientific or Other Prescribed Purposes Licence obtainable from DEC for a small annual fee. This licence does not entitle the holder to sell any of the flora taken, or use it for any commercial purpose.

If the flora is being taken from Crown land for commercial uses, including for sale, a commercial purposes licence is required. Before it can be issued, the applicant must demonstrate that they have an area on which they can harvest flora. This will include the written permission of any government agency that is managing the land. There is an annual fee for a commercial purpose licence.

Special restrictions apply to the taking of flora from nature reserves, national parks or conservation parks, and such reserves are normally excluded to commercial pickers.

Under Section 23D, no Wildlife Conservation Act licence is required for taking flora from private property, but the permission of the land owner must first be obtained. However, a licence is required to cover the sale of any protected flora taken from the property. This includes the sale of seed that has been collected for revegetation use.

Rare (threatened) flora are provided with additional (special) protection under Section 23F(4) of the Act, whereby the written consent of the Minister must first be obtained before such flora can be taken, irrespective of whether a licence to take protected flora or the permission of the land owner has been granted, or a clearing permit issued. This requirement applies to any person on any land (Crown and private) throughout the state. The penalty for taking rare flora without obtaining the consent of the Minister is a fine of up to $10,000.

Species may also be listed as nationally threatened under the national *Environment Protection and Biodiversity Conservation Act 1999*. See the listing under *Environment Protection and Biodiversity Conservation Act 1999* for more detail.

The Western Australian Government has made a commitment to the repeal and replacement of the *Wildlife Conservation Act 1950* with a Biodiversity Conservation Act that will include the elements expected in a modern biodiversity conservation legislation.

➤ For more information on flora licenses and permits see the DEC flora licensing webpage.[12]

Threatened ecological community: naturally occurring biological assemblages that occur in a particular type of habitat that has been endorsed by the WA Minister for Environment as being subject to processes that threaten to destroy or significantly modify it across much of its range

extra information

Threatened ecological communities

The three main elements of biodiversity are genetic diversity, species diversity and ecosystem diversity. Modern biodiversity conservation strategies are aimed at conserving all these elements. Threatened biodiversity conservation strategies were traditionally aimed at species, however, species conservation now includes consideration of genetic diversity, and the interaction of species is accounted through ecological community conservation.

Ecological communities are defined as naturally occurring biological assemblages that occur in a particular type of habitat. They are the sum of species within an ecosystem and, as a whole, they provide many of the processes which support specific ecosystems and provide 'ecological services'. Those ecological communities that are determined to be at risk of being totally destroyed or significantly modified across much of their range are termed **threatened ecological communities** (TECs).

extra information

Threatened ecological communities (cont'd)

There is currently no state legislation specifically covering the listing of TECs. Instead, an informal, non-statutory process is in place, with formal endorsement of TECs being provided by the Minister. Recommendation on TECs are made to the Minister by the Western Australian Threatened Ecological Communities Scientific Committee (TECSC). This committee is appointed by the Minister for Environment, with administrative support provided by DEC. Anyone can submit a nomination for listing or amending the listing of a TEC to the TECSC. Currently there are sixty-nine TECs endorsed by the WA Minister for Environment. Of these, thirty-seven are wetland communities (see Appendix 3 for more information).

TECs receive a level of protection through reference in environmental and planning policies, and environmental impact assessment under the *Environmental Protection Act 1986*. TECs are listed as special environmental areas in the *Environmental Protection (Environmentally Sensitive Areas) Notice 2005*, and are one of the clearing principles under Part V of the EP Act, and consequently receive specific consideration under the Environmental Protection (Clearing of Native Vegetation) Regulations 2004.

Ecological communities may also be listed as nationally threatened under the national *Environment Protection and Biodiversity Conservation Act 1999*. See the listing under *Environment Protection and Biodiversity Conservation Act 1999* for more detail.

For more information, see 'WA's threatened ecological communities' webpage: www.dec.wa.gov.au/management-and-protection/threatened-species.html and DSEWCaP's 'Threatened species and ecological communities' webpage: www.environment.gov.au/biodiversity/threatened/index.html

The *Conservation and Land Management Act 1984*

The *Conservation and Land Management Act 1984* provides for the use, protection and management of certain public lands and waters and the flora and fauna in them, and for establishment of authorities responsible for these lands.

The Act relates to state forest, timber reserves, national parks, conservation parks, nature reserves, marine nature reserves, marine parks, marine management areas and other land reserved by the Minister for Lands under the *Land Administration Act 1997*.

Many of the state's high conservation value wetlands are within these areas. For example, approximately 60 percent (56,977 hectares) of the nationally important wetlands within the south west agricultural zone area are managed by DEC as part of the conservation estate.[13]

The Act also establishes a number of statutory bodies to facilitate the protection and management of public lands, including DEC and the Conservation Commission of Western Australia. Terrestrial conservation reserves in WA are vested in (owned by) the Conservation Commission of Western Australia.[14]

➤ More information about the role of the Conservation Commission is provided in the topic 'Roles and responsibilities' in Chapter 5.

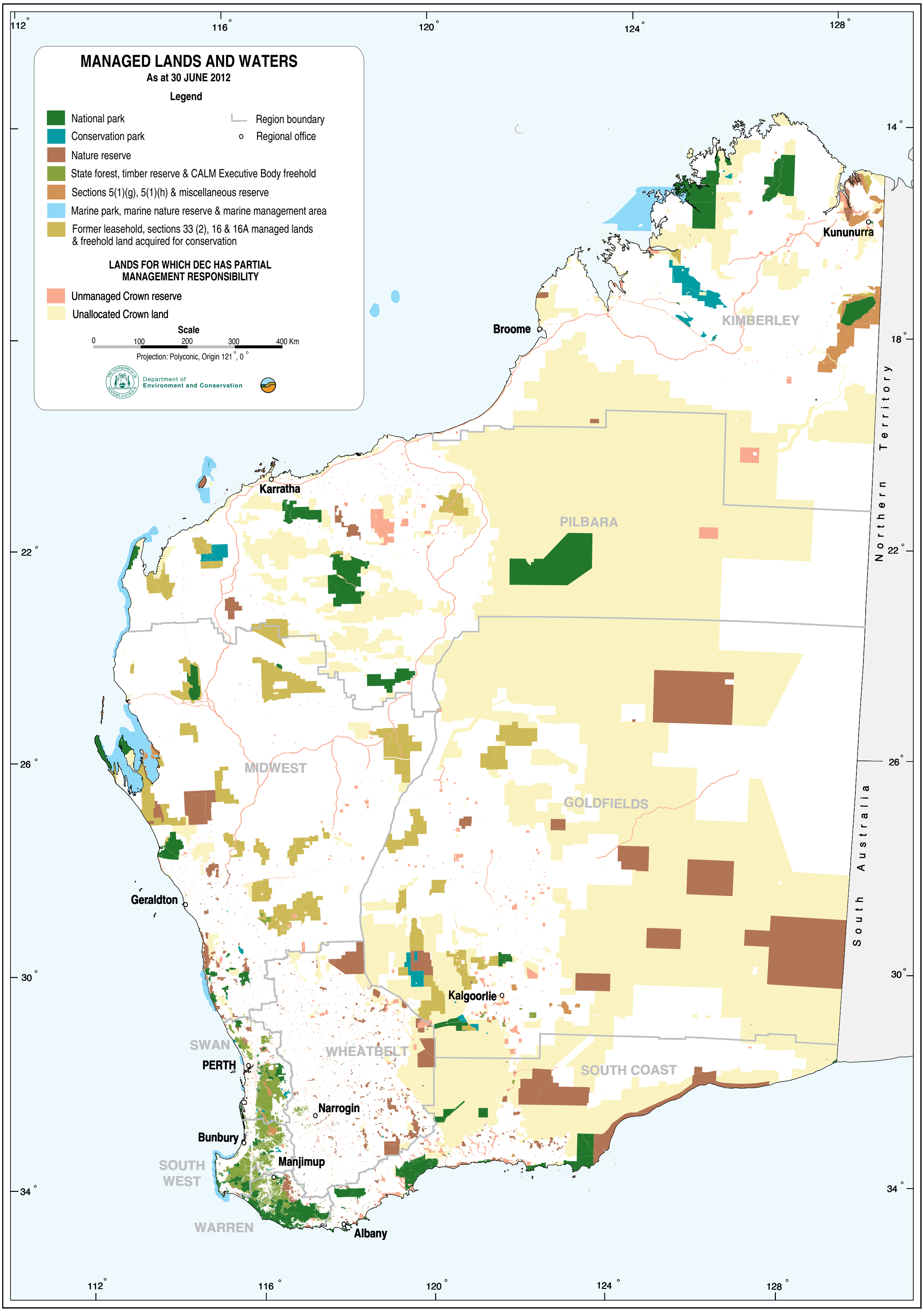

Figure 5. DEC managed lands and waters at 30 June 2012.

Where an **endorsed management plan** exists for a national park, conservation park or nature reserve, DEC must manage the reserve in accordance with the plan. If there is no management plan for a reserve, DEC must undertake only 'necessary operations' or 'compatible operations'. DEC's management of conservation land is subject to performance review by the Conservation Commission.

Endorsed management plan: a management plan that has been approved and/or modified by the Minister for Environment as he/she thinks fit

The Act specifies offences and the penalties and prosecution powers available to the relevant authority under the Act.

The operation of the CALM Act cannot derogate (override) the operation of the *Mining Act 1978, Petroleum Act 1967* (or any other Act relating to minerals or petroleum). However in relation to mining on 'reserved land' (a sub-category of crown land that includes all land formally managed under the CALM Act) the Minister for Mines must (according to the class and category of reserve) obtain either the agreement or recommendations of the Minister responsible for the reserve regarding whether and under what conditions mining or exploration activities may proceed. In relation to CALM Act lands, this Minister is the Minister for Environment.

In relation to the Petroleum Act, the Minister responsible for the reserve is required to be consulted by the Minister responsible for the Petroleum Act before the tenement holder may access the reserved land to carry out activities or operations authorised under the Act.

Under the Mining Act or Petroleum Act the Minister for Mines may grant tenements without consulting the responsible Minister, however, under the Mining Act the convention is normally to consult the responsible Minister before grant of tenure over reserved lands. Exceptions are the grant of a mining lease over national park or class A nature reserve, which requires support of both Houses of Parliament.

extra information

Regional parks

Regional parks are a land management system that provides the opportunity for a coordinated planning and management approach by a number of management agencies and private landowners for areas identified as having regionally significant conservation, landscape and recreation values.

These parks are not afforded special legal status, but are rather a recognition of geographically related areas thathave a common management focus. DEC coordinates management but they are not reserved under the *Conservation and Land Management Act 1984*, and hence DEC does not have management responsibility for these areas. They comprise a range of land tenures vested in a range of managing authorities.[14]

Many significant wetlands are within Perth's regional parks, including the Rockingham Lakes Regional Park, Herdsman Lake Regional Park, Yellagonga Regional Park, Jandakot Regional Park and Beeliar Regional Park.

The *Planning and Development Act 2005*

The *Planning and Development Act 2005* (PD Act) is the principal land use planning legislation in WA, providing for efficient land use planning in the State. It is administered by the Western Australian Planning Commission (WAPC), with the authority for some decisions delegated to the Department of Planning.

Land use planning is carried out at state, regional and local scales. Figure 6 shows how state, regional and local planning processes interact.

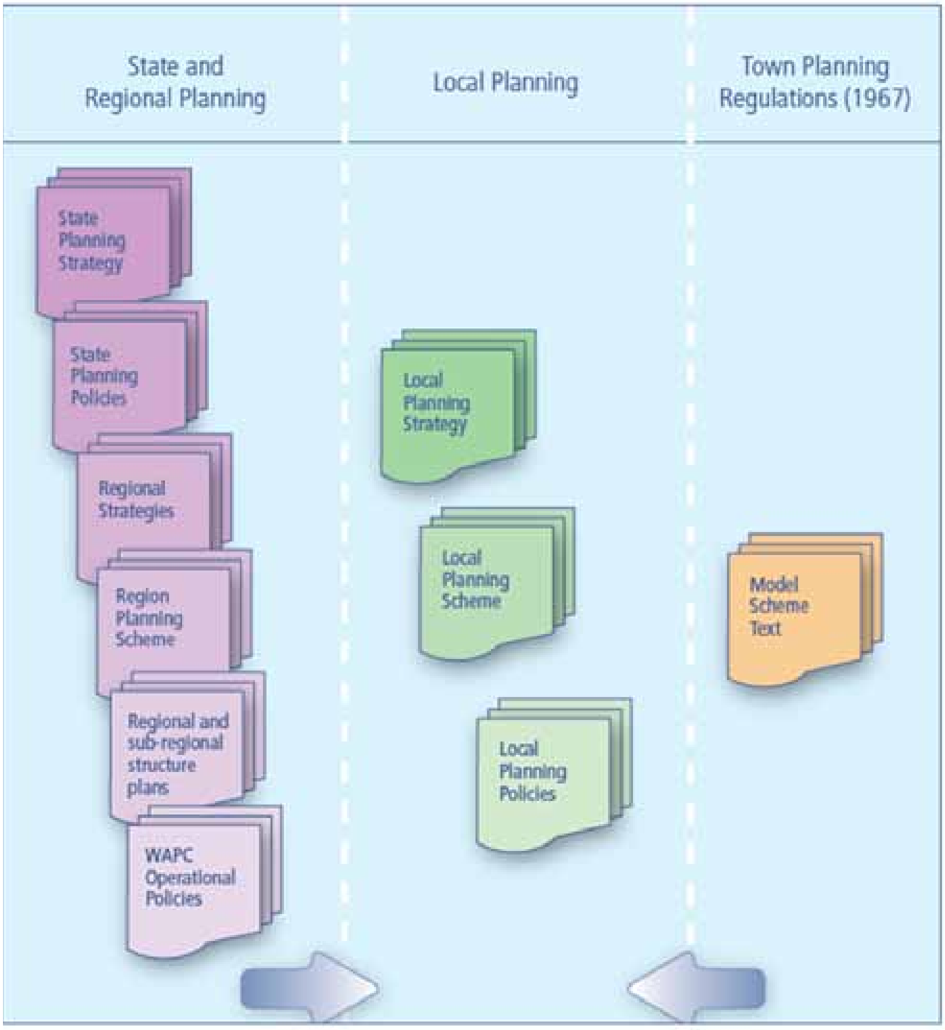

Figure 6. State, regional and local planning instruments. Image – Western Australian Planning Commission.[15]

Land use planning plays a decisive role in the protection afforded to wetlands, particularly in urban areas. It can determine whether a wetland is protected or if it may be developed over or altered into an artificial system. It can also determine what activities can occur in the catchment that will ultimately have a significant effect on the long-term integrity of wetland ecosystems. Therefore, the *Planning and Development Act 2005* is critical to wetland protection in WA.

This Act primarily replaces three repealed planning Acts: the *Western Australian Planning Commission Act 1985; Metropolitan Region Town Planning Scheme Act 1959;* and the *Town Planning and Development Act 1928*. These Acts were amalgamated to simplify planning legislation, make it more accessible to users, provide greater consistency and certainty in planning decision making and promote the sustainable use and development of land.[16]

The PD Act prescribes key planning processes including:

- Part 3 - state planning (policies, structure planning and planning strategies and bulletins)
- Part 4 - region schemes
- Part 5 - local planning schemes
- Part 8 - improvement plans
- Part 9 - subdivision and development
- Part 13 - enforcement and legal proceedings
- Part 14 – applications for review.

An overview of the application of these planning processes in the context of wetland protection is provided below.

State planning policies

Part 3 of the PD Act provides for the preparation of policies on state planning matters by the Western Australian Planning Commission. These are called state planning policies (SPPs) and are statutory policies prepared under the Act, approved by the Minister for Planning and the Governor and published in the Government Gazette.

These policies are concerned with broad general planning and facilitate the coordination of planning throughout the state by all local governments. SPPs can be made for matters which may be the subject of a local planning scheme or which relate to a specific region or area of the state. Examples include statewide policies for coastal planning and rural land use planning, and specific regional policies for the protection of bushland, the Peel-Harvey coastal plain catchment and Gnangara and Jandakot groundwater mounds.

The WAPC prepares SPPs in consultation with Western Australian Local Government Association. The WAPC and local governments must have 'due regard' to the provisions of state planning policies when preparing or amending local planning schemes. The State Administrative Tribunal is also required to have due regard for relevant state planning policies when determining applications for review.

The consultative requirements for development of SPPs facilitate input from community, local government, and agencies into these policies. Copies of SPPs must be made publicly available and a notice published in a daily and Sunday newspaper stating the purpose of the SPP and detailing a submission period of sixty days or more within which submissions can be made.[16]

➤ A number of state planning policies have a significant bearing on wetland conservation and protection in WA. These include:

  - *State Planning Policy 2: Environment and Natural Resources*
  - *State Planning Policy 2.1: Peel-Harvey Coastal Plain Catchment*
  - *State Planning Policy 2.2: Gnangara Groundwater Protection*
  - *State Planning Policy 2.3: Jandakot Groundwater Protection*
  - *State Planning Policy 2.8: Bushland Policy for the Perth Metropolitan Region*
  - *State Planning Policy 2.9: Water Resources*

  These policies are described in this topic in the section 'Policies for wetland conservation'.

Region planning schemes

Part 4 of the PD Act provides for the continuation and preparation of **region planning schemes**. These schemes outline objectives for state and regional development and provide a statutory mechanism to assist strategic planning, coordinate the provision of major infrastructure and set aside areas for **regional open space** (Figure 7) and other community purposes. Examples include the Metropolitan Regional Scheme, Greater Bunbury Regional Scheme and Peel Regional Scheme. The Greater Bunbury Regional Scheme and Peel Regional Scheme are subsidiary legislation made under the PD Act.

A region planning scheme usually covers more than one local government area. The content of the scheme may vary for each region, but generally regional schemes establish broad land use **zones** or policy areas and identify land required for regional purposes. Regional schemes generally outline the broad framework within which local planning schemes are developed under.

Figure 7. Lightning Swamp in Noranda, a suburb in Perth, has been reserved under the Metropolitan Region Scheme. Photo – J Lawn.

For areas not covered by a region planning scheme, the classification of scheme reserves and zones is generally made through local planning schemes.[16]

The PD Act states that during the preparation or amendment of a region planning scheme, the scheme must be referred to the EPA for consideration of the need for an environmental assessment. Other relevant regulators and/or interested groups may also be invited to comment. The EPA may issue an instruction to the responsible authority to undertake an environmental review, which must be completed before the scheme is advertised during the public exhibition period of the scheme.[16]

Region planning scheme (region scheme): a planning scheme prepared for matters of state or regional importance to enable effective planning and coordination of land use and development. Also known as a region scheme.[16]

Regional open space: land defined under a region scheme, regional structure plan or sub-regional structure plan as a parks and recreation reserve or regional open space reserve, to accommodate active and passive recreation such as major playing fields and/or regional conservation and environmental features[17]

Zone: designates uses within a specified area of land as being permitted, prohibited or requiring approval

extra information

The Metropolitan Region Scheme – Perth's blueprint

The Metropolitan Region Scheme (MRS) is a region planning scheme for land use in the Perth metropolitan area. It has been in operation since 1963 and provides the basis for planning in the Perth metropolitan region. The scheme is amended as necessary.

The area covered by the MRS stretches from south of Rockingham to north of Yanchep and east of Mundaring.

The principle functions of the MRS are to:

- reserve land required for public purposes and acquire it as necessary
- identify non-reserved land and classify it into zones such as urban, industrial or rural
- control development on reserved and zoned land, particularly by issuing decisions on development applications.

More detailed plans, known as 'local planning schemes' are prepared by local governments. Local planning schemes must be consistent with the MRS. Where there is an inconsistency the MRS prevails and the local planning scheme is to be amended.

The MRS consists of a set of maps and a scheme text. The scheme text provides planning rules for zones and reservations that are shown on the maps in different colours and patterns. The scheme maps and text are updated to reflect changing needs.[16]

It, and the other region schemes, is available to view online at www.planning.wa.gov.au including in GIS format at https://www.landgate.wa.gov.au/foundationr2/enter_planning_channel.do

Local planning scheme: a set of provisions that identifies the way land in the scheme area is to be used and developed. It may comprise a scheme map(s), a text and an explanatory report[16]

The Minister can consent to public submissions being sought on the proposed region planning and any environmental submissions made during the public exhibition time must addressed by the EPA. The Minister may then approve or refuse the scheme and may impose environmental conditions into the scheme.

Local planning schemes

Part 5 of the PD Act provides for the development of **local planning schemes**. They are developed and administered by local government authorities and have the force of law following approval by the Minister for Planning and publication in the Government Gazette. The Town Planning Regulations 1967 prescribe the procedures for initiating, preparing, advertising and approving local (town) planning schemes and their amendments.

Local planning schemes set out the way land is to be used and developed. This is done by dividing land in the scheme area into zones and reserves. This classifies areas for land use and includes provisions to coordinate infrastructure and development in a locality. This usually includes a zoning or land use class table and controls to ensure long-term strategic planning objectives are achieved.

Local planning schemes complement the provisions of a region planning scheme by detailing land uses. For example, region planning schemes have a broad urban zone. In the urban zone the local planning scheme may detail residential density, identify commercial sites, local open space, primary school sites, light and service industrial areas and other uses.[16]

Local planning schemes are an important mechanism for wetland protection. Schedule 7 of the Act specifically provides for the conservation of the natural environment and the conservation of water to be dealt with by planning schemes. Wetlands can be protected in various ways including reservation, appropriate zoning, and special control areas. Wetlands and buffers may be **reserved** for public purposes as **public open space** for the purpose of conservation. Reserves may be purchased by government or ceded to government, but cannot be developed without approval. The Act provides that an affected owner can claim for compensation for land that is reserved under certain circumstances. The local government can also buy the land instead of paying compensation.

Reserved: set aside for public purposes

Public open space: land used or intended for use for recreation or conservation purposes by the public; it includes district, neighbourhood and local open spaces and parks, but excludes regional open space or foreshore reserves[15,17]

➤ More information on public open space can be found in Development control policy 2.3: Public open space in residential areas.[18]

Controls on development in and near wetlands may also potentially be achieved by the use of special control areas (SCAs). SCAs apply planning controls to clearly defined areas within local planning schemes, and can be used to designate controls on development on and near wetlands. These clearly defined areas may be shown as overlays to the zoning map or on a separate scheme map or maps. The SCAs provide planning controls for a variety of purposes; those most relevant to wetlands include SCAs for the purposes of:

- landscape protection
- establishment of buffers and setbacks
- protection of water catchments
- development controls in flood-prone land
- development controls in bush fire prone areas.

The provision of a SCA include its purpose, and where necessary, specific development requirements and/or performance criteria to be applied to development within SCAs.

SCAs have, for example, been applied to wetlands of conservation significance within local planning schemes in WA, and detailed the development requirements in relation to these sites.

➤ For more information, refer to section 3.5.7 of the *Local Planning Manual: a guide to the preparation of local planning strategies and local planning schemes in Western Australia*.[15]

For a local planning scheme or scheme amendment to be considered for approval it must be submitted to the WAPC and EPA for consideration of the need for an environmental assessment (as outlined in Division 3 of Part IV of the *Environmental Protection Act 1986*). If an environmental assessment is required, the EPA issues an instruction and the local government must undertake an environmental review.

➤ For more information, see the section in this document entitled '*Environmental Protection Act 1986*'.

Section 88 of the Act specifies that local governments are to consolidate their planning scheme or prepare a new scheme every five years. This enables the Minister, WAPC and the community an opportunity to comment on the development of a locality.

extra information

Structure planning – also referred to as outline development plans and subdivision guide plans

Some aspects of land use planning are dealt with by operational policy rather than specific provisions in the TP Act. Structure planning is one such planning mechanism.

Structure planning can be a particularly crucial phase for wetland protection. Structure plans are sometimes also known as *outline development plans* and *subdivision guide plans*. Structure plans incorporate a report, map and additional technical supporting documents. They provide a framework for the coordinated provision and arrangement of land use, subdivision and development in new urban areas ('greenfield' sites) and the redevelopment of areas ('brownfield' sites). They coordinate many aspects of land use including transport networks, public open space, utility services, urban water management and environmental protection and management (as shown in the Stirling City Centre Structure Plan map in Figure 8).

There are several different types of structure plans that are relevant to wetland protection:

- sub-regional structure plans
- district structure plans
- local structure plans

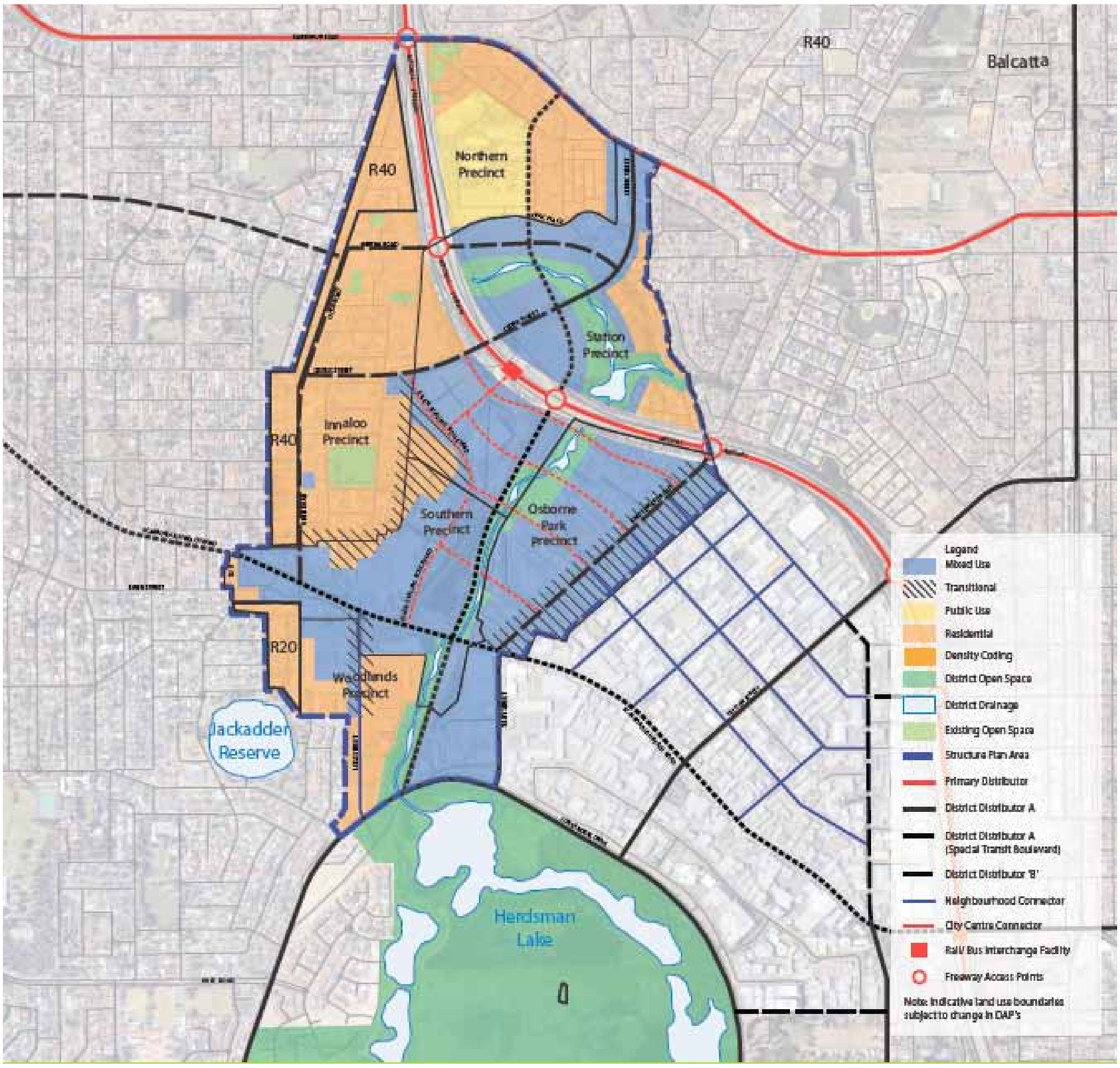

Figure 8. Stirling City Centre Structure Plan. Image – Stirling City Centre Alliance, www.stirlingcitycentre.com.au

extra information

Structure planning – also referred to as outline development plans and subdivision guide plans (cont'd)

WAPC's *Structure plan preparation guidelines*[17] states that structure plans should identify:

- the wetlands present in the structure plan area, including an aerial photo showing their location and extent
- their significance
- existing and proposed conservation areas
- the tenure of the land containing wetlands
- buffers
- a structure plan overlay showing the proposed structure plan over the wetland and buffer
- an environmental assessment and management strategy for the structure plan area, including wetlands, by a qualified environmental consultant
- discuss how the wetlands have been addressed by the structure plan, including any relevant environmental studies, analyses and management measures
- discuss how identified or potential water issues are to be addressed and management, including the requirements for sustainable water supply and existing/new bore licences
- provision of open space for significant conservation and water management functions
- management arrangements and responsibilities for the proposed open spaces
- water management strategy in accordance with *Better Urban Water Management*[19]
- the proposed drainage network and infrastructure
- mosquito constraints

Structure plans can be statutory or non-statutory. Non-statutory structure plans include sub-regional and most district structure plans. These are prepared for land that is either not yet zoned for urban land use or requires a guiding framework to ensure coordination of subsequent layers of more detailed planning and development is achieved.[17] They often cover more than one local government area. District structure plans include a map and text. Wetlands and buffers can be identified as sites to be protected in a district structure plan. Water management requirements to protect the water regime of a wetland can also be addressed through the district structure plan.

Statutory structure plans are required and prepared in accordance with the provisions of a local planning scheme. They are statutory once endorsed by the WAPC. These are usually local structure plans and activity centre structure plans (which are at the neighbourhood scale, that is two suburbs or less, and activity centre scale respectively). Local structure plans are a bridge between the local planning scheme and the subdivision stage of land use planning. New regulations, the Planning and Development (General Provisions for Local Planning Schemes) Regulations, have been proposed to provide a uniform statutory process for the approval and modification of structure plans.[17]

The WAPC states that consultation with stakeholders is essential when preparing a structure plan.[17]

Subdivision and development control

Subdivision: the division of land into lots

Subdivision and development of land occurs once land has been appropriately zoned in a region planning scheme or local planning scheme and any required preliminary planning, for example a structure planning process, has been finalised.

Part 10 of the Act requires the approval of the WAPC for the **subdivisions** or amalgamation of lots. The WAPC is not to give approval that is inconsistent with the local planning scheme, unless provided for in circumstances outlined under section 138 of the PD Act.

Subdivision proposals are referred for comment to local government, relevant public authorities (such as DEC and Department of Health) and utility service providers (such as Water Corporation, Telstra, Western Power and Alinta Gas). Referral bodies have forty-two days to respond to the WAPC (unless otherwise agreed), after which it will be deemed that the referral body has no objection or recommendation. The WAPC may consider some referral agencies' advice to be critical to the assessment of an application, and on that basis can provide referral agencies with additional time to provide a recommendation.[16]

Following review of comments, a report and recommendation is made to the WAPC who will then consider the application in respect to any region or local planning scheme, together with any relevant planning policies. The WAPC has ninety days from the date the plans are submitted to approve or refuse the application with or without imposing conditions. If an applicant is not satisfied with the WAPC's decision, they can request WAPC to reconsider their decision or can apply to the State Administrative Tribunal for a review.

Conditions of subdivision may be applied for many purposes, including the conservation or protection of wetlands. Conditions of subdivision are applied by the WAPC and the applicant is responsible for complying with their requirements. If the WAPC is satisfied that conditions have been complied with, it is to endorse the diagram or plan of survey that enables the Registrar of Titles to issue certificate of titles for the new lots.

Proponents who propose to subdivide an area which encompasses a wetland are often required, as a condition of subdivision, to prepare and implement a wetland management plan. The standard condition is: 'Prior to the commencement of subdivisional works a wetland management plan is to be prepared and approved to ensure the protection and management of the site's environmental assets with satisfactory arrangements being made for the implementation of the approved plan'.[20] DEC or the local government authority is commonly the clearing agency for this condition. Urban water management plans are generally also required in urban areas where water issues are of concern, such as when significant wetlands are in or near the subdivision. The standard condition applied is: 'Prior to the commencement of subdivisional works, an urban water management plan is to be prepared and approved, in consultation with the Department of Water, consistent with any approved Local Water Management Strategy/Drainage and Water Management Plan'.[20] Local government is commonly the clearing authority for this condition.

➤ The *Model Subdivision Conditions Schedule*[20] provides the wording of commonly applied subdivision conditions. It is available at www.planning.wa.gov.au/dop_pub_pdf/Model_Subdivision_Conditions_3_October_2012.pdf

Most types of development approvals are delegated by WAPC to the local government authority to administer through their local planning schemes. Where the WAPC considers types of development may have regional significance, it has the power to retain or regain development control.

Enforcement

The enforcement of local planning schemes and conditions of planning approvals are the responsibility of the local government. The Minister for Planning may give orders to local government or may utilise powers in order to enforce the local planning scheme and approvals. The contravention of a planning scheme or undertaking unauthorised works is deemed an offence and so the person committing the offence may be liable to a penalty.

If a development contravenes a planning scheme or approval, the responsible authority can direct the landowner or person undertaking the development to stop and rectify the contravention even if this involves measures such as removing or pulling down structures and restoring the land. The responsible authority may also apply to the Supreme Court to grant an injunction to restrain a person from continuing to contravene a planning scheme or approval.

Infringement notices can be issued under the *Planning and Development Act 2005*. These notices deal with minor offences where a contravention is clear and apparent. For example: the unlawful use of buildings or illegal parking of commercial vehicles in residential areas.

To ensure environmental conditions are met in the implementation of a development, the Minister for Planning may also issue a written order to the person undertaking development to immediately cease for 24 hours and cause the responsible authority to serve a notice and take necessary steps to rectify any non-compliance with conditions.

➤ The following resources provide more information on the *Planning and Development Act 2005*:

- *An introduction to the Western Australian Planning System*[16]
- *Fact sheet 3: Planning laws*[21]
- *Fact sheet 4: Development controls*[22]

The *Rights in Water and Irrigation Act 1914*

The *Rights in Water and Irrigation Act 1914* (RIWI Act) provides for the regulation, management, use and protection of water resources. It is the principal legislation governing the allocation and management of water resources for consumptive use. Under the Act, the taking and use of that water without appropriate authorisation (such as a water allocation licence) is prohibited. It is administered by the Department of Water.

The objectives of the Act are to:

- provide for the sustainable use and development of water resources and for the protection of the environment
- promote the orderly, equitable and efficient use of water resources
- foster consultation with members of local communities and to enable them to participate in administration
- assist the interaction of the management of water resources with the management of other natural resources.

A 5C licence allows the licence holder to ‘take’ water from a watercourse, wetland or underground source. Under the provisions of section 5C of the RIWI Act, unless a person holds a licence, any unauthorised taking of water is prohibited except where a person has another right to do so or is exempt from licensing. The stock, domestic and riparian rights allow water to be taken without a licence in some circumstances, although this is generally limited to taking it for domestic purposes, fire fighting and for watering stock not held under intensive conditions.

Figure 9. Groundwater abstraction is licensed by the Department of Water under the *Rights in Water and Irrigation Act 1914*. Image – Department of Water.

A 26D licence is issued under the provisions of 26D of the Act to construct or alter wells. A 25D licence is required to commence, construct, enlarge, deepen or alter any artesian well or commence, construct, enlarge, deepen or alter any non-artesian well in a proclaimed groundwater area.

The Department may grant or refuse licenses based on whether the application is in the public interest, ecologically sustainable and environmentally acceptable.

The impacts of accessing the state's water resources are managed by placing appropriate terms and conditions in licences to take and use water, granted under section 5C and 26D of the RIWI Act.

extra information

RIWI Act licences: a critically important mechanism for wetland protection

There are more than 14,000 RIWI Act licences in WA.[23] To find out more about the water allocation planning process, see the following resources:

- *Water allocation planning in Western Australia 2011*[24] provides a summary of the policy and planning framework for these licensing decisions
- *Groundwater risk-based allocation planning process*[25] provides information on how ecological water requirements for groundwater dependent ecosystems are taken into consideration in the allocation planning process.
- Department of Water's webpage: www.water.wa.gov.au/allocationplanning

The Act also provides for the protection of water resources (and associated wetland/riparian land) by requiring permits for activities that interfere with the beds and banks in proclaimed rivers, surface water management areas and irrigation districts (Sections 17, 11 and 21A). Outside proclaimed areas, the powers extend to interferences for taking water from Crown-owned watercourses or wetlands with public access (Sections 11 and 21A).

The Department of Water may grant or refuse permits based on whether the application is in the public interest, ecologically sustainable, environmentally acceptable and consistent with land use planning instruments and other agency policies (Clause 7(2) of Schedule 1 and Regulation 7 Part 2 of the *Rights in Water and Irrigation Regulations 2000*).

Conditions can be made in relation to the use, management, protection and enhancement of any water resource and its ecosystem, including the wider environment around the water resource (Appendix to Schedule 1).

Obstructing or destroying watercourses is an offence (Sections 18 and 25). Under section 5E a "person taking or using water from a water resource" is required to "take all reasonable steps to minimise the degradation of the resource". Degradation is defined in this Act as "the sensible diminishing of the quality or quantity of water" (Section 2(1)).

A direction is a written notice given under the provisions of the Act. The department (on behalf of the Minister for Water) has the power to issue a direction to any person in any part of the state, irrespective of whether they hold a licence or permit.

The *Soil and Land Conservation Act 1945*

The *Soil and Land Conservation Act 1945* (SLC Act) controls land degradation, including the drainage of saline land and applies to all agricultural and pastoral land in WA. The SLC Act is administered for the Minister for Agriculture by the Commissioner of Soil and Land Conservation through the Office of the Commissioner.

The management of drainage of saline land is a critical wetland management issue in agricultural areas affected by salinity. The use of downstream wetlands as 'sacrificial' wetlands that receive saline drainage from agricultural land can significantly degrade these wetlands, even those that are naturally saline.

Figure 10. Drainage of saline land is subject to the *Soil and Land Conservation Act 1945*.

The Soil and Land Conservation Regulations 1992 were introduced to control the drainage of saline land in WA. Regulation 5 requires landholders (owner or occupier) intending to drain or pump water from under the land surface to notify the Commissioner of Soil and Land Conservation at least 90 days before work commences. This includes draining or pumping within the same property.

The aim of the notification is to allow for an assessment of the proposed works to be carried out and to ensure that neighbouring landholders and affected public authorities are given the opportunity to comment on the proposal.

Regulation 6 states that within the Peel-Harvey catchment area, a notice of intention is required for any draining or pumping works.

It is an offence not to give notice of intent to drain when required to do so. The penalty is $2,000 for individuals and up to $10,000 for companies. Furthermore approvals often apply under other legislation. For example, drainage may involve approvals to develop, clear, take groundwater and undertake earthworks on the bed or banks of watercourses. Unauthorised actions may cause environmental harm under the *Environmental Protection Act 1986*.

A soil conservation notice (SCN) may be applied where land degradation has occurred, or is likely to occur, on a pastoral or agricultural land. 'Land degradation' includes salinity, erosion, flooding and the removal or deterioration of natural or introduced vegetation.

➤ Although drainage and groundwater pumping for salinity control are regulated under the SLC Act, the Act does not clearly define the roles of all the participants of these schemes. The *Policy framework for inland drainage*[26] defines the roles and responsibilities of drainage practitioners and other stakeholders including regulators. It also provides the principles for assessing drainage proposals.

➤ A publication series entitled 'Conservation practices for agricultural land' outlines best management practice standards for graded banks, grassed waterways, leveed deep drains, open deep drains and shallow relief drains. See www.agric.wa.gov.au/PC_93235.html?s=1532050204.

The *Land Administration Act 1997*

The Land Administration Act 1997 (LA Act) is the key Act governing the use of pastoral leases. It is administered by the Pastoral Lands Board (through the Department of Regional Development and Lands) and applies to pastoral lessees, and has implications for wetland management on pastoral lands.

It requires that:

- pastoral lessees must use methods of best pastoral and environmental management practice
- land is not to be used for any other purpose other than pastoral except in accordance with the permit
- the lessee must maintain the indigenous pasture and other vegetation on the land
- non-indigenous pasture cannot be sown on a lease without a permit
- permits to clear or develop pastoral land cannot be approved unless the requirements under other legislation, including the Wildlife Conservation Act 1950 and Soil and Land Conservation Act 1945, have been complied with.[1]

Figure 11. Pastoral areas of the state encompass many wetlands of conservation significance. The *Land Administration Act 1997* requires pastoral lessees to use methods of best pastoral and environmental management practice. Photo – L Bayley/Department of Agriculture and Food.

The *Aboriginal Heritage Act 1972*

The Aboriginal Heritage Act 1972 (AH Act) provides for the protection of Aboriginal cultural heritage. The AH Act provides protection for all places and objects of importance to Aboriginal people in WA because of connections to Aboriginal culture. These places are referred to as 'Aboriginal sites of significance'. Many of these sites are wetlands or are near wetlands.

Figure 12. Many wetlands are designated 'Aboriginal sites of significance' under the *Aboriginal Heritage Act 1972*. This mosaic was prepared as a collaborative art project by students of Newton Moore Senior High School and the Bunbury Learning Centre in recognition of the importance of the Big Swamp environment, Bunbury. Photo – J Lawn/DEC.

The Act provides for the establishment (section 28) and operation (section 39) of the Aboriginal Cultural Material Committee, to evaluate the importance of places and objects and record and preserve information relating to them and advise the Minister of Indigenous Affairs and trustees.

In accordance with Section 18 of the Act, the Department of Indigenous Affairs (DIA) maintains a Register of Aboriginal Sites as a record of places and objects of significance to which the Act applies. Information on the register that is not culturally sensitive is available to the public. It is the duty of anyone who becomes aware of an Aboriginal site to report it to DIA. The presence of an Aboriginal site places restrictions on what can be done to the land. Anyone who wants to use land for research, development or any other cause, must investigate whether there is an Aboriginal site of significance on the land.

Under the Act it is an offence for anyone to excavate, damage, destroy, conceal or in any way alter an Aboriginal site without the Minister's permission. The AH Act protects all Aboriginal sites whether or not they are recorded on the Register of Aboriginal Sites or otherwise known to the Registrar of Aboriginal Sites, DIA or the Aboriginal Cultural Material Committee. The register operates primarily as a form of notice that places may be of Aboriginal site of significance, and indicate that a place has been assessed by the ACMC and has met the criteria for definition as an Aboriginal site, and hence the provisions of the Act will apply.

➤ For more information, see the Department of Indigenous Affairs website: www.dia.wa.gov.au

The *Fish Resources Management Act 1994*

The *Fish Resources Management Act 1994* (the FRM Act) regulates the management, utilisation and conservation of fish (which includes all aquatic organisms except reptiles, birds, mammals and amphibians) and their habitat. This includes all waters of the state and therefore includes its inland wetlands, estuaries and waterways. The Act also prohibits any person from engaging in any activity if it causes pollution or is likely to pollute the aquatic environment. The Department of Fisheries is responsible for administering this Act.

The FRM Act lists the objectives for the management and conservation of fish and their habitats and provides a number of tools for the Department of Fisheries to use when managing fish resources. These tools include subsidiary legislation established under the Act, including the Fish Resources Management Regulations 1995, management plans, notices and orders. Under this legislation, the Minister for Fisheries can declare fish habitat protection areas and can regulate or prohibit the taking of certain fish species or can regulate or restrict certain activities in a designated area.

Under the FRM Act, the Department of Fisheries is responsible for controlling the introduction and spread of introduced fish and crayfish, and regulating fishing and fish stocking of state water bodies. It maintains the noxious fish species list and operates the FISHWATCH Service, which is responsible for receiving reports of sightings of freshwater fish species (including introduced freshwater crustaceans), mass fish kills and illegal fishing activity. The FRM Act also contains controls on establishment of **aquaculture** farms.

Aquaculture: the keeping, breeding, hatching, or culturing of fish

Figure 13. The destructive, introduced eastern gambusia, *Gambusia holbrooki*, is listed as a noxious species. Photo – C Lawrence/Department of Fisheries.

➤ The noxious fish species list is available from www.fish.wa.gov.au/Sustainability-and-Environment/Aquatic-Biosecurity/Translocations-Moving-Live-Fish/Pages/Noxious-Banned-Fish.aspx

extra information

Regulation of aquaculture in WA

Aquaculture operations in inland and marine environments are managed under the Act through provisions in the Fish Resources Management Regulations 1995 which are established under the Act.

Due to the intensive nature of farms, the need for clean water and high output of phosphorus and nitrogen, they have the potential to cause significant environmental harm. For this reason, there are various restrictions on starting and operating an aquaculture farm. A person must apply for an aquaculture licence to engage in aquaculture, sell fish or take fish for the purpose of sale from waters on private land or to receive or purchase fish taken from private land for the purpose of sale. Exemptions do apply such as in an instance where fish are kept for display or ornamental purposes or fish are kept at a restaurant for the purpose of serving it as a meal to the public. Depending on the location and scale of a proposal, the Environmental Protection Authority may also need to assess it. Licensees must develop Management and Environmental Monitoring Plans (MEMPs) in support of their licences (with the exception of marron licences). The penalty for engaging in aquaculture without a licence is a maximum fine of up to $10,000 for an individual and $20,000 for a body corporate.[27]

Under the FRM Act, Aboriginal people are not required to hold a recreational fishing licence provided that they are fishing in accordance with continuing Aboriginal tradition and that the fish taken are for the individual or his or her family and not for a commercial purpose.

The Western Australian Government has initiated reform of fisheries legislation, and advised of the commencement of work on a new Act of Parliament to replace the *Fish Resources Management Act 1994*.[28]

NATIONAL LEGISLATION

The *Environment Protection and Biodiversity Conservation Act 1999*

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) provides a legal framework to protect and manage nationally and internationally listed species, critical habitats, and heritage places, defined in the Act as matters of national environmental significance (NES). The Act is administered by the Australian Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) and the Australian Minister for Environment is the decision-making authority.

There are seven matters of national environmental significance that are protected under the EPBC Act:

- World Heritage properties
- National Heritage places
- Wetlands of international importance
- Listed threatened species and ecological communities
- Migratory species protected under international agreements
- Commonwealth marine areas
- Nuclear actions (including uranium mines)

In order to understand how the *Environment Protection and Biodiversity Conservation Act 1999* can benefit wetland conservation, the matters of national environmental that relate most specifically to wetlands conservation are outlined below.

Wetlands of international importance (Ramsar wetlands)

The Convention on Wetlands of International Importance Especially as Waterfowl Habitat is an international treaty that focuses on the conservation of internationally important wetlands. The Convention was signed in 1971 at a meeting in the town of Ramsar, in Iran – hence the Convention is better known as the 'Ramsar Convention'.

The EPBC Act enhances the management and protection of Australia's Ramsar wetlands through recognition of these sites as matters of national environmental significance. A 'declared Ramsar wetland' is an area that has been designated under Article 2 of the Ramsar Convention or declared by the Australian Minister for Environment to be a Ramsar wetland under the EPBC Act.

Figure 14. Lake Argyle is a declared Ramsar wetland. Photo – A Shanahan.

As a matter of national environmental significance, an action that has, will have, or is likely to have, a significant impact on the ecological character of a Ramsar wetland must be referred to the Minister and undergo an environmental assessment and approval process. An action includes a project, development, undertaking, activity, or an alteration of any of those things.

The EPBC Act provides the following definition for 'significant impact':

an action that has, will have or is likely to result in:

(i) areas of the wetland being destroyed or substantially modified

(ii) substantial and measurable change in the hydrological regime of the wetland (e.g. a substantial change to the volume, timing, duration and frequency of water flows to the wetland)

(iii) seriously affected the habitat of native species dependant upon the wetland or

(iv) a substantial and measurable change in the salinity, nutrient or pollutant levels of the wetland.

Failure to refer a proposal which has a significant impact is an offence, and is liable to a maximum civil penalty of $550,000 for an individual and $5.5 million for a corporation.

The EPBC Act also establishes a process for identifying Ramsar wetlands and encourages best practice management through nationally consistent management principles. The purpose of management is to (i) describe and maintain the ecological character of the wetland and (ii) to develop and implement planning that promotes conservation of the wetland and wise and sustainable use of the wetland for the benefit of humanity in a way that is compatible with the natural properties of the ecosystem.

These principles have been set out in regulations and cover matters relevant to the preparation of management plans, environment assessment of actions that may affect the site, and the community consultation process.

A management plan for a Ramsar wetland cannot be endorsed unless it is in accordance with these principles. The principles may also be used for the management of any wetland throughout Australia.

➤ For information on roles and responsibilities for nominating, listing and managing Ramsar wetlands, see the topic 'Roles and responsibilities' in Chapter 5.

Listed threatened species and ecological communities

The EPBC Act provides for the listing of nationally threatened native species and ecological communities, native migratory species and marine species.

The EPBC Act protects Australia's native species and ecological communities by providing for:

- identification and listing of species and ecological communities as threatened
- development of conservation advice and recovery plans for listed species and ecological communities
- development of a register of critical habitat
- recognition of key threatening processes
- where appropriate, reducing the impacts of these processes through threat abatement plans.

Any person may nominate a native species, ecological community, or threatening process for listing under any of the categories specified in the EPBC Act. An invitation to nominate is extended each year by the Minister ahead of a new assessment cycle. Nominations submitted within the advertised invitation period and that satisfy the EPBC regulations are forwarded to the Commonwealth Threatened Species Scientific Committee, who prepare a proposed priority assessment list of nominations for consideration by the Minister.

As matters of national environmental significance, any action that is likely to have a significant impact on listed threatened species and ecological communities under the EPBC Act must be referred to the Minister and undergo an environmental assessment and approval process.

Under the EPBC Act, activities in Commonwealth areas that may result in killing, injuring, taking, trading, keeping, or moving a member of a listed threatened species or ecological community, a member of a listed migratory species or a member of a listed marine species are illegal without a permit.

Most State-listed threatened species are also listed as nationally threatened under the EPBC Act. The State and Commonwealth Governments are working cooperatively to better align the State and Commonwealth threatened species lists to reduce confusion when dealing with both legislative processes.

Many of the ecological communities endorsed as TECs by the WA Minister for Environment are also listed as nationally TECs, such as those included in the listing of claypans of the Swan Coastal Plain, including Drummond claypan (Figure 15 and 16).

Figure 15. Drummond claypan, one of the claypans of the Swan Coastal Plain listed as critically endangered. Photo – J Lawn/DEC.

Figure 16. Herbs in Drummond claypan, near Toodyay, in spring, prior to the claypan drying out. Photo – M Kruger/DEC.

➤ DSEWCaP's 'Threatened species and ecological communities' webpage: www.environment.gov.au/biodiversity/threatened/index.html

➤ To find out which species and ecological communities are listed as threatened under the EPBC Act, go to the 'EPBC Act lists' webpage of the DSEWPC website: www.environment.gov.au/epbc/about/lists.html#species

Listed migratory species

Migratory species are those animals that migrate to Australia and its external territories, or pass through or over Australian waters during their annual migrations. Examples of migratory species are species of birds (such as albatrosses and petrels), mammals (such as whales) or reptiles (such as marine turtles).

Section 209 of the EPBC Act provides for the listing of those migratory species that are listed in the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention), China-Australia Migratory Bird Agreement (CAMBA), Japan-Australia Migratory Bird Agreement (JAMBA) and Republic of Korea-Australia Migratory Bird Agreement (RoKAMBA).

All species on the list of migratory species are matters of national environmental significance under the EPBC Act. An action will require approval if the action has, will have, or is likely to have, a significant impact on a listed migratory species. The action must be referred to the Minister and undergo an environmental assessment and approval process. Note that some migratory species are also listed as threatened species.

➤ The migratory species list is available from the 'EPBC migratory species lists' webpage of the DSEWPC website: www.environment.gov.au/cgi-bin/sprat/public/publicshowmigratory.pl

POLICIES FOR WETLAND CONSERVATION

The term 'policy' is often defined as a goal or position, an official strategy to achieve an objective, a framework to manage a resource, or guidelines to assist stakeholders. The policies considered below are all government policies.

Environmental policies can be statutory or non-statutory. Administrative policies and guidelines are non-statutory instruments that state how particular laws are to be enforced and administered in practice. For instance, the EPA publishes administrative policies to establish environmental values for particular environments, provide guidance on specific matters such as threatened species and environmental offsets, and publish the position of the EPA on specific aspects of environmental protection, such as wetland protection. Non-statutory policies include EPA guidelines.

Statutory policies are those which are legally binding and enforceable by law. Examples are state planning policies (SPPs) and environmental protection policies (EPPs).

This section outlines key policies for wetland management and protection in WA as outlined in Table 2.

Wetlands Conservation Policy for Western Australia

The *Wetlands Conservation Policy for Western Australia* (Government of Western Australia 1997) is the primary policy for wetland conservation in WA. It outlines the state government's commitment to the goal of identifying, maintaining and managing wetland resources in the state, including the full range of wetland values. It also facilitates coordination across state government in matters affecting wetlands and wetland conservation.

The Wetlands Coordinating Committee was established in 1998 by the then Minister for Environment to oversee the implementation of the policy. The committee aims to implement the policy via a cooperative approach to wetland conservation involving, in particular, all levels of government, as well as the community, local groups and the private sector.

The scope of the policy applies to the full range of wetland types covered by the Ramsar definition; however, the strategy for implementation applies principally to those types of environments that are traditionally regarded as wetlands, and does not cover waterways, estuaries, floodplains or marine environments.

The policy has two main components; a statement of policy and a strategy for implementation. The five primary objectives in the statement of policy provide a framework for actions for implementation listed in the strategy.

The five primary objectives of the policy are:

1. To prevent the further loss or degradation of valuable wetlands and wetland types, and promote wetland conservation, creation and restoration.
2. To include viable representatives of all major wetland types and key wildlife habitats and associated flora and fauna within a statewide network of appropriately located and managed conservation reserves which ensure the continued survival of species, ecosystems and ecological functions.
3. To maintain, in viable wild populations, the species and genetic diversity of wetland-dependent flora and fauna.
4. To maintain the abundance of waterbird populations, particularly migratory species.
5. To greatly increase community awareness and appreciation of the many values of wetlands, and the importance of sound management of the wetlands and their catchments in the maintenance of those values.

The strategy for implementation outlines specific priority actions and the state government agency with primary (but not exclusive) responsibility for each action.

The Wetlands Coordinating Committee has overseen a review of the policy with a view to updating it.

➤ Web link: www.dec.wa.gov.au/management-and-protection/wetlands/publications/policies.html

➤ Web link to Wetlands Coordinating Committee: www.dec.wa.gov.au/management-and-protection/wetlands/wetlands-coordinating-committee.html

➤ For more information on the Wetlands Coordinating Committee, see the topic ‘Roles and responsibilities’ in Chapter 5.

Draft Framework for mapping, classification and evaluation of wetlands in Western Australia

This draft framework outlines a statewide process for the mapping, classification and evaluation of wetlands in WA. Specifically the framework aims to provide the following outcomes:

- coordination and consistency across the state in the approach to wetland mapping, classification and evaluation in WA
- greater certainty that data is collected using valid methodologies

- avoidance of repetition in project planning
- assist establishment of achievable aims in terms of scope and detail
- a mechanism to ensure that data is made publicly available
- a mechanism to endorse the results at a state level

Each stage of the mapping, classification and evaluation process is discussed independently within the framework, giving guidance on the important aspects of each stage for consideration.

➤ The *Draft Framework for mapping, classification and evaluation of wetlands in Western Australia*[29] is available on request from wetlands@dec.wa.gov.au; and when finalised will be available from the 'Wetlands' webpage of DEC website: www.dec.wa.gov.au/wetlands

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

Draft Guideline for the determination of wetland buffer requirements

This document provides guidance on determining an appropriate buffer distance between a wetland and a land use located in the vicinity of a wetland.

The objectives of the guideline are to:

- provide a clear, concise and repeatable method to determine a **wetland buffer**
- provide guidance on acceptable buffer distances that will ensure a wetland's values will be maintained, if not enhanced
- provide guidance on acceptable management and use of the wetland buffer area which will complement wetland conservation and protection and buffers
- provide guidance on the recommended contents in the wetland buffer report.

In essence, the guideline takes users through a logical step by step process to apply the guideline by assessing the values of the wetland, identifying the threats from the surrounding land use and determining the need and extent of a wetland buffer including management outcomes.

➤ Once finalised, the *Guideline for the determination of wetland buffer requirements* will be available from the 'Wetlands' webpage of DEC website: www.dec.wa.gov.au/wetlands

Guidelines checklist for preparing a wetland management plan

These guidelines are for use when a wetland management plan is required to be prepared to the satisfaction of DEC as a condition of development, subdivision or scheme amendment approval or similar.

The guidelines provide a checklist of information that should be provided in the plan.

➤ See: www.dec.wa.gov.au/management-and-protection/wetlands/publications.html

WA Environmental Offsets Policy

The Western Australian Government's policy position on **offsets** is outlined in this document. It serves as an overarching framework to underpin environmental offset assessment and decision-making in Western Australia, with associated guidelines and an environmental offset register to be developed.

The policy defines direct and indirect offsets, and principles for the use of offsets. It states that the use of environmental offsets will not replace proper on-site environmental practices, such as avoidance and mitigation. It seeks to ensure that environmental offsets are applied in specified circumstances in a transparent manner to engender certainty and predictability, while acknowledging that there are some environmental values that are not readily replaceable.

➤ The direct web link to the *WA Environmental Offsets Policy* is www.epa.wa.gov.au/EPADocLib/WAEnvOffsetsPolicy-270911.pdf

Environmental offset: an offsite action or actions to address significant residual environmental impacts of a development or activity[30]

Environmental protection policies (EPPs)

As described in the 'Legislation for wetland conservation' section, environmental protection policies are prepared by the EPA under Part III of the *Environmental Protection Act 1986*. Once ratified by Parliament and published in the Western Australian Government Gazette, EPPs have the force of law.

➤ EPPs are available from the EPPs webpage[31] of the EPA website www.epa.wa.gov.au

➤ Associated digital mapping can be downloaded from the 'Spatial data' webpage[32] of the EPA website.

Environmental Protection (Swan Coastal Plain Lakes) Policy 1992

Commonly referred to as the 'Lakes EPP', the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992* prohibits the filling, excavating, mining, discharge or disposal of effluent or drainage into or out of an identified wetland on the Swan Coastal Plain, unless authorised under the EP Act or any other written law. Typically, authorisation involves referral of the proposal to the EPA for environmental impact assessment.[3]

Figure 17. Lake Gwelup, in the northern Perth suburb of Gwelup, is one of many wetlands protected under the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992*.

'Identified wetlands' protected by the Lakes EPP are those that held 1,000 square metres or more of water on December 1, 1991. These are identified on the Department of Land Administration Miscellaneous Plan No. 1815. The map can now also be viewed in digital format (see below). The method of identifying which areas on the Swan Coastal Plain were to be subject to this policy was for the purpose of identifying administrative boundaries. Its purpose was not to use scientific methods for identifying wetland boundaries. This is an important distinction that explains why there are two wetland mapping datasets for the Swan Coastal Plain; one is administrative, identifying areas of inundation at a given date, while the other identifies the full spatial extent of a full range of wetland types. There is no process by which wetlands can be removed from Miscellaneous Plan No. 1815 or from being identified for protection by this policy.

Any prohibited activity, such as filling or excavation of an identified wetland, is required to be referred to the EPA for environmental impact assessment. Upon referral, the EPA will assess the values of the wetland and the potential impact of the proposal.

If the EPA considers that there is no significant environmental impact caused by the activity, due to the limited remaining values of the wetland or management of the activity, the EPA is unlikely to require a formal assessment.

DEC is responsible for investigating potential breaches of the Lakes EPP. A fine of $62,500 plus $12,500 per day for a continuing offence applies to individuals, and $125,000 plus $25,000 per day for a continuing offence applies to a body corporate.

➤ Miscellaneous Plan No. 1815 can be viewed at DEC's Perth library. The digital mapping of listed wetlands can be downloaded from the 'Spatial data' webpage[31] of the EPA website www.epa.wa.gov.au

The draft Wetlands EPP – proposed but not enacted

As required under section 36 of the EP Act, a review of the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992* was initiated by the EPA in 1999. The EPA proposed a draft revised policy, the *Environmental Protection (Swan Coastal Plain Wetlands) Policy 2004*, widely referred to as the 'draft Wetlands EPP'. The draft Wetlands EPP proposed to prohibit a range of activities in and close to all high value wetlands on the Swan Coastal Plain. It extended its scope from those that are permanently or seasonally inundated to those wetland types that are only waterlogged. After consideration of public submissions and the advice of an independent regulatory panel in 2006, the Minister for the Environment announced to Parliament his decision not to gazette the draft revised policy and in accordance with section 31(e) of the Act published the reasons for this decision in the Government Gazette (Refusal to approve draft Environmental Protection Policy (Swan Coastal Plain Wetlands) Order 2006; No. 193, 21 November 2006). The reason for the Minister's decision was essentially that the existing mechanisms to protect wetlands, including the Environmental Protection (Clearing of Native Vegetation) Regulations 2004, were adequate, and an additional statutory mechanism was not warranted. Accordingly, the Lakes EPP remains in force.

Environmental Protection (South West Agricultural Zone Wetlands) Policy 1998

The *Environmental Protection (South West Agricultural Zone Wetlands) Policy 1998* (herein 'South West Wetlands EPP') protects wetlands registered under the policy from further degradation by such damaging human activities as filling, excavating, discharging of effluent, draining and damaging or clearing fringing native vegetation. It also promotes the rehabilitation of wetlands in the south west agricultural zone of the State. This area is, broadly speaking, from north of Geraldton, to east of Merredin and east Esperance.

Wetlands may be nominated for registration under the policy if they are on Crown land or on private land where landowner consent has been given. Currently there are only two wetlands on the Register of Protected Wetlands: Lake Monjingup in the Shire of Esperance and Koojedda Swamp in the Shire of Northam.[33]

The EPA commenced a review of the policy in 2005, in accordance with the statutory requirement that EPPs be reviewed after seven years of operation (section 36 of the EP Act). The EPA published a report entitled *Review of the Environmental Protection (South West Agricultural Zone Wetlands) Policy 1998*[13] and invited submissions on this report. The EPA acknowledged that complex pressures such as salinity and altered catchment water balances are outside the scope of the policy, with many of the pressures impacting wetlands not able to be prevented through the use of a single legislative instrument such as the South West Wetlands EPP.

The EPA is responsible for preparing a revised draft policy and recommendations to be submitted to the Minister for Environment for consideration. In the interim, the existing policy remains in force.

Environmental Protection (Western Swamp Tortoise Habitat) Policy 2011

The western swamp tortoise (*Pseudemydura umbrina*) (Figure 18) is the most endangered tortoise/turtle species on Earth. It is listed under the *Wildlife Conservation Act 1950*, the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999* and the United Nations Convention on International Trade of Endangered Species (CITES) as a critically endangered species.

Figure 18. Adult male *Pseudemydura umbrina* at Ellen Brook Nature Reserve. Photo - G Kuchling.

The purpose of the Western Swamp Tortoise Habitat EPP is to protect habitat suitable for the long-term survival of the wild populations of the western swamp tortoise. It designates a policy area encompassing the known wild habitat of the tortoise (Twin Swamps Nature Reserve, Bullsbrook and Ellen Brook Nature Reserve, Upper Swan and surrounding areas in the City of Swan, north-east of Perth on the Swan Coastal Plain). The EPP outlines a range of decision or actions taken under various Acts which must have regard to the policy, and a range of activities that are considered may degrade the tortoise habitat, including the abstraction of groundwater, the use of fertilisers and pesticides, waste disposal, mining, clearing and lighting unauthorised fires. The EPP outlines a program of protection for landowners and local and state government to implement.

This policy replaces the E*nvironmental Protection (Western Swamp Tortoise Habitat) Policy 2002*. The policy should be read in conjunction with the environmental assessment guideline Guidance Statement No. 7 *Protection of the Western Swamp Tortoise Habitat, Upper Swan/Bullsbrook* (described below).

Environmental Protection Authority environmental protection bulletins

EPA environmental protection bulletins (formerly position statements) are published as a means of informing the public about the EPA's views on matters of environmental importance and to define important environmental values and functions. They are not statutory documents.

➤ EPA environmental protection bulletins are available from the EPA website: www.epa.wa.gov.au

Two environmental protection bulletins are considered most specific and/or pertinent to wetland protection and management:

- Position Statement No. 4 *Environmental Protection of Wetlands*
- Position Statement No. 9 *Environmental Offsets*

Position Statement No. 4 Environmental Protection of Wetlands

Position Statement No. 4 presents the EPA's principles and overarching goals for wetlands and the aspects of wetland protection that are considered important in guiding decisions and advising government.

It lists significant environmental values and functions of wetlands, including primary production, recreational and landscape amenity, hydrological balance, water quality protection and wildlife habitat, and recognises wetlands as being among the most biologically productive and diverse habitats in the State.

It states that the EPA's overarching goals for wetlands are:

- to protect the environmental values and functions of wetlands in Western Australia;
- to protect, sustain and, where possible, restore the biological diversity of wetland habitats in Western Australia;
- to protect the environmental quality of the wetland ecosystems in Western Australia through sound management in accordance with the concept of 'wise use', as described in the Ramsar Convention, and ecologically sustainable development principles, regardless of land use or activity; and
- to have as an aspirational goal, no net loss of wetland values and functions.

Position Statement No. 9 Environmental Offsets

Note: the EPA has stated that Position Statement No. 9 is being updated.

Position Statement No. 9 establishes the EPA's policy on emissions and ecological offsets. The focus of this position statement is those proposals that are deemed to pose significant adverse impacts to ecosystems and or contribute emissions to the environment.

The EPA policy position is that environmental offsets should be used with an aspirational goal of achieving a 'net environmental benefit'. This position recognises that the environment has been significantly compromised in the past and that halting and reversing the decline of the environment is now a priority.

Achieving a net environmental benefit means that each offset proposal should address **direct offsets** and **contributing offsets** to meet the following offset principles:

- environmental offsets should only be considered after all other reasonable attempts to mitigate adverse impacts have been exhausted
- an environmental offset package should address both direct offsets and contributing offsets
- environmental offsets should ideally be 'like for like or better'
- positive environmental offset ratios should apply where risk of failure is apparent
- environmental offsets must entail a robust and consistent assessment process
- environmental offsets must meet all statutory requirements
- environmental offsets must be clearly defined, transparent and enforceable
- environmental offsets must ensure a long lasting benefit.

Position Statement No. 9 also establishes **critical environmental assets**. These represent the most important environmental assets in the state that must be fully protected and conserved. The position statement establishes the EPA's presumption against recommending approval for proposals that are likely to have significant adverse impacts to 'critical assets'. The EPA does not consider it appropriate to validate or endorse the use of environmental offsets where projects are predicted to have significant adverse impacts to critical assets. Many wetlands are identified as critical assets:

- Ramsar wetlands core conservation areas
- wetlands listed in *A Directory of Important Wetlands in Australia*, 3rd edition[34] and more recent additions as contained in the *Australian Wetlands Database*[35]
- environmental protection policy (EPP) wetlands
- conservation category wetlands identified in the *Geomorphic Wetlands Swan Coastal Plain* dataset[36,3] (see also EPA 2008[3])

Many wetlands also support critical assets such as threatened ecological communities, declared rare flora and threatened fauna.

Direct offsets: activities which counterbalance the environmental impact of a proposal and are in addition to normal environmental management requirements. This includes restoration (offsite), rehabilitation (offsite), re-establishment, sequestration and acquisition of other land/s under threat for inclusion into conservation estate.

Contributing offsets: complementary activities which, together with direct offsets, meet the offset principles. These include education, research, removal of threats, and or contribution to an approved credit trading scheme or trust fund.

Environmental Protection Authority environmental assessment guidelines statements

Environmental assessment guidelines (formerly guidance statements) are developed by the Environmental Protection Authority specifically to assist proponents, responsible authorities, consultants and the public to achieve environmentally acceptable outcomes. In particular, guidance statements aim to inform stakeholders about aspects of the environmental impact assessment process, views of the EPA and the minimum requirement for environmental management that the EPA would expect to be met when a proposal is considered during the process. Proponents are encouraged to do better than the minimum.

Critical environmental assets: the most important environmental assets in the state that should be protected and conserved

➤ EPA environmental assessment guidelines are available from the EPA website: www.epa.wa.gov.au/Policies_guidelines/EAGs/guidance/Pages/ReportPages.aspx

Five environmental assessment guidelines are considered most specific and/or pertinent to wetland protection and management:

- Guidance Statement No 7 *Protection of the Western Swamp Tortoise Habitat, Upper Swan/Bullsbrook*
- Guidance Statement No 10 L*evels of assessment for proposals affecting natural areas within the System 6 region and the Swan Coastal Plain portion of the System 1 region*
- Guidance Statement No 19 *Environmental offsets*
- Guidance Statement No 28 *Protection of Lake Clifton catchment*
- Guidance Statement No 33 *Environmental guidance for planning and development*
- Guidance Statement No 40 *Management of mosquitoes by land developers*

Guidance Statement No. 7 Protection of the Western Swamp Tortoise Habitat, Upper Swan/Bullsbrook

The purpose of guidance statement no. 7 is to protect the habitat of the critically endangered western swamp tortoise (*Pseudemydura umbrina*) in the Ellen Brook Nature Reserve, Bullsbrook and the Twin Swamps Nature Reserve, Upper Swan (managed by DEC). These are the only two areas where populations of the western swamp tortoise have been continuously recorded since the 1960s. The policy area is as defined in the *Environmental Protection (Western Swamp Tortoise Habitat) Policy 2011* (the western swamp tortoise habitat EPP), which contains the surface and groundwater catchment around the Twin Swamps Nature Reserve and Ellen Brook Nature Reserve. These catchments are poorly understood and therefore application of the precautionary principle prevails in defining the boundary of the policy area and in managing the habitat for the tortoise.

This guidance statement identifies activities and development that are incompatible near the tortoise habitat, such as intensive animal industries, subdivision and vegetation clearing. The guidance statement provides guidance on the environmental impact assessment of proposals that may impact on the tortoise habitat areas.

➤ Direct link: www.epa.wa.gov.au/EPADocLib/2138_GS7.pdf

Guidance Statement No. 10 Level of assessment for proposals affecting natural areas within the System 6 region and the Swan Coastal Plain portion of the System 1 region

The purpose of guidance statement no. 10 is to address the environmental impact assessment of proposals, planning schemes and scheme amendments involving the clearing of, or other significant impacts to, natural areas within the System 6 region and Swan Coastal Plain portion of the System 1 area (Figure 19).

Specifically, the intended purpose of this guidance statement is to ensure that proponents or responsible authorities planning and designing schemes and proposals potentially impacting on bushland protected by *Bush Forever* and other regionally significant natural areas are guided on the likely manner in which the EPA will assess their schemes and proposals. It aims to ensure developments are compatible with the identified conservation values of these areas.

Wetlands identified as other regionally significant areas under this guidance statement include wetlands listed as nationally significant in A *Directory of Important Wetlands in Australia*[34,35] and conservation category wetlands in the *Geomorphic Wetlands Swan Coastal Plain* dataset.[36]

➤ Direct link: www.epa.wa.gov.au/EPADocLib/1015_GS10.pdf

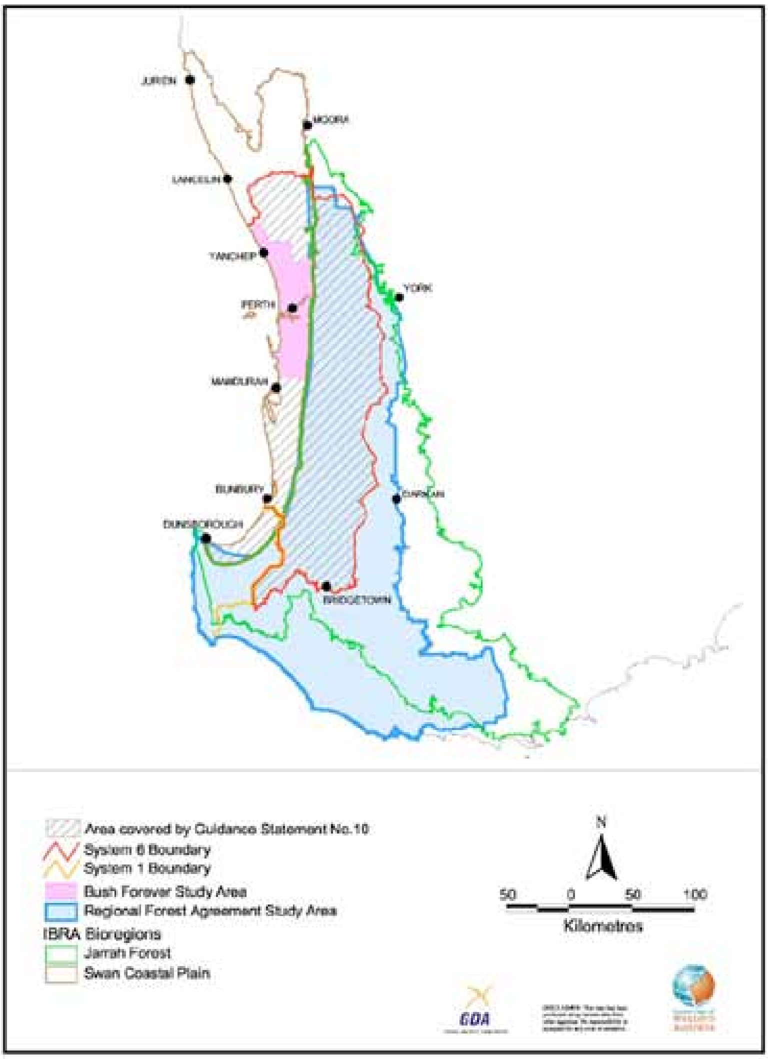

Figure 19. Area covered by Guidance Statement No. 10 and areas referred to in the guidance statement.

Guidance Statement No. 19 Environmental offsets

Guidance Statement No. 19 specifically addresses environmental offsets for proposals or schemes subject to environmental impact assessment that impact on biodiversity. It should be read in conjunction with Position Statement No. 9 *Environmental Offsets* (EPA 2006). The guidance statement was developed to augment the position statement in order to clarify several issues relating to its interpretation and implementation.

This guidance statement provides clarification of these issues, particularly in relation to the technical application of biodiversity offsets and the presentation of offsets packages to the EPA. Generally, it outlines the EPA's expectations and requirement for environmental offsets associated with development proposals and planning schemes subject to environmental impact assessment. It also encourages proponents and responsible authorities to demonstrate that requirements in this guidance statement are incorporated into proposals and schemes, in a way that ensures that they are enforceable and auditable.

➤ Direct link: www.epa.wa.gov.au/EPADocLib/2783_GS19OffsetsBiodiv18808.pdf

Thrombolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate

Guidance Statement No. 28 Protection of the Lake Clifton catchment

The purpose of this guidance statement is to describe the position of the EPA in relation to protection of Lake Clifton, identified by the EPA as one of the most significant wetlands in Western Australia. It describes environmental criteria established by the EPA as a basis for managing new land uses and changes to certain existing land uses on private land within the catchment of Lake Clifton.

Environmental criteria described in the guidance statement focus on maintaining the ecological integrity of Lake Clifton to support its internationally significant, threatened ecological community of **thrombolites** (Figure 20). In particular the guidance statement addresses the need to maintain water balance in the Lake Clifton catchment, and manage nutrient loads and developments in order to protect the thrombolites, wetland vegetation and the buffer of Lake Clifton.

➤ Direct link: www.epa.wa.gov.au/EPADocLib/1023_GS28.pdf

Figure 20. The ancient thrombolites of Lake Clifton. Photo – K Wilson.

Guidance Statement No. 33 Environmental Guidance for Planning and Development

Chapter B4 of EPA Guidance Statement No. 33 is a key reference for information on the management and protection of wetlands via WA's land use planning and development processes.

It provides an extensive list of wetlands that, for the purposes of environmental impact assessment, the EPA considers to be of high conservation significance and to require a high level of protection. This list is available on page 4 of Chapter B4. A proposal that is likely, if implemented, to have a significant impact on any of these wetlands is likely to require referral to the EPA for environmental impact assessment under Part IV of the EP Act. Examples of significant impacts include: clearing of native vegetation, mining, filling, excavating, draining or disposal of waste, allowing emissions into the wetland, and activities located near the wetland without the provision of an appropriate setback or buffer, such as clearing or groundwater abstraction.

Other chapters outline how other environmental factors, such as water in the landscape more generally, should be managed via the land use planning system.

It should be noted that some information in the guidance statement is now out of date. In particular, the information regarding the levels of assessment that EPA may assign to a proposal is no longer current, with the previous five levels superceded by two levels. Furthermore a range of appeal rights previously available within the environmental impact assessment process have been removed.

➤ Direct link: www.epa.wa.gov.au/EPADocLib/2717_GS33.pdf

Guidance Statement No. 40 Management of Mosquitoes by Land Developers

Guidance no. 40 provides information on what the EPA will consider when assessing proposals where mosquito management is a relevant environmental factor in an environmental impact assessment. Importantly, it identifies that responsibility for managing mosquitoes lies with land developers as well as local government authorities.

Physical, chemical and biological methods of controlling nuisance mosquito populations can have significant environmental impacts on wetlands. In this guidance statement the EPA establishes its expectation that mosquito control measures should maintain healthy wetland ecosystems and minimise the physical alteration of wetlands. The use of water sensitive urban design principles is also encouraged to ensure appropriate management of urban stormwater.

➤ Direct link: www.epa.wa.gov.au/EPADocLib/1025_GS40.pdf

State Planning Policies

The Western Australian Planning Commission develops state planning policies in accordance with the statutory procedures set out under Part 3 of the *Planning and Development Act 2005*. These are statutory instruments concerned with broad planning controls and/or specific matters, which may be the subject of a local planning scheme or relate to a specific region or area of the state. Some are titled 'statements of planning policy' while others are a 'state planning policy', though all are generically referred to as 'state planning policies' (or SPPs for short) and identified as such in this topic. There are a number that relate specifically to wetlands or are pertinent to wetland protection and management:

- *State Planning Policy 2 Environment and Natural Resources Policy* (2003)
- *State Planning Policy 2.1 Peel-Harvey Coastal Plain Catchment* (1992)
- *State Planning Policy 2.2 Gnangara Groundwater Protection* (2005)
- *State Planning Policy 2.3 Jandakot Groundwater Protection* (1998)
- *State Planning Policy 2.8 Bushland Policy for the Perth Metropolitan Region (2005)*
- *State Planning Policy 2.9 Water Resources (2006)*

➤ State planning policies are available from www.planning.wa.gov.au/5132.asp

State Planning Policy 2 Environment and Natural Resources Policy

SPP 2 is a broad, overarching state planning policy that addresses environmental protection and the use of the state's natural resources.

In regards to wetlands, it identifies areas of high biodiversity and/or conservation value, including the following wetlands:

- Ramsar wetlands and wetlands recognised as habitat for migratory species
- nationally significant wetlands listed in the *Directory of Important Wetlands in Australia*[34,35]
- wetlands identified in any relevant Environmental Protection Policy (EPP), such as the Swan Coastal Plain Lakes EPP and the South-West Agricultural Zone EPP

SPP 2 states that planning strategies, schemes and decision-making should protect these areas via the use of protection mechanisms; avoiding potential impacts of land use or development; the establishment of a comprehensive, adequate and representative reserve system; suitable ecological linkages and habitat corridors; use of planning controls and conservation covenants and management plans.

SPP 2 also recognises that the careful management of water resources, both in terms of quantity and quality, is essential to support natural ecosystems. With respect to wetlands it states that planning strategies, schemes and decision-making should consider mechanisms to protect, manage, conserve and enhance these groups of wetlands; ensure maintenance of water quality and quantity for the environment; encourage water sensitive design in the urban environment to protect wetlands; ensure adequate setbacks (buffers) to maintain and improve their ecological function; and consider the risks associated with nuisance or disease vector insects (midge and mosquitoes) and manage potential conflict with amenity, health and environmental values.

➤ Direct link: www.planning.wa.gov.au/publications/1161.asp

State Planning Policy 2.1 Peel-Harvey Coastal Plain Catchment

SPP 2.1 establishes appropriate planning controls to prevent land use changes within the catchment of the Peel-Harvey estuarine system that are likely to cause environmental damage to the estuary. The catchment of the estuary contains extensive areas of wetland, including many significant wetlands. A key purpose of this policy is to ensure that landowners seek development approval prior to committing their investments. The policy does not require a new series of approvals for existing developments. This policy has implications for wetlands in the catchment of the estuary, through restrictions placed on rezoning of land for urban processes, management of intensive agriculture to reduce or eliminate nutrient export from the land, restrictions placed on vegetation clearing and keeping of livestock and specific drainage and sewage requirements for specific development proposals.

➤ Direct link: www.planning.wa.gov.au/publications/1162.asp

State Planning Policy 2.2 Gnangara Groundwater Protection

The purpose of SPP 2.2 is to prevent, control and manage development and land use changes in Gnangara, Wanneroo and Mirrabooka that are likely to cause detrimental effects to the groundwater resources in the policy area. The policy area extends into the Cities of Wanneroo and Swan and the Shires of Gingin and Chittering. The policy applies to all land use activities on zoned and reserved land, recreational land uses, and public areas in the policy area. SPP 2.2 facilitates the identification and zoning/reservation of land for groundwater protection purposes.

The main objectives of the policy are to:

- ensure that all land use changes in the policy area are compatible with the long-term protection and management of groundwater quality and quantity for public drinking water supply. This is assisted by the identification of priority areas for source protection and the activities deemed acceptable within each of these priority areas
- protect groundwater quality and quantity in order to maintain the dependent ecosystems, ecological values and integrity of wetlands and native vegetation, in accordance with recognised conservation values
- protect and/or enhance the quality and quantity of groundwater, in accordance with accepted water quality guidelines and standards for various uses.

➤ Direct link: www.planning.wa.gov.au/publications/1164.asp

State Planning Policy 2.3 Jandakot Groundwater Protection

The purpose of SPP 2.3 is to ensure development over the Jandakot groundwater mound is compatible with long-term use of groundwater for human consumption. Under SPP 2.3 land use changes within the policy area that are likely to cause detrimental effects to the groundwater are brought under planning control and prevented or managed. The policy area extends into the following local governments: the cities of Armadale, Canning, Cockburn, Gosnells; the Town of Kwinana and the Shire of Serpentine-Jarrahdale.

The objectives of the policy are to:

- ensure that all land use changes in the policy area are compatible with the long-term protection and management of groundwater for public supply and maintenance of ecosystems
- to prevent land uses likely to result in contamination of groundwater through nutrient or contamination export
- to balance environmental protection with the economic viability of the existing land uses
- to maintain or increase natural vegetation cover over the policy area and
- to protect groundwater quality and quantity in the policy area in order to maintain the ecological integrity of important wetlands hydraulically connected to that groundwater, including wetlands outside the policy area.

➤ Direct link: www.planning.wa.gov.au/publications/1165.asp

State Planning Policy 2.8 Bushland Policy for the Perth Metropolitan Region

SPP 2.8 provides a statutory policy and implementation framework to ensure bushland protection and management issues in the Perth Metropolitan Region (PMR) are appropriately addressed and integrated with broader land use planning and decision-making, to secure long-term protection of biodiversity and associated environmental values.

It addresses the protection and management of the 51,200 hectares of regionally significant bushland contained within 287 Bush Forever sites identified in *Bush Forever*.[37,38] Many of these sites contain significant wetlands. SPP 2.8 outlines policy measures which are to apply to any proposal or decision-making that is likely to have an adverse impact on regionally significant bushland within Bush Forever sites.

It also addresses bushland (inclusive of wetlands) with regional values that were not designated as Bush Forever sites due to wider social and economic considerations. It supports the preparation of local bushland/biodiversity protection strategies by all local governments within the Perth Metropolitan Region, which in turn, should inform local and regional planning strategies.

SPP 2.8 states that proposals or decision-making should support a general presumption against clearing of bushland or other degrading activities in natural areas that support values, including significant wetlands including conservation category wetlands, wetlands protected under the *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992*; and their buffers.

➤ Direct link: www.planning.wa.gov.au/publications/1170.asp

State Planning Policy 2.9 Water Resources

The purpose of SPP 2.9 is to ensure water resources are conserved and their quality protected where possible through the land use planning system.

The objectives of SPP 2.9 are to:

- protect, conserve and enhance water resources that are identified as having significant economic, social, cultural and/or environmental values
- assist in ensuring the availability of suitable water resources to maintain essential requirements for human and all other biological life with attention to maintaining or improving the quality and quantity of water resources
- promote and assist in the management and sustainable use of water resources.

In regards to wetlands, SPP 2.9 specifically states that planning should contribute to their protection and wise management by ensuring local and regional planning strategies, structure plans, schemes, subdivisions, strata subdivision and development applications:

- protect, manage, conserve and enhance the environmental attributes, functions and values of significant wetlands, such as Ramsar wetlands, conservation category wetlands and wetlands identified in any relevant environmental protection policy
- manage, conserve and, where possible, restore the environmental attributes, functions and values of resource enhancement wetlands
- ensure use of best management practices in the development and use of multiple use wetlands, consistent with the principles of total water cycle management
- ensure adequate and appropriate buffering of wetlands to maintain or enhance the environmental attributes, functions and values of the water resource and minimise the impact of nearby land uses, both existing and future.

➤ Direct link: www.planning.wa.gov.au/publications/742.asp

Planning bulletin 64/2009: Acid sulfate soils

The purpose of this planning bulletin is to provide advice and guidance on matters that should be taken into account in the rezoning, subdivision and development of land that contains acid sulfate soils.

This planning bulletin introduces a set of revised *Acid sulfate soils planning guidelines*, which outline the range of matters which need to be addressed at various stages of the planning process to ensure that the subdivision and development of land containing acid sulfate soils is planned and managed to avoid potential adverse impacts on the natural and built environment.

The bulletin supersedes *Planning Bulletin 64 Acid sulfate soils* (2003), and the planning guidelines and risk maps appended to it.

➤ Direct link: www.planning.wa.gov.au/publications/726.asp

Acid sulfate soils planning guidelines

The guidelines outline the range of matters which need to be addressed at various stages of the planning process.

This is to ensure that the subdivision and development of land containing acid sulfate soils is planned and managed to avoid potential adverse impacts on the natural and built environment.

➤ Direct link: www.planning.wa.gov.au/publications/725.asp

Policy framework for inland drainage

This aim of this policy is to facilitate the use of drainage as an option to manage salinity and waterlogging in inland WA. This policy addresses the key areas of governance, risk management, planning and assessment, and operation and maintenance of drainage projects in inland Western Australia. In doing so, the framework seeks to guide better management of water resources and public assets, including wetlands of conservation value.

Appendix 1 of the framework outlines roles and responsibilities of a range of stakeholders. Appendix 2 outlines the principles for drainage proposal assessment.

➤ Direct link: www.water.wa.gov.au/PublicationStore/first/104329.pdf

Better Urban Water Management Strategy

The purpose of the *Better Urban Water Management Strategy* is to facilitate water sensitive urban design on the Swan Coastal Plain with particular concern for the Swan-Canning and Vasse-Geographe catchments. The implementation of this strategy is a critical to the protection of wetlands on the Swan Coastal Plain.

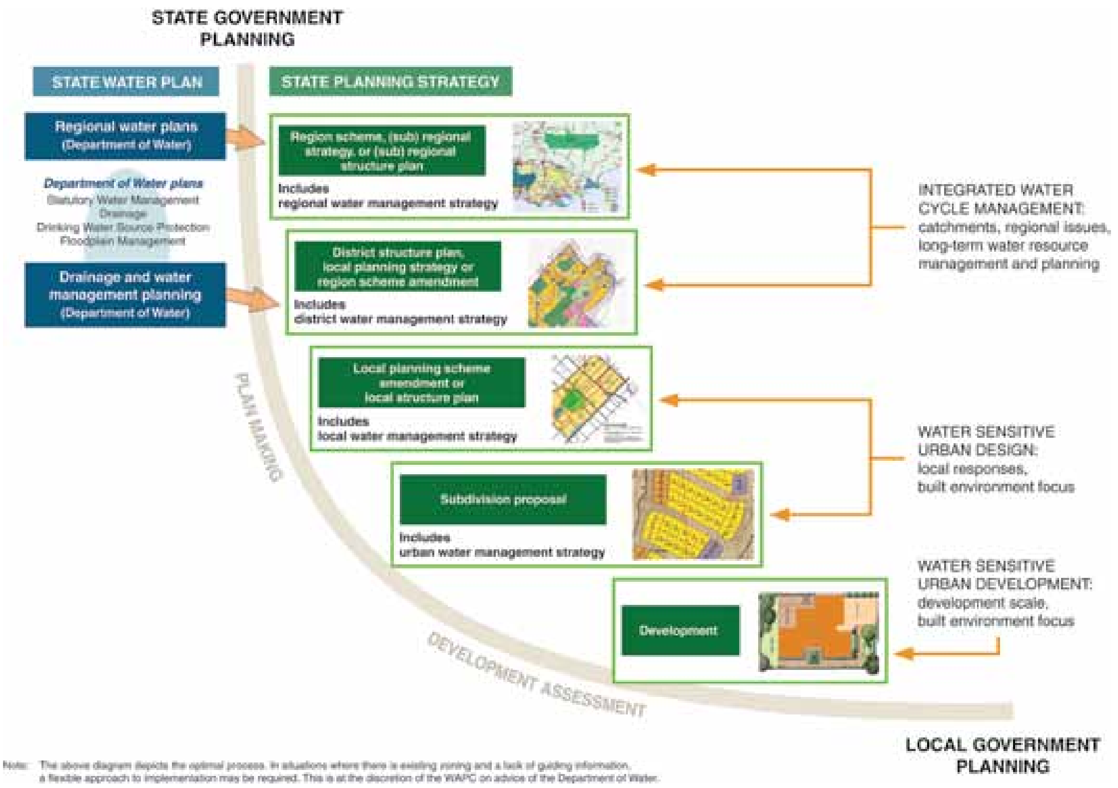

Figure 21. Better integration of land and water planning processes, as established in *Better Urban Water Management*, means more holistic consideration of wetlands and better wetland outcomes. Figure – Western Australian Planning Commission.

This strategy provides guidance on urban water management matters which need to be considered by the Western Australian Planning Commission, local governments and applicants when reviewing planning proposals and applications for new residential, rural-residential, commercial and industrial areas.

The strategy facilitates better management and use of urban water resources by providing a framework for consideration of water resources at each planning stage (Figure 21). It also identifies the agencies responsible for provision of water resource information.

The design criteria identified as a guide for development of better urban water management systems include:

- water conservation and efficiency
- water quantity management
- water quality management
- stormwater modelling criteria
- disease vector and nuisance insect management.

➤ Direct link: www.planning.wa.gov.au/publications/741.asp

State Water Plan

The *State Water Plan 2007* provides a framework for water resources management in Western Australia, with a planning horizon to 2030. It is a whole-of-government initiative with 11 agencies sharing more than 100 priority actions over the first five years. It addresses the challenges of climate change and variability, resource scarcity and the increasing demand for water. It takes a whole-of-the-water-cycle approach – from protecting water resources to recycling. This improves certainty of future water availability for the environment, the community and all water users.

It establishes the vision: '*Our precious water resources are managed and developed in a sustainable manner to maintain and enhance our natural environment, cultural and spiritual values, our quality of life and the economic development of the state*.'

This vision is underpinned by seven key objectives:

- use and recycle water wisely
- plan and manage water resources sustainably
- invest in science, innovation and education
- protect ecosystems, water quality and resources
- enhance the security of water for the environment and use
- develop water resources for a vibrant economy
- deliver services for strong and healthy communities.

➤ Direct link: www.water.wa.gov.au/PublicationStore/first/74923.pdf

Water allocation planning in Western Australia: a guide to our process

This Department of Water document describes the water allocation planning process, which governs how much water can be licensed for abstraction under clauses 5D and 26D of the *Rights in Water and Irrigation Act 1914* and how much water is left in the system for the environment.

It outlines the documents prepared and the opportunities for community input into these documents at various stages in the planning process.

Associated resources include:

- *Groundwater risk-based allocation planning process*[25] provides information on how ecological water requirements for groundwater dependent ecosystems are taken into consideration in the allocation planning process.
- Department of Water's webpage: www.water.wa.gov.au/allocationplanning

➤ Direct link: www.water.wa.gov.au/PublicationStore/first/100774.pdf

Stormwater management manual for Western Australia (DoW 2004–2008)

The stormwater management manual has been developed to provide best practice advice and **stormwater** management options that may be suitable to a range of built environments across WA.

Stormwater: water flowing over ground surfaces and in natural streams and drains as a direct result of rainfall over a catchment

The manual identifies objectives for stormwater management in WA, that have significant potential to positively impact wetland management and protection:

- water quality - to maintain or improve the surface and groundwater quality within the development areas relative to pre development conditions
- water quantity - to maintain the total water cycle balance within development areas relative to pre development conditions.
- water conservation - to maximise the reuse of stormwater.
- ecosystem health - to retain natural drainage systems and protect ecosystem health.
- development - to ensure delivery of best practice stormwater management through planning and development in accordance with sustainability and precautionary principles.

➤ Direct link: www.water.wa.gov.au/Managing+water/Urban+water/Stormwater/default.aspx#1

Decision process for stormwater management in WA (DoW 2009)

Within the manual, a decision process is outlined which provides a framework for the planning and design of stormwater management systems and provides guidance to identify what stormwater management issues need to be addressed during land development and redevelopment projects.

The methodology outlined in the decision process also aims to minimise changes to the volume of surface water flows and peak flows resulting from the urbanisation of an area.

The management of these changes has important implications for wetland management and protection by reducing negative impacts on the water regime, water quality, habitat diversity and biodiversity in receiving water bodies.

It states that wetlands should be retained and restored; that no new constructed stormwater infrastructure should be installed in conservation or resource enhancement management category wetlands or their buffers, or other wetlands of high conservation significance or their buffers unless authorised by DEC or EPA. It also states a presumption against the creation of artificial lakes or permanently inundated water bodies.

➤ Direct link: www.water.wa.gov.au/Managing+water/Urban+water/Stormwater/Decision+process+and+management+objectives/default.aspx#1

Figure 22. Requirements regarding the placement of stormwater infrastructure in and near wetlands is outlined in the *Decision process for stormwater management in WA*. Photo – J Lawn.

Wetland Policy of the Commonwealth Government of Australia (Commonwealth Government of Australia 1997)

The purpose of the Commonwealth wetland policy is to build wetland conservation into the daily business of the Commonwealth Government. The stated goal of the policy is to conserve, repair and manage wetlands wisely. To achieve this, the policy sets out six strategies, which encompass Commonwealth responsibilities from managing commonwealth lands and waters, to international actions.

GLOSSARY

Aquaculture: the keeping, breeding, hatching, or culturing of fish

Authorisation: a licence, permit, approval or exemption granted, issued or given under the Part V environmental regulations

Clearing: any act that kills, destroys, removes or substantially damages native vegetation in an area. This includes severing or ringbarking of trunks or stems, draining or flooding of land, burning of vegetation and grazing of stock or any other act or activity that causes damage to some or all of the native vegetation in an area.

Contributing offsets: complementary activities which, together with direct offsets, meet the offset principles. These include education, research, removal of threats, and or contribution to an approved credit trading scheme or trust fund.

Critical environmental assets: the most important environmental assets in the state that should be protected and conserved

Decision making authority: a public authority empowered to make a decision in respect of a proposal. Often abbreviated to DMA.

Derived proposal: a proposal referred to the Environmental Protection Authority under section 38 of the *Environmental Protection Act 1986* that is declared by the EPA to have been identified in a strategic proposal that has been assessed and granted approval under Part IV of the Act[4]

Direct offsets: activities which counterbalance the environmental impact of a proposal and are in addition to normal environmental management requirements. This includes restoration (offsite), rehabilitation (offsite), re-establishment, sequestration and acquisition of other land/s under threat for inclusion into conservation estate.

Enacted: to make into law

Endorsed management plan: a management plan that has been approved and/or modified by the Minister for the Environment as he/she thinks fit

Environmental impact assessment: an orderly and systematic process for evaluating a scheme or proposal, including its alternatives where relevant, and its effects on the environment, including the mitigation and management of those effects

Environmental offset: an offsite action or actions to address significant residual environmental impacts of a development or activity[29]

Environmental protection policies: whole of government policies which have been agreed to by Parliament and have the force of law as if part of the Act

Government Gazette: a government publication issued by the State Government which includes details of statutory matters, available from the State Law Publishers

Local planning scheme: a set of provisions that identifies the way land in the scheme area is to be used and developed. It may comprise a scheme map(s), a text and an explanatory report.[16]

Metropolitan Regional scheme (MRS): the region planning scheme for the Perth region

Native vegetation: native aquatic or terrestrial vegetation, and includes dead vegetation unless that dead vegetation is of a class declared by regulation to be excluded from this definition but does not include vegetation in a plantation or which was intentionally sown, planted or propagated unless that vegetation was sown, planted or propagated as required under law

Prescribed premises: premises prescribed for the purposes of Part V of the *Environmental Protection Act 1986* as specified in Schedule 1 of the E*nvironmental Protection Regulations 1987*

Proponent: the person who is responsible for the proposal, or the public authority on which the responsibility for the proposal is imposed under a written law

Public open space: land used or intended for use for recreational purposes by the public; it includes district, neighbourhood and local open spaces and parks, but excludes regional open space or foreshore reserves[17]

Red list criteria: developed by the International Union for the Conservation of Nature (IUCN) to allocate species of flora and fauna into threat categories of critically endangered, endangered and vulnerable, based on their likelihood of becoming extinct

Regional open space: land defined under a region scheme, regional structure plan or sub-regional structure plan as a parks and recreation reserve or regional open space reserve, to accommodate active and passive recreation such as major playing fields and/or regional conservation and environmental features[17]

Region planning scheme (region scheme): a planning scheme prepared for matters of state or regional importance to enable effective planning and coordination of land use and development. Also known as a region scheme.[16]

Regulation: a law made under the authority of an Act of Parliament

Reserved: set aside for public purposes

Scheme: a redevelopment scheme, a region planning scheme, a local planning scheme or a State planning policy to which section 32 of the *Planning and Development Act 2005* applies, or an amendment to any of these

Significant proposal: a proposal likely, if implemented, to have a significant effect on the environment

State Environmental Policies (SEPs): non-statutory policies which are developed by the EPA under provisions of Part II of the EP Act through public consultation and are adopted following Cabinet consideration and approval

Statute: a law enacted by the State or the Federal Parliament

Strategic proposal: a future proposal that will be a significant proposal; or future proposals likely, if implemented in combination with each other, to have a significant effect on the environment

Structure plan: a plan that provides a framework for the coordinated provision of land use, development, infrastructure and allocation of services at either the regional, district or local level. Not always a statutory requirement.

Stormwater: water flowing over ground surfaces and in natural streams and drains as a direct result of rainfall over a catchment[49]

Subdivision: the division of land into lots

Threatened ecological community: naturally occurring biological assemblages that occur in a particular type of habitat that has been endorsed by the WA Minister for Environment as being subject to processes that threaten to destroy or significantly modify it across much of its range

Threatened fauna: fauna that is rare or likely to become extinct and gazetted as such by the Minister for Environment

Threatened flora: flora that has been assessed as being at risk of extinction or is rare or otherwise in need of special protection and gazetted as such by the Minister for Environment. These species are commonly referred to as declared rare flora

Thrombolite: a type of microbial structure formed by microbial communities precipitating calcium carbonate

Wetland buffer: an interface adjoining a wetland that is designated to assist in protecting the wetland's natural values from the threats posed by the surrounding land use(s)

PERSONAL COMMUNICATIONS

Name	Date	Position	Organisation
Dr Ken Atkins	17/12/2012	Manager, Species and Communities Branch	Department of Environment and Conservation, Western Australia

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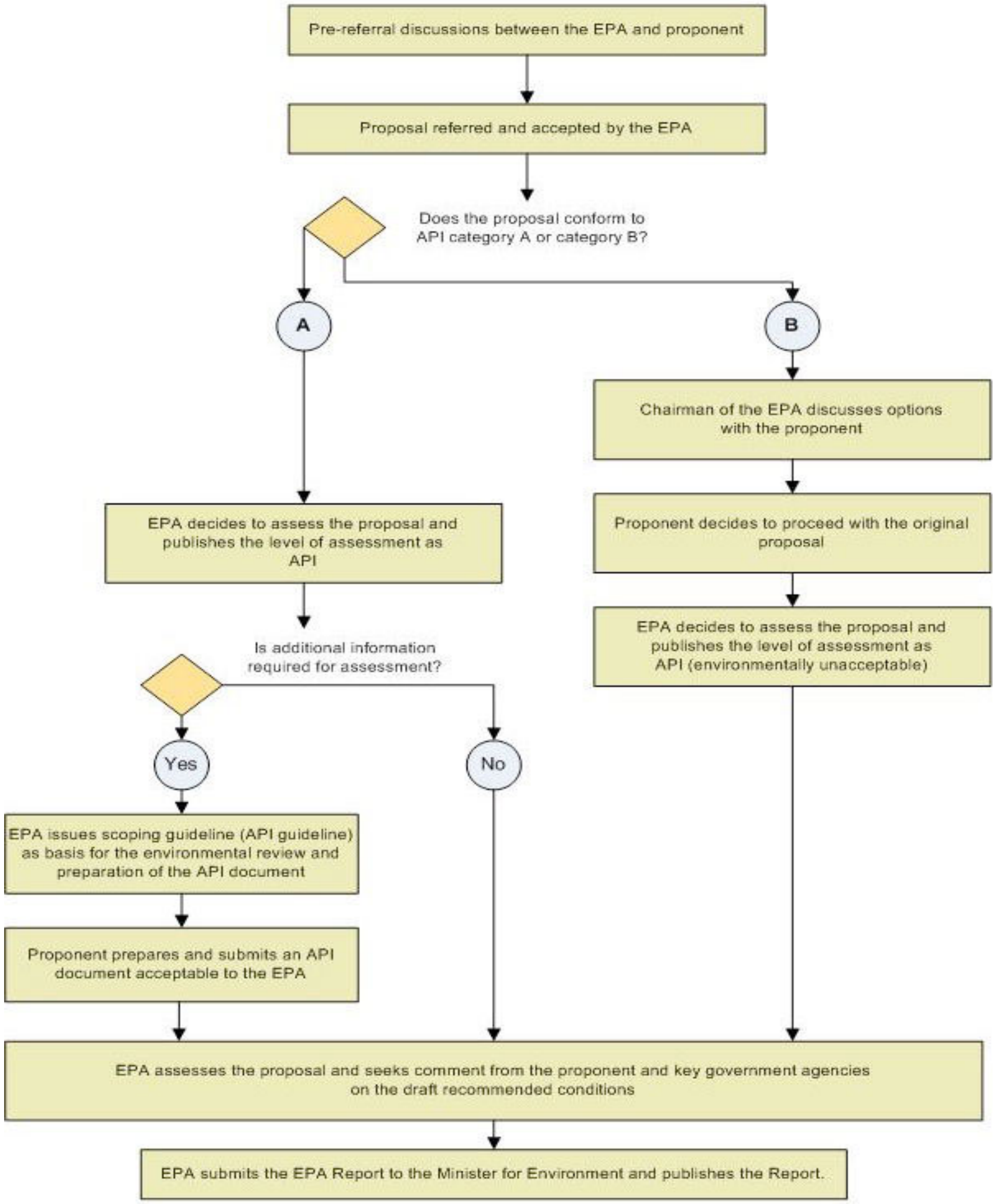
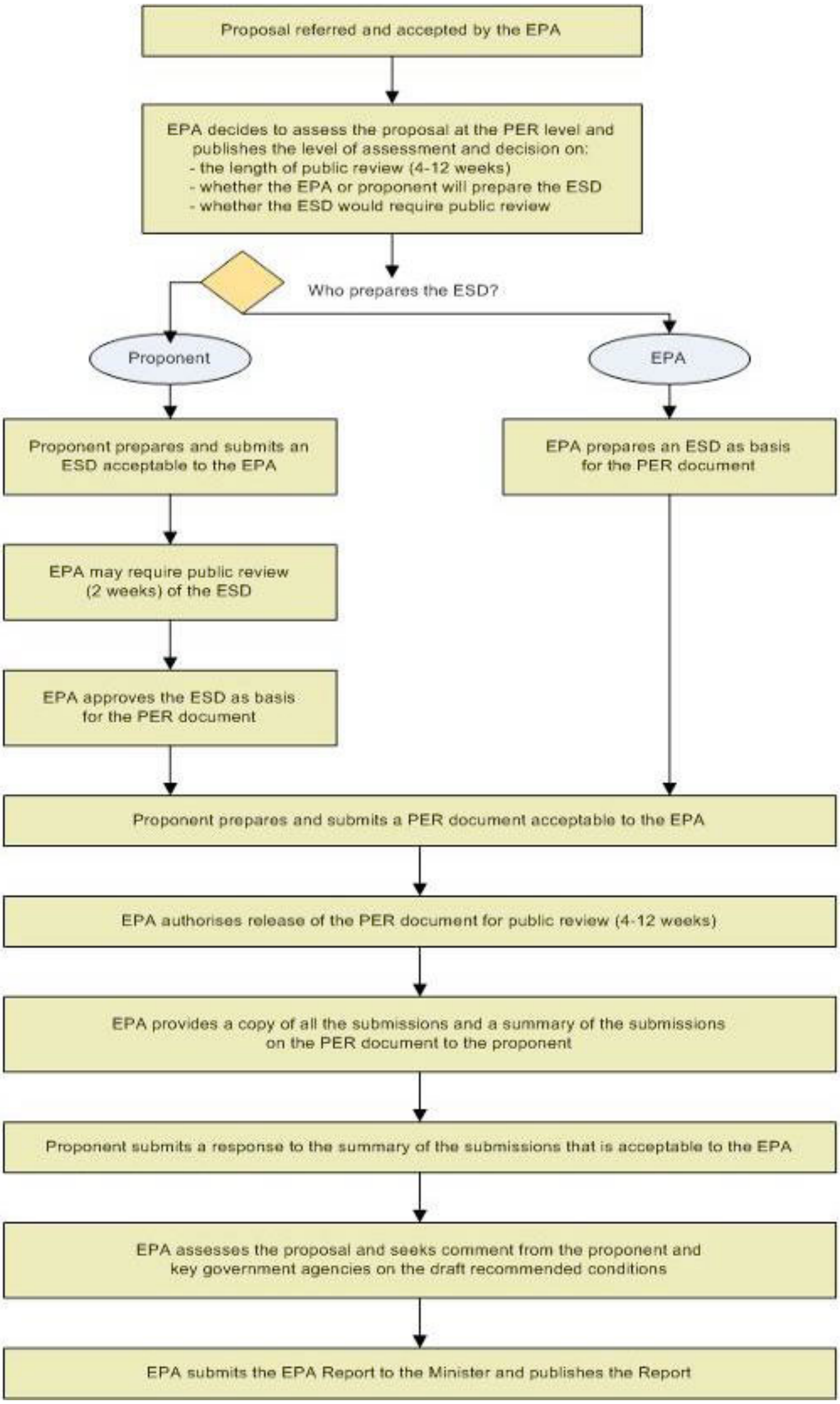
APPENDIX 1. EIA PROCESS DIAGRAM - ASSESSMENT ON PROPONENT INFORMATION

Source: Environmental Protection Authority website



APPENDIX 2. EIA PROCESS DIAGRAM – PUBLIC ENVIRONMENTAL REVIEW

Source: Environmental Protection Authority website



APPENDIX 3

Source: the Department of Environment and Conservation's Threatened Ecological Community Database endorsed by the Minister for the Environment (DEC, sourced April 2012)

Community identifier	Community name	General location (IBRA regions)
2. Toolibin	Perched wetlands of the Wheatbelt region with extensive stands of living Swamp Sheoak (*Casuarina obesa)* and Paperbark (*Melaleuca strobophylla*) across the lake floor.	Avon Wheatbelt
3. SCP10b	Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)	Swan Coastal Plain
4. SCP19	Sedgelands in Holocene dune swales of the southern Swan Coastal Plain	Swan Coastal Plain
5. Clifton-microbialite	Stromatolite like freshwater microbialite community of coastal brackish lakes	Swan Coastal Plain
6. Richmond-microbial	Stromatolite like microbialite community of coastal freshwater lakes	Swan Coastal Plain
7. Mound Springs SCP	Communities of Tumulus Springs (Organic Mound Springs, Swan Coastal Plain)	Swan Coastal Plain
10. Nthiron	Perth to Gingin Ironstone Association	Swan Coastal Plain
11. Muchea Limestone	Shrublands and woodlands on Muchea Limestone	Swan Coastal Plain
14. SCP18	Shrublands on calcareous silts of the Swan Coastal Plain	Swan Coastal Plain
15. SCP02	Southern wet shrublands, Swan Coastal Plain	Swan Coastal Plain
16. SCP3a	*Eucalyptus calophylla - Kingia australis* woodlands on heavy soils, Swan Coastal Plain	Swan Coastal Plain
17. SCP3c	*Eucalyptus calophylla - Xanthorrhoea preissii* woodlands and shrublands, Swan Coastal Plain	Swan Coastal Plain
18. Thetis-microbialite	Stromatolite community of stratified hypersaline coastal lakes	Geraldton Sandplain
19. Scott Ironstone	Scott River Ironstone Association	Warren
21. SCP15	Forests and woodlands of deep seasonal wetlands of the Swan Coastal Plain	Swan Coastal Plain
32. SCP07	Herb rich saline shrublands in clay pans	Swan Coastal Plain
33. SCP08	Herb rich shrublands in clay pans	Swan Coastal Plain
34. SCP09	Dense shrublands on clay flats	Swan Coastal Plain
35. SCP10a	Shrublands on dry clay flats	Swan Coastal Plain
38. Morilla swamp	Perched fresh-water wetlands of the northern Wheatbelt dominated by extensive stands of living *Eucalyptus camaldulensis* (River Red Gum) across the lake floor.	Avon Wheatbelt
40. Bryde	Unwooded freshwater wetlands of the southern Wheatbelt of Western Australia, dominated by *Muehlenbeckia horrida* subsp. *abdita* and *Tecticornia verrucosa* across the lake floor	Avon Wheatbelt
42. Greenough River Flats	*Acacia rostellifera* low forest with scattered *Eucalyptus camaldulensis* on Greenough Alluvial Flats.	Geraldton Sandplain
46. Themeda Grasslands	Themeda grasslands on cracking clays (Hamersley Station, Pilbara). Grassland plains dominated by the perennial Themeda (kangaroo grass) and many annual herbs and grasses.	Pilbara
49. Bentonite Lakes	Herbaceous plant assemblages on Bentonite Lakes	Avon Wheatbelt

63. Irwin River Clay Flats	Clay flats assemblages of the Irwin River: Sedgelands and grasslands with patches of *Eucalyptus loxophleba* and scattered *E. camaldulensis* over *Acacia acuminata* and *A. rostellifera* shrubland on brown sand/loam over clay flats of the Irwin River.	Avon Wheatbelt
72. Ferricrete	Ferricrete floristic community (Rocky Springs type)	Geraldton Sandplain
74. Herblands and Bunch Grasslands	Herblands and Bunch Grasslands on gypsum lunette dunes alongside saline playa lakes	Esperance Sandplain
80. Theda Soak	Assemblages of Theda Soak rainforest swamp	North Kimberley
81. Walcott Inlet	Assemblages of Walcott Inlet rainforest swamps	North Kimberley
82. Roe River	Assemblages of Roe River rainforest swamp	North Kimberley
84. Dragon Tree Soak	Assemblages of Dragon Tree Soak organic mound spring	Kimberley Region, Great Sandy Desert Bioregion
85. Bunda Bunda	Assemblages of Bunda Bunda organic mound spring	West Kimberley, Dampierland Bioregion
86. Big Springs	Assemblages of Big Springs organic mound springs	West Kimberley, Dampierland Bioregion
89. North Kimberley mounds	Organic mound spring sedgeland community of the North Kimberley Bioregion	North Kimberley
92. Black Spring	Black Spring organic mound spring community	North Kimberley
95. Mandora Mounds	Assemblages of the organic springs and mound springs of the Mandora Marsh area	West Kimberley, Dampierland and Greats Sandy Desert Bioregions
97. Mound Springs (Three Springs area)	Assemblages of the organic mound springs of the Three Springs area	Avon Wheatbelt