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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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.

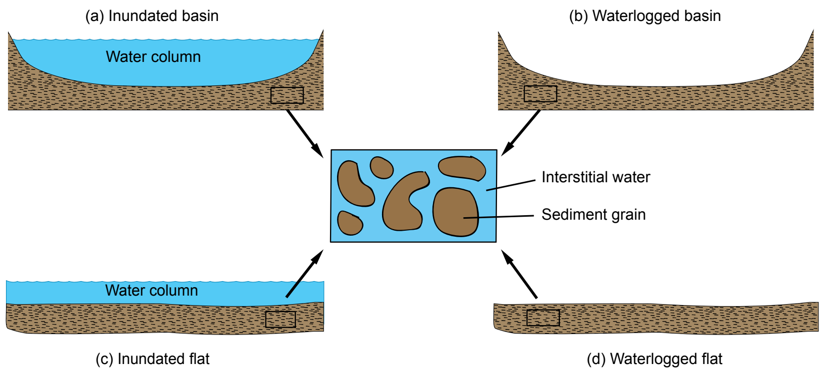

Figure 1. Water columns and sediment pore waters. Image – J Higbid/DEC.

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.

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

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).

Figure 4. Lake Eda, near Broome, is a seasonally inundated wetland in northern WA. Photo – Wetlands Section/DEC.

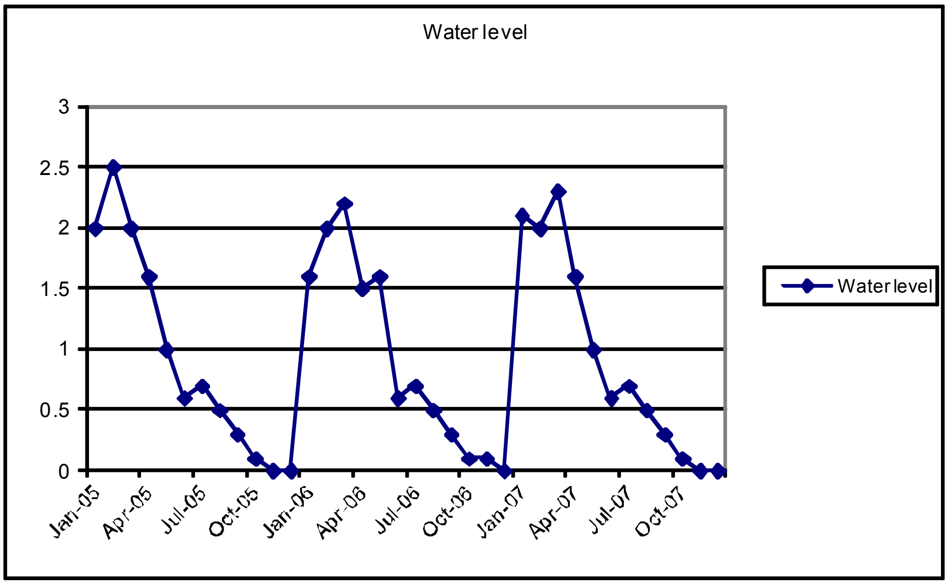

Figure 5. Hydrograph showing the estimated water levels in Lake Eda from January 2005 to December 2007. Water levels estimated from local rainfall data.

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

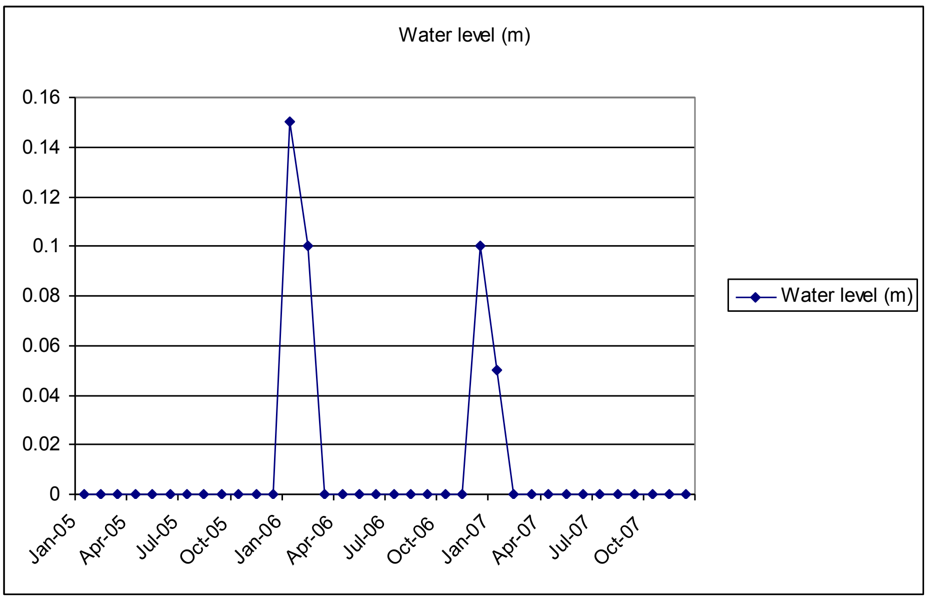

Figure 7. Hydrograph showing the estimated water levels in Mungkili claypan from January 2005 to December 2007. Water levels estimated from local rainfall data.

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.

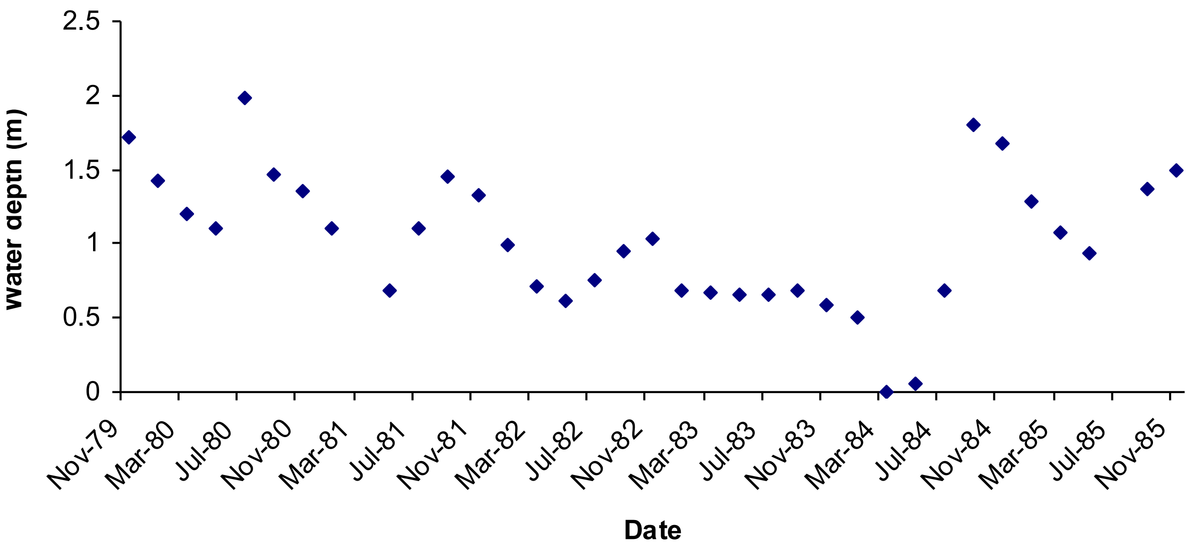

Figure 10. Hydrograph showing the recorded water depths in Lake Gore from November 1979 to November 1985.

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.

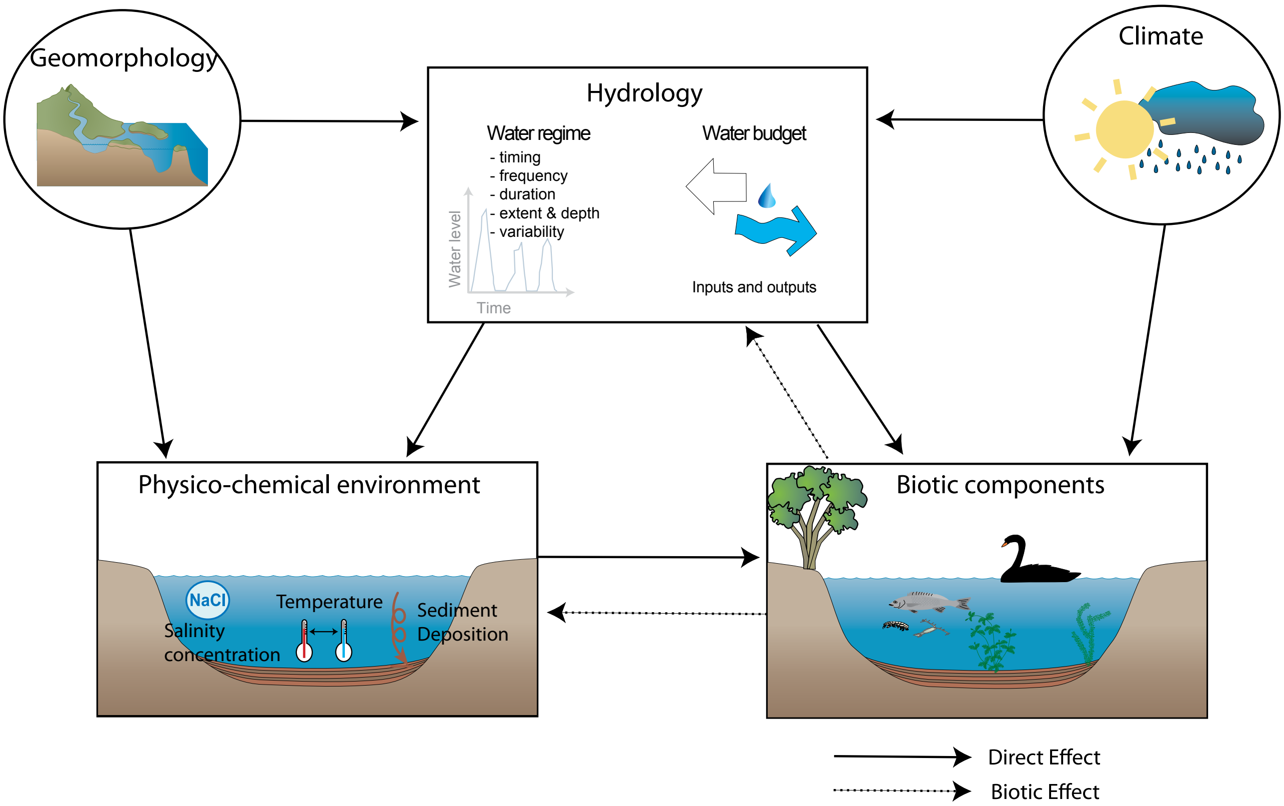

Figure 11. Conceptual model of wetland ecology, illustrating climate and geomorphology as the 'drivers' of wetland hydrology and the inter-relationship between wetland hydrology, physical and chemical components of wetlands and wetland plants and animals. Adapted from Mitsch and Gosselink (2007).[19]

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.

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

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.

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.

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

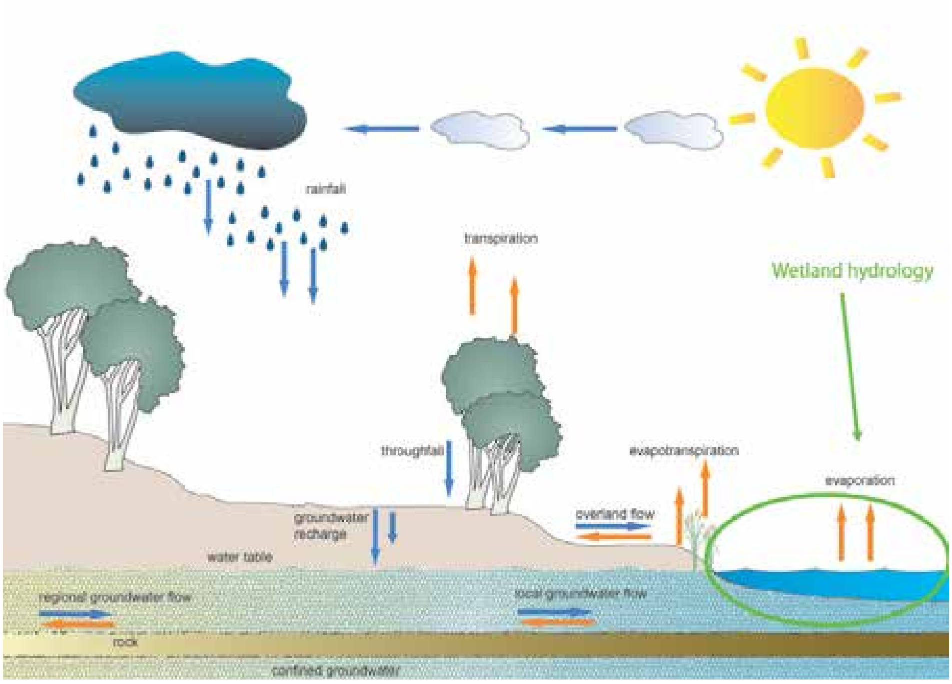

Figure 17. Aspects of wetland hydrology.

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]

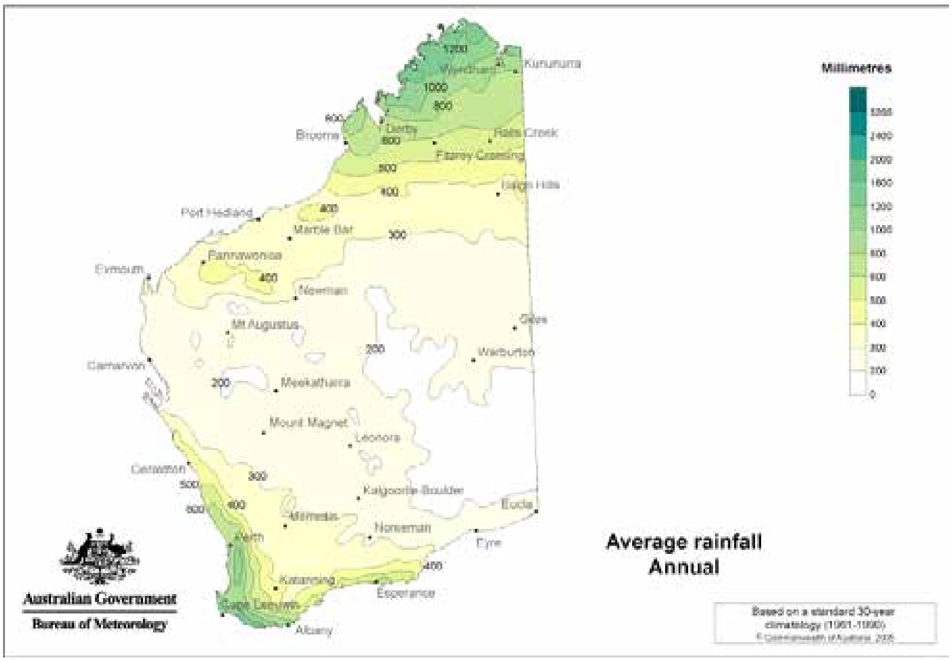

Figure 18. Average annual rainfall for Western Australia. Courtesy Bureau of Meteorology.

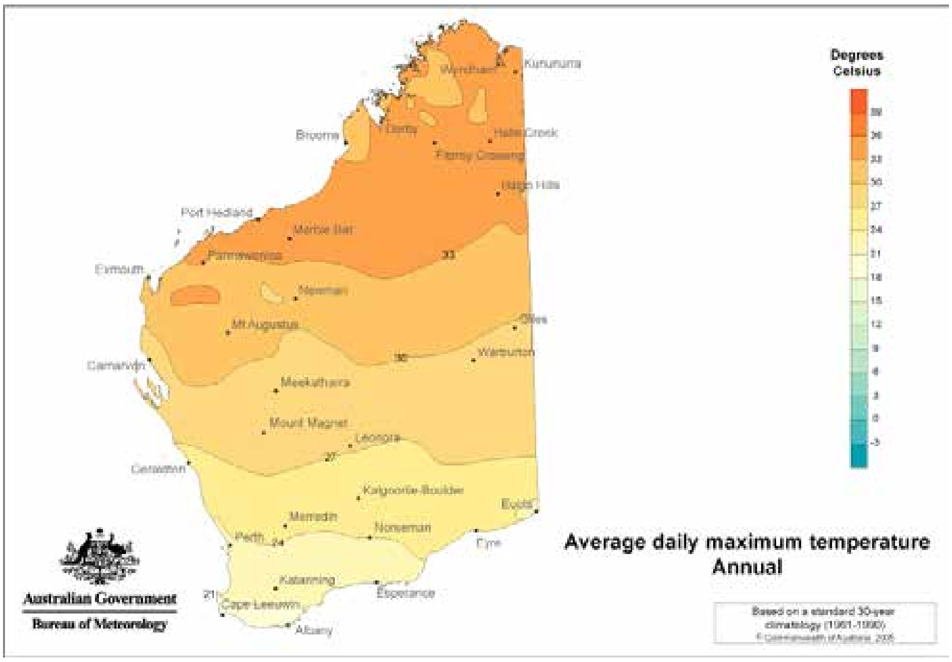

Figure 19. Average annual daily maximum temperature for Western Australia. Based on a standard 30-year climatology (1961–1990). Image - courtesy Bureau of Meteorology.

➤ 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

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

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.

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.

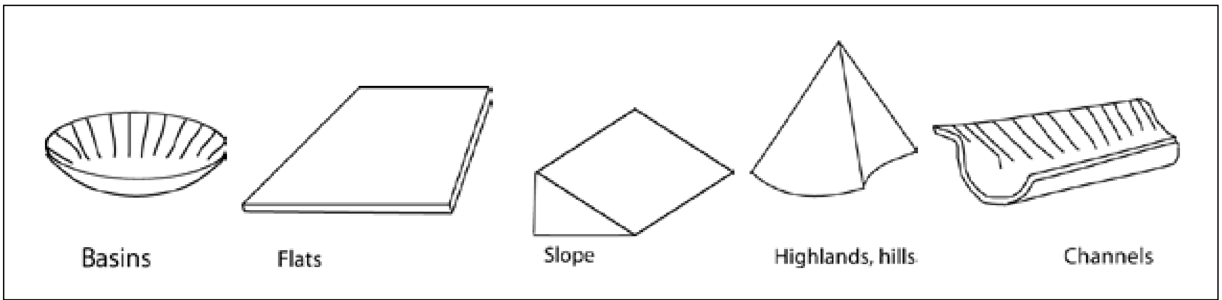

Figure 24. Landforms that become host to wetlands (basins, flats, slopes and highlands) and waterways (channels). Other wetlands, such as mound springs, are self emergent rather than developing in a host landform. Source: adapted from Hill et al. 1996.[5]

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').

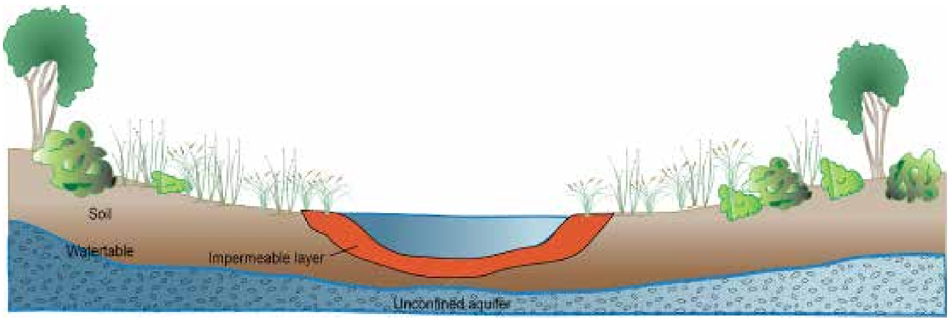

Figure 25. A perched wetland, which receives water from rainfall and overland flow. In this case, although there is groundwater in the vicinity of the base of the wetland, the thick impermeable sediment layer is a barrier between the wetland and the groundwater.

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).

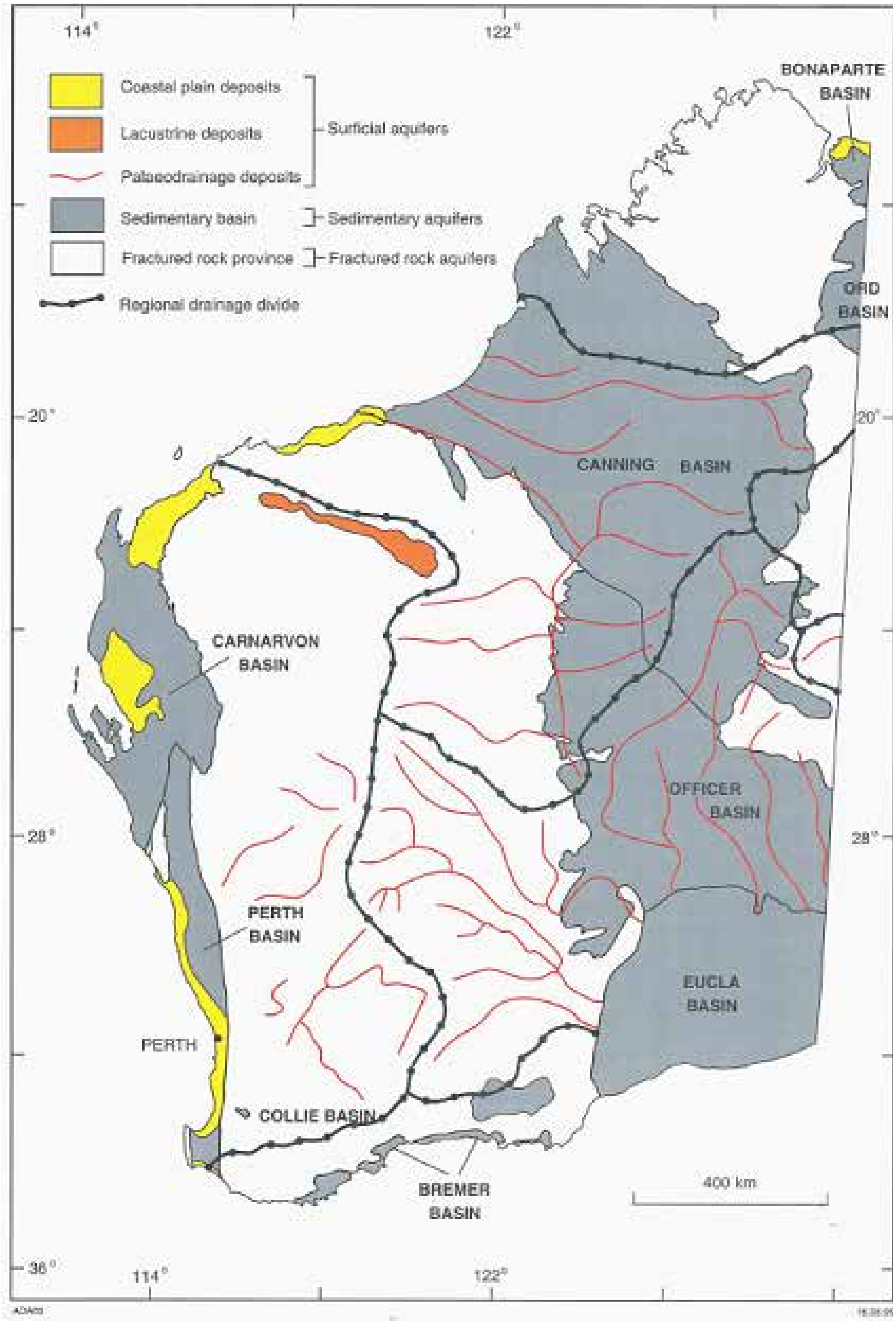

Figure 30. The general location of WA's surficial, sedimentary and fractured rock aquifers. Image – Allen (1997).[43]

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

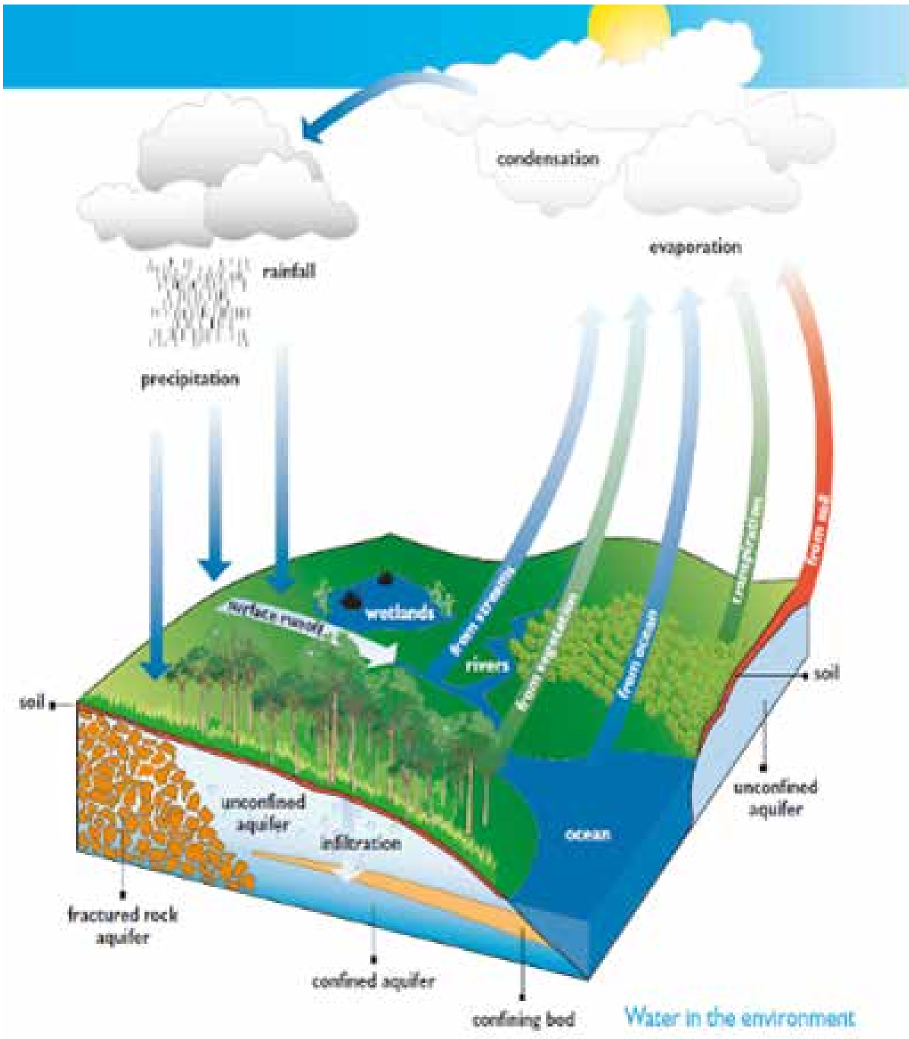

Figure 31. Confined and unconfined aquifers. Diagram – courtesy of Department of Water.[44]

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]).

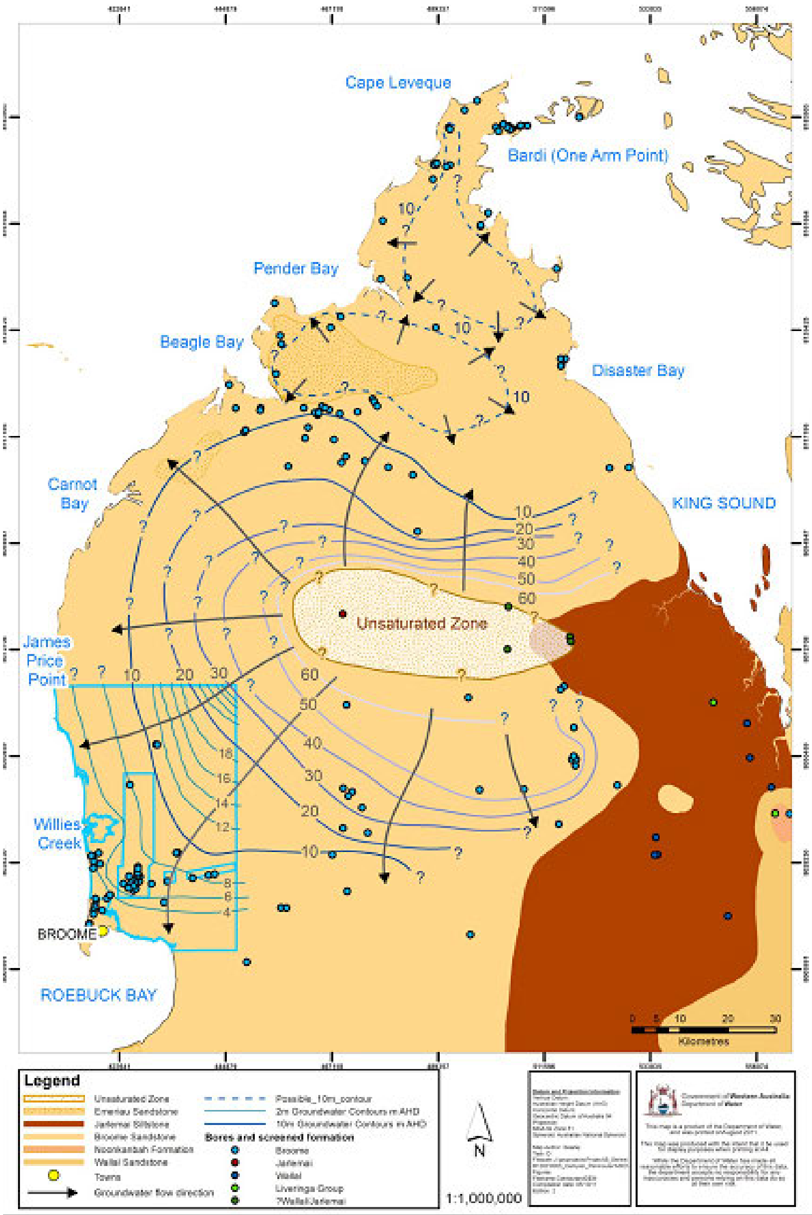

Figure 32. A map of the Broome area, showing multiple aquifers, inferred regional groundwater contours and groundwater flow direction. The circle in the centre represents the top of the mound, and the arrows indicate the inferred direction of groundwater flow. Source – courtesy of the Department of Water.[48]

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.

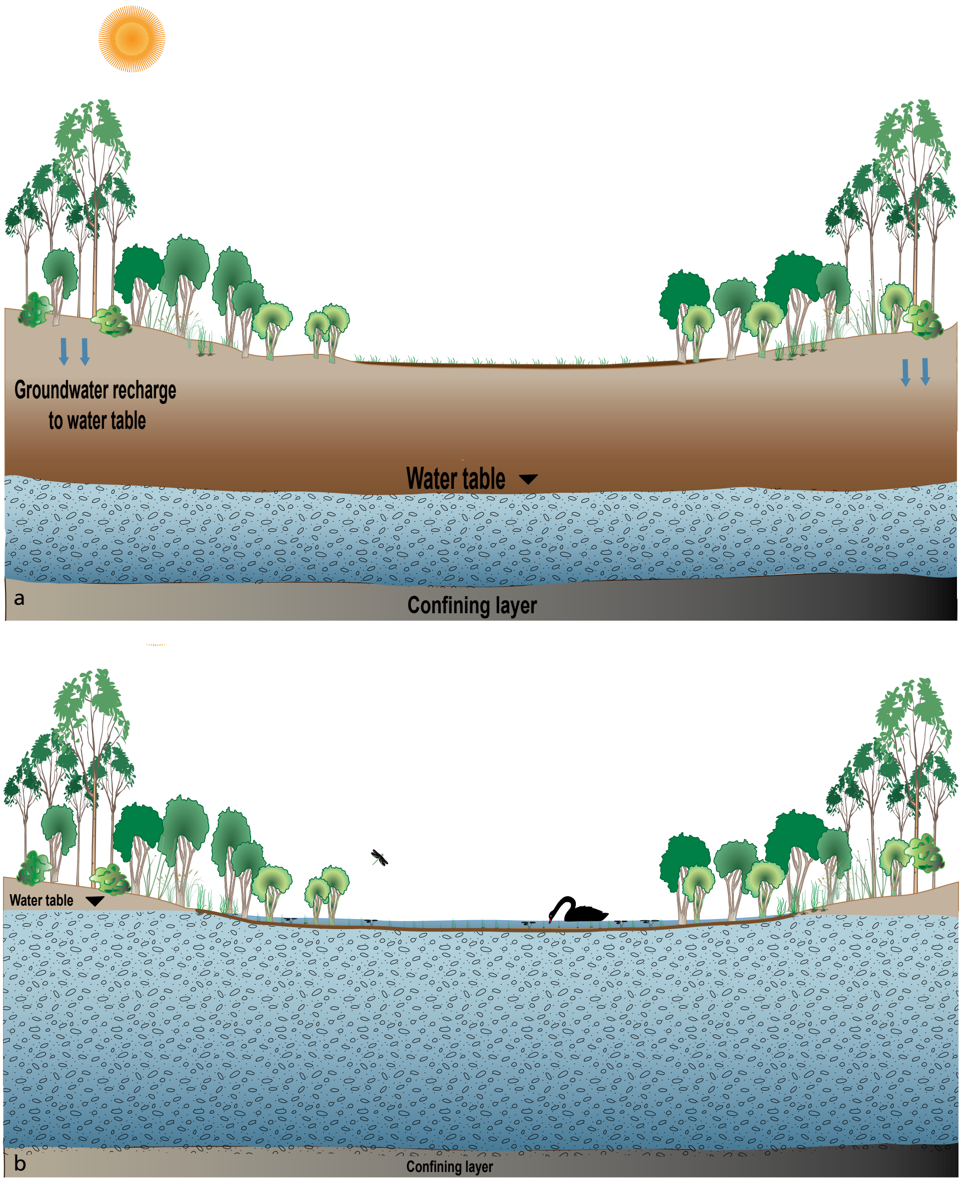

Figure 33. A simplified diagram of groundwater flux; (a) when the water table is far below the wetland, the wetland is disconnected from the groundwater; (b) when the water table is as high as the base of a wetland, water may flow into the wetland. Such wetlands are often said to be 'groundwater fed'. 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]

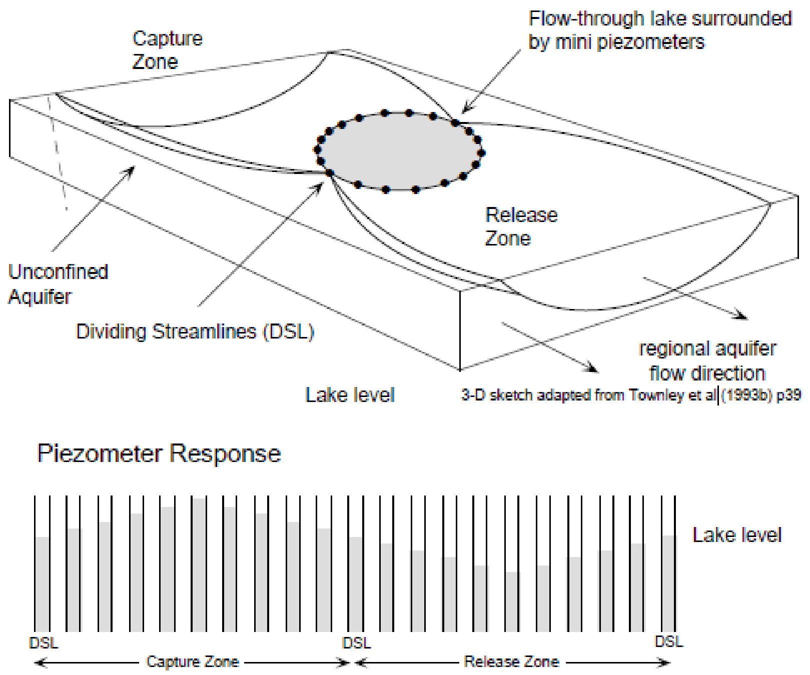

Figure 34. A schematic diagram showing the local capture and release zone of a flow-through wetland relative to the regional groundwater flow. Image - Integrated Mass, Solute, Isotopic & Thermal Balances of a Coastal Wetland: Wetland Research at Perry Lakes, Western Australia 1993-1998[52]

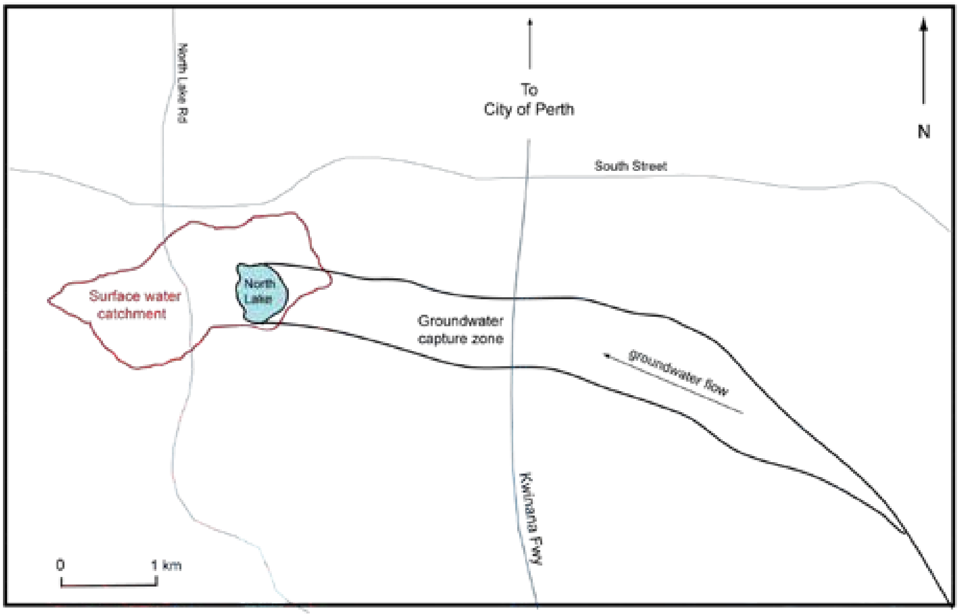

Figure 35. Schematic view of a wetland natural (prior to human modification) surface water catchment and groundwater capture zone, based on North Lake in Perth's southern suburbs.

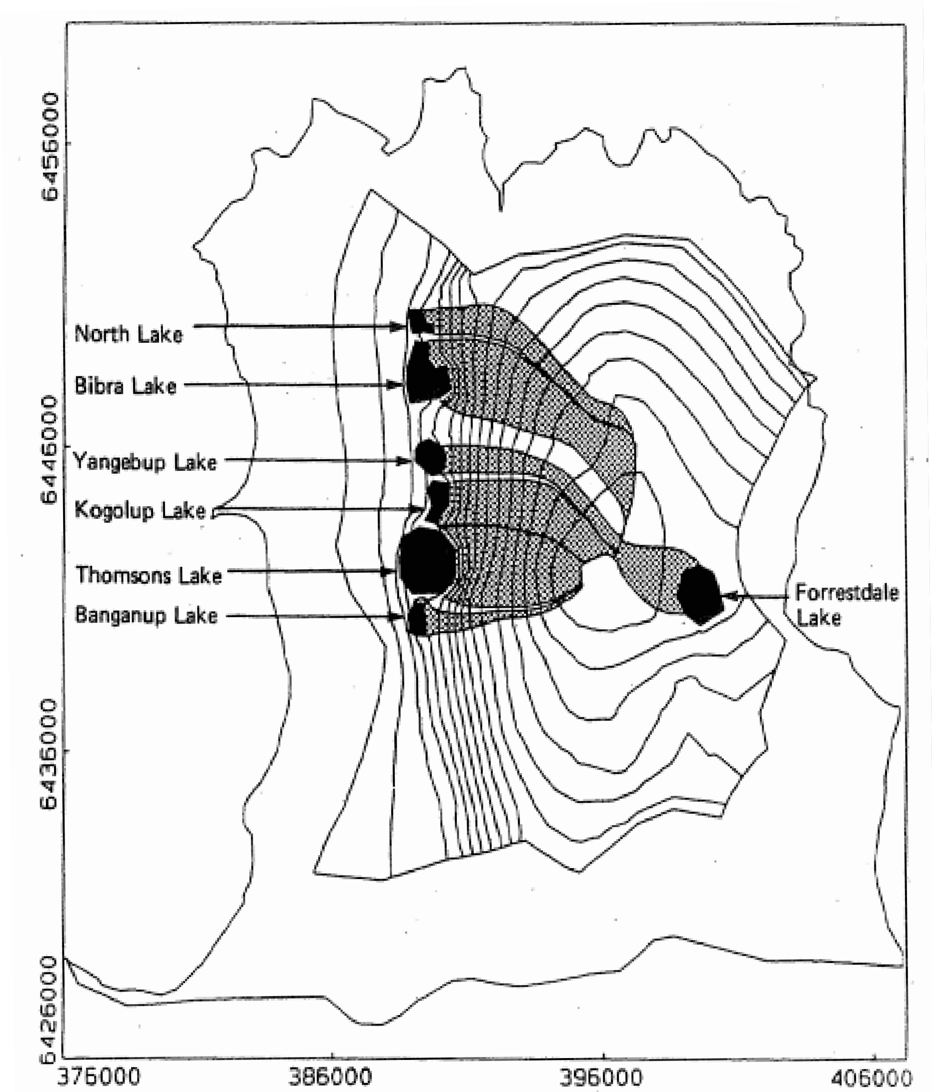

Figure 36. Predicted capture zones for seven lakes on the Jandakot Mound. Source – Townley et al.[52]

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

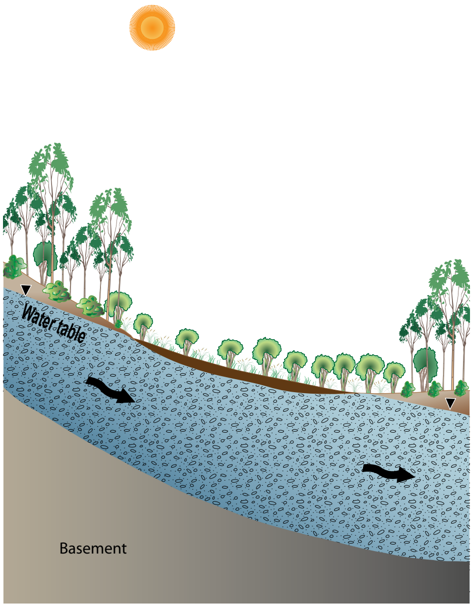

Figure 37. Wetlands can form on slopes, by seepages at the break of slope.

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).

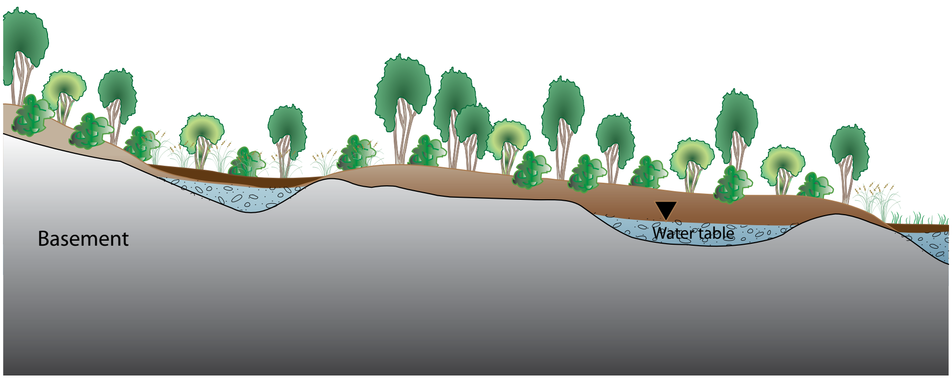

Figure 39. Bedrock highs trap water and force it to the surface, creating wetlands.

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.

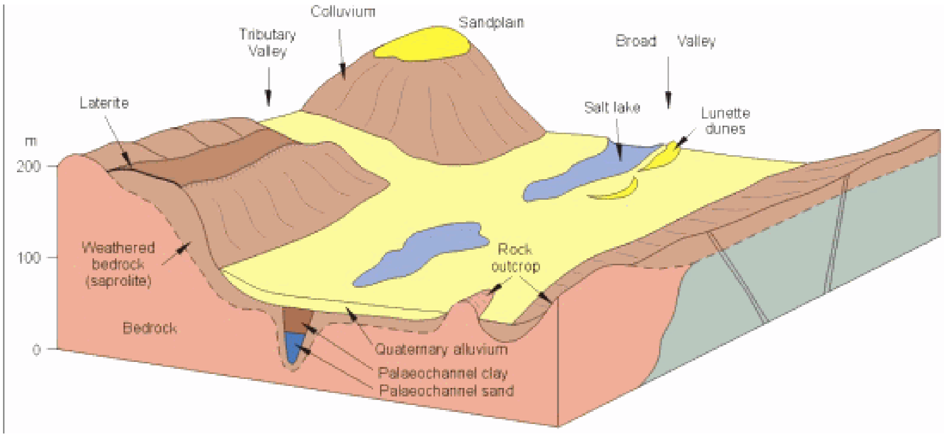

Figure 40. A stylised depiction of Wheatbelt valley geology including a palaeochannel. Image - Commander (2001).[54]

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.

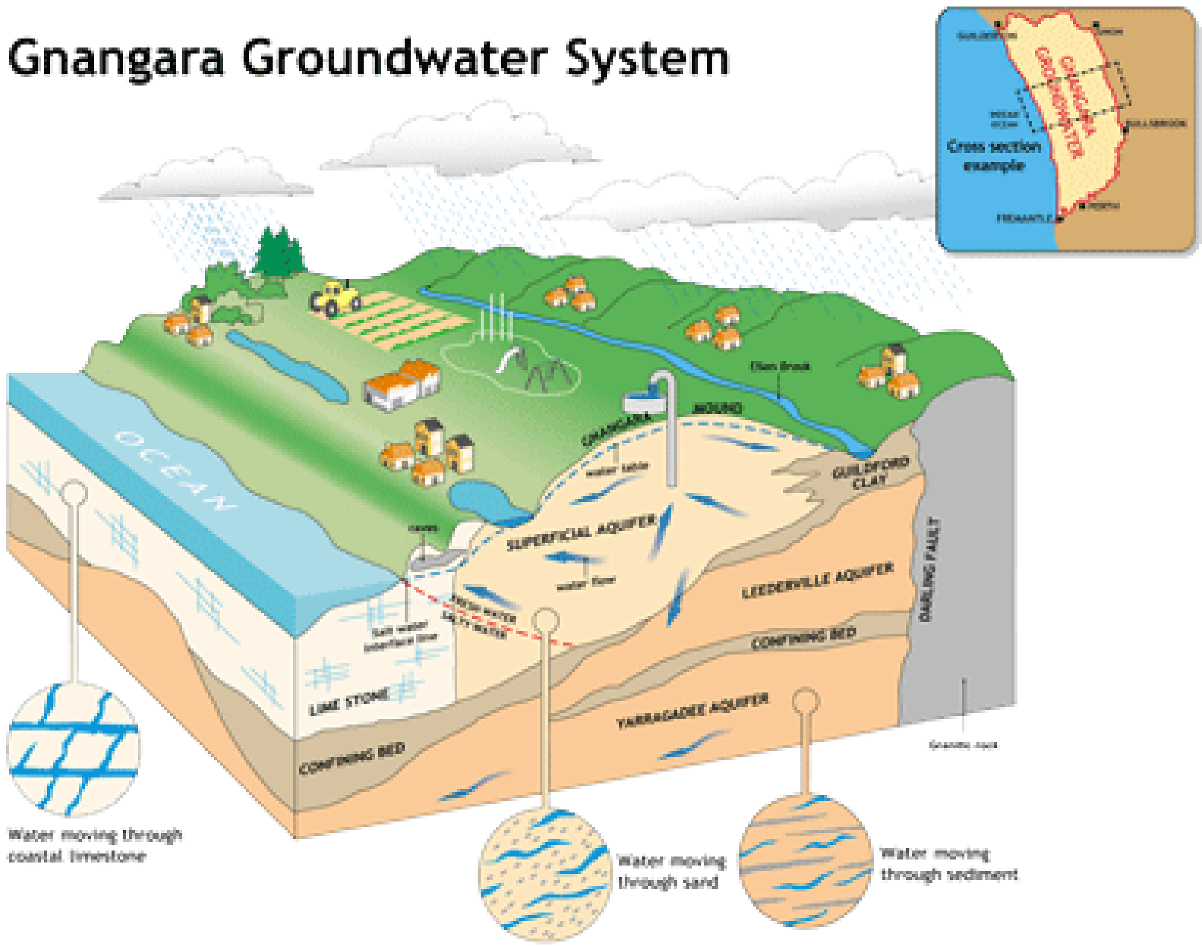

Figure 42. The Gnangara groundwater system in plan view. Image – courtesy of the Department of Water.

extra information

The Gnangara groundwater system (cont'd)

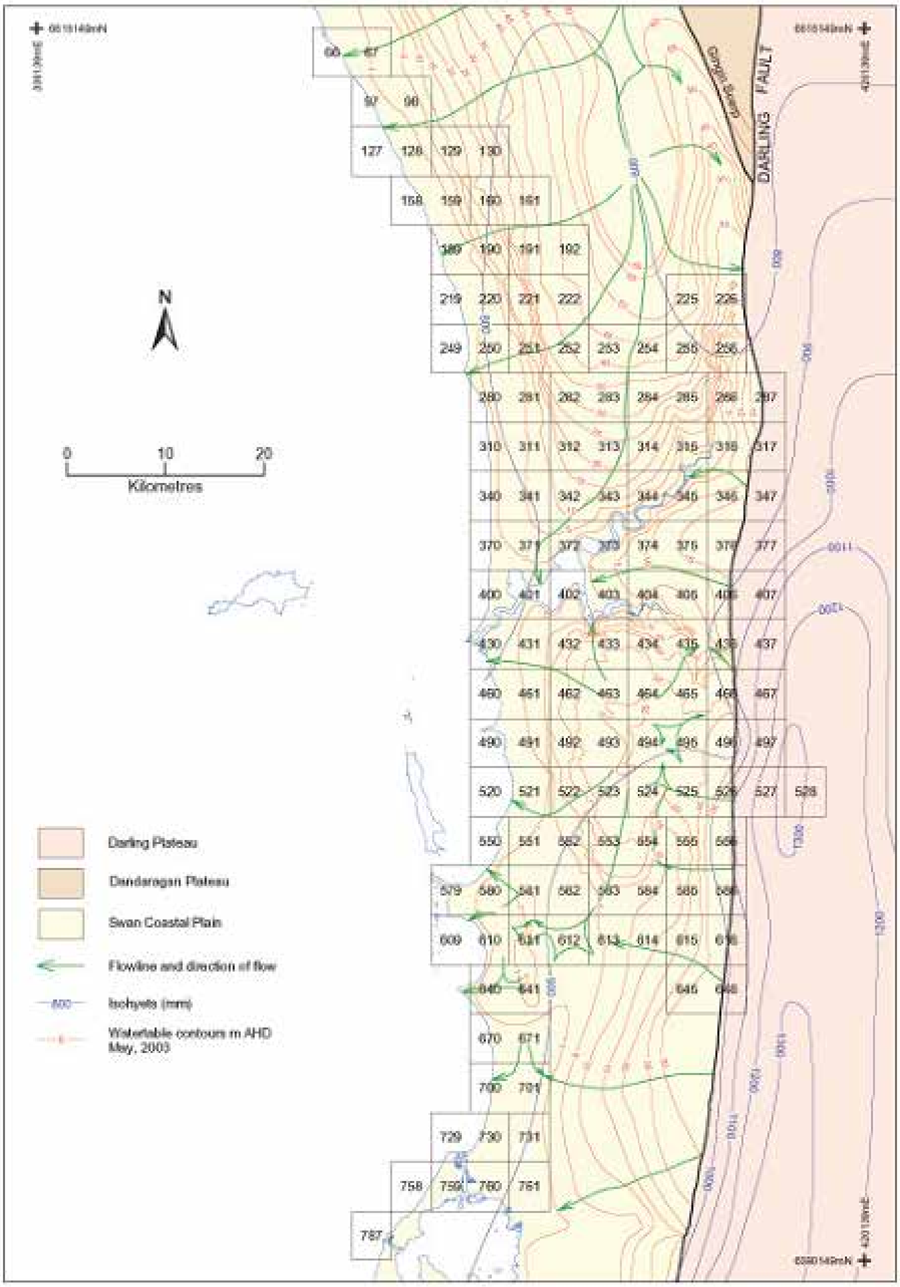

Figure 43. A map of the Gnangara (northern) and Jandakot (southern) groundwater mounds. Source – courtesy of the Department of Water.[56]

- 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

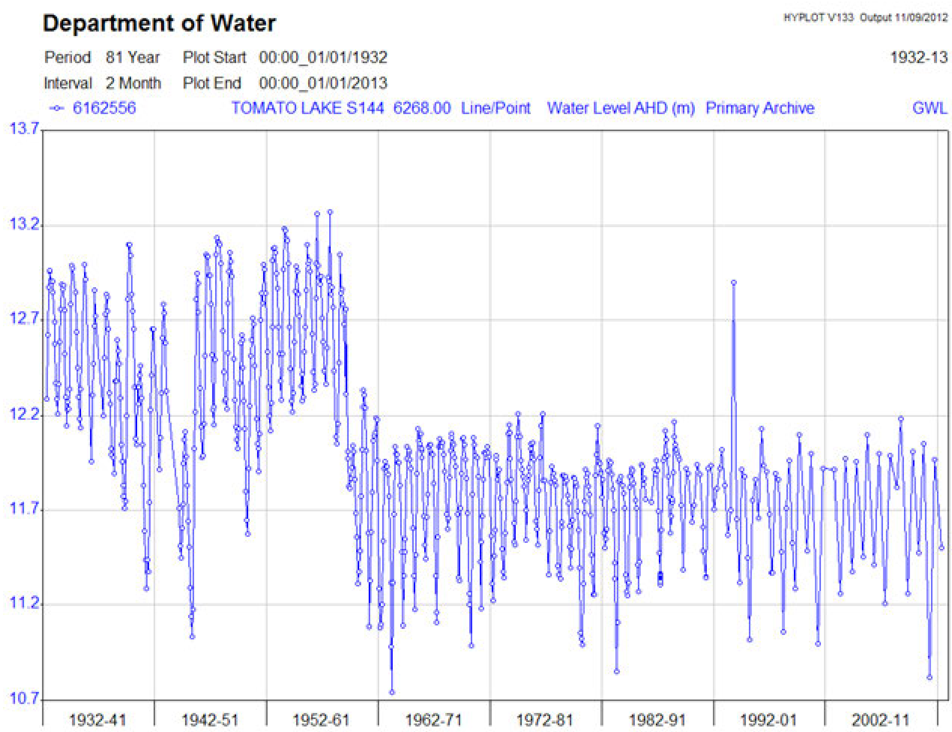

Figure 45. Groundwater measurements can be plotted in the form of hydrographs to show trends over time. Image – courtesy of Department of Water.[58]

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]

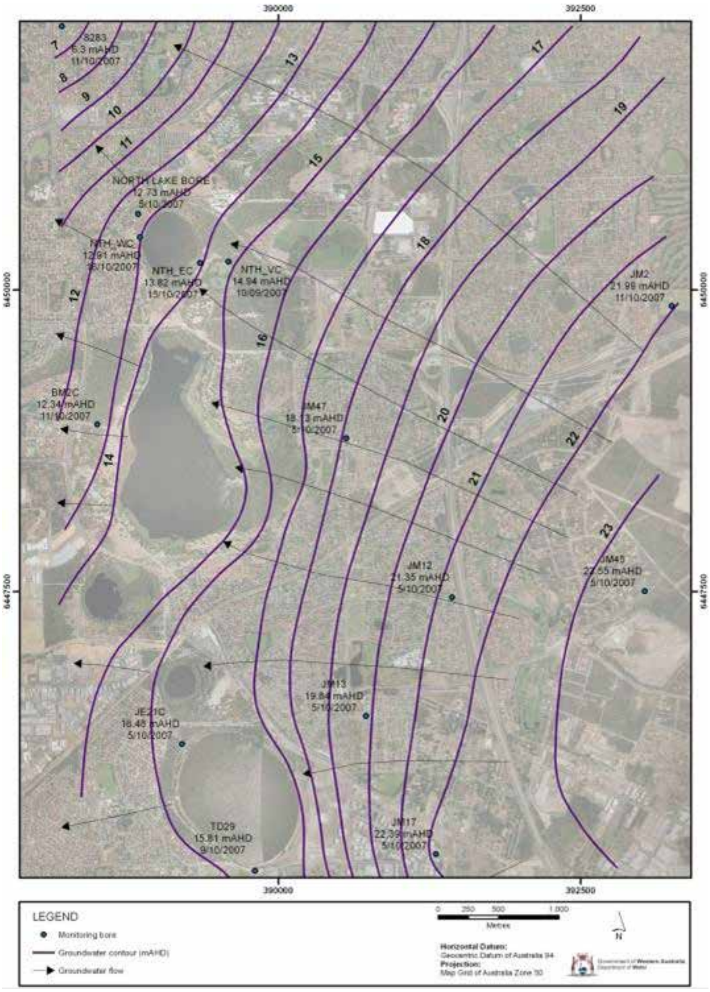

Figure 46. Mapping of the height of groundwater (contours) in the southern Perth area. The arrows indicate the direction of groundwater flow. Image – courtesy of Department of Water.

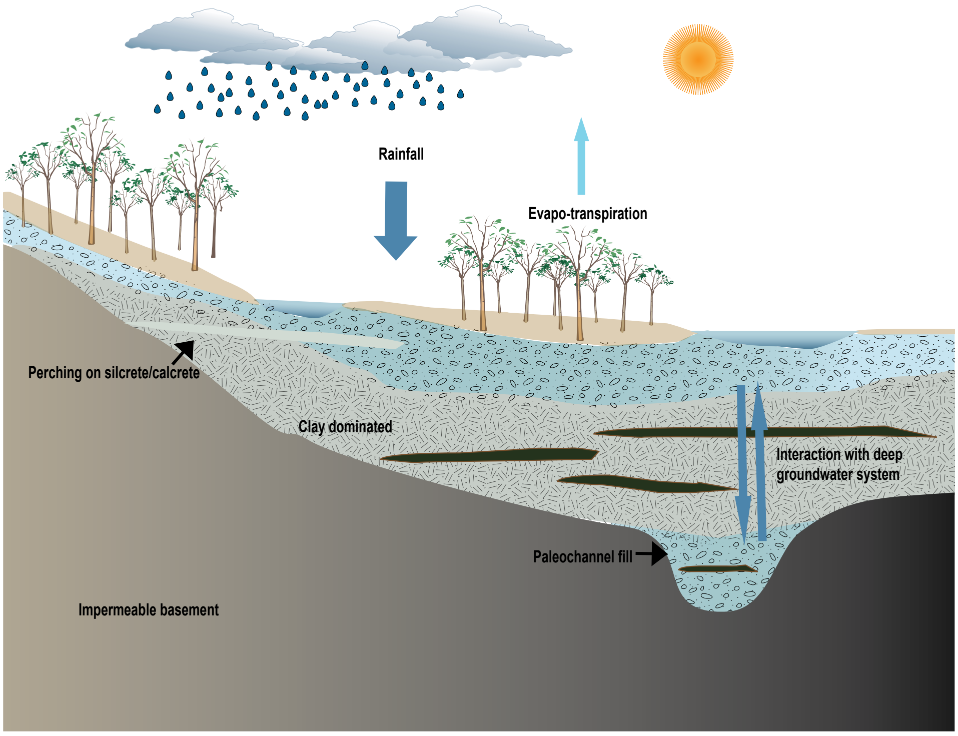

Figure 47. Complex below-ground layering can lead to complex groundwater conditions.

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]

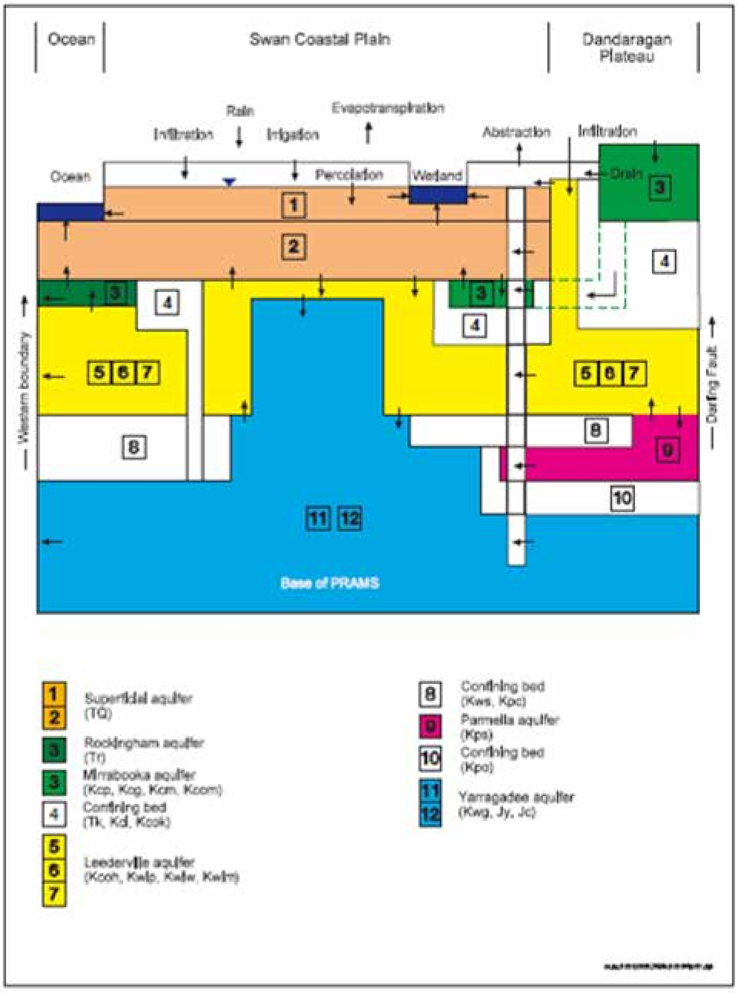

Figure 48. A conceptual hydrogeological model of the Perth groundwater system. Source – Department of Water. [62]

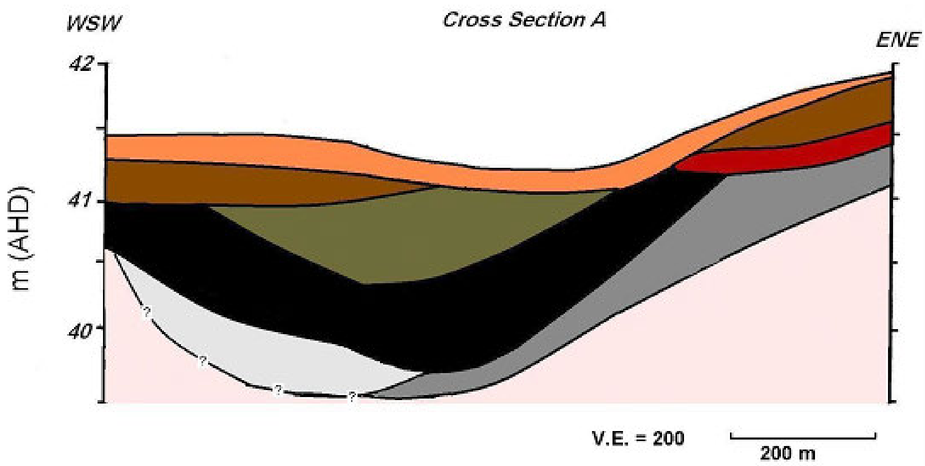

Figure 49. Many wetland sediments are not uniform across a wetland, such as those of Lake Mariginiup, represented here in cross-section. Image – Department of Water.[63]

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.

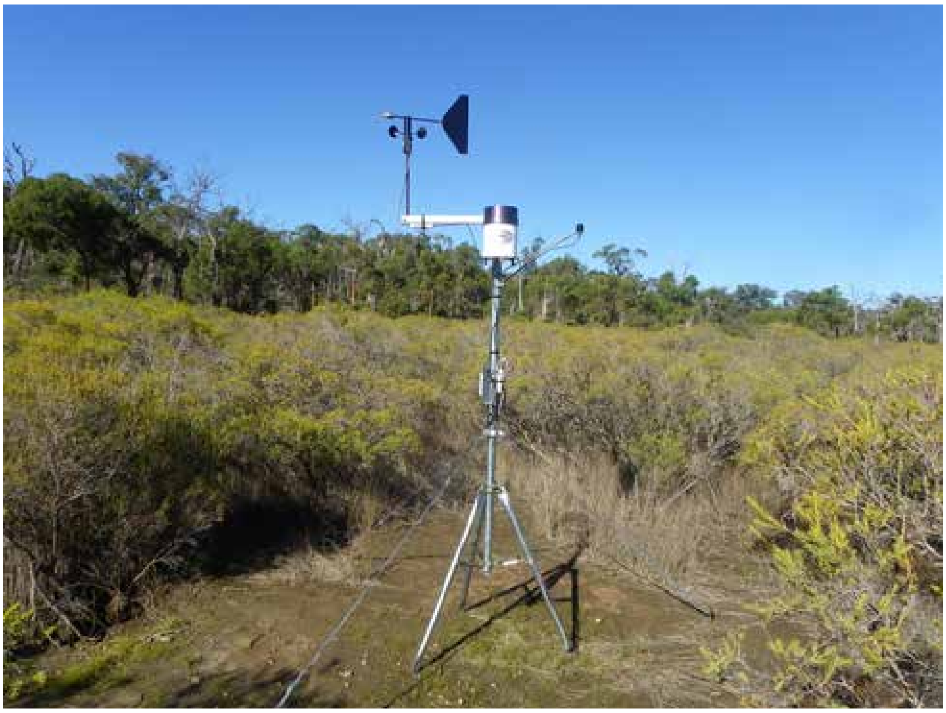

Figure 50. Understanding of the hydrology of a claypan in Drummond Nature Reserve, in the Northern Jarrah Forest region, is being aided by detailed field measurements. Photo – J Lawn/ DEC.

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.

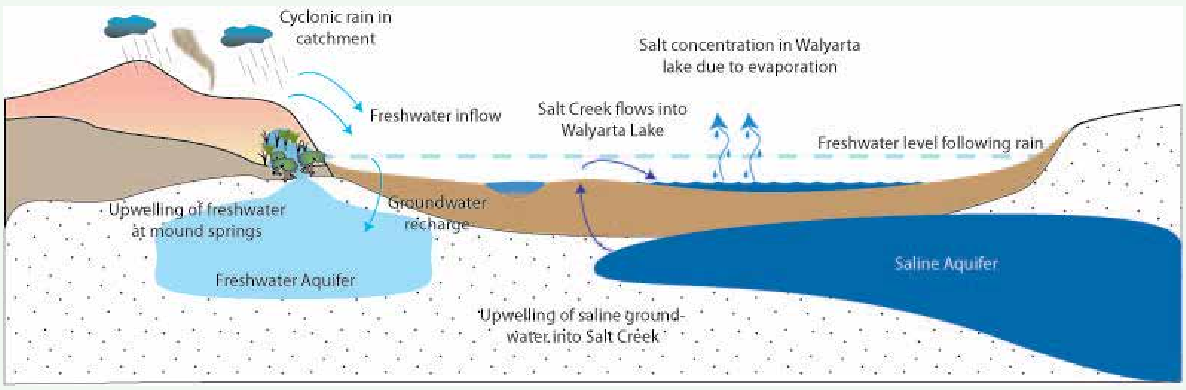

Figure 53. A conceptual model of the water inputs and outputs to Mandora Marsh.[69]

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.

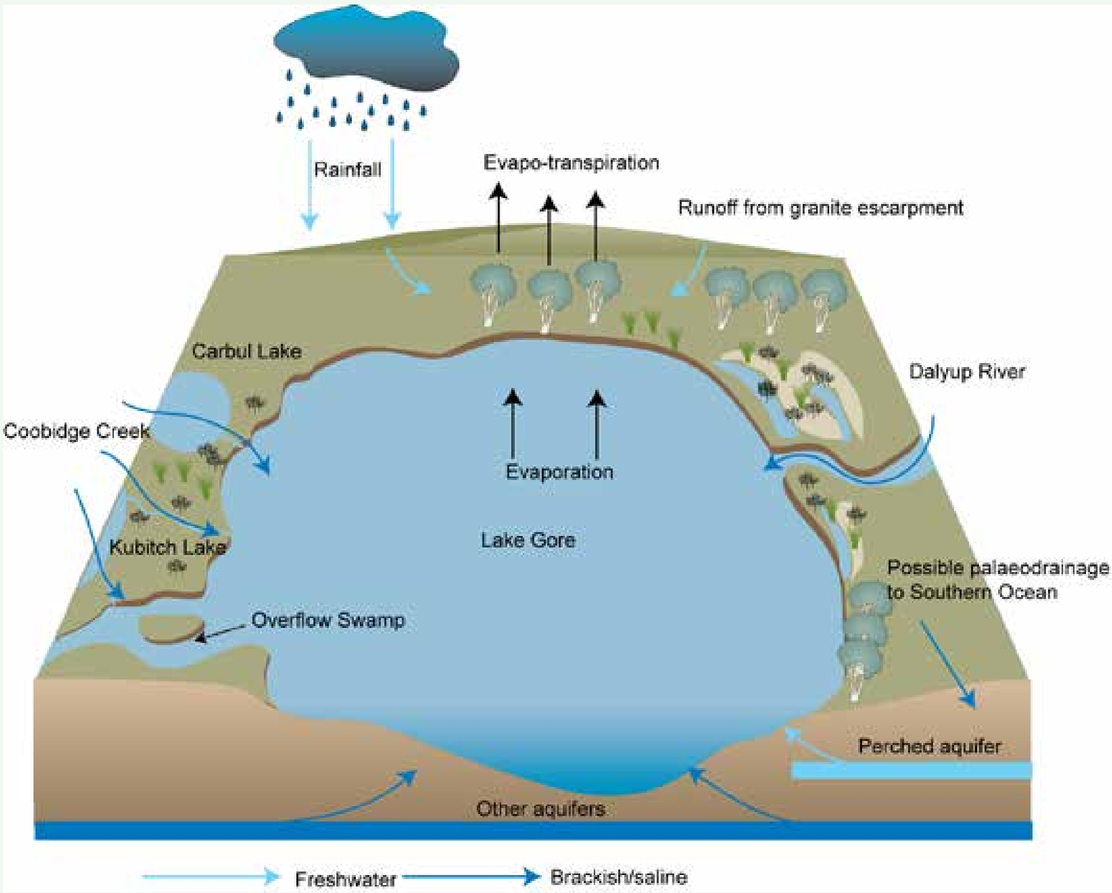

Figure 56. A conceptual model of inputs and outputs of Lake Gore. Image - Watkins (2008).[70]

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

Johnson, S.L. and Wright, A.H. (2001). *Hydrogeological record series 8: Central Pilbara Groundwater Study*. Water and Rivers Commission, Perth, Western Australia.

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

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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.

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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'.

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.

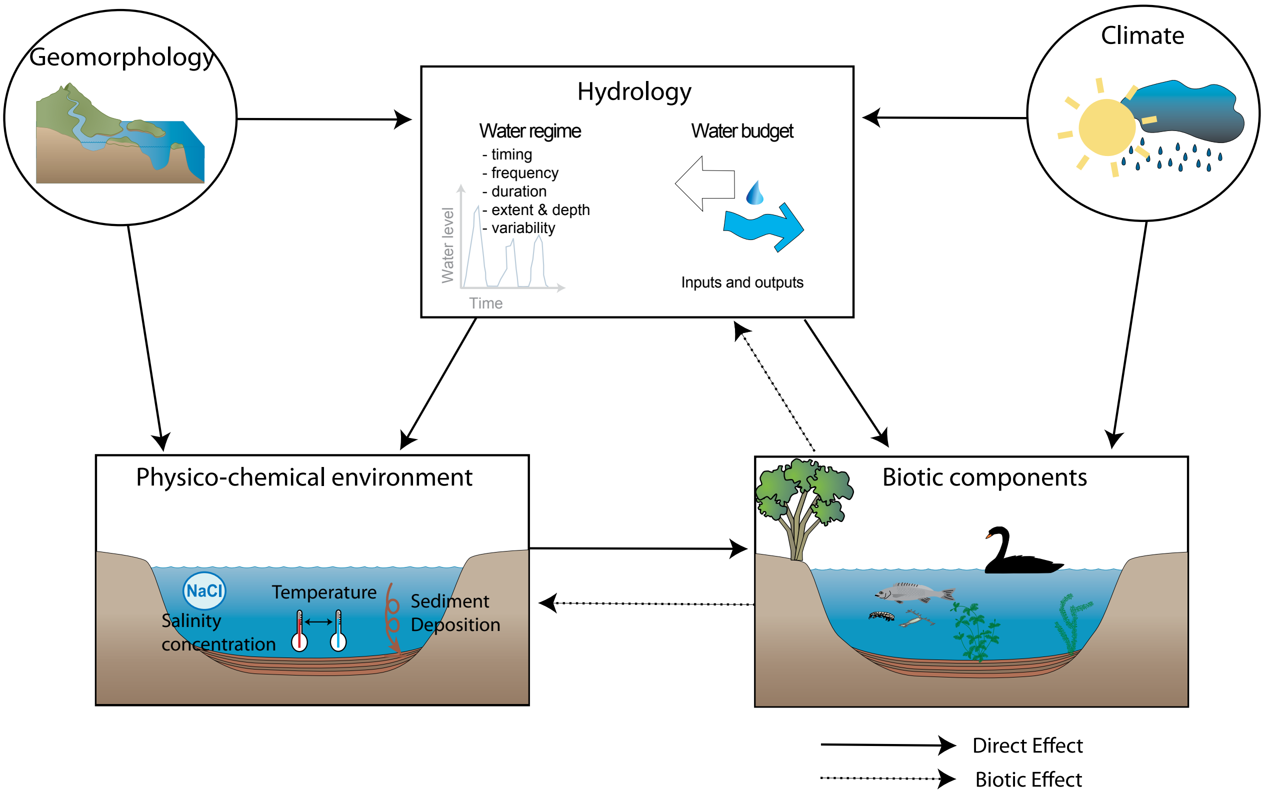

Figure 1. The physico-chemical environment has an important effect on the living conditions of a wetland (adapted from Mitsch and Gosselink 2007).[1]

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.

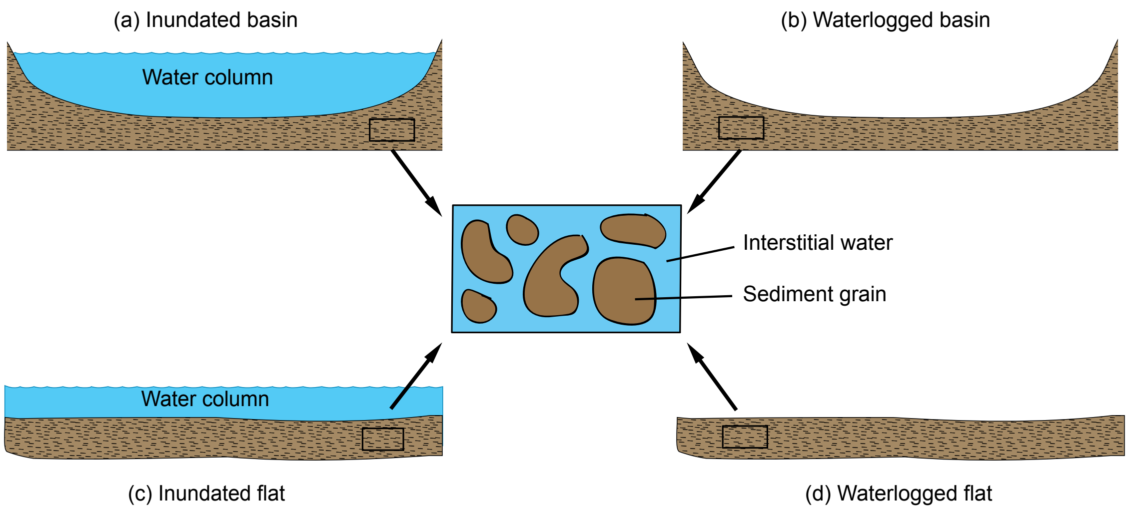

Figure 2. Water columns and sediment pore waters of different types of wetlands: (a) inundated basins; (b) waterlogged basins; (c) inundated flats; and (d) waterlogged flats (also applicable to slopes and highlands). Image – J Higbid/DEC.

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

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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'.

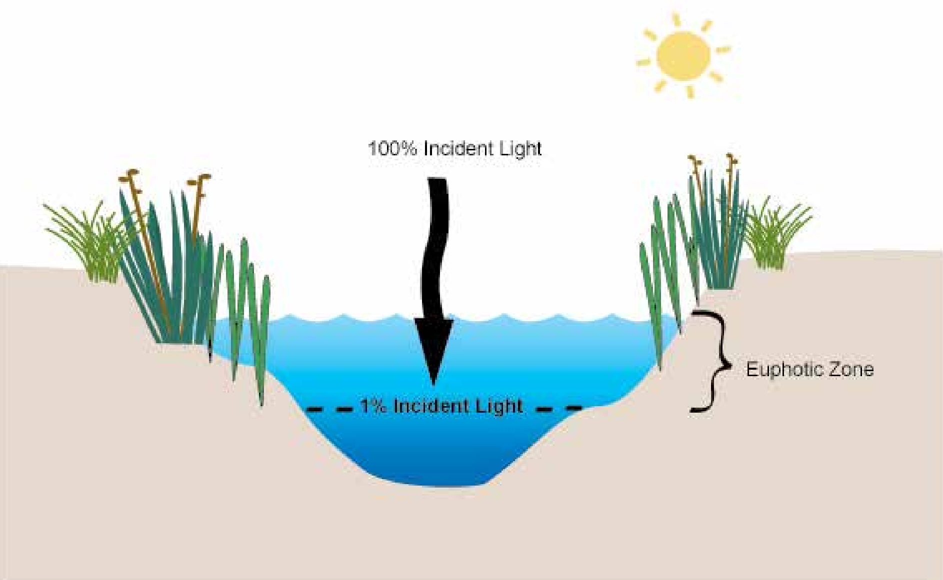

Figure 3. The euphotic zone of an inundated wetland.

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.

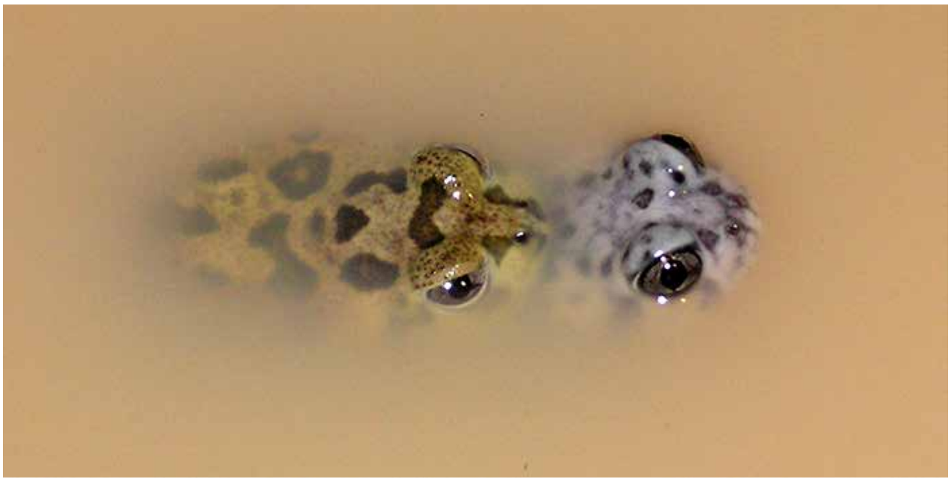

Figure 7. Turbid pools provide protection for tadpoles of the Wheatbelt frog, *Neobatrachus kunapalari*. Photo – courtesy of FrogWatch http://frogwatch.museum.wa.gov.au/

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'.

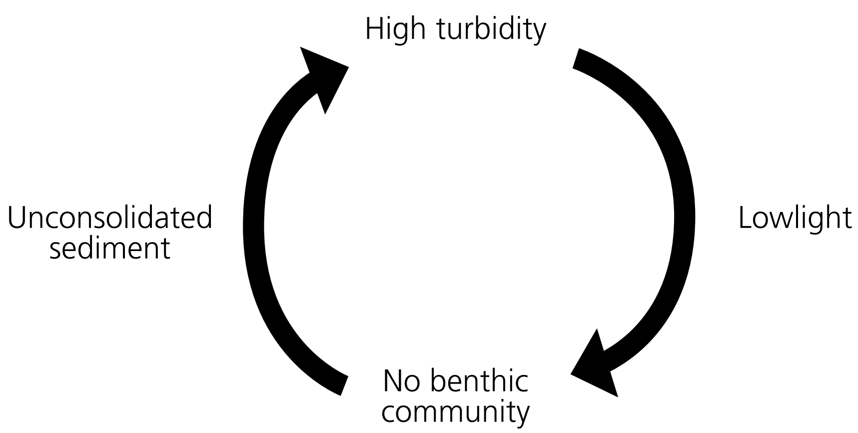

Figure 8. Feedback loop promoting turbid conditions in wetlands. Image – M Bastow/DEC.

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]

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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

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]

Ion: an atom that has acquired an electrical charge by the loss or gain of one or more electrons.

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)

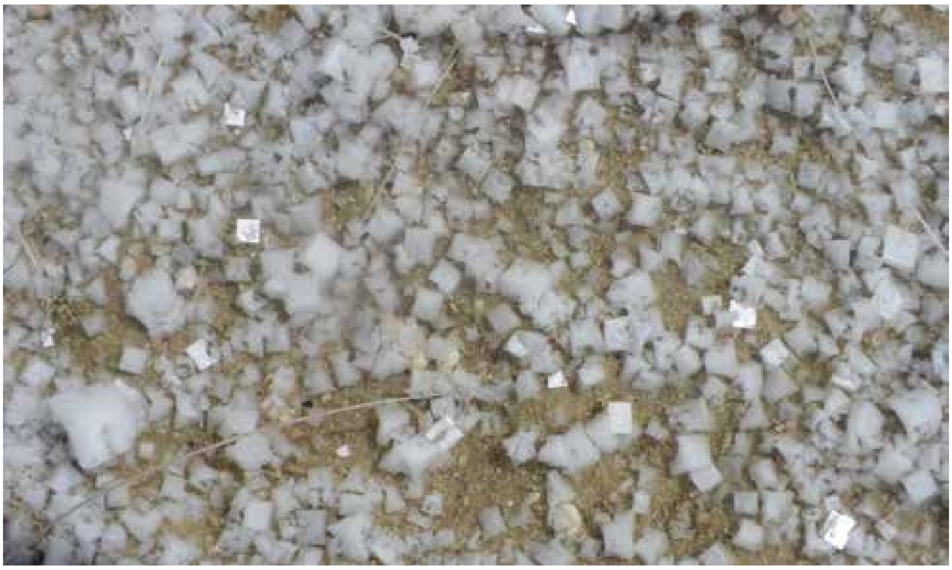

Figure 15. Salt crystals in a wetland in Jurien in the midwest of WA. Photo – J Lawn/DEC.

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, µS 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 µS 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

Department of Agriculture and Food (2004) 'Salinity measures, units and classes'.[18]

Department of Agriculture and Food (2004) 'Salinity in Western Australia'.[19]

Hammer, UT (1986) 'Chapter 2 The saline lake concept', *Saline lake ecosystems of the world*.[14]

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.

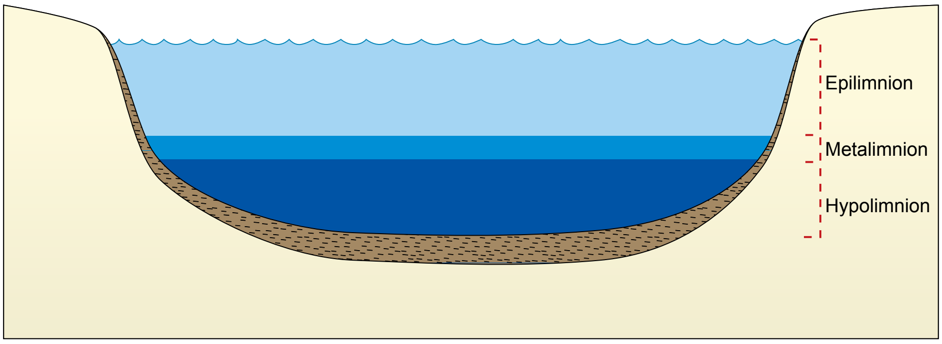

Figure 19. Stratification of a wetland into epilimnion, metalimnion and hypolimnion.

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]

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

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.

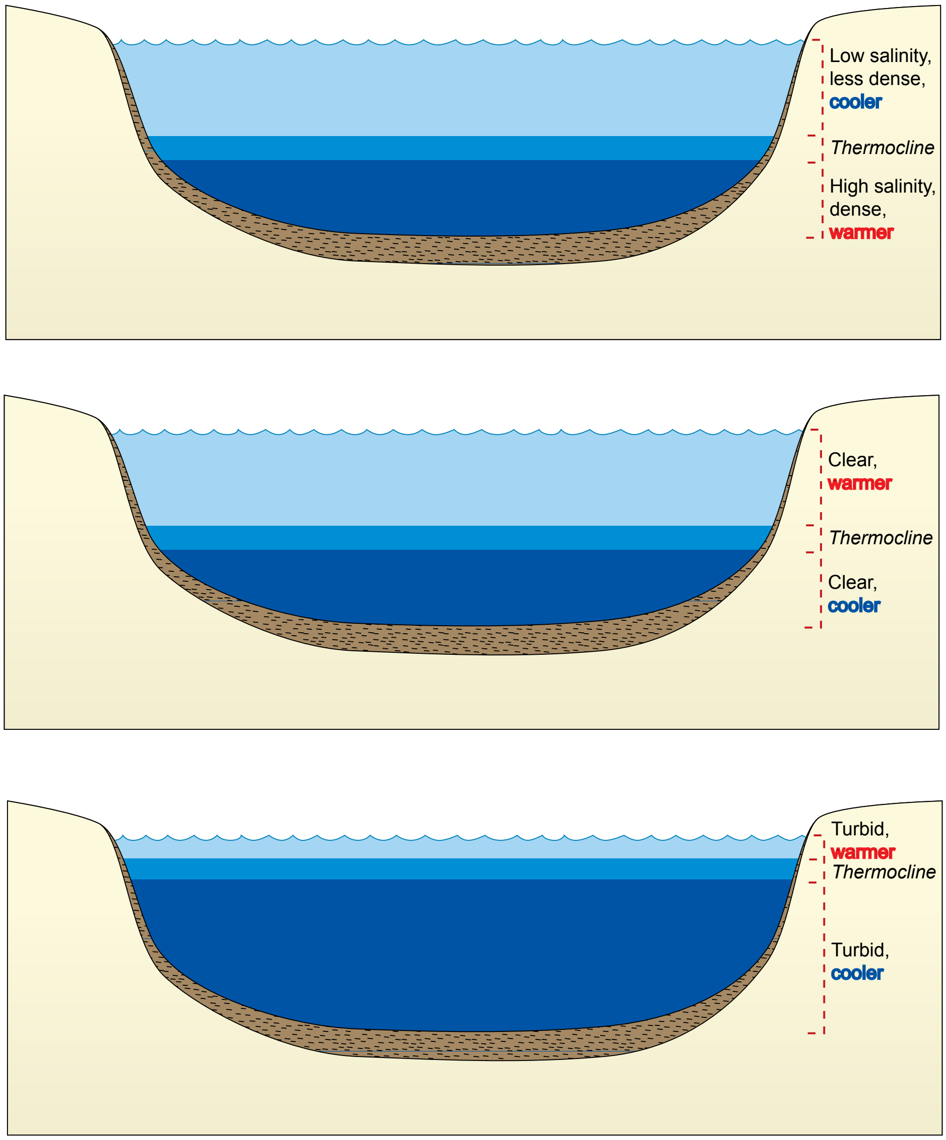

Figure 21. Diagrams of Western Australian stratified wetlands: (top) salinity-stratified; (middle) thermally-stratified; and (bottom) stratified due to suspended particulates.

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.

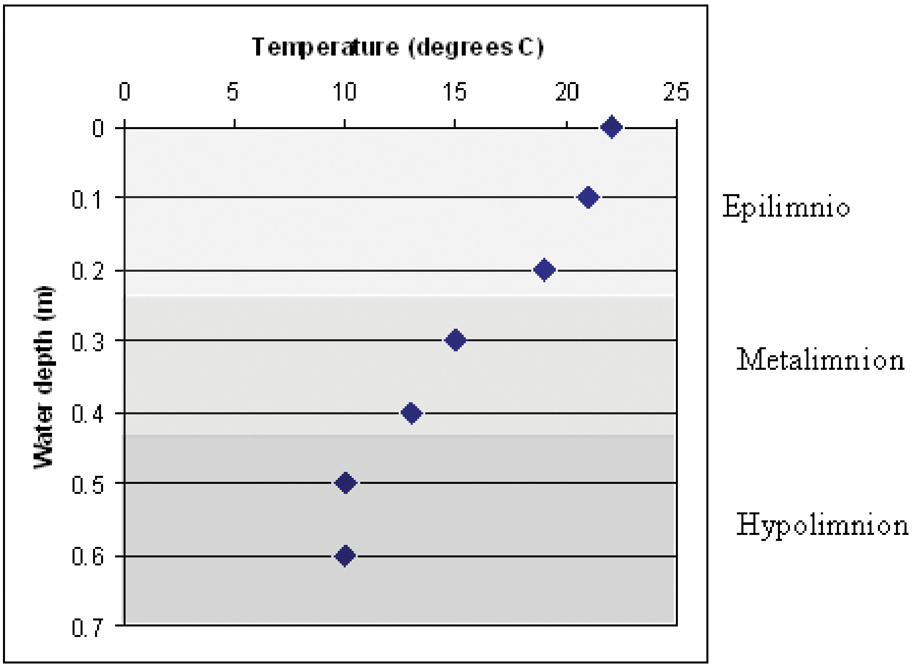

Figure 22. Example of a thermocline, showing difference between temperatures at the top (0 metres) and bottom (0.6 metres) of the water column

Sources of more information on wetland stratification

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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

What are acidity and alkalinity?

Ion: an atom that has acquired electrical charge by the loss or gain of one or more electrons

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.

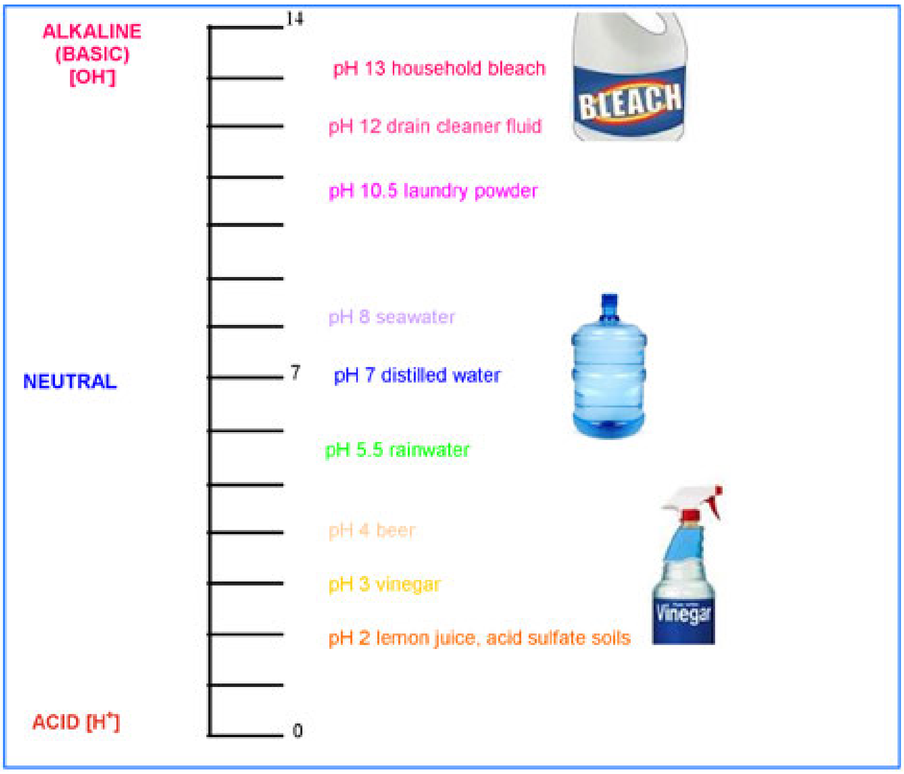

Figure 23. pH scale from acid to alkaline showing examples of acidic and alkaline solutions.

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]

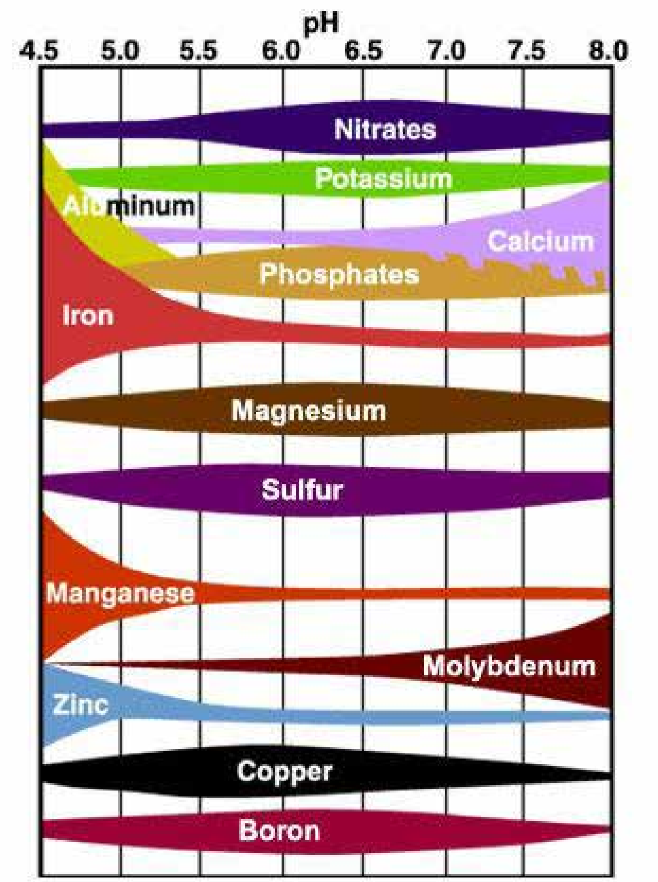

Figure 24. The effect pH has upon nutrient availability under general soil conditions. Image – University of Minnesota.

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.

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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

Anoxic: deficiency or absence of oxygen

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).

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

Boon, PI 2006, 'Biogeochemistry and bacterial ecology of hydrologically dynamic wetlands', in DP Batzer & RR Sharitz (eds), *The ecology of freshwater and estuarine wetlands*, University of California Press, New York.[3]

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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.

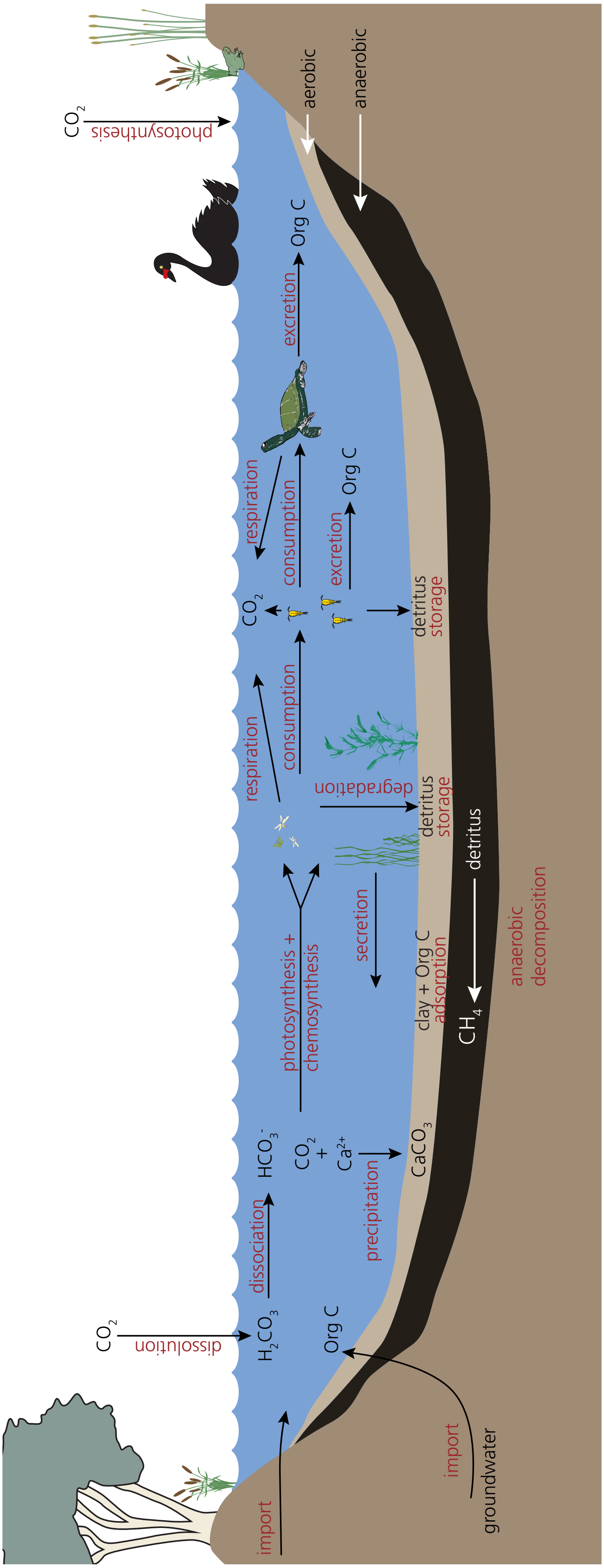

Figure 28. Simplified depiction of the wetland carbon cycle.

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.

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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.

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

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.

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).

Flocculent: loosely massed

Epiphyte: a plant or algae that grows upon or attached to a larger, living plant

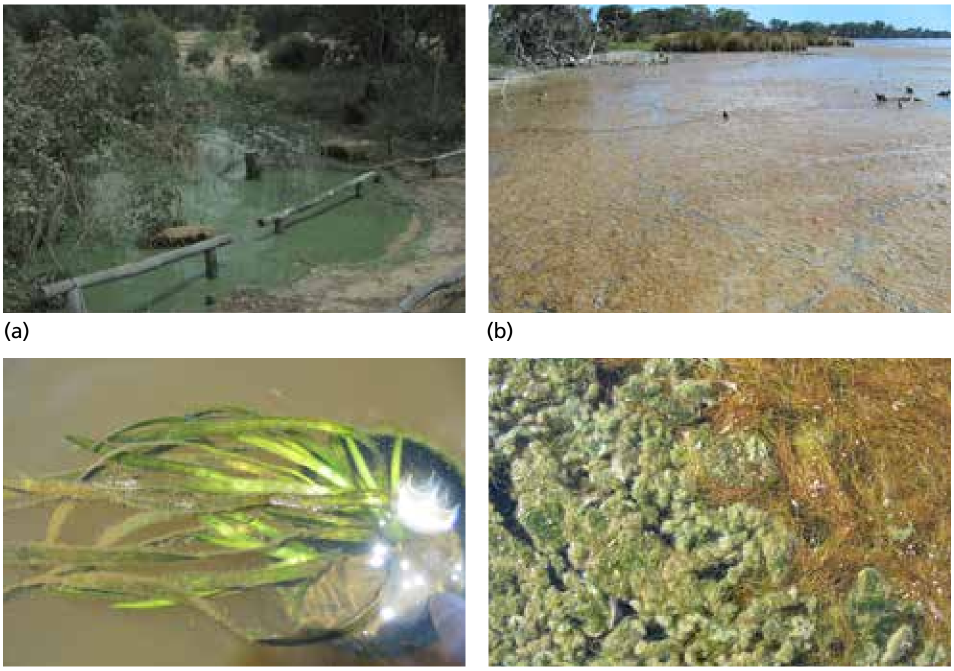
Filamentous: a very fine threadlike structure

Anoxic: deficiency or absence of oxygen

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.



(a) (b) (c) (d)

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 ($\mu g\ L^{-1}$)**					
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.

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 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.

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.

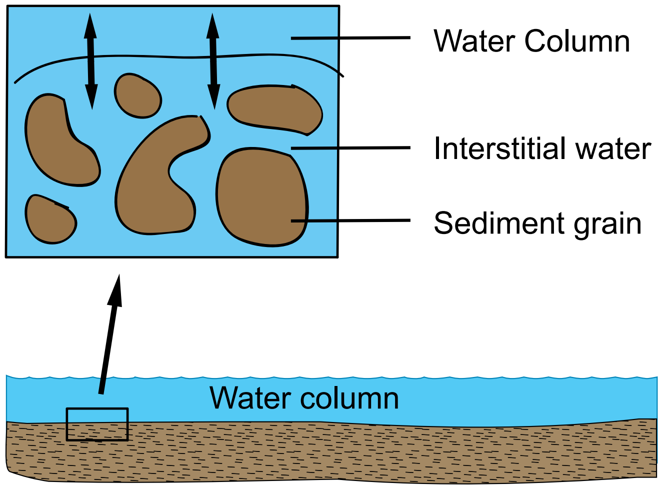


Figure 32. The sediment–water interface, where surface waters and pore waters meet, is where a lot of transformations of nitrogen take place. Image – J Higbid/DEC.

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).

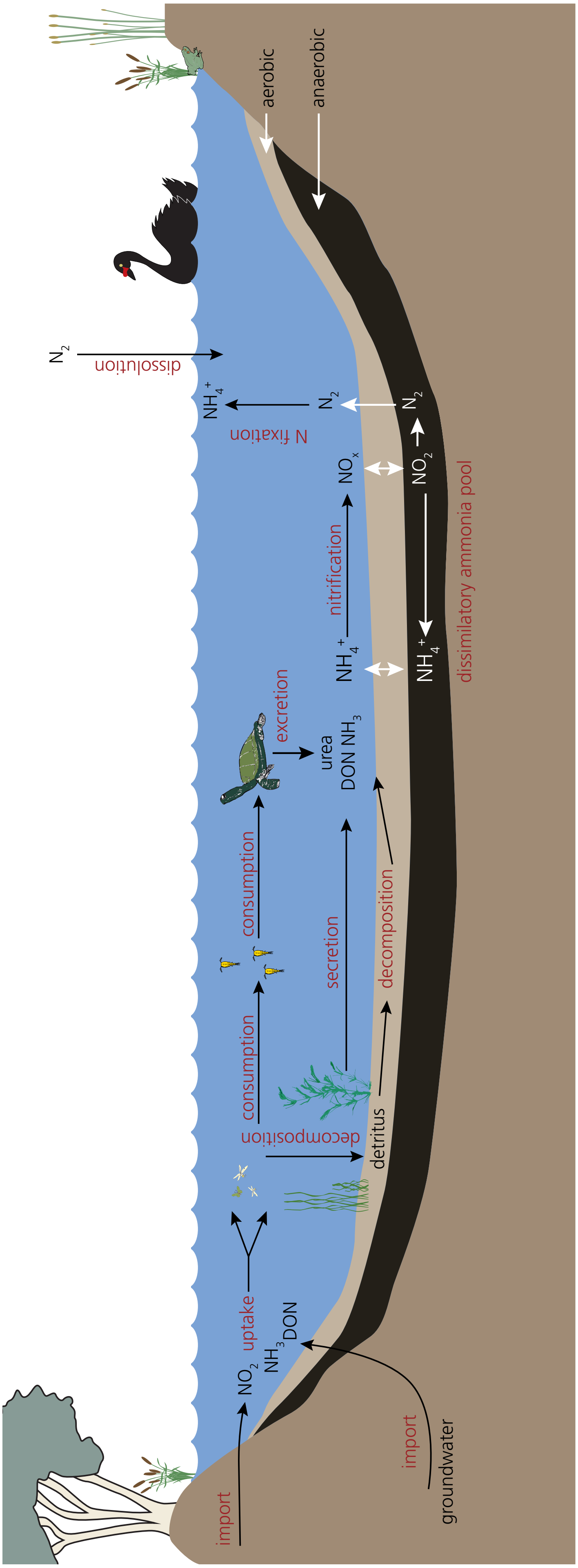


Figure 33. The wetland nitrogen cycle.

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.

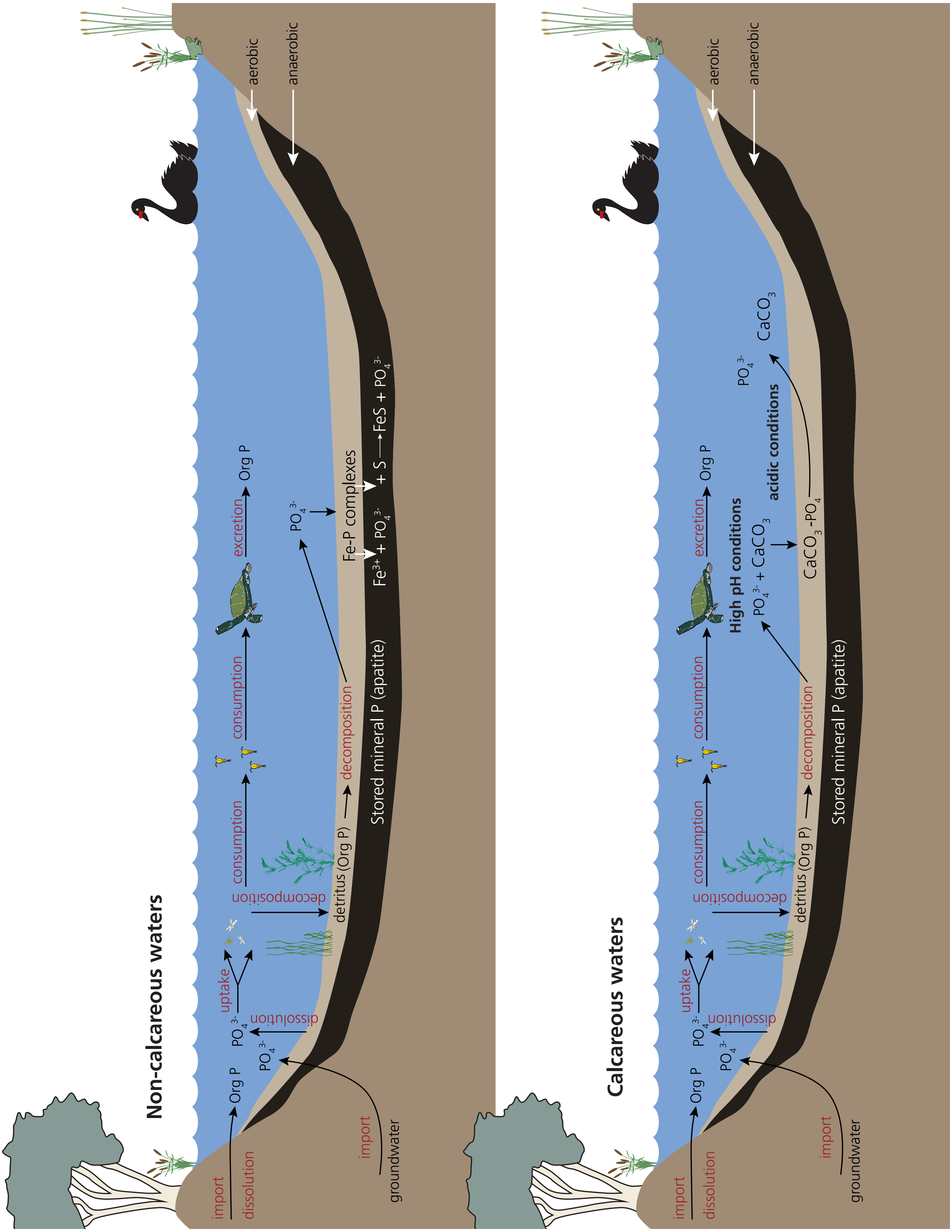


Figure 34. Diagram of the wetland phosphorus cycle.

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}).

Sources of more information on nutrients in wetlands

The topic 'Water quality' in Chapter 3, for information on human-induced changes.

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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]

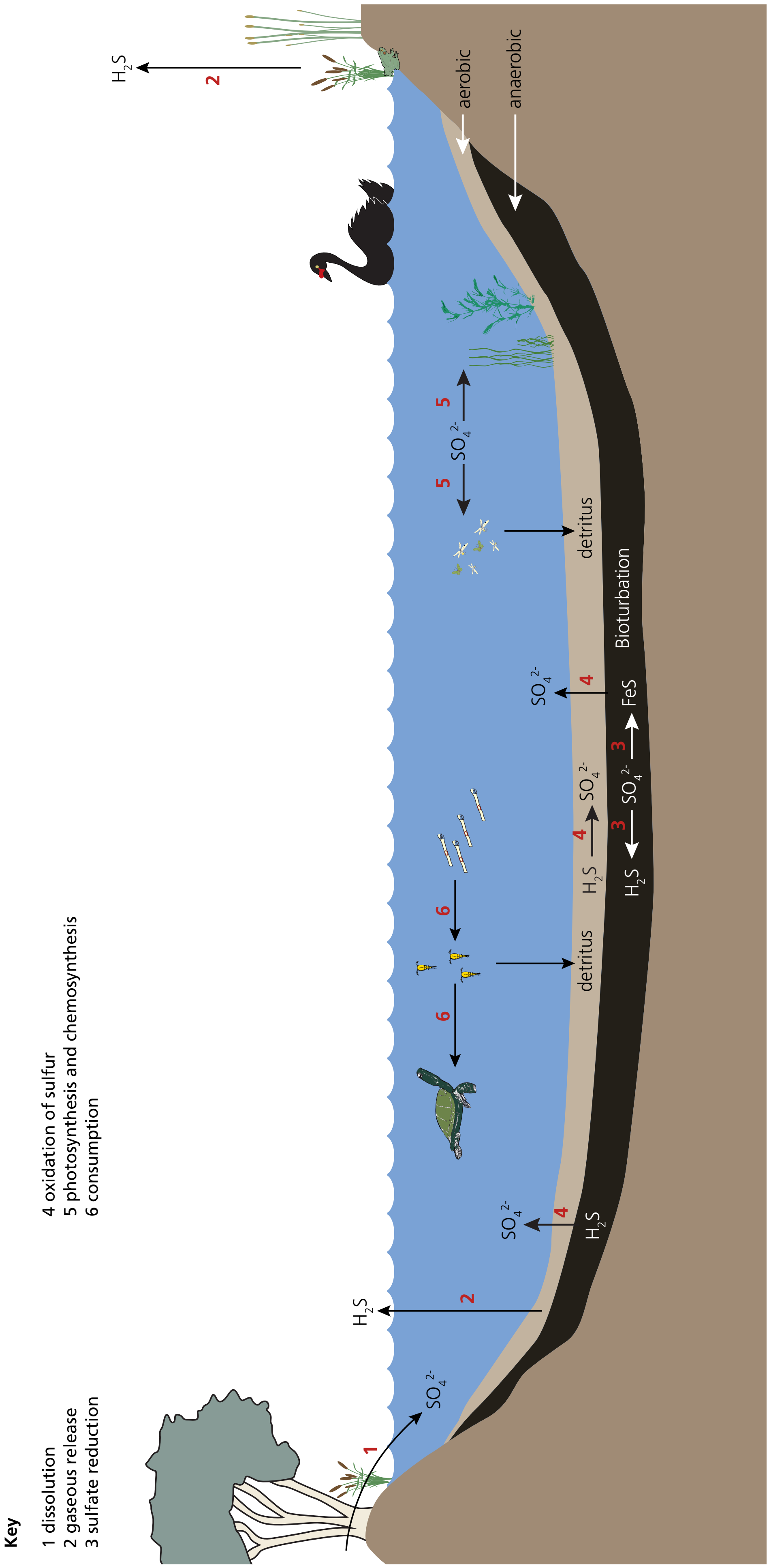

Figure 35. Diagram of the wetland sulfur cycle.

Anoxic: deficiency or absence of oxygen

Key components of sulfur cycling in wetlands include:

- dissolution
- sulfate reduction
- oxidation of sulfur
- photosynthesis and chemosynthesis
- consumption
- gaseous release

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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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'. 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.

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

Organism: any living thing

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.

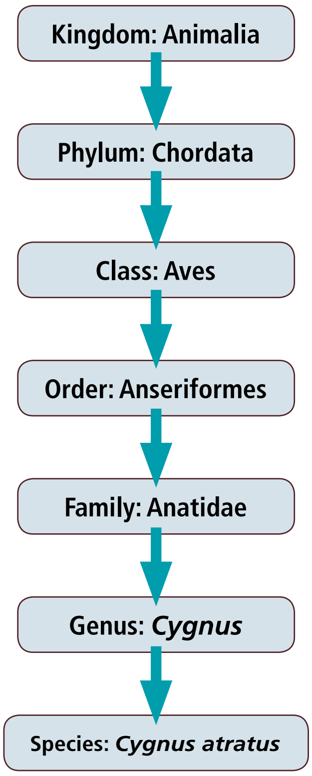

Figure 1. The taxonomic groups that the black swan (*Cygnus atratus*) belongs to.

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.

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

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.

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.

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)

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 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]

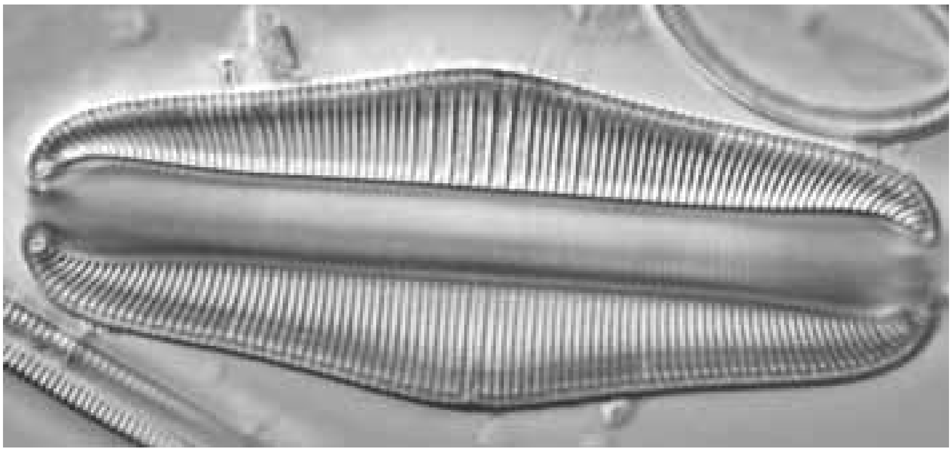

Figure 11. ***Rhopalodia gibba***, a diatom that is common in wetlands. Photo – courtesy of Monash University.

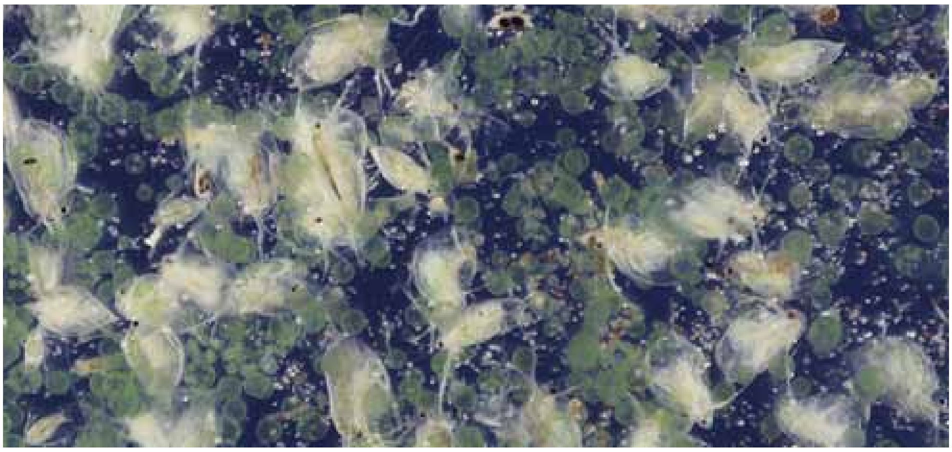

Figure 12. The green alga *Volvox*, with the water flea, *Daphnia*, in a water sample from Jualbup Lake, Shenton Park. Photo – J Davis.

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).

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)

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, 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]

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

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]

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]

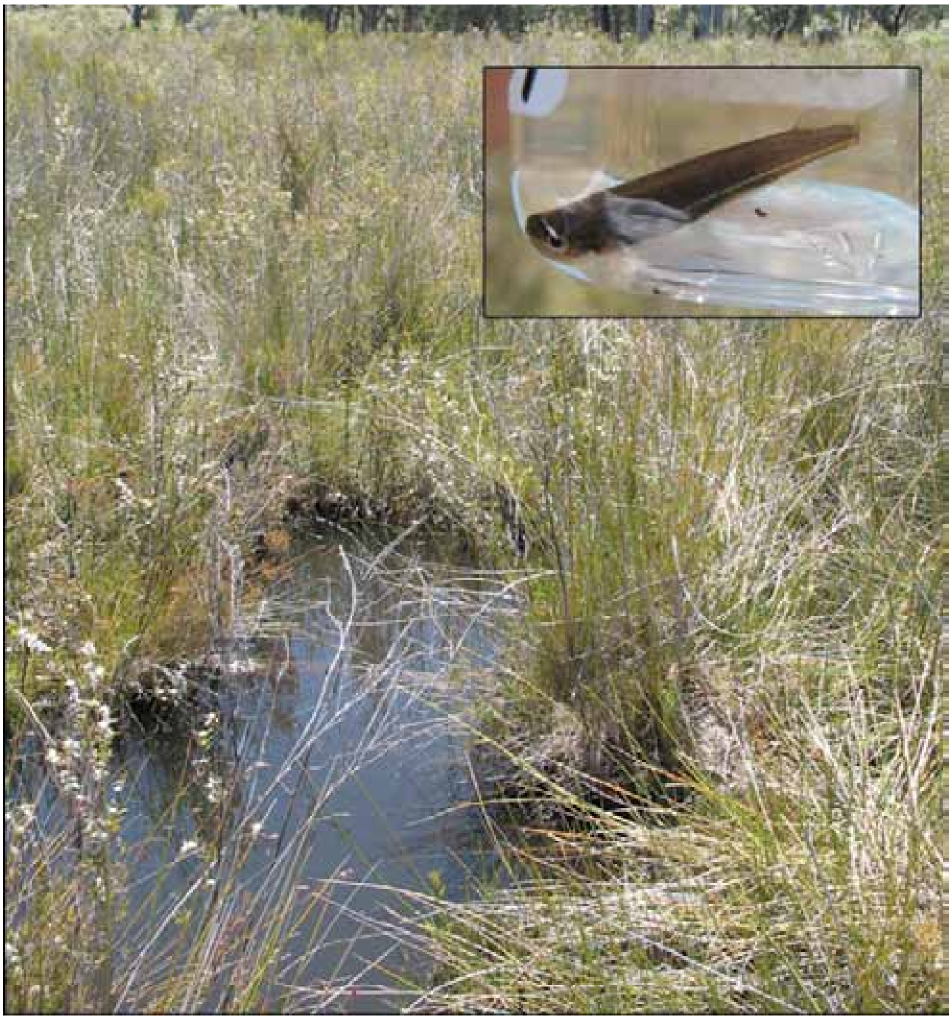

Figure 20. Inundated vegetation is important habitat for native fish in WA's wetlands, such as this western mud minnow, *Galaxiella munda,* found during water sampling in a densely vegetated wetland east of Margaret River. Photos – M Bastow/DEC.

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.

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.

➤ 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

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.

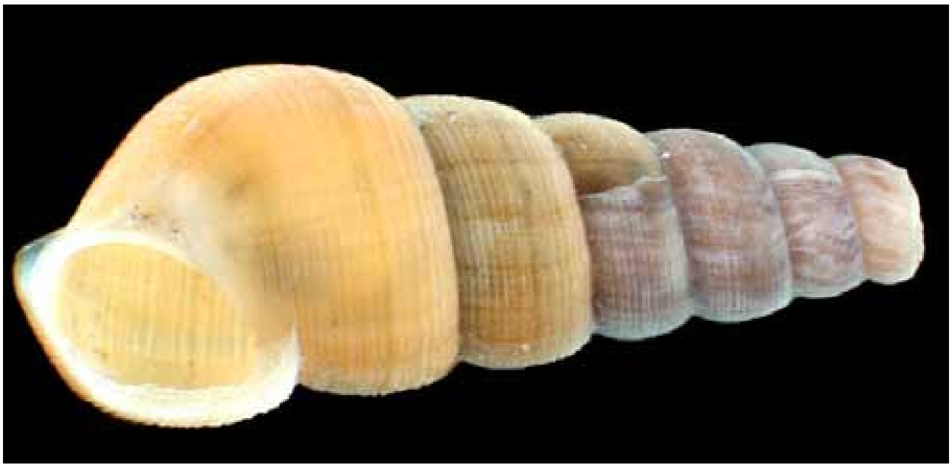

Figure 37. A close up photo of *Coxiella* snails, recognisable by their colourful banded spires which are often broken off at the tip. Photo – A Pinder/DEC.

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 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]

Particulate: in the form of particles (small objects)

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]

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 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**.

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.

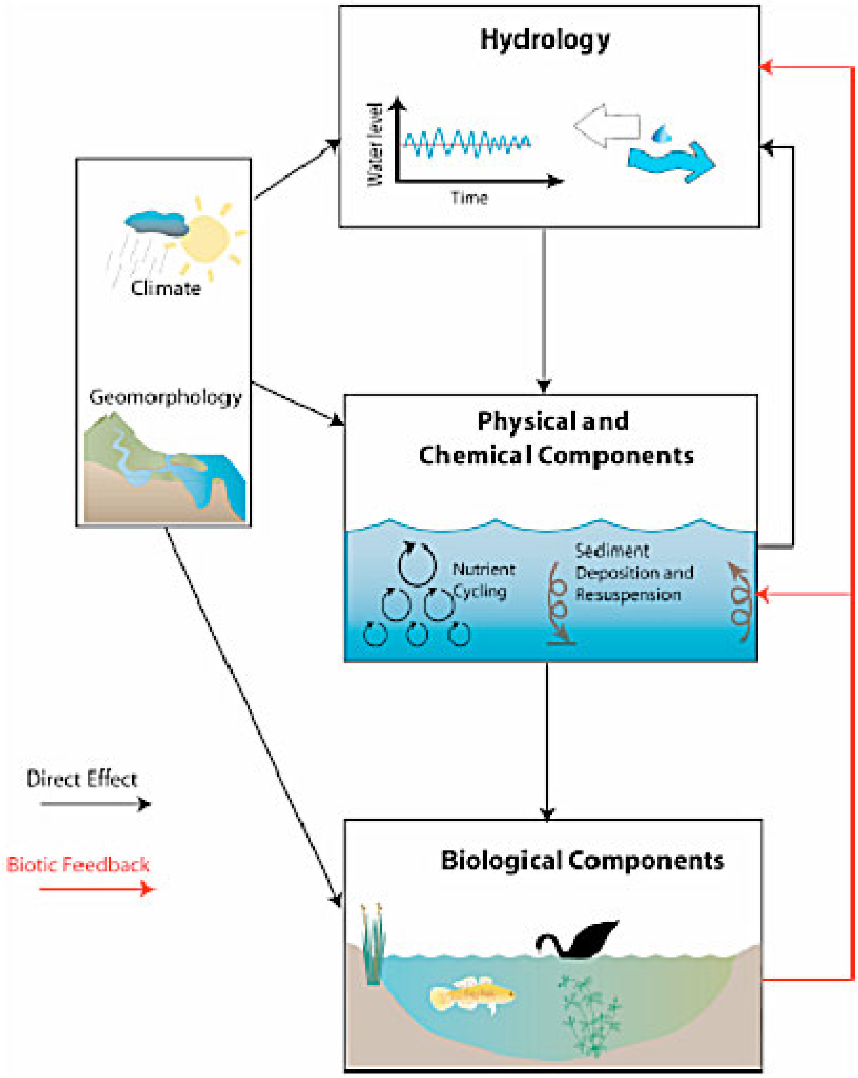

Figure 45. Connectivity between living and non-living parts of wetlands: linkages between physical, chemical and biological aspects. Adapted from Mitsch and Gosselink (2007).[223]

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.

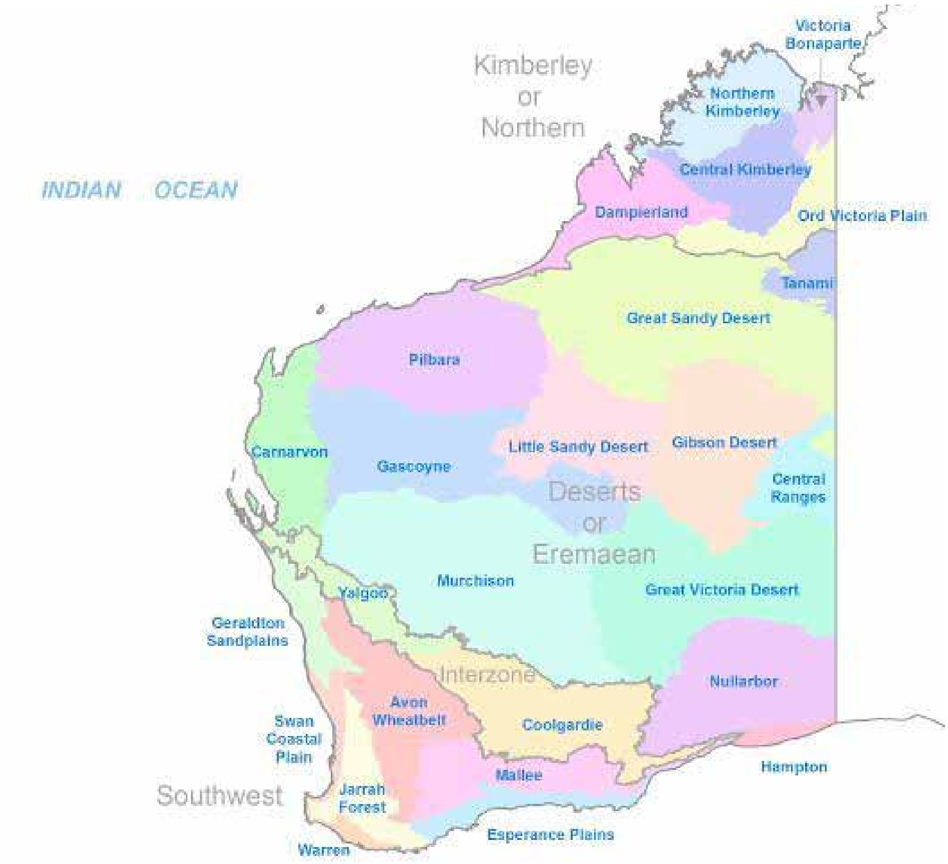

Figure 47. The three zones of wetland vegetation: the Kimberley, the deserts and the south west. Image - C Auricht/Auricht Projects

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].

Thresholds: points at which a marked effect or change occurs

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]

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.

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

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 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

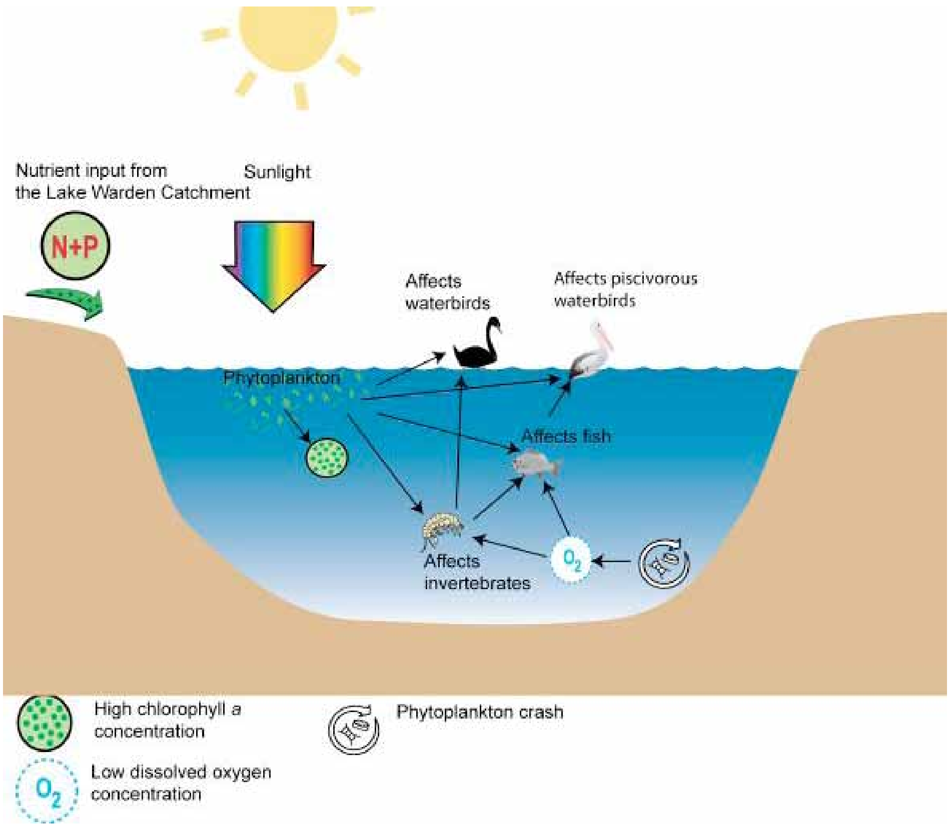

Figure 50. A stylised conceptual model of the potential effect of nutrient enrichment from the catchment at the Lake Warden System Ramsar Site, Esperance. Image - G Watkins.

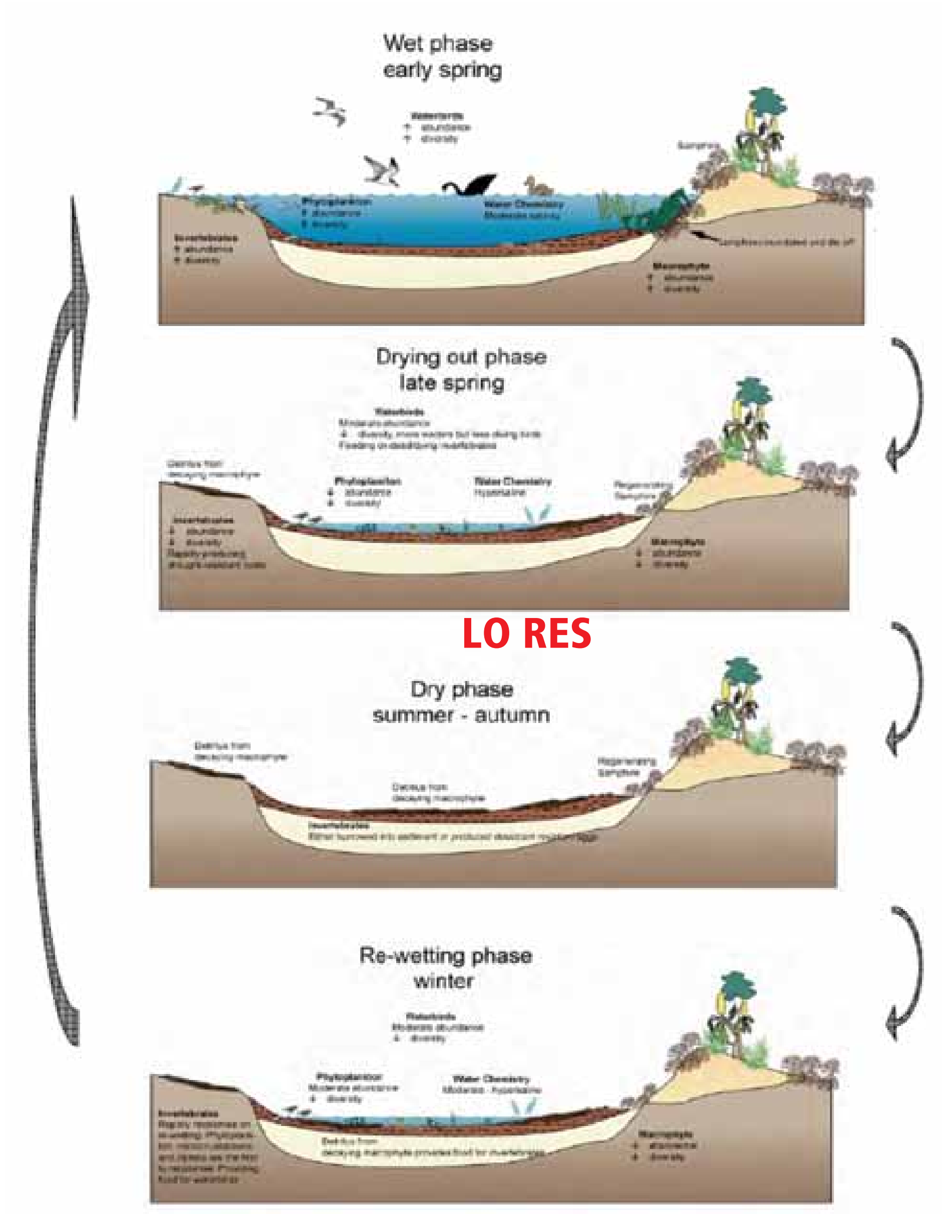

Figure 51. A conceptual model of a naturally saline playa, showing changes in wetland organisms over the course of a year. Image – Jones et al.[32]

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
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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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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

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]

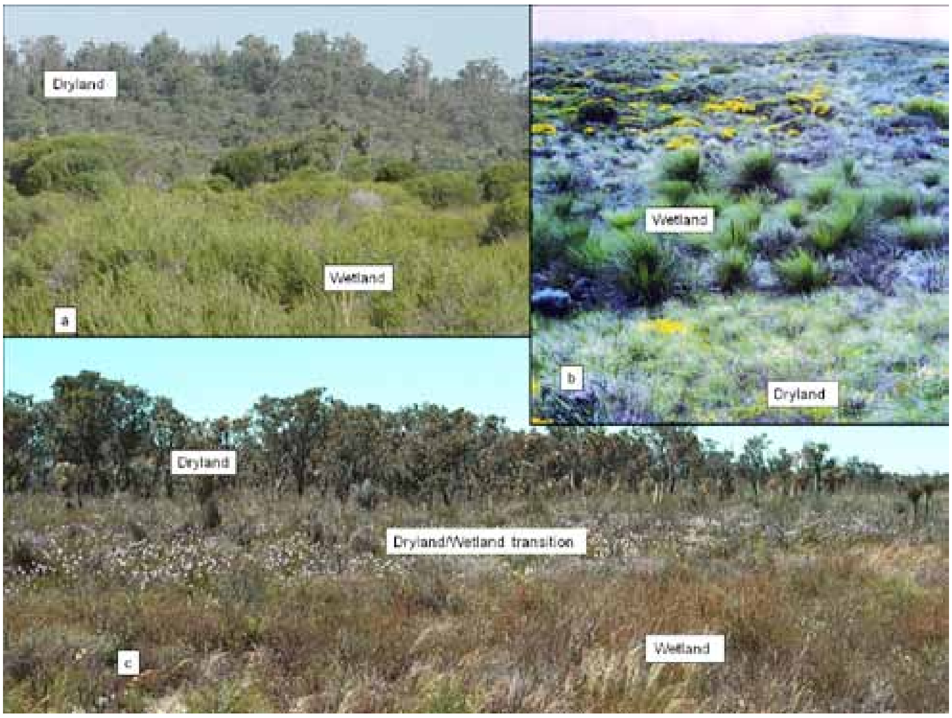


Figure 6. Three fully vegetated wetlands of the Swan Coastal Plain with a variety of wetland habitats and wetland/dryland boundaries.

(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.

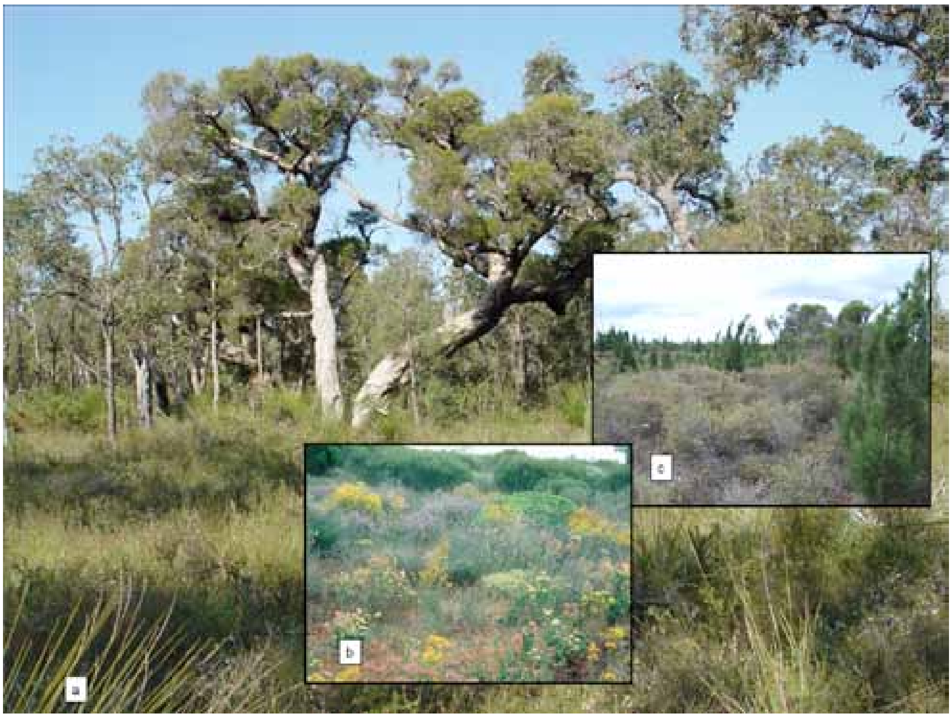


Figure 8. Vegetation of three Swan Coastal Plain seasonally waterlogged wetlands.

(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.

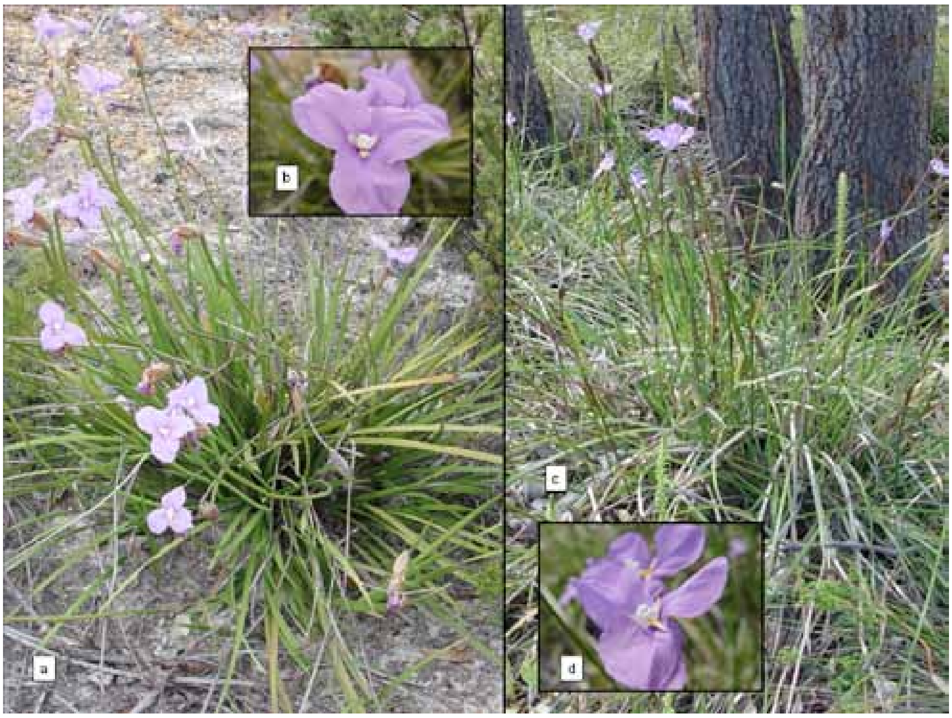


Figure 13. Dryland and wetland varieties of *Patersonia occidentalis* in the Southwest. These two photos were taken in two habitats in the same bushland patch, north-east of Perth on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(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

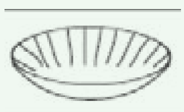
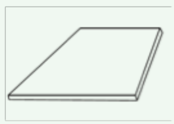
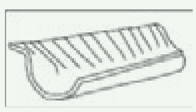
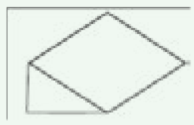
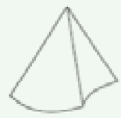
The WA Herbarium provides a public reference herbarium, a public access collection of typical specimens of all known plant species in the state. It is used widely by consultants, researchers and the public to help identify wildflowers and other plants. The WA Herbarium and associated regional herbaria 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.

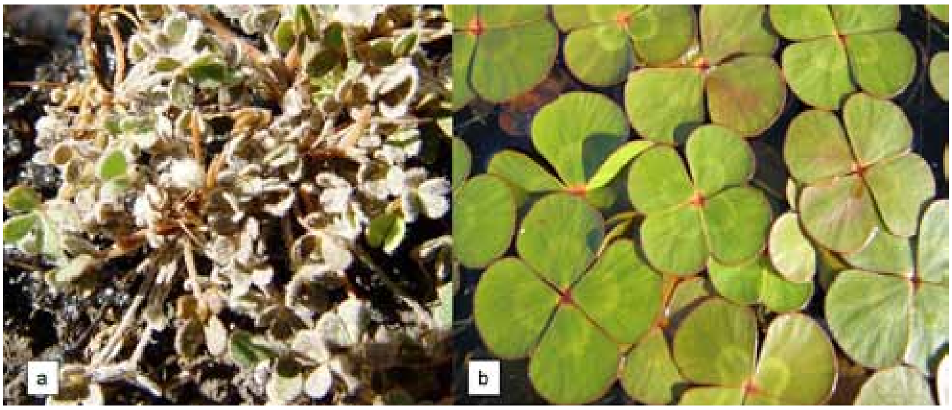


Figure 16. *Marsilea*. (a) plant. Photo – B Keighery/OEPA and (b) leaves. Photo – A Matheson/DEC.

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.

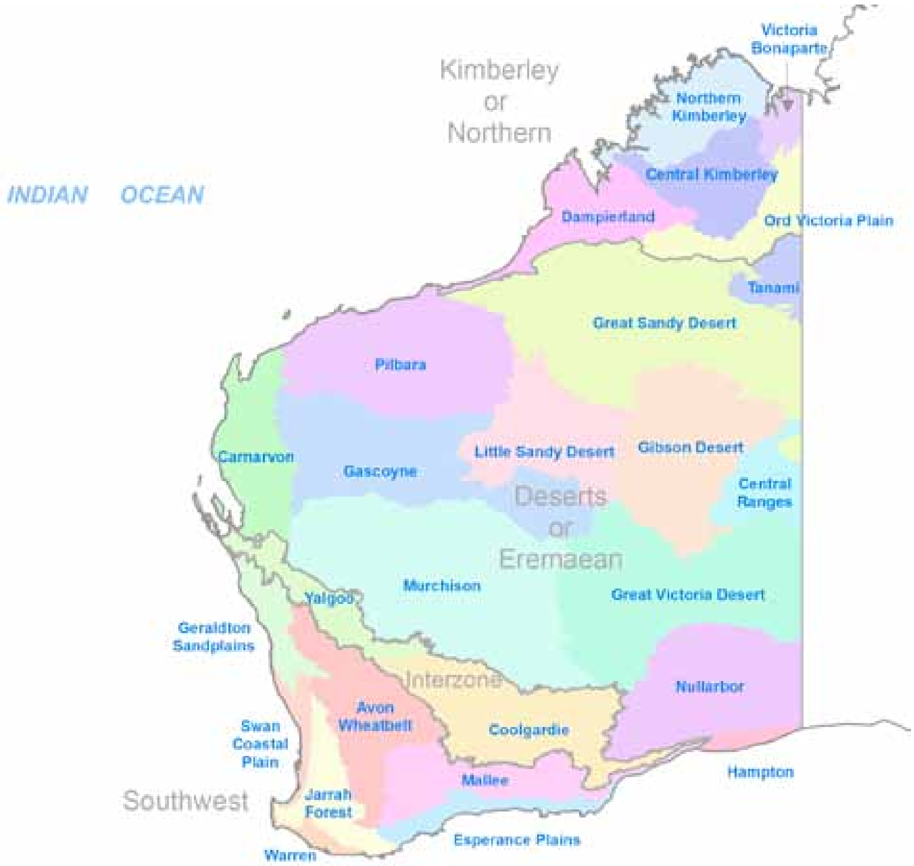


Figure 19. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

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).

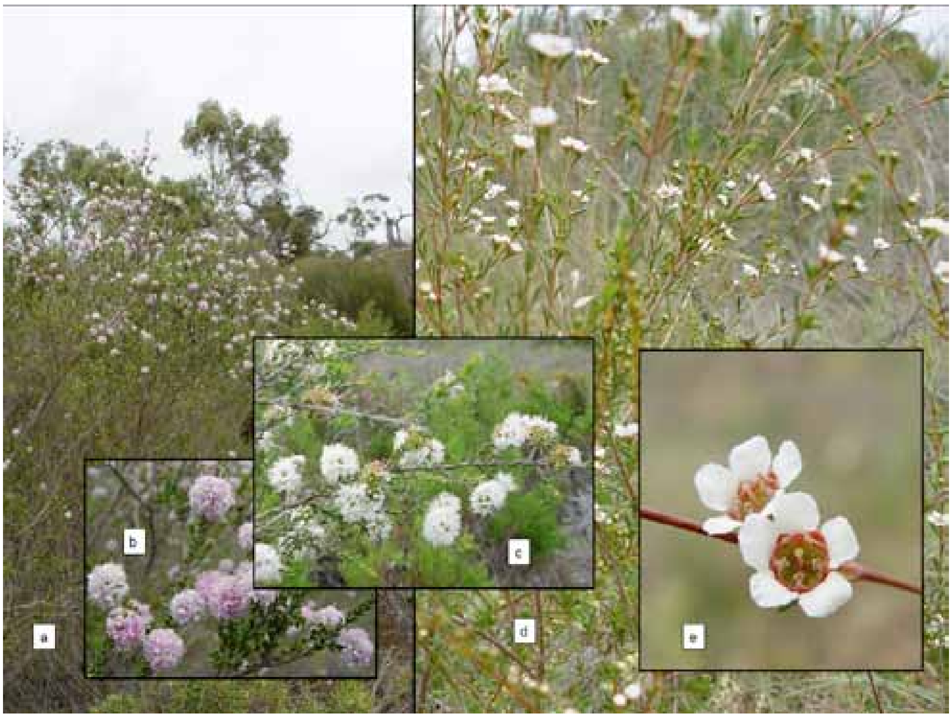


Figure 27. Members of the family Myrtaceae such as *Melaleuca* and many other genera are common in wetlands. Two examples of relatively widespread Southwest shrub taxa are illustrated here. Photos – B Keighery/OEPA.

(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.

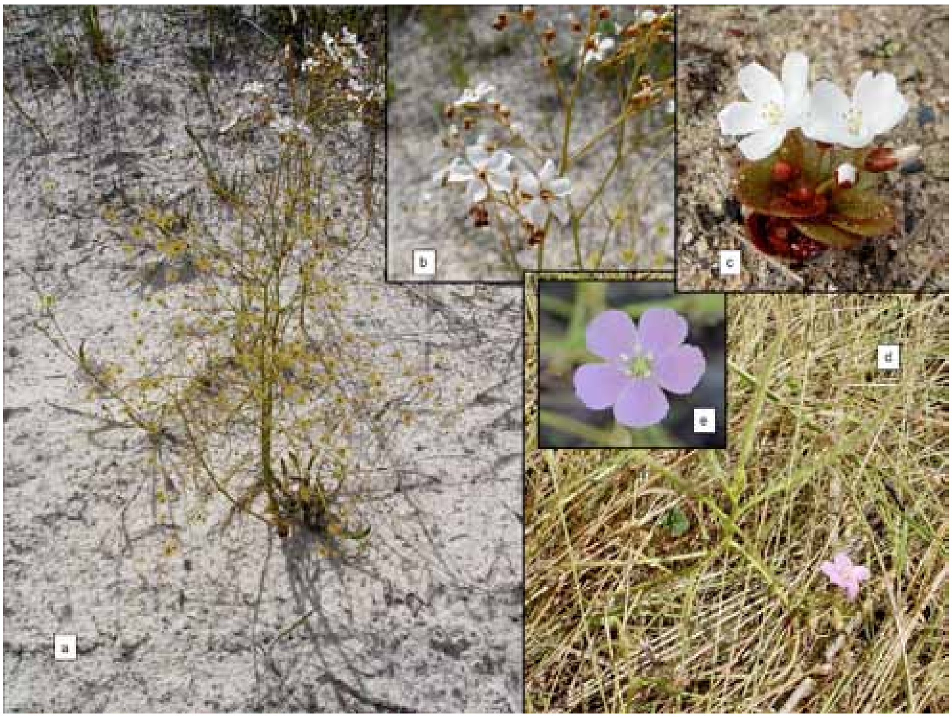


Figure 28. A selection of *Drosera* species found in wetland habitats. The genus *Drosera* is species diverse in the Kimberley and Southwest. Disjunct populations of some species are found in Desert wetlands. Photos – B Keighery/OEPA.

(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.

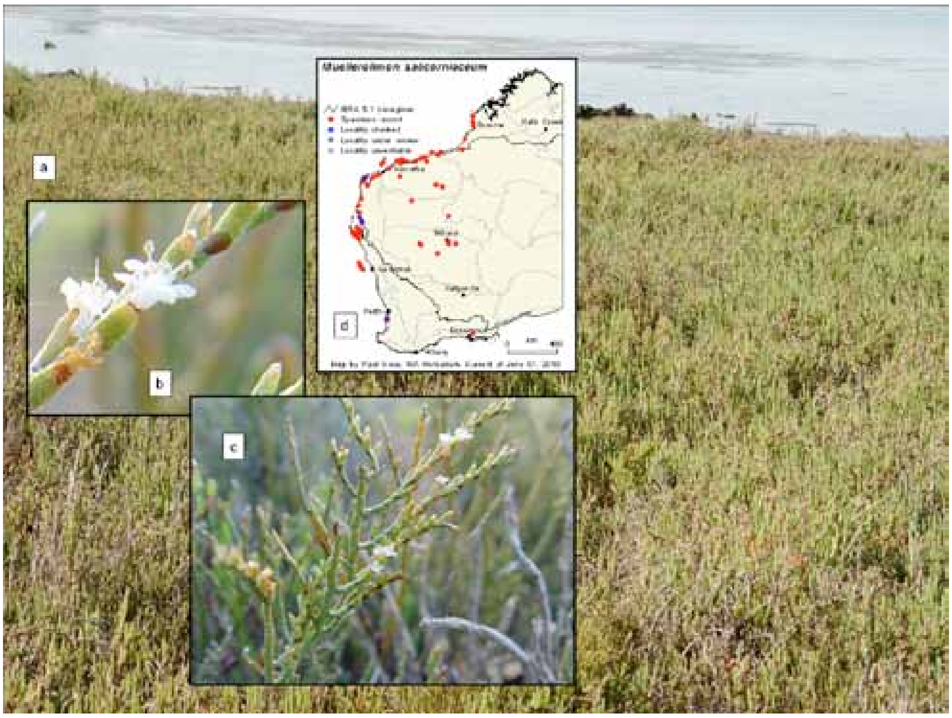


Figure 33. An example of a species, native status (*Muellerolimon salicorniaceum*), with a number of highly disjunct populations. Photos (a)–(c) – B Keighery/OEPA.

(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.

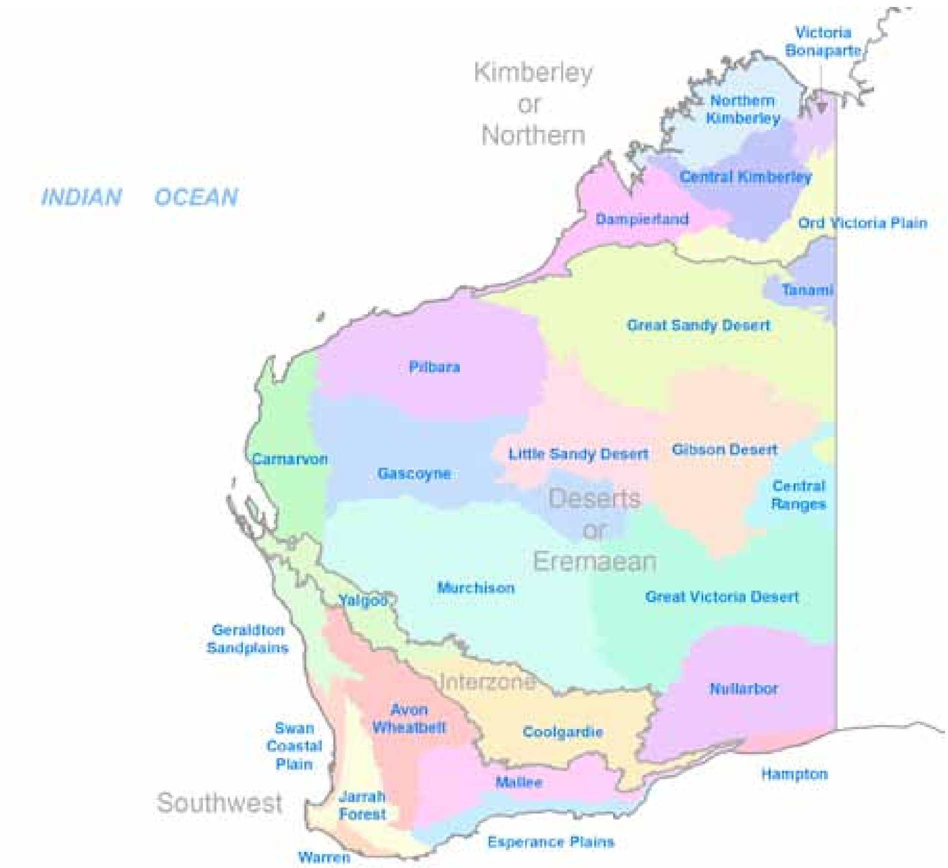


Figure 34. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

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

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					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

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					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

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					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.

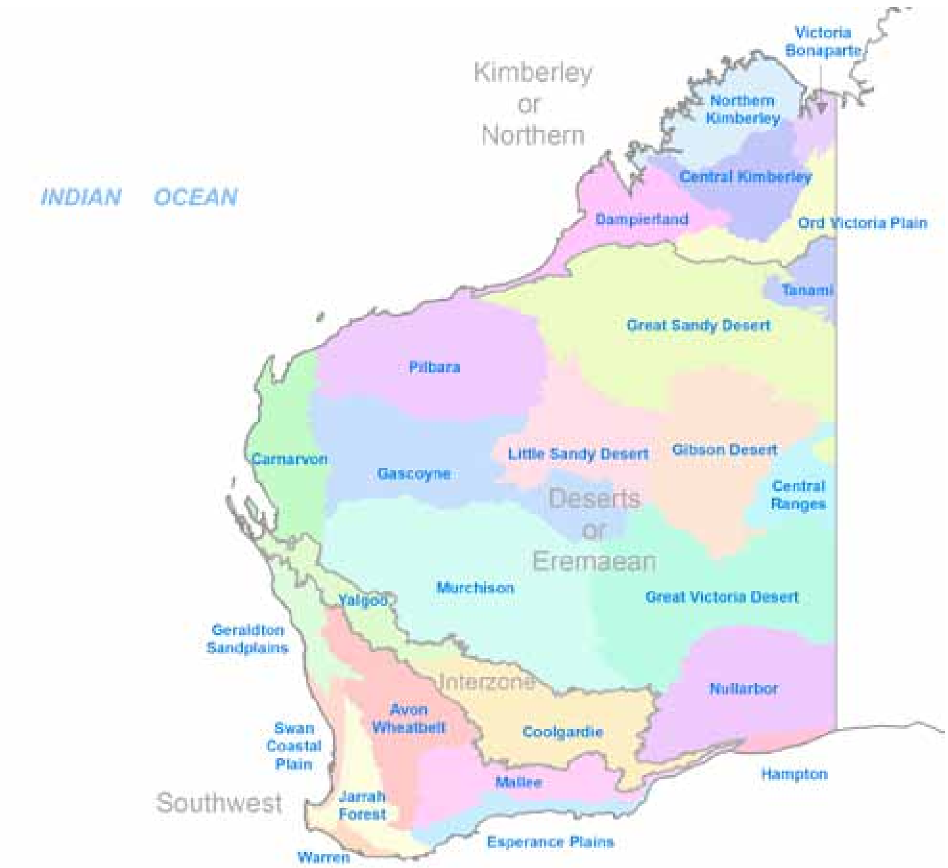

Figure 35. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

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.

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.

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

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.

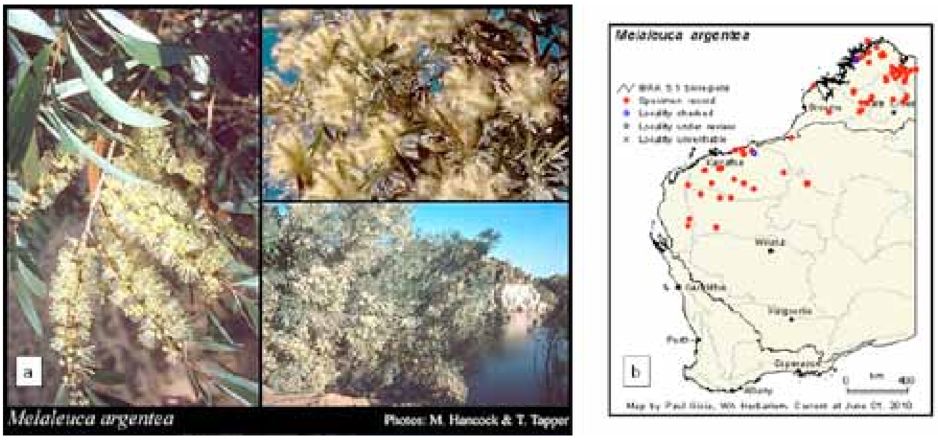

Figure 37. (a) and (b) *Melaleuca argentea* is a widespread wetland species in the Kimberley and Externally Drained Deserts. Photos – M Hancock and T Tapper. Mapping – P Gioia.

Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

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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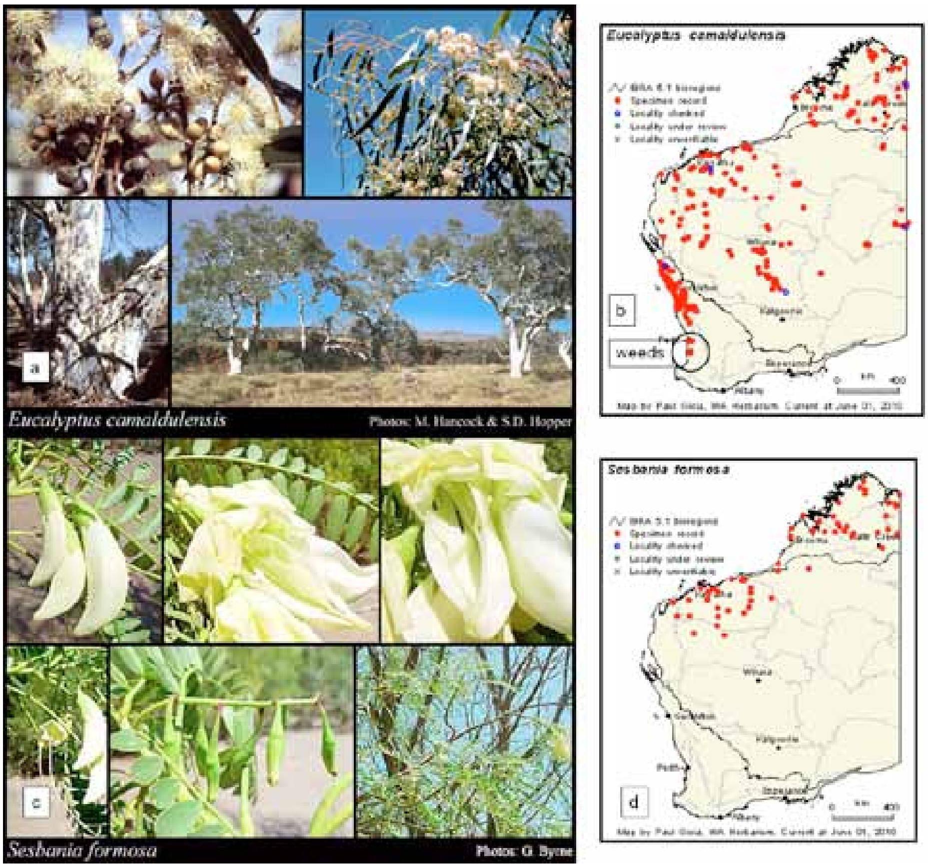

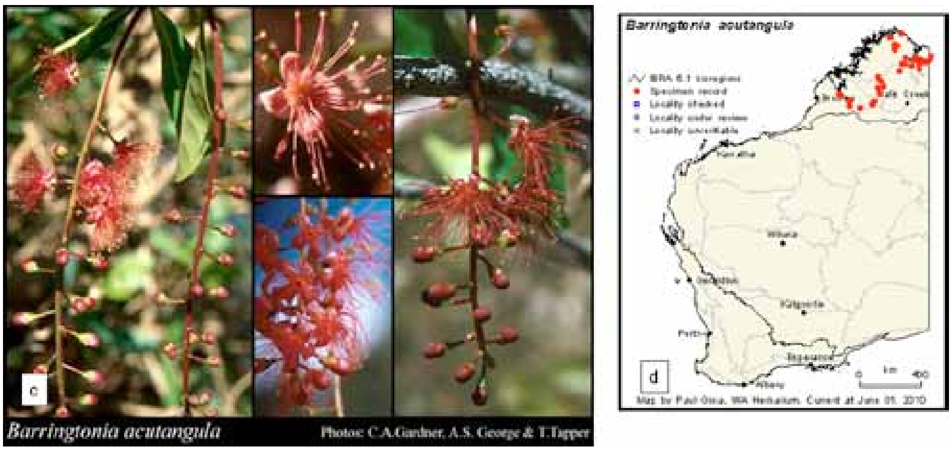

Figure 39. *Barringtonia acutangula* is a common dominant wetland tree that is virtually confined to the Kimberley. Photos – CA Gardner, AS George and T Tapper. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC.
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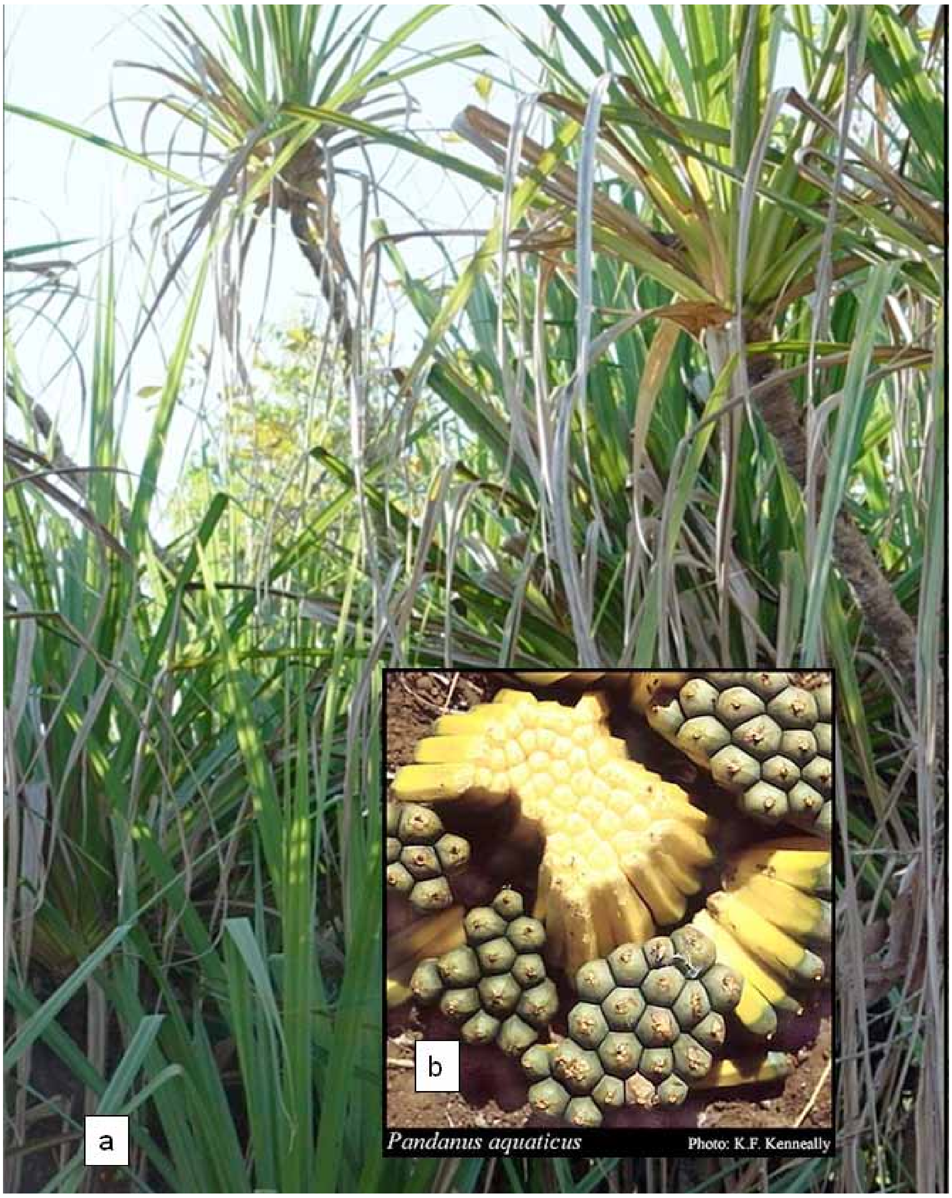

Figure 40. *Pandanus aquaticus* is a widespread tropical wetland shrub (a) with conspicuous fruit (b). Photo (a) taken in the Northern Territory. Photos – (a) B Keighery/OEPA (b) KF Kenneally. Image used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

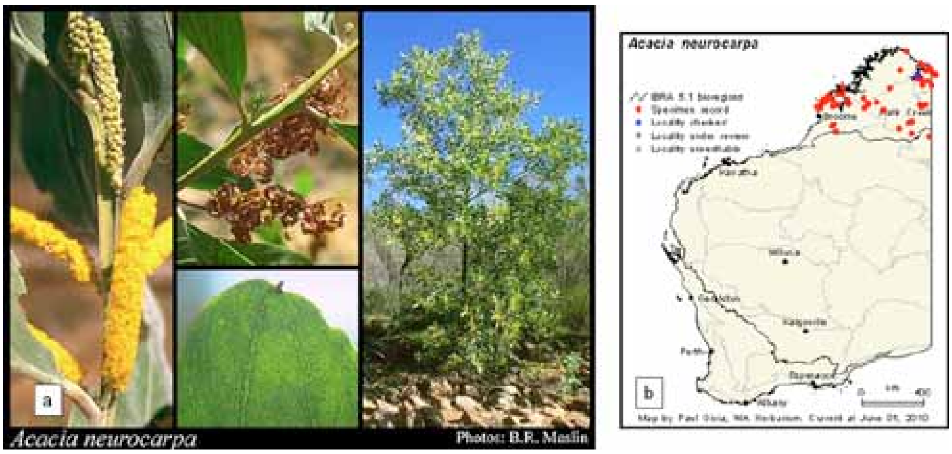

Figure 41. *Acacia neurocarpa* (a) is virtually confined to the Kimberley (b). Photo – BR Maslin. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

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).

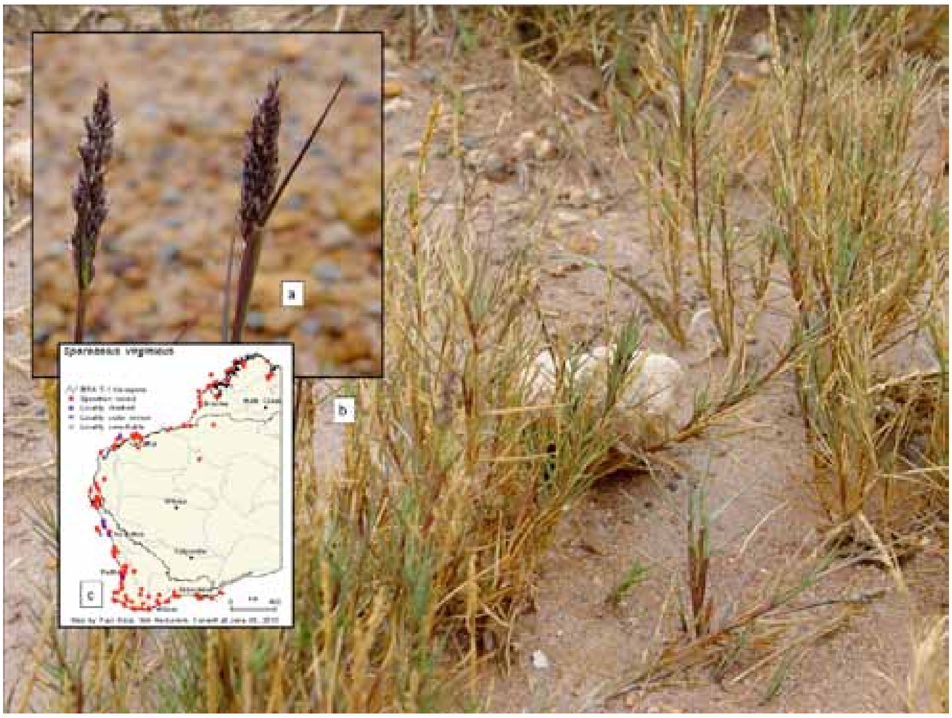

Figure 42. *Sporobolus virginicus* flowers (a) and habit (b), a widespread, virtually cosmopolitan, generally coastal species of saline wetlands (c) in WA. Photos – B Keighery/OEPA. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

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.

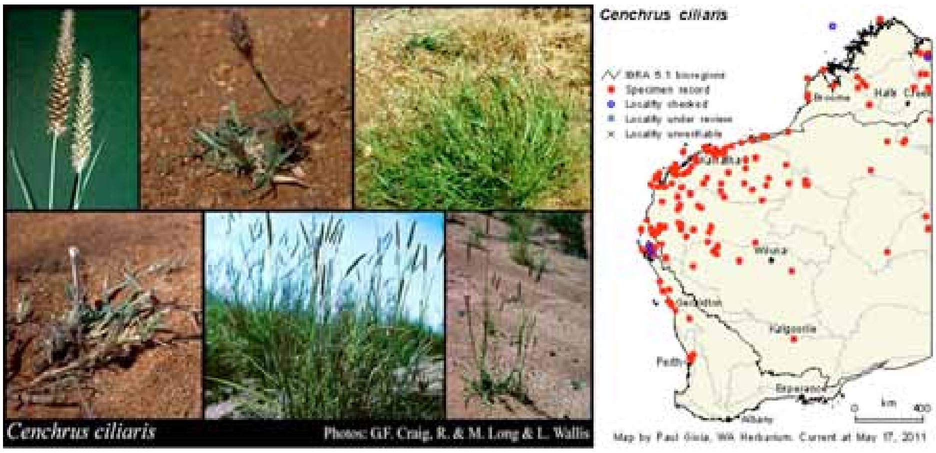

Figure 43. Buffel grass (*Cenchrus ciliaris*) (a) is a widespread weed (b) which has replaced a suite of perennial grasses in the saline wetlands of the Roebuck Plains. Photos – GF Craig, R & M Long and L Wallis. Mapping – P Gioia. Images used with the permission of the Western Australian Herbarium, 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. Accessed 21/06/2011.

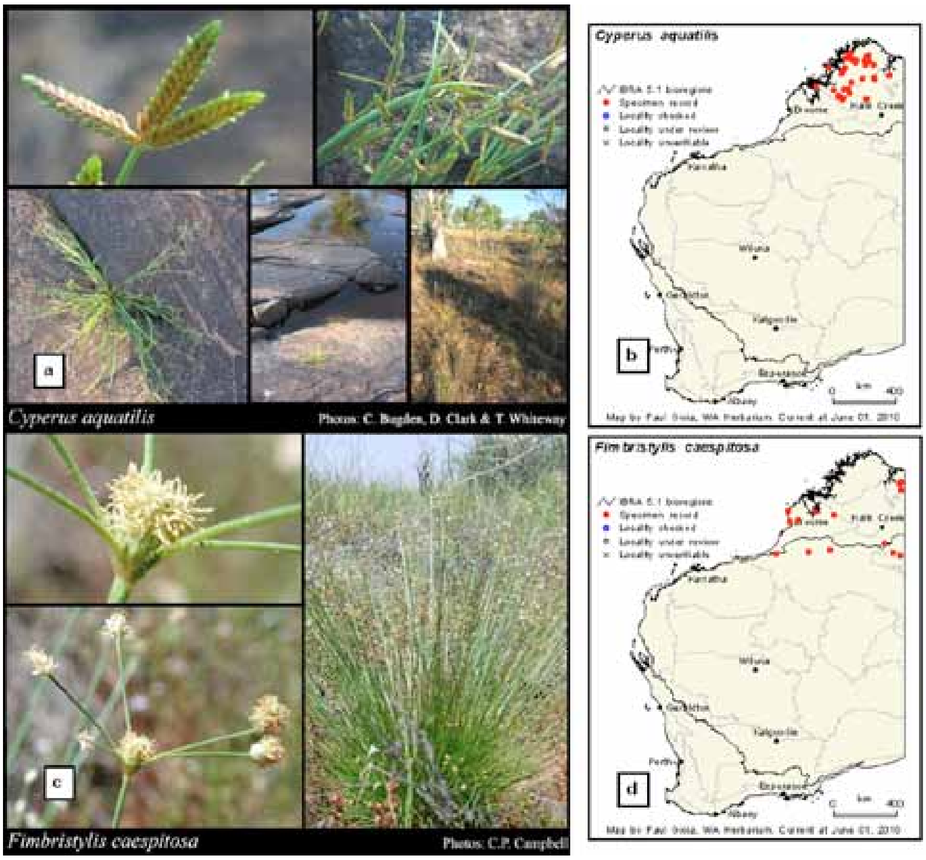

Figure 57. A tropical wetland with *Eucalyptus* forest over a sedgeland dominated by *Xyris complanata* (a), with detail of the *Xyris* flowers (b). This photo was taken in the Northern Territory. Members of the *Xyris* genus are found in Kimberley and Southwest wetlands; they all have yellow flowers. 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.

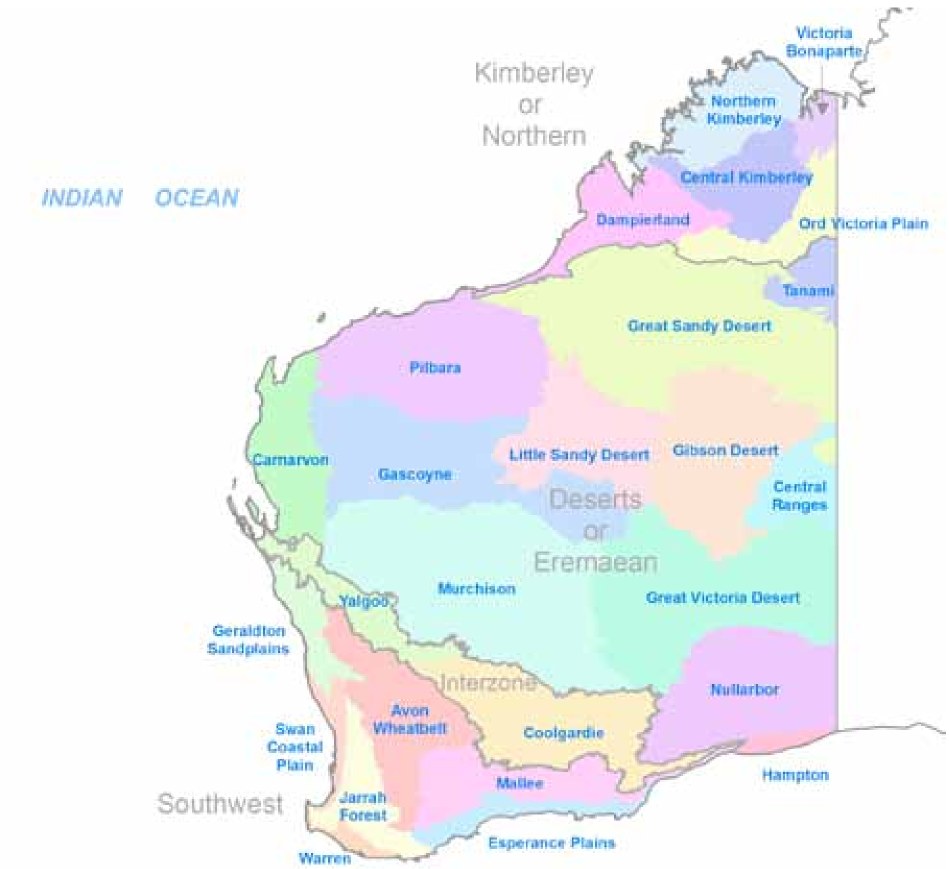

Figure 58. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

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.
Images (a) and (b) used with the permission of the Western Australian Herbarium, DEC. Accessed 21/06/2011.

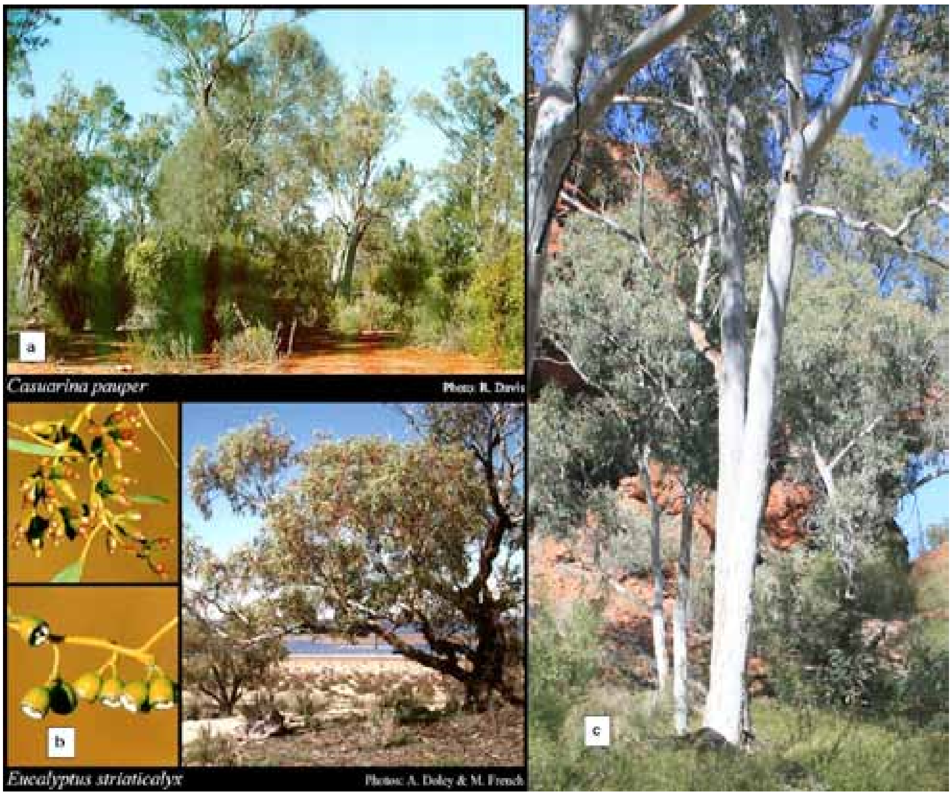

Figure 61 (below). Two shrubs of Desert wetlands.
(a) *Frankenia cinerea*. Photo – R Davis and (b) Distribution in WA. Mapping – P Gioia.
(c) *Muehlenbeckia florulenta*. Photo – SJ Patrick and (d) Distribution in WA. Mapping – P Gioia.
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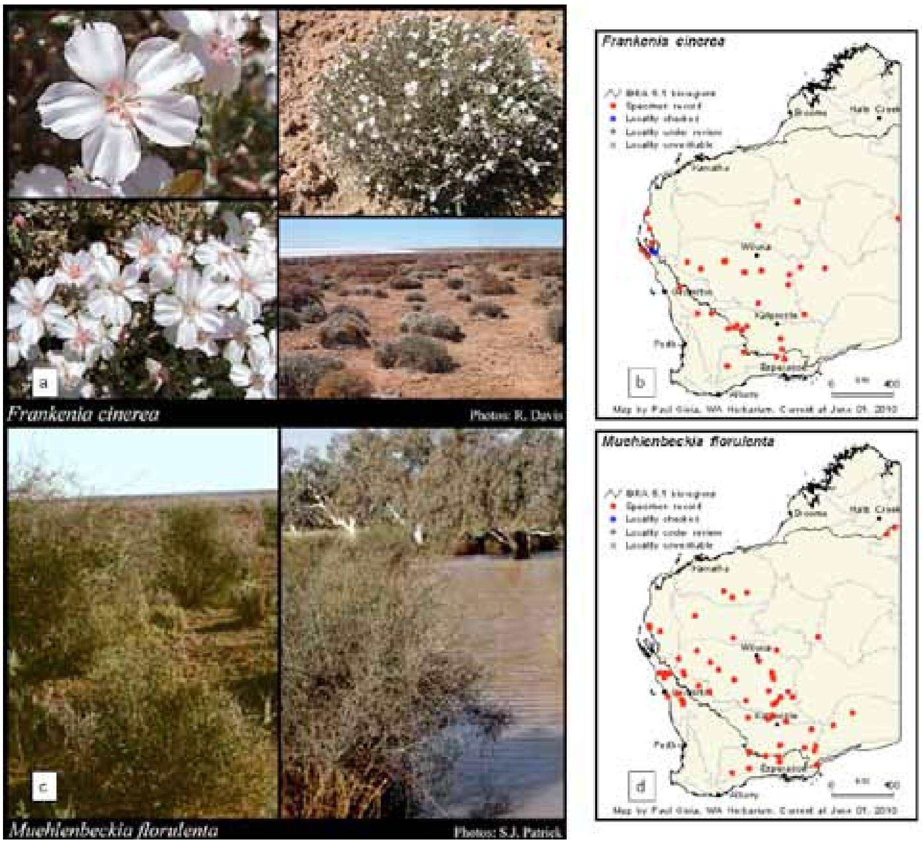

The wetland vegetation of the Internally Drained Desert is generally very poorly documented and around eighty vegetation units are described in the available publications and reports. This is obviously an underestimate as the detailed studies of Lake Way (near Wiluna, Murchison) by Blackwell and Trudgen[64] 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.

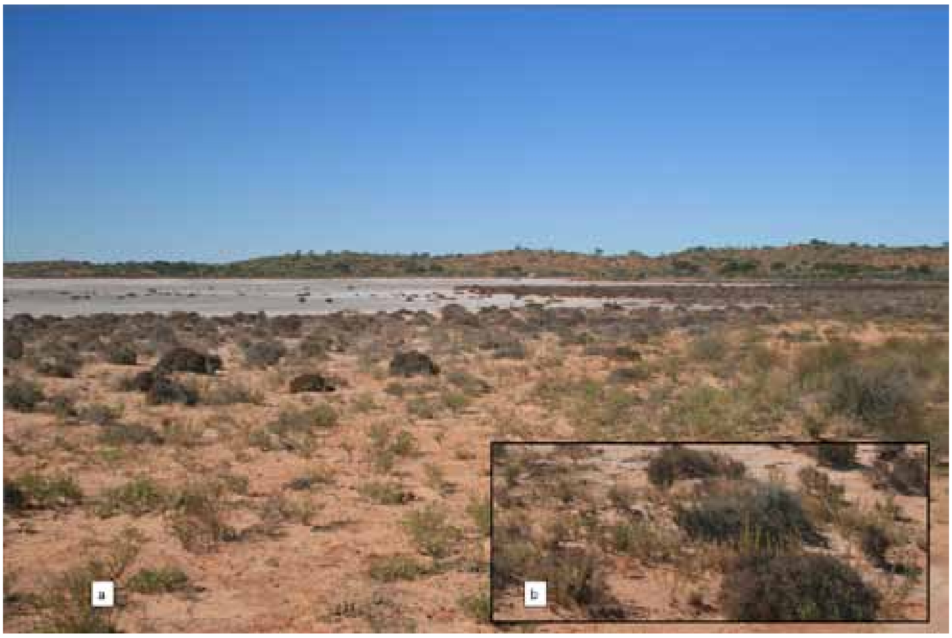

Figure 63. An area of Lake Disappointment (Tanami) showing a broader band of samphire shrubland and other salt tolerant shrubs (detail in b) and surrounding low dunes. Photo – W Thompson.

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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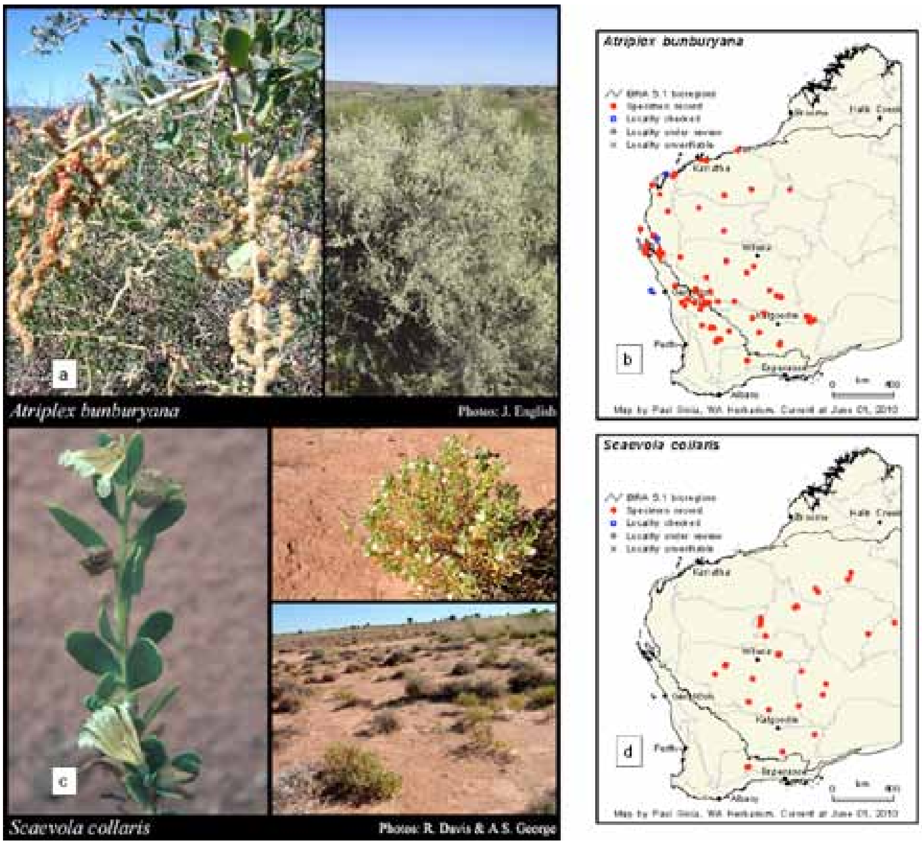

Associated with the salt lakes are two groups of flat wetlands subject to waterlogging.[65] The first of these are on the calcrete surfaces (hardened calcium carbonate deposits). Drainage in these areas is via sheet flow and open flow lines into the salt lakes. These are covered in ‘calcrete woodlands’ 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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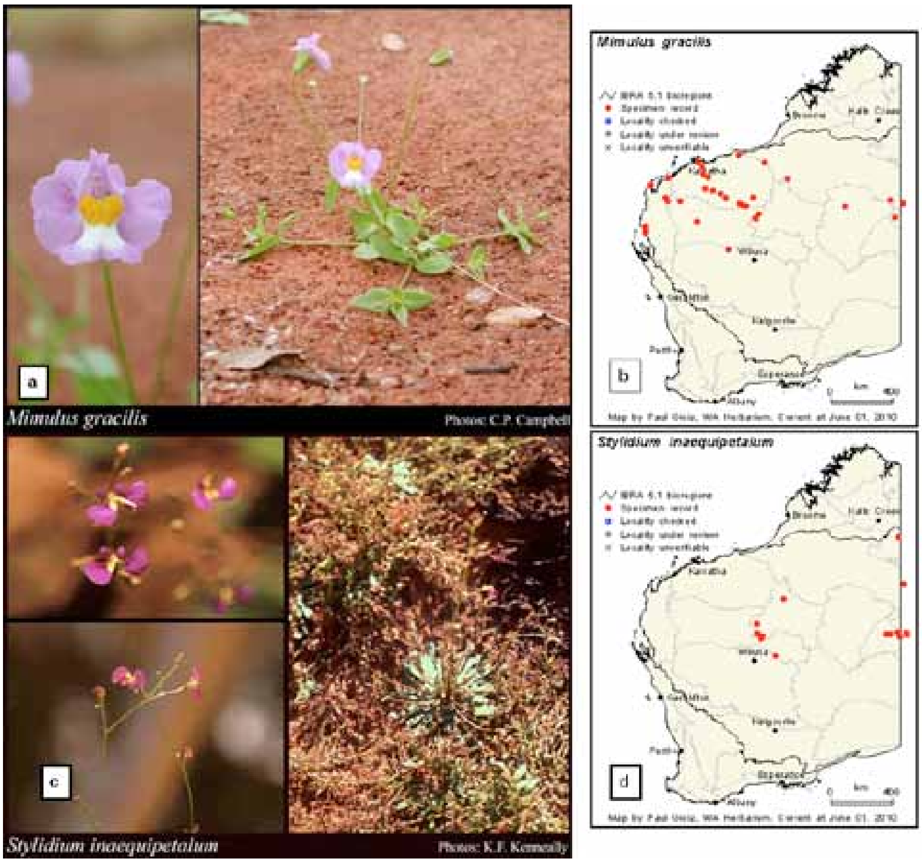

Claypans

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.

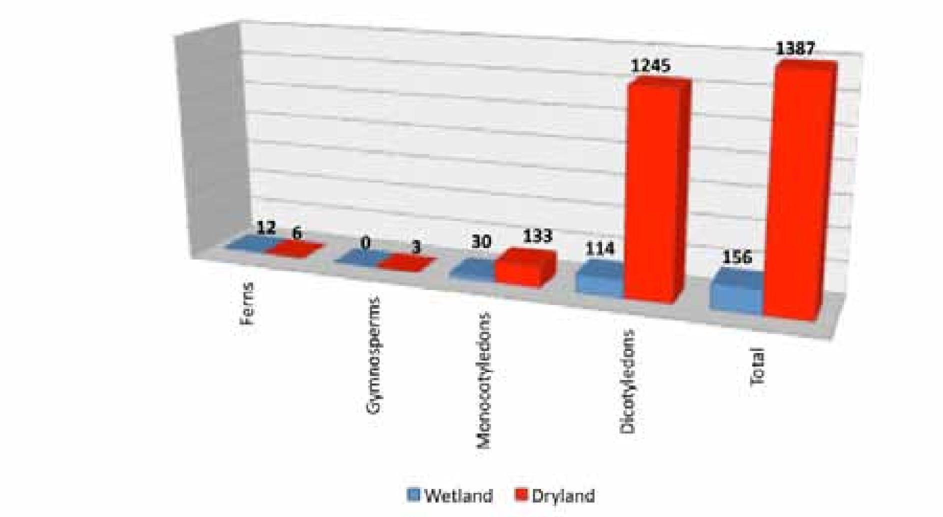

Figure 69. Internally Drained Desert wetland and dryland vascular plant taxa found in various plant groups (after Jessop[27]).

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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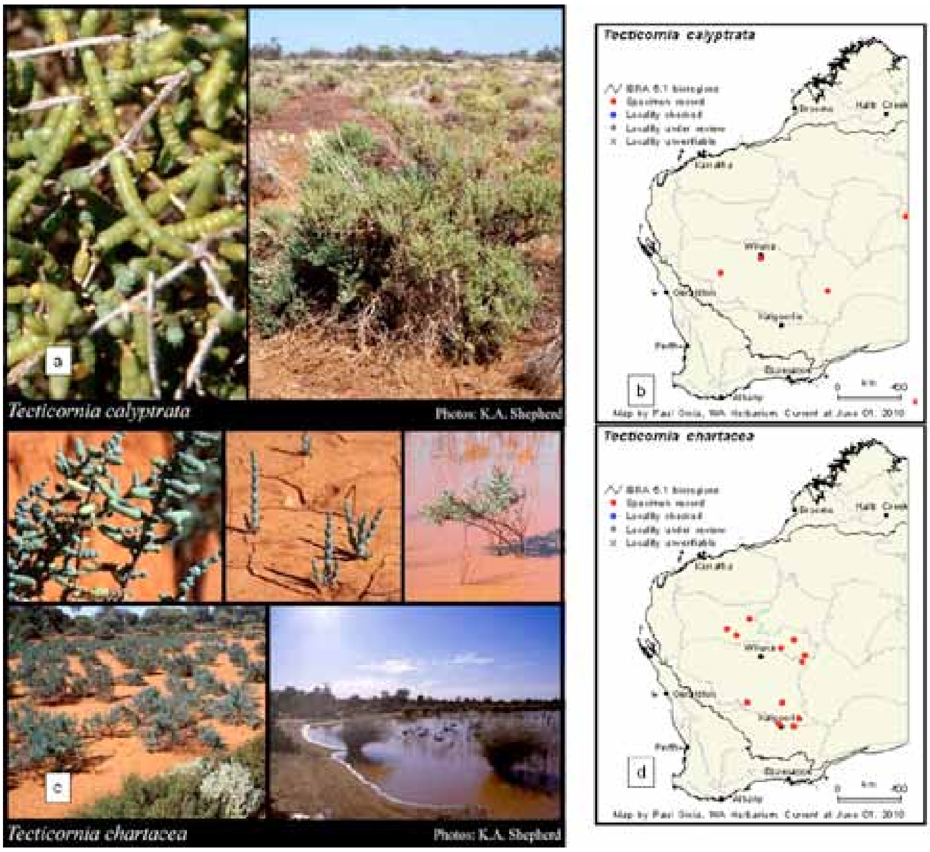

Typically all Desert freshwater wetlands support fringing species with a few claypan taxa from genera such as *Peplidium*, *Glossostigma* and *Elatine*. Aquatic species are also uncommon, being confined to permanently inundated sites to those inundated on a semi-permanent basis, and include *Myriophyllum 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*.

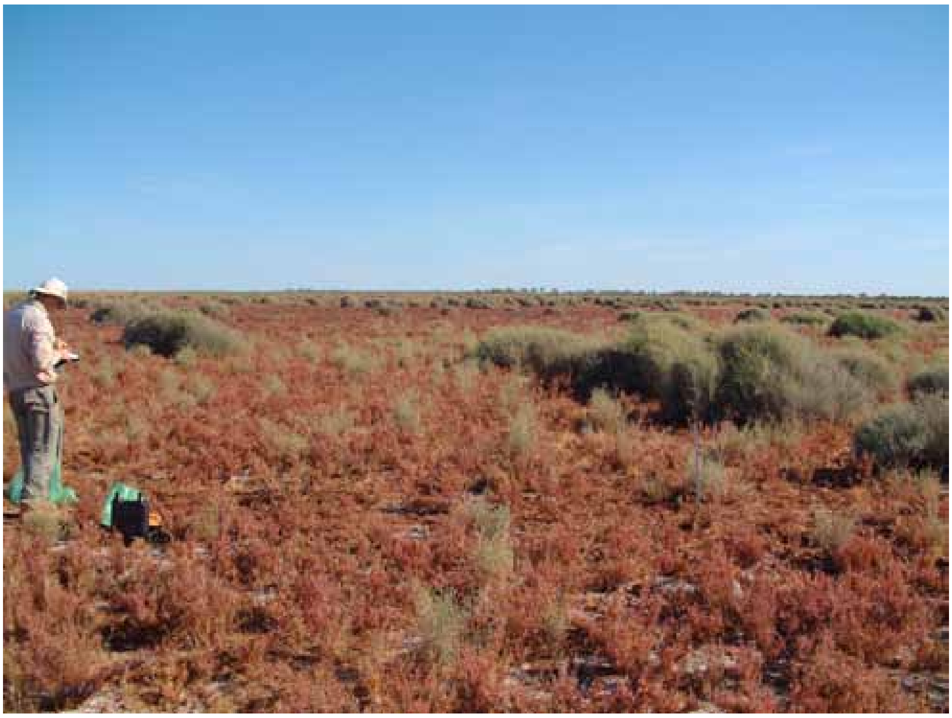

Figure 72. Samphire shrubland with *Tecticornia pergranulata*, *T. auriculata* and *T. undulata* on the outer edge of Fortescue Marsh (Pilbara), with scattered *Muellerolimon salicorniaceum*. Photo – M Lyons/DEC.

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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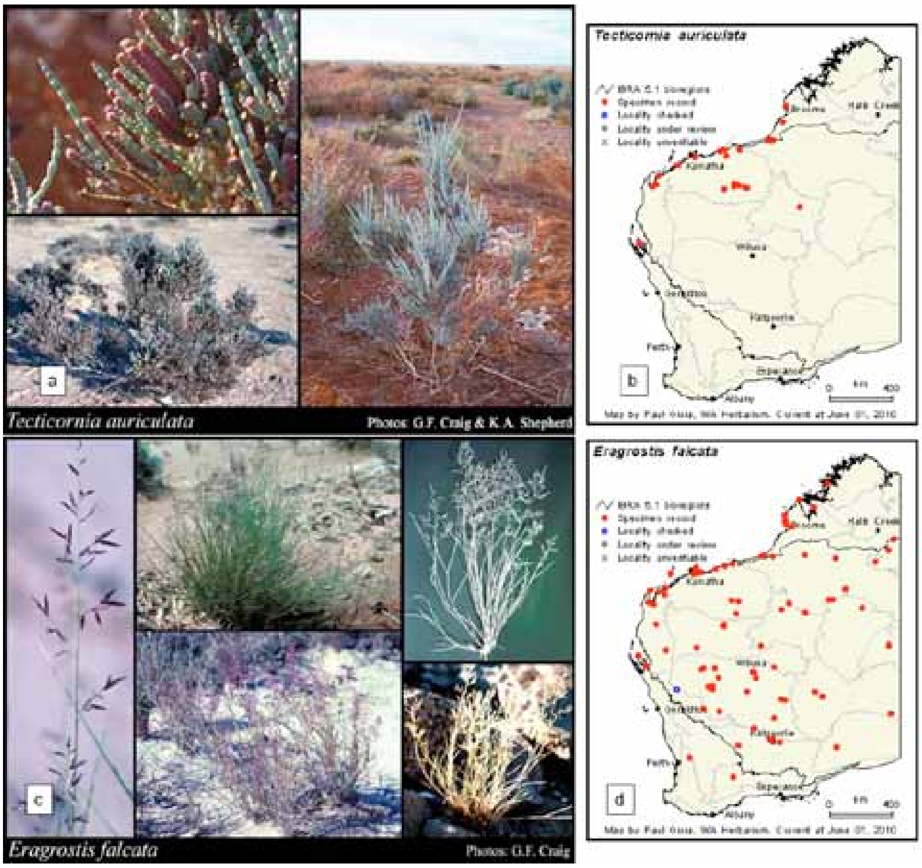

Figure 75 (below). Two restricted shrubs of the Desert wetlands.

(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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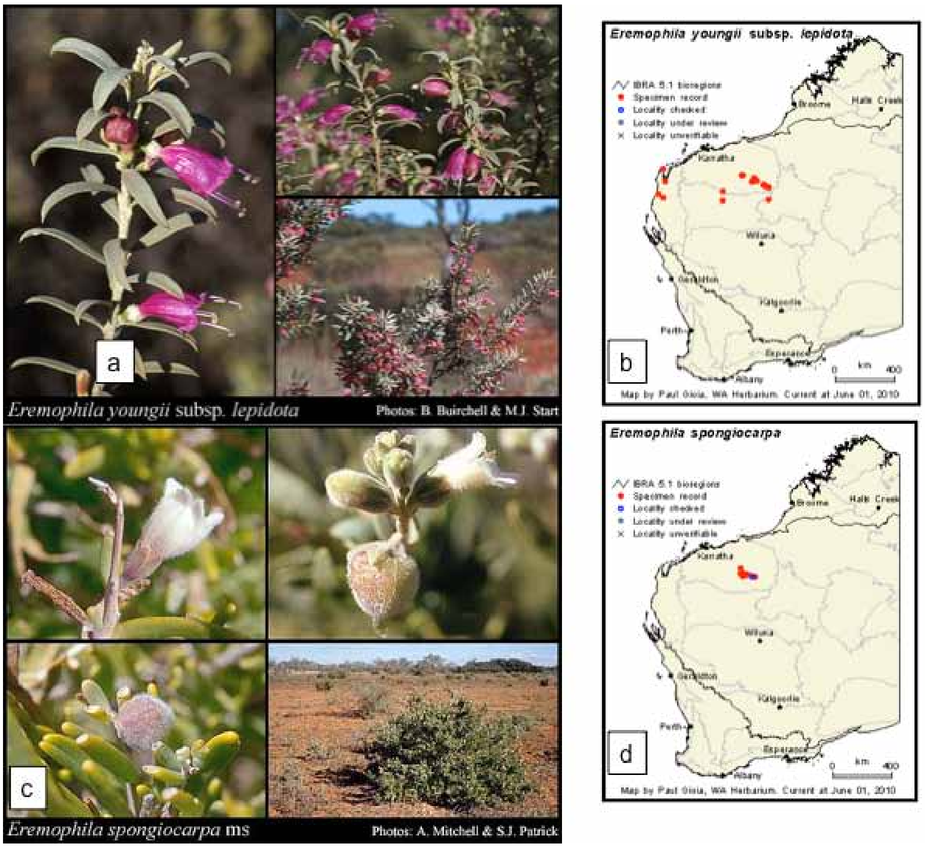


Birrida: a local Aboriginal name for a seasonally inundated, hypersaline, gypsum saltpan wetland in sand dunes in the Shark Bay area. Some have a distinctive central raised platform and moat feature.

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.

Cosmopolitan: an organism that is widespread in its distribution

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).

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.

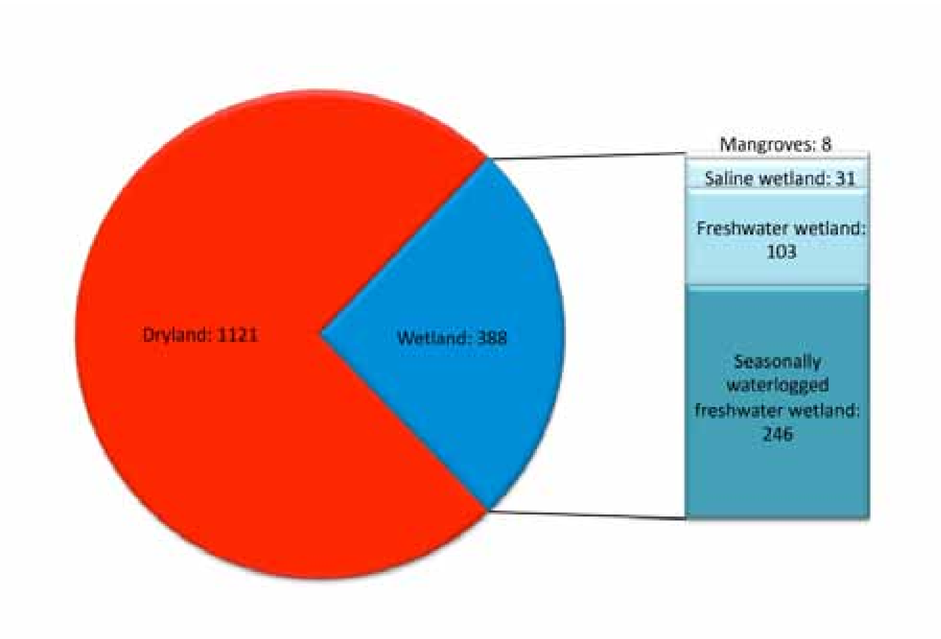


Figure 84. Pilbara wetland and dryland vascular plant taxa found in various plant groups (after Western Australian Herbarium[81]).

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.

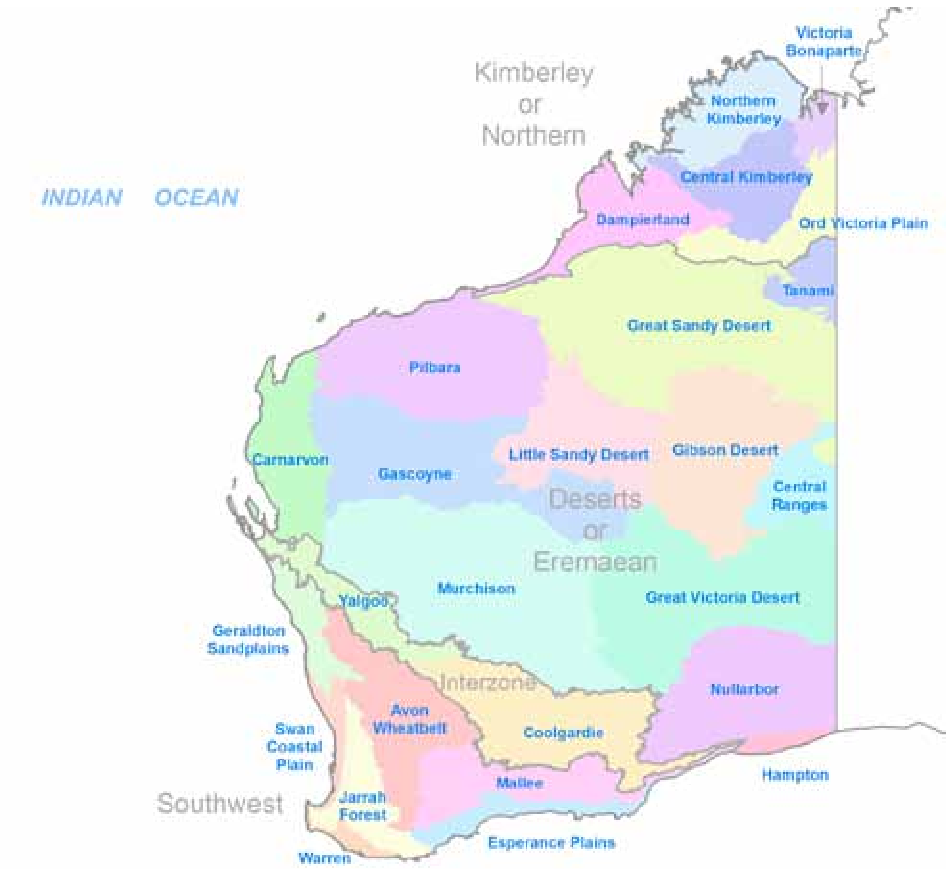


Figure 86. WA's bioregions and the three climatic zones used in this topic. Image – C. Auricht, Auricht Projects.

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.

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

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.

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.

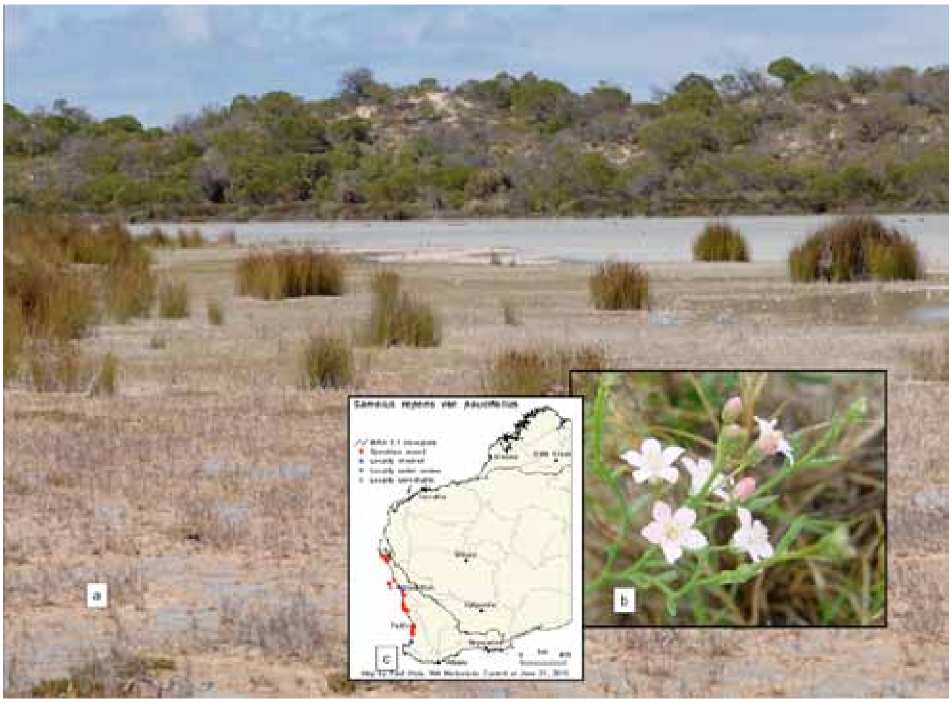


Figure 89. Another view of the Hutt Lagoons (Geraldton Sandplains). Photos – B Keighery/OEPA.

(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.

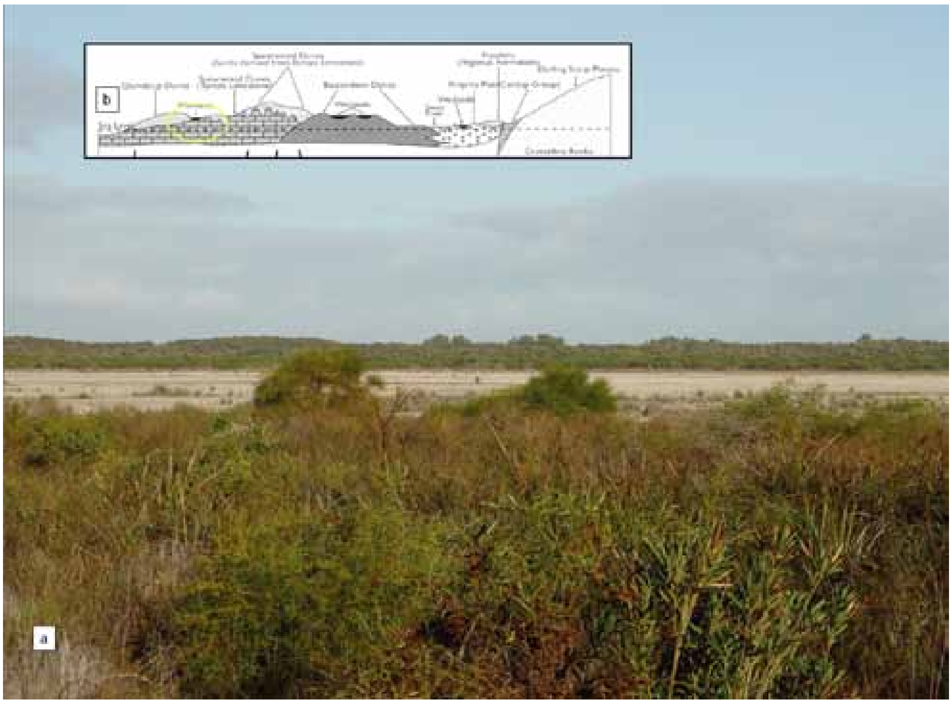


Figure 90. Lake Walyungup, a salt lake near Rockingham (Swan Coastal Plain).

(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.

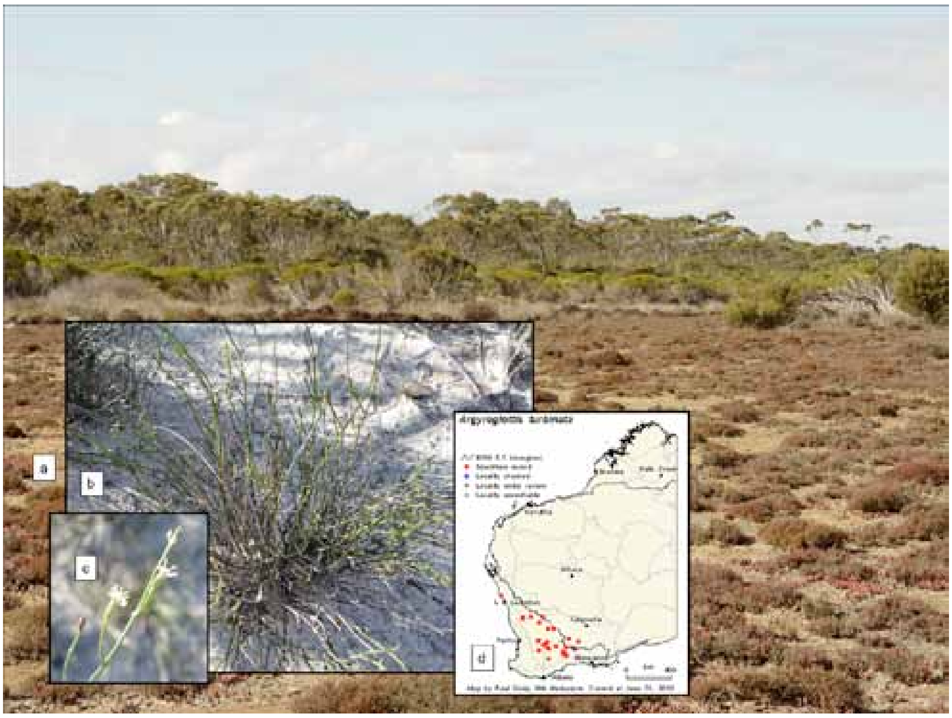


Figure 94. A saline wetland in Truslove Nature Reserve (Esperance Sandplain). Photos – B Keighery/OEPA.

(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).

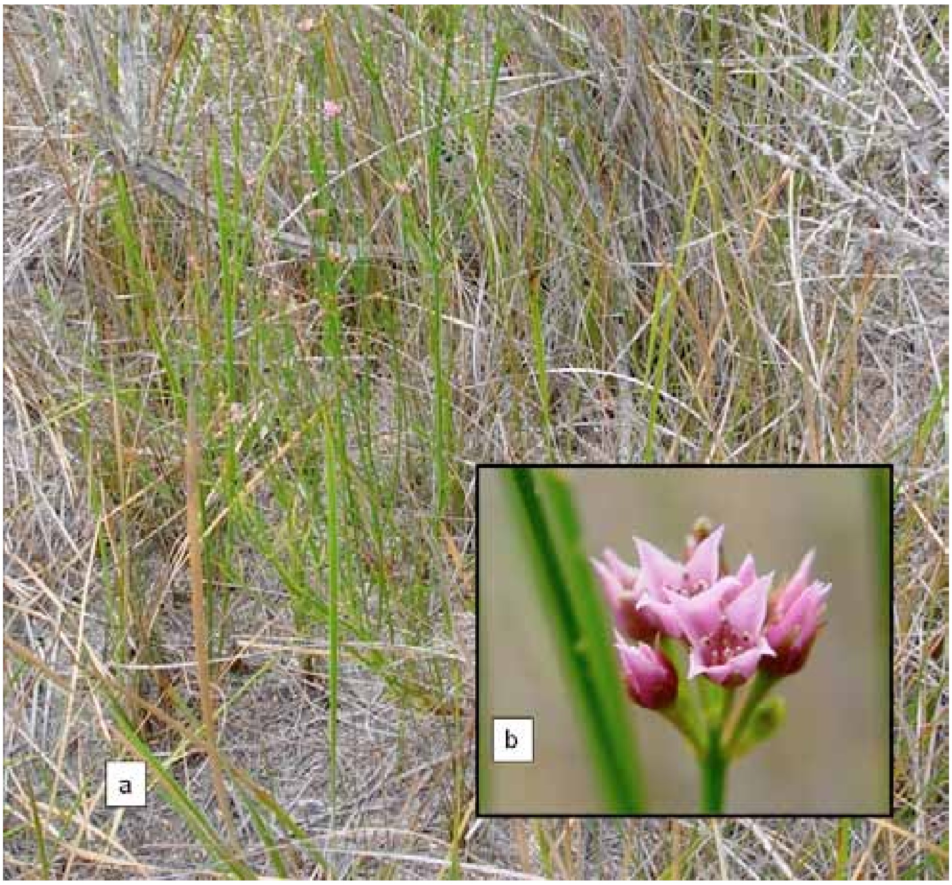


Figure 102. *Boronia juncea* subsp. *juncea*, an uncommon wetland shrub confined to the wetlands in the Kemerton area on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(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.

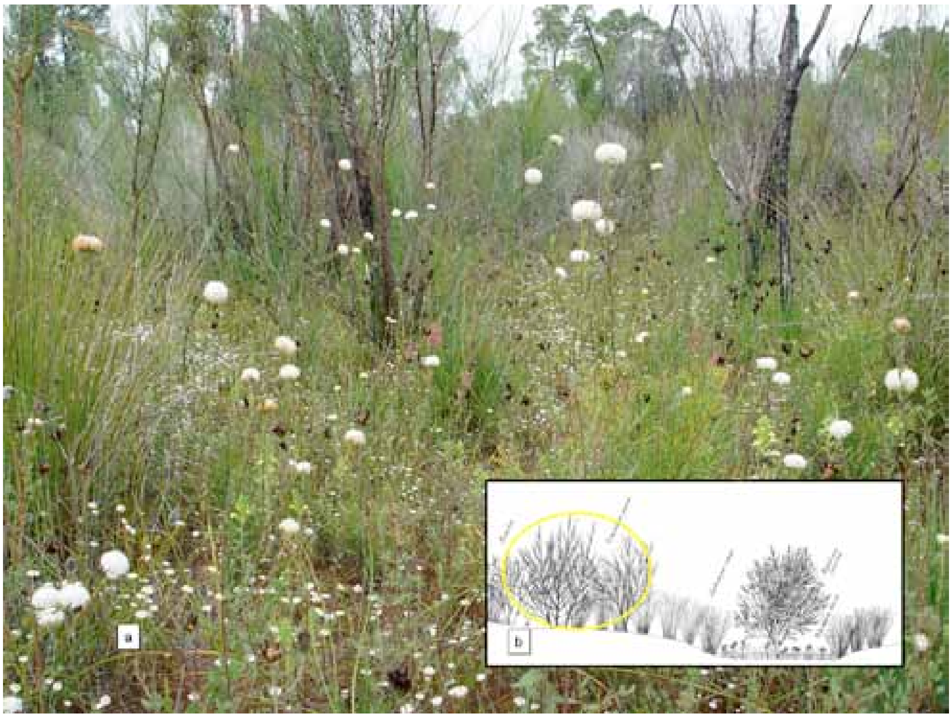


Figure 109. A plant community of the seasonally inundated clayflats in the Brixton Street Wetlands (Swan Coastal Plain) in spring.

(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.

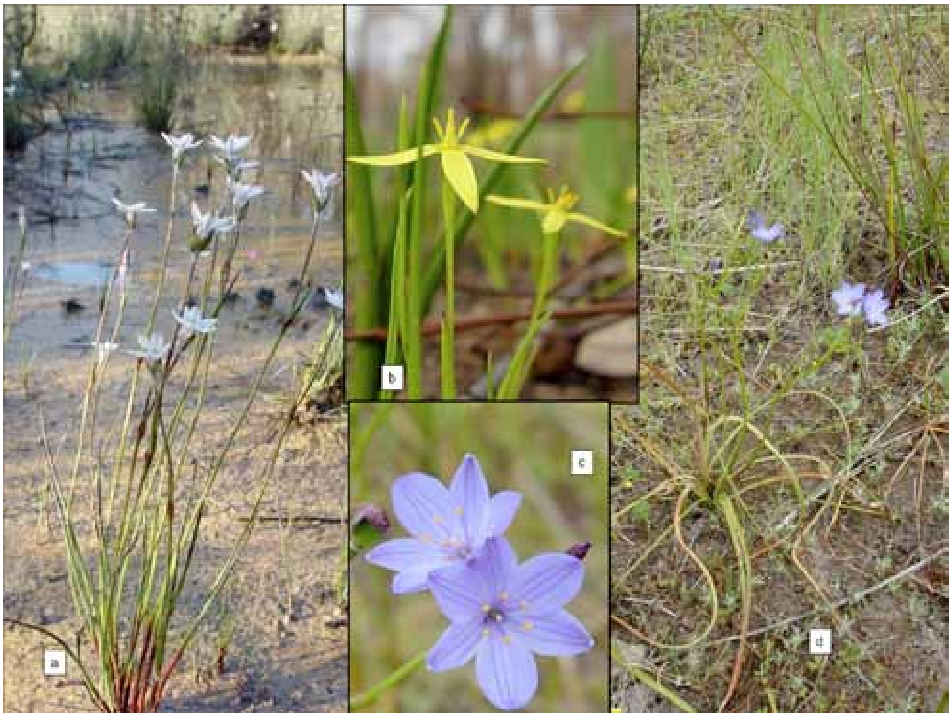


Figure 114. Three plants which, following inundation, are annually renewed from bulbs, corms, rhizomes or tubers, from wetlands on the Swan Coastal Plain. Photos – B Keighery/OEPA.
(a) *Tribonanthes uniflora* (bulbs)
(b) *Hypoxis occidentalis* (corm)
(c) *Chamaescilla gibsonii* flowers and (d) plant (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

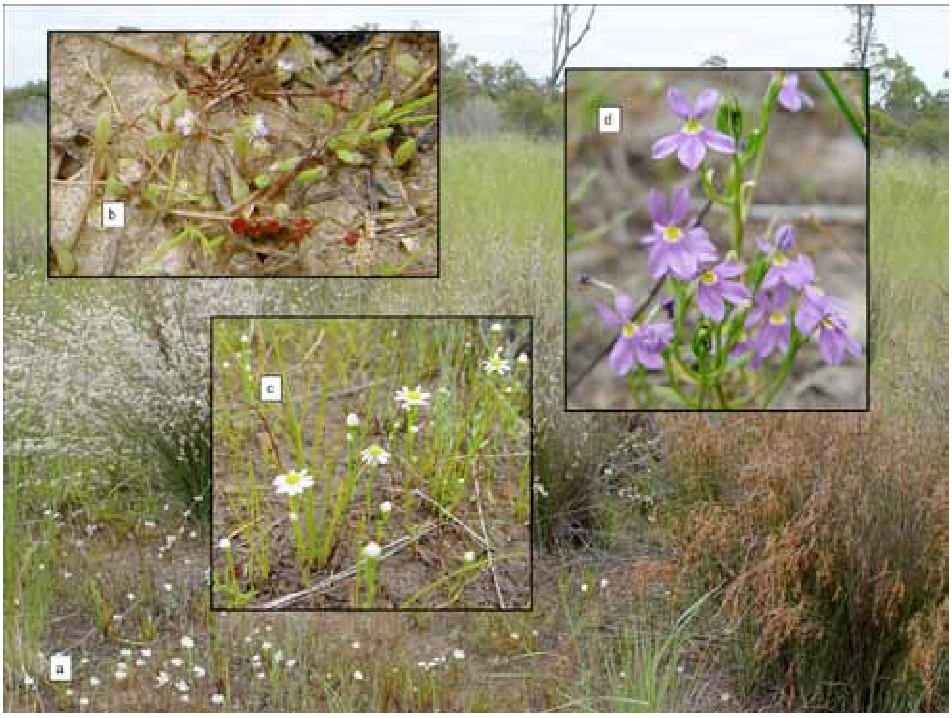


Figure 117. A large variety of annual herbs flower in the drying soils of clayflats and claypans. These are all renewed from seed. Photos – B Keighery/OEPA.

(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.

- 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.

Bentonite: a type of clay (aluminium phyllosilicate)

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.

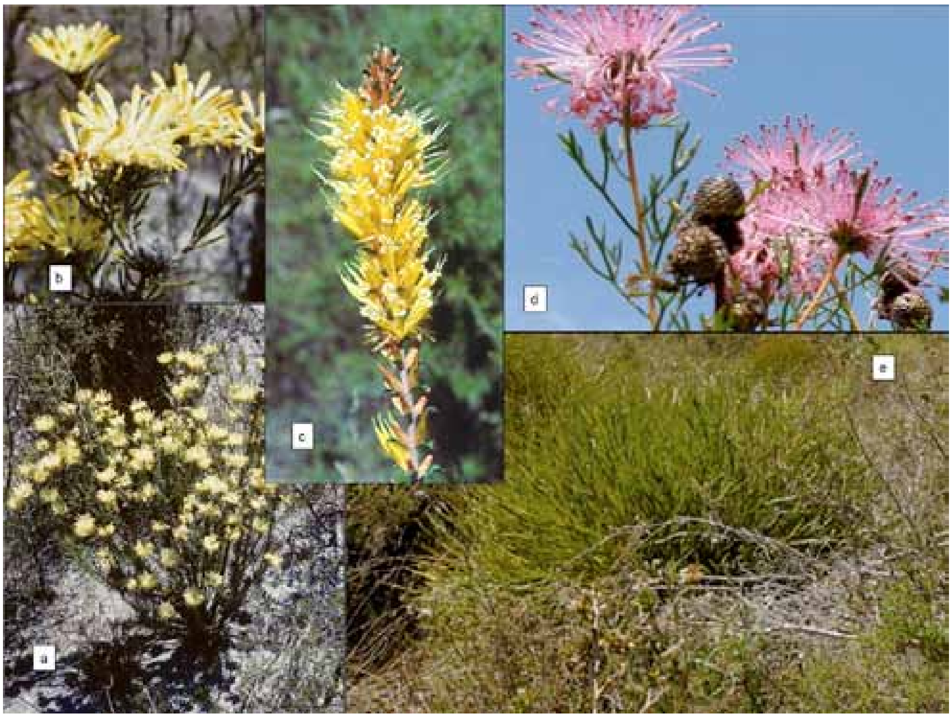


Figure 123. The TEC 'Shrublands on southern Swan Coastal Plain Ironstones (Busselton area)' or Busselton Ironstones contain many restricted and rare plants, including a number from the Proteaceae family.

(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)).

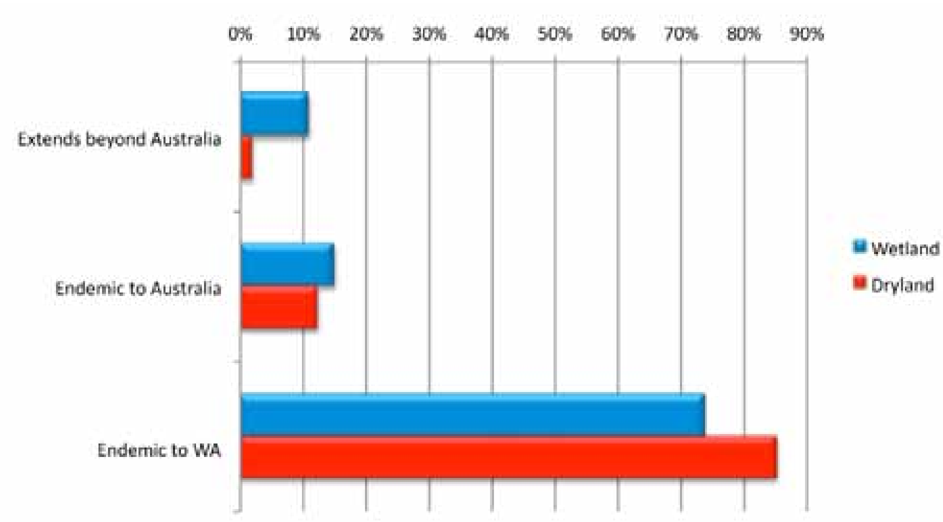


Figure 133. Endemism of wetland and dryland vascular plant taxa of the southern Swan Coastal Plain

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).

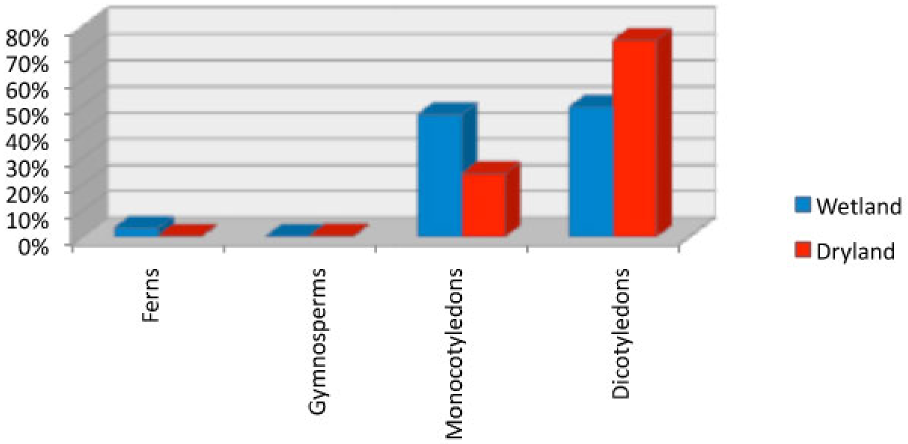


Figure 134. Plant groups of the wetland and dryland vascular plant taxa of the southern Swan Coastal Plain.

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.

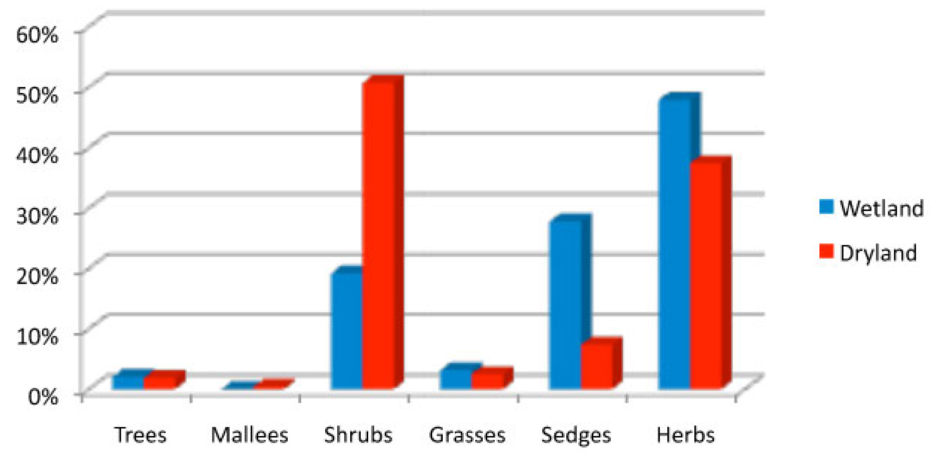


Figure 138. Growth forms groups of wetland and dryland vascular plants of the southern Swan Coastal Plain.

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.

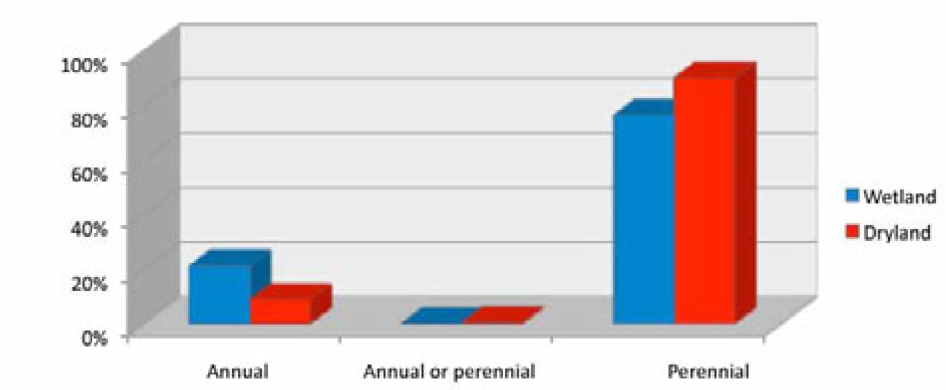


Figure 139. Life forms of wetland and dryland vascular plants of the southern Swan Coastal Plain.

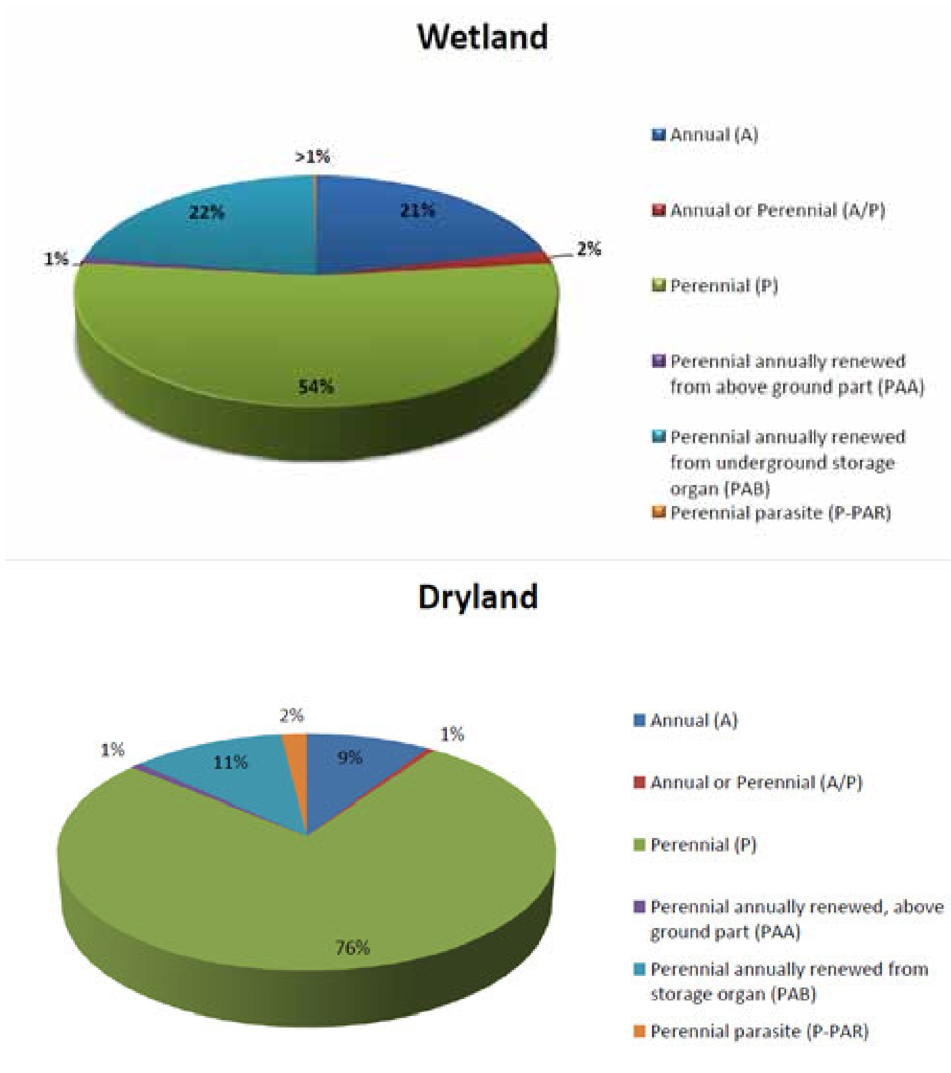


Figure 140. Life form groups of wetland and dryland vascular plants of the southern Swan Coastal Plain.

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).

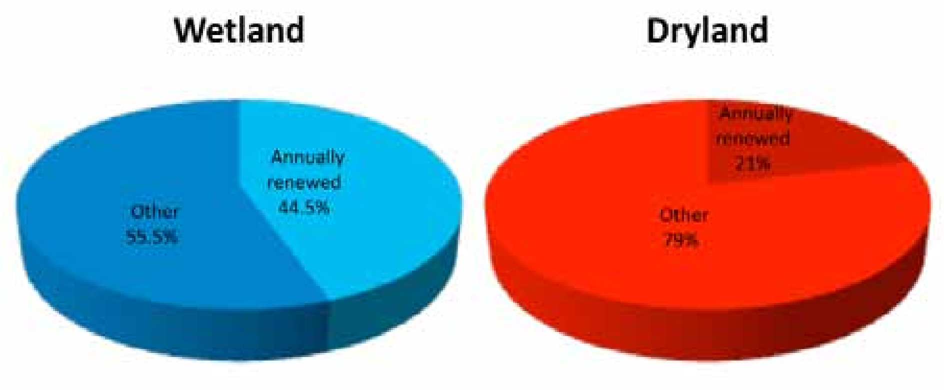


Figure 142. Life form of annually renewed groups of wetland and dryland plants of the southern Swan Coastal Plain.

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.

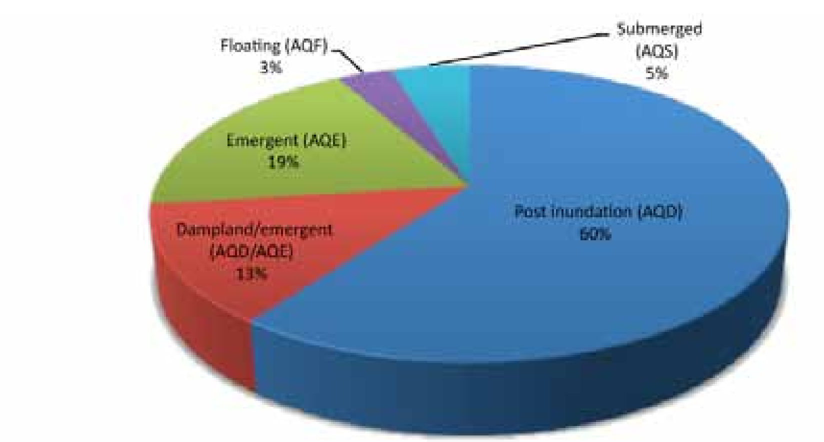


Figure 144. Life forms of aquatic vascular plants of the southern Swan Coastal Plain.

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.

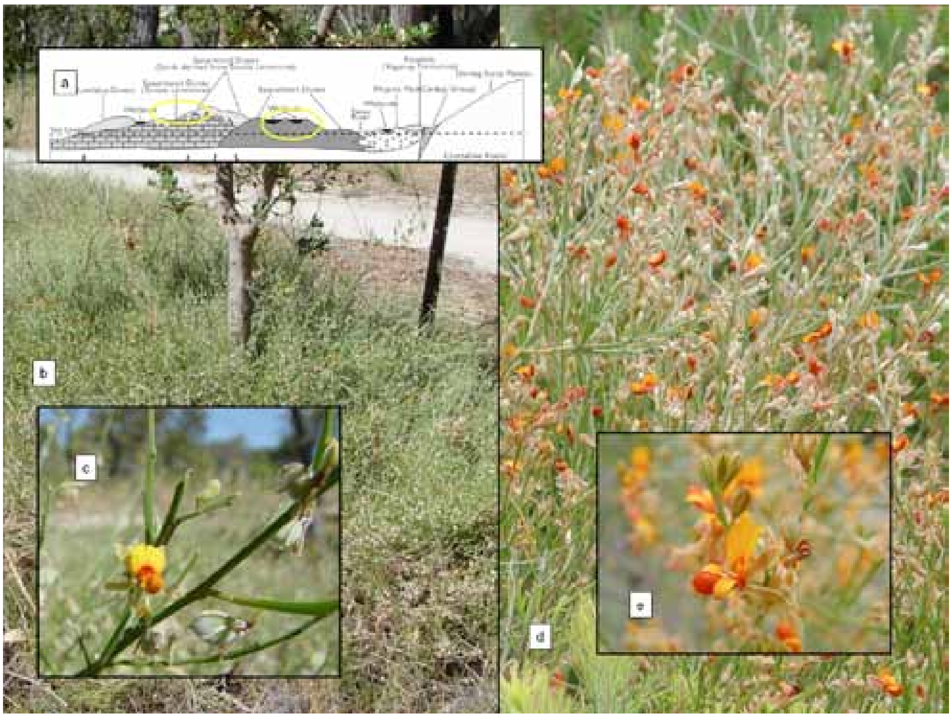


Figure 147. Many wetland plants have closely related species in the drylands. Two Swan Coastal Plain endemic *Jacksonia* species illustrate this relationship. Photos – B Keighery/OEPA.

(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.

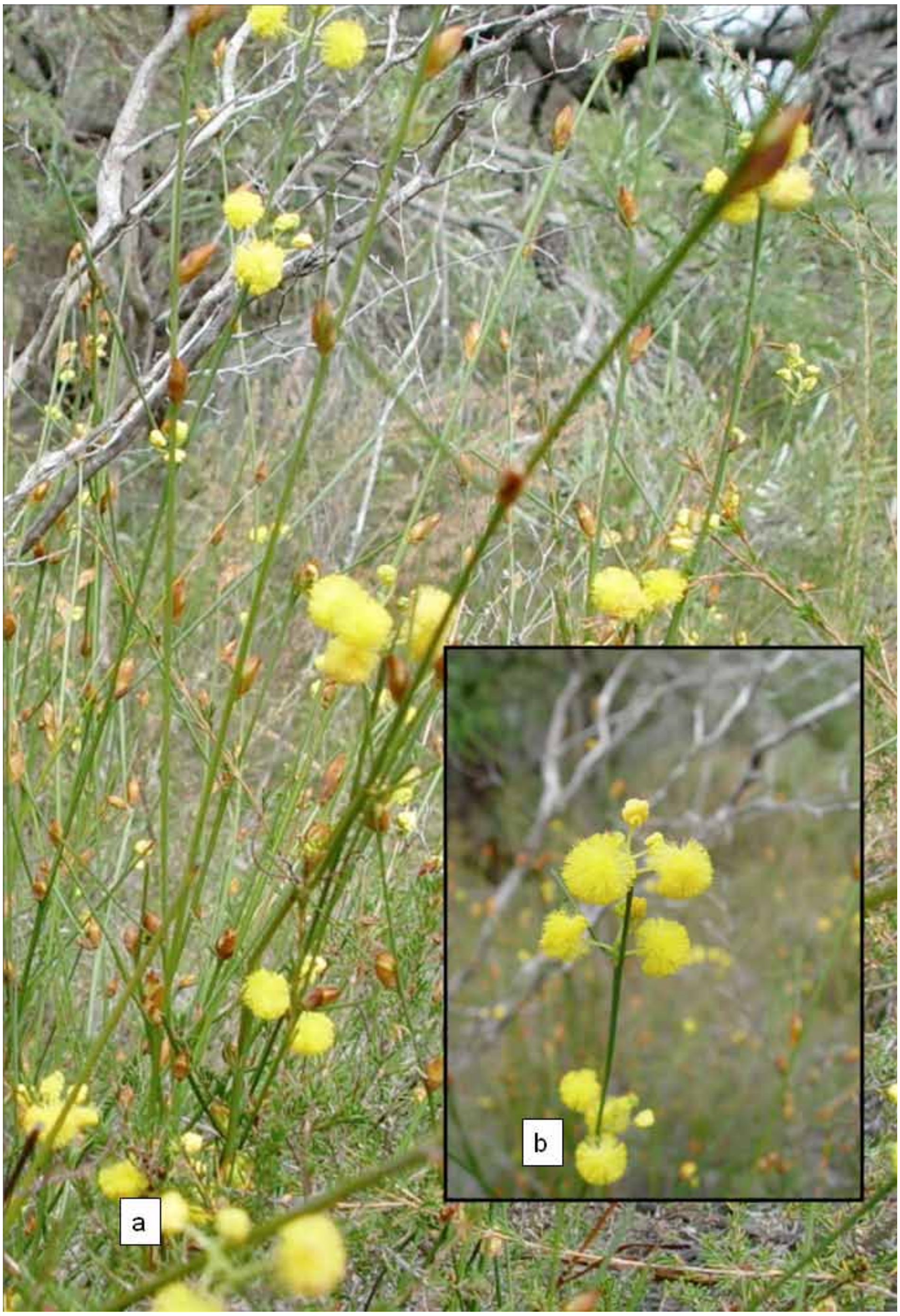


Figure 149. *Acacia flagelliformis*, an uncommon wetland shrub confined to the wetlands in the Bunbury/Busselton area principally on the Swan Coastal Plain. Photos – B Keighery/OEPA.

(a) Plant.

(b) Flowers.

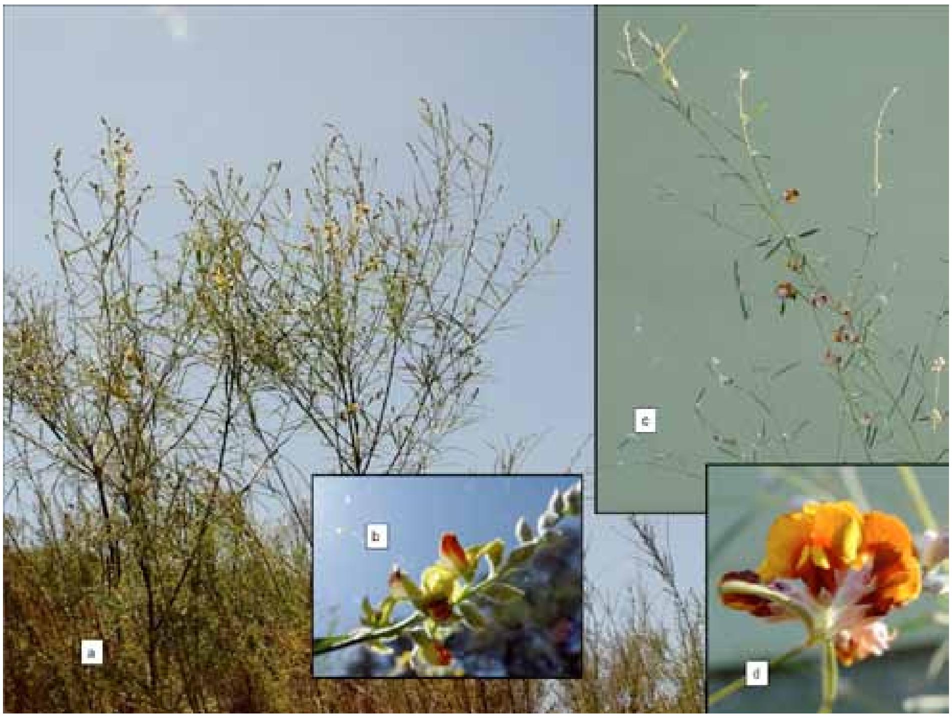


Figure 150. Members of the family Fabaceae are found in wetlands. Many of these are uncommon or rare. Photos – B Keighery/OEPA.

(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

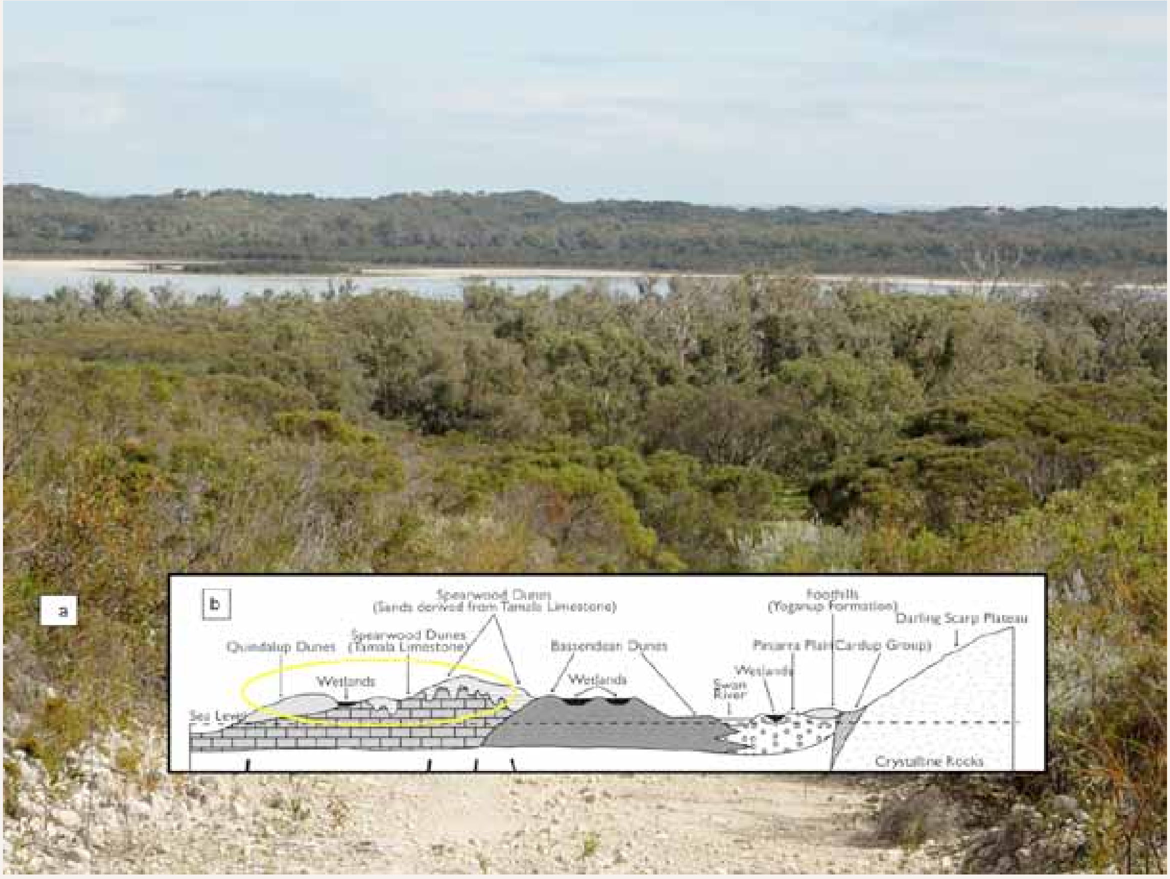


Figure 154. Quindalup and Spearwood dunes in Yalgorup National Park.

(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

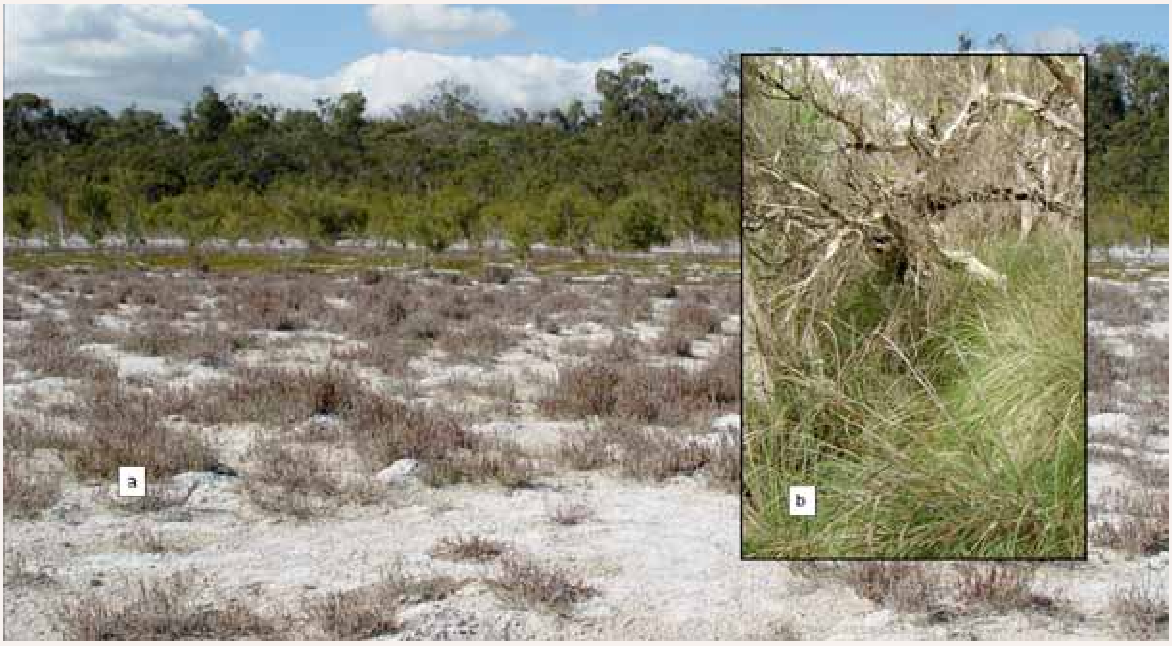


Figure 155. Plant communities visible from the water's edge.
(a) Samphire shrubland on the water margin, to *Melaleuca* forest, then tuart forest.
(b) *Melaleuca* forest underlain by a dense layer of the sedge *Gahnia trifida*, a freshwater community.
Photos – B Keighery/OEPA.

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.

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.

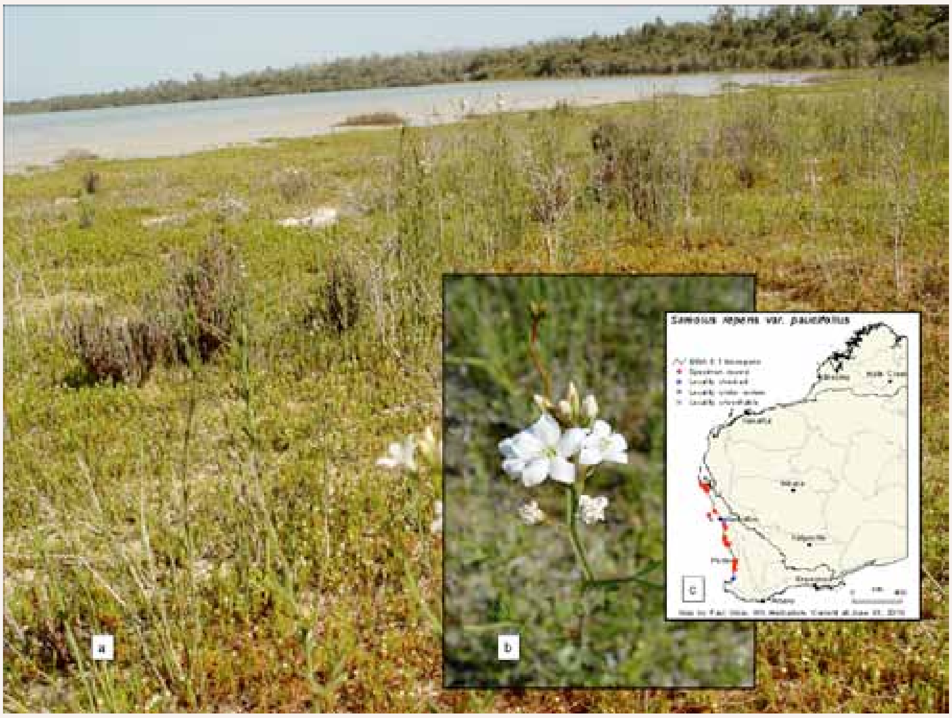


Figure 158. *Samolus repens* var. *paucifolius*. Photos – B Keighery/OEPA.

(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

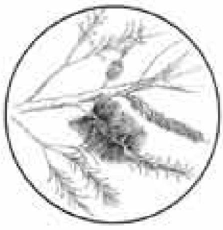
Delicate Treasure

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.

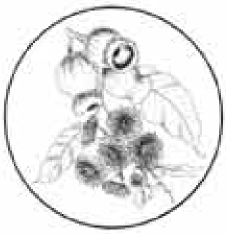
This unique and special place is now protected, saved from development as a housing estate. However, it's a fragile ecosystem and needs careful management to survive. Treat it with care and it will reward you with its many delights.

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

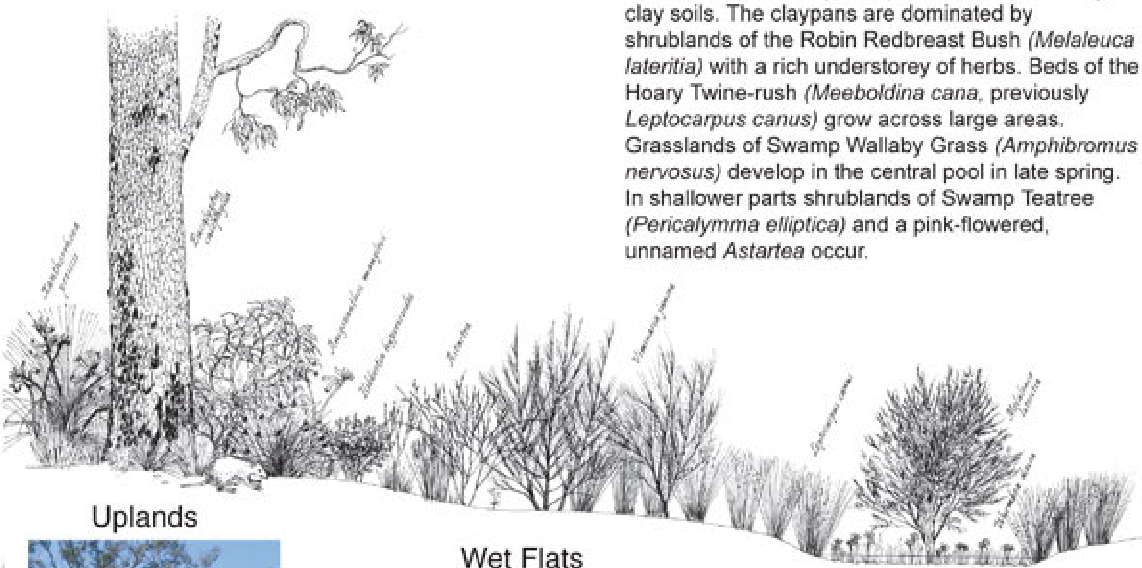
These occur on slight rises between the wetlands and support a woodland of Marri *(Corymbia calophylla*, previously *Eucalyptus calophylla)* with an understorey of various shrubs, herbs and sedges.

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

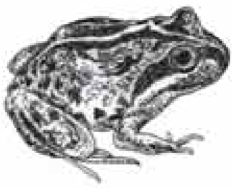
Fields of bright green Swamp Wallaby Grass (*Amphibromus nervosus*) surrounded by clumps of the Hoary Twine-rush (*Meeboldina cana*, previously *Leptocarpus canus*) in the central part of the flooded claypans during winter.

wetland profile

The Brixton Street Wetlands

Frogs and Feather Flowers

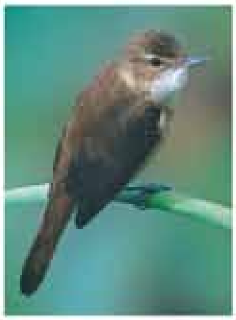
Fauna
The Brixton St Wetlands support a diverse array of fauna, each depending on different aspects of the vegetation and surface water to provide shelter, food and suitable conditions for breeding. Many of these animals, especially the birds, are present seasonally.



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.

Birds
Over forty bird species have been recorded so far, many such as waders and waterbirds are seasonal visitors during winter and spring.



The Australian Reed-Warbler (*Acrocephalus australis*), a shy bird of reed beds with a beautiful melodious song.

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.

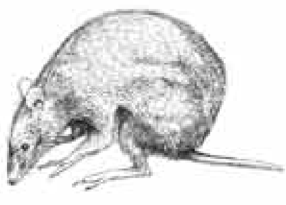
In late spring Feather Flowers of various types form a sea of pink foam across the Wet Flats.

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 cymosa*) 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.

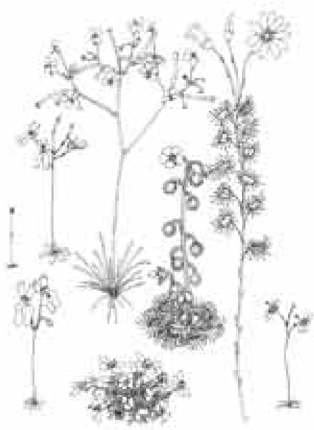
Careful removal of bulbous weeds.

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.

1. Bacon and Eggs (Wemia capitata) 2. Flannel Flower (Tribonanthes uniflora), a clay pan endemic. 3. Pink Rainbow (Drosera menziesii) 4. Swamp Spider Orchid (Caladenia paludosa) 5. Pink Morning Lily (Chamaescilla glauca), a clay pan endemic. 6. Love Creeper (Comesperma volubile)



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.

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