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.

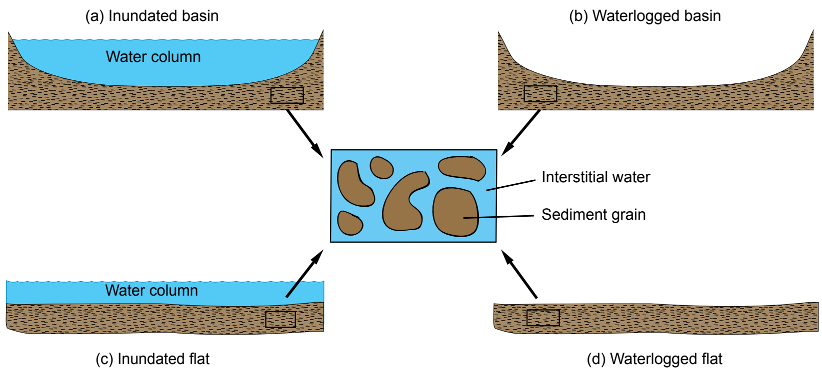

Figure 1. Water columns and sediment pore waters. Image – J Higbid/DEC.

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.

Permanently waterlogged wetlands

Permanently waterlogged areas also occur in areas of WA. **Mound springs** are a type of permanently waterlogged wetland fed by deep, continuously discharging groundwater sources. The area where groundwater discharges is elevated above the surrounding landscape. It is elevated through the build up of sediment such as clay and/or calcareous (calcium) material brought to the surface, and by the accumulation of **peat** as a result of the wetland vegetation, forming a mound around the area of discharge. These mounds can rise up to two metres above the surrounding landscape and be up to several hundred metres across, and many have a moat of fresh or brackish water surrounding the mound.[8] Mound springs are found in the Kimberley, Pilbara and Midwest regions, the arid interior and Swan Coastal Plain (Figure 3), and include the Mandora Marsh Mounds, Dragon Tree Soak, Bunda Bunda, Big Springs, Black Spring, the North Kimberley Mounds, Mount Salt (calcareous) and Three Spring suite. WA's peat mound springs, often known as **tumulus** mound springs, differ to those of eastern Australia, which are comprised of calcareous **tufa** rather than peat mounds.[8]

Figure 3. A mound spring. Photo – J Lawn/DEC.

Mound springs support a variety of vegetation types, including sedgeland-herbfields, forests, woodlands, monsoon vine thickets and even mangroves. Because they are permanently damp, mound springs have significant conservation value as refuges for plants and animals from the surrounding dry landscape, and they support both **endemic** species and isolated outliers (that is, populations outside of the main distribution of that species).[9] Over geological time, species have had to adapt to changing conditions driven by rising and falling sea levels, aridity and ice ages; most of those that did not change significantly have become extinct or remain only in **refugia** including mound springs and permanently inundated wetlands.[10] For example, the fern *Cyclosorus **interruptus*** appears to be found only where permanently wet peaty habitat is present.[9] It is found in the Gingin Brook area north of Perth, and in mound springs in the Kimberley, with no records in between.

Seasonally inundated wetlands

In the north and south of WA there are many seasonally inundated wetlands. Lake Eda near Broome is an example (Figure 4). In the north of the state, the wet season usually falls between October and April and these wetlands typically have their maximum water levels in March following high rainfall between January and March (Figure 5).

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

Peat: partially decayed organic matter, mainly of plant origin

Tumulus mound spring: peat-formed mound spring

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

Endemic: naturally occurring only in a restricted geographic area

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

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

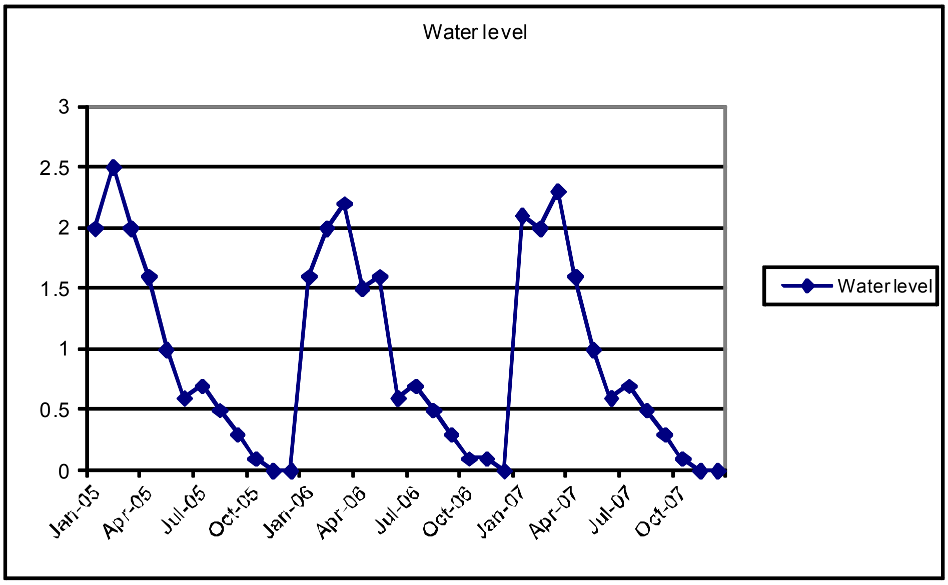

Figure 5. Hydrograph showing the estimated water levels in Lake Eda from January 2005 to December 2007. Water levels estimated from local rainfall data.

Seasonally inundated wetlands typically support a diversity of plants and animals, of which a relatively high proportion of plants are endemic.[11] In addition to perennial species of plants, they typically support a suite of annually renewed species that make many of these wetlands species-rich. They are also important breeding areas for many waterbirds. Small, poorly defined wetlands inundated for a few months account for more than half of the breeding by ducks.[12] On the Swan Coastal Plain, these wetlands are of extreme importance for breeding Pacific black duck and grey teal in south-western Australia.[13] Additionally, in the north these areas are used by crocodiles. Wherever these wetlands occur, they are habitat for frogs adapted to the cyclic wet and dry conditions. A number of seasonally inundated wetlands in the south-west and south coast of the state are inhabited by endemic crayfish adapted to the cyclic wet and dry conditions. For example, the seven *Engaewa* species of crayfish burrow down into the soil as the water recedes, remaining in the damp soil below during the summer dry season. Three of the species are either endangered or critically endangered, due to either the loss of these wetlands or as a result of them becoming drier to the extent that the crayfish cannot survive. Other crayfish, such as gilgies and koonacs, also survive drying by burrowing into damp soils. This burrowing life strategy, an incredible adaptation to WA's seasonally inundated wetlands, is also shared by two species of wetland fish that occur in the south west: the salamanderfish *Lepidogalaxias salamandroides* and the black-stripe minnow *Galaxiella nigrostriata*. Only twenty-two other fish world-wide are known to employ this life strategy.[14]

Intermittently inundated wetlands

Many wetlands in WA are intermittently inundated, including those in the arid interior, as well as some in the south-west. Mungkili Claypan near Wiluna is one such wetland (Figure 6, Figure 7). Some may remain dry for years at a time. These wetlands rely on cyclonic rainfall for inundation. In the arid parts of the state, cyclonic rainfall generally occurs between January and March, however, this may vary from year to year and is likely to continue to do so with climate change.

Intermittently inundated wetlands tend to be subject to high evaporation rates. The sediments tend to accumulate the salts that remain following evaporation of wetland water, meaning that these wetlands can have very saline sediments.

Figure 6. Mungkili Claypan, near Wiluna, is an intermittently inundated wetland in the arid interior of WA. Photos – G Daniel/DEC

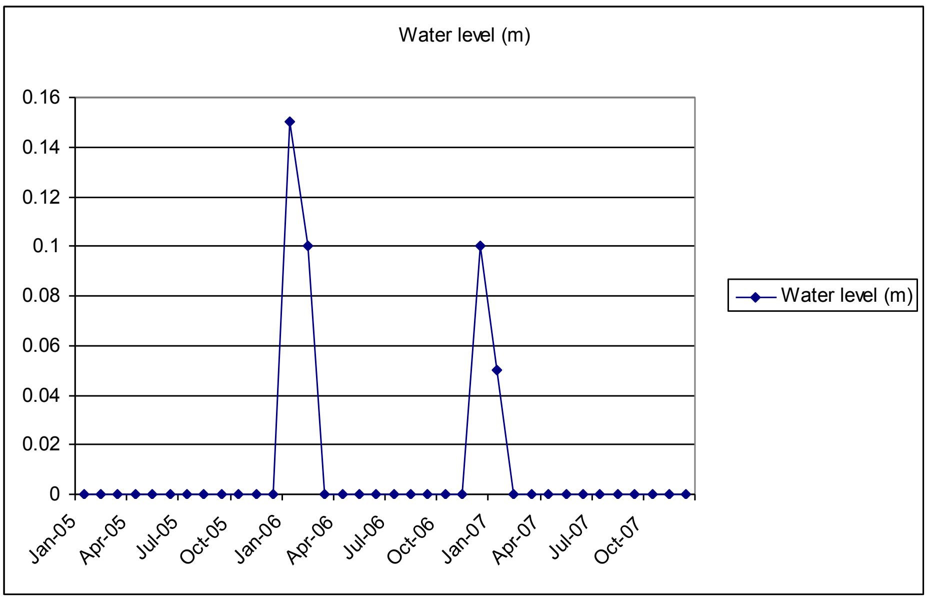

Figure 7. Hydrograph showing the estimated water levels in Mungkili claypan from January 2005 to December 2007. Water levels estimated from local rainfall data.

Intermittently inundated wetlands may seem devoid of life when dry. However, they tend to support resting eggs of small animals, seeds of plants, and spores and cysts of algae and bacteria that can withstand hot, dry conditions. When wet, these wetlands often support an abundance of life, particularly of macroinvertebrates and algae, that while often species-poor, can help drive boom populations of larger animals. Arid zone frogs rapidly respond to the presence of water in these wetlands, with breeding followed by rapid development of tadpoles as water levels fall. More than twelve frog species occur in the arid zone, from a total of eighty-one known in WA. The flat-shelled turtle, *Chelodina steindachneri*, inhabits the most arid region of any Australian turtle: intermittently inundated wetlands in the Pilbara and midwest, extending into the desert. It aestivates for periods of years at a time and can migrate long distances to find water.

Intermittently inundated wetlands can be extremely important waterbird breeding habitat. For example, Lake Ballard (Figure 8), north of Menzies, is inundated once every five or so years on average, usually by single major, summer-autumn rain events of tropical origin; a shallow level of water may persist six to nine months.[15] Brine shrimps, *Parartemia* sp., which survive as cysts during the dry phase, are abundant when the lake fills. These are the main food of the Australian endemic banded stilt *Cladorhynchus leucocephalus* adults and chicks. Lake Ballard is one of the most important breeding sites in Australia for the banded stilt as well as an important migration stopover for many other species of waterbird. Breeding is thought to occur whenever depth over most of the lake reaches 0.3 metres or more. Nests are prepared, typically ten per square metre, on small low islets in colonies of hundreds to tens of thousands. Eggs may be laid within weeks of the lake filling.[15]

Figure 8. Lake Ballard is an intermittently inundated wetland north of Menzies. Photo – Wetlands Section/DEC.

Permanently inundated wetlands

Permanently inundated wetlands are the wetland type that most people think of when they think of wetlands. Permanently inundated wetlands, or lakes, are common in many areas of the world, and have traditionally been the focus of wetland studies in the northern hemisphere. By international standards, WA's lakes are very shallow, and do not freeze over, and as such many aspects of these studies are not as applicable to WA's lakes. In number and area, lakes make up a relatively small proportion of WA's wetland types, but they are often extremely important habitats for specialised wetland species as well as many mobile species that visit wetlands in times of need. In addition to most species of fish, turtles and many species of waterbird, the iconic yet cryptic rakali or water rat, *Hydromsy chrysogaster*, relies on permanent water, including permanently inundated wetlands for its survival. In WA this fascinating mammal occurs in isolated coastal populations in the Pilbara and Kimberley and from Moore River in the midwest to the Fitzgerald River on the south coast.

Lakes are most prevalent on the south coast (Figure 9) and south west but do occur in other regions. They account for less than 5 per cent of the wetlands on the Swan Coastal Plain.[16] They fluctuate in depth and extent of inundation but naturally almost always retain a water column (Figure 10). Most are not more than a few metres deep[15], although a few reach depths greater than 10 metres, such as Lake Jasper on the south coast. Some of the deepest wetlands are artificial (for example, Lake Argyle in the eastern Kimberley, which is 45 metres deep[15]) and many have been artificially deepened (for example, Herdsman Lake in Perth, which has been dredged to a depth of 9 metres in some areas[16], and Lake Richmond in Rockingham, which receives stormwater from the surrounding urban catchment). Countless seasonally waterlogged and inundated wetlands have been dug out, lined or flooded to create permanently inundated wetlands, causing a loss of habitat for the species that originally inhabited these wetlands.

Figure 9. Lake Gore, a permanently inundated wetland east of Esperance. Photo – Wetlands Section/DEC.

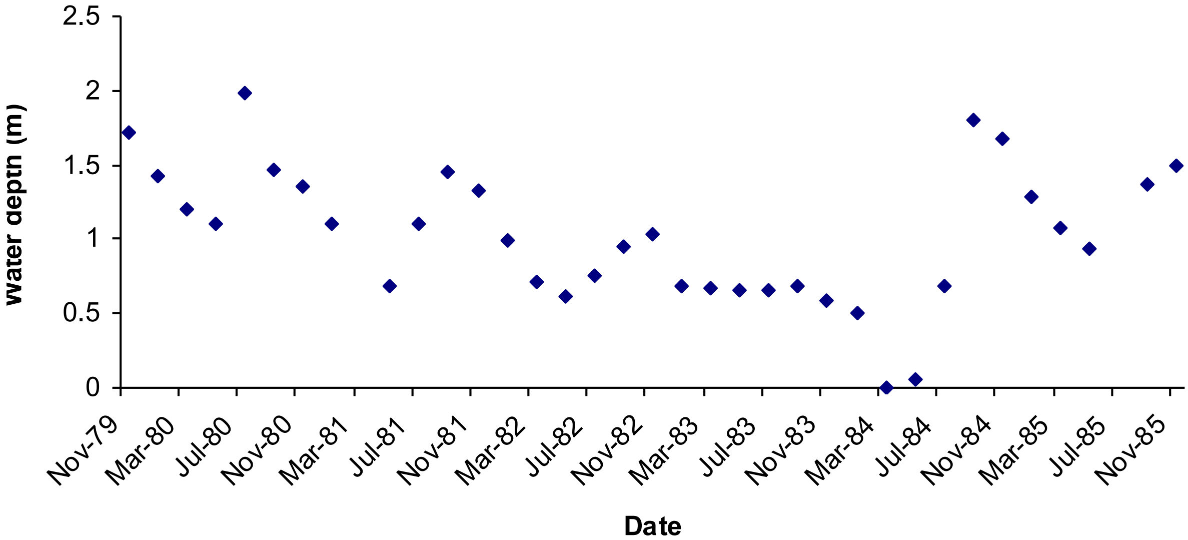

Figure 10. Hydrograph showing the recorded water depths in Lake Gore from November 1979 to November 1985.

Wetland water regime

The **water regime** of a wetland is the specific pattern of when, where and to what extent water is present in a wetland.[17] The components of water regime are the timing, frequency, duration, extent and depth and variability of water presence.[18] These are outlined in Table 2. Wetland water regime is also referred to as 'hydropattern' or 'hydrological regime' in many texts.

Table 2. Features of the water regime of wetlands. Adapted from Bunn et al., 1997.[17]

Feature	Definition
Timing	The timing of a wetland being waterlogged or inundated. Within-year patterns are most important in seasonally waterlogged or inundated wetlands (that is, what time of year) whereas between-year patterns and the variability in timing may be more important to intermittently inundated wetlands.
Frequency	How often wetting and drying occur. Ranging from not at all in wetlands that are permanently inundated (lakes) to wetting and drying many times a year. The rate at which wetting and drying occur can also be important.
Duration	The length of time of waterlogging and/or inundation. Duration in days, weeks or even years, varying within and between wetlands.
Extent and depth	The area of waterlogging or inundation and the depth of the water.
Variability	The degree to which the features mentioned above change at a range of time scales (variability in timing mentioned above). Variability is recognised as a significant part of wetland water regime.

Wetland water regime is another term that is used in different ways by different people. Sometimes it is used interchangeably with the term 'hydroperiod'. Although wetland water regime and hydroperiod both relate to when and how much water is present in a wetland, the wetland water regime encompasses much more detailed, specific characteristics of a wetland than its hydroperiod, such as frequency, extent, depth and variability. Knowledge of these specific characteristics can be used by wetland managers when designing wetland management objectives for wetlands of conservation value.

For example, Lake Warden, a permanently inundated wetland near Esperance, naturally fluctuates in depth each year, each dry season exposing a shoreline that is used by wading birds. With clearing of surrounding agricultural land, rising groundwater has resulted in increasing water levels in the wetland, submerging the natural summer shoreline used by waders and slowly killing the dryland vegetation. With their knowledge of Lake Warden's natural wetland water regime, wetland managers have implemented a plan to reinstate the natural hydrology in order to recover the summer shoreline to maintain the wetland's natural values. This accounts for the timing of inundation of the shoreline, how rapidly it is exposed, how long it is exposed, how much is exposed and how much these factors vary naturally from year to year.

Another example relates to the protection of the habitat of burrowing crayfish (species of *Engaewa* and most *Cherax*) in seasonally inundated wetlands in the south-west and south coast. While these wetlands may still remain seasonally inundated, they may not retain the wetland water regime needed for the crayfish to survive. In addition to ensuring that these wetlands inundate to the depth, extent and duration required by the crayfish during winter and spring, it is necessary to ensure that the soil below the wetland remains damp during the dry season, for a given depth and duration, to ensure the crayfish survive the hot, dry summers of the south of the state.

Water regimes can be characterised using a range of parameters which define features of the water regime (timing, frequency, duration, extent, depth and the variability in these). The water regime parameters used might vary between wetlands, because a parameter that is meaningful to describe one water regime may be irrelevant in another. For example, 'season of maximum inundation' might be a meaningful parameter to define a predictable, seasonally inundated wetland, but is irrelevant for a wetland that could contain surface water in any season, or for a wetland that naturally experiences waterlogging but not inundation.

Some of the parameters used to characterise water regimes at wetlands are:

- timing (season or month) of driest and wettest conditions
- frequency of driest and wettest conditions
- duration of driest and wettest conditions
- maximum and minimum depth of inundation or waterlogging/depth to groundwater
- extent (area and location) of inundation or waterlogging
- rate of change in water depth or extent

Extensive studies of wetlands on the Gnangara Mound carried out by wetland scientists of Edith Cowan University, Perth, provides details of wetland water regime at a number of wetlands. The data collected are being used to help develop wetland and groundwater management strategies. For example, Carine Swamp, in the northern Perth suburb of Carine, used to be permanently inundated up until 1996. It now dries out each summer. It reaches its maximum water level, on average 0.89 metres, between August and November. However, it is showing a progressive trend of drying earlier and quicker in the years since 1996. Compounding this, it is showing a progressive trend of greater seasonal variation in surface water levels. This has been attributed to increased stormwater run-off from the surrounding suburbs.[13]

Water regime parameters are best described by a range of values rather than a definitive value. For example, the recorded maximum water depth of a seasonally inundated wetland might vary 'between X and Y metres' in a 10, 20 and 100 year period. When characterising the water regime, the extremes should be recognised as natural to the wetland, unless there is evidence to suggest that the extremes have been caused by altered hydrology. The natural variability should therefore be taken into account when deciding whether a wetland's water regime (and therefore its hydrology) has been altered.

➤ For more information on altered hydrology see the topic 'Managing hydrology' in Chapter 3.

HOW DOES A WETLAND'S HYDROLOGICAL CHARACTERISTICS AFFECT IT?

Water is commonly referred to as the 'driver' of wetland ecosystems. This is because it has such a significant influence on the ecological character of a wetland, from its physical characteristics, to its chemical makeup, to the life that inhabits it.

In particular, water has the following effects on wetlands:

- All life on Earth has particular water requirements, and how much water is present and when it is present in a wetland is one of the factors that determine whether particular plants, animals, fungi, algae and bacteria can inhabit it at a given point in time.
- Water in the environment is physically variable in terms of properties, such as the amount of light it will transmit to plants living in it and the amount of oxygen available in it for animals. These properties are another factor that determines whether particular plants, animals, fungi, algae and bacteria can inhabit a wetland at a given point in time.

- The chemically variable properties of water make it a variable habitat. How salty, acidic or nutrient-laden a wetland is are all factors that determine whether particular plants, animals, fungi, algae and bacteria can inhabit a wetland at a given point in time.

Figure 11 summarises how water shapes the ecological character of wetlands.

The biological, chemical and physical effects of water in a wetland create unique environments. In managing wetlands, it is important to maintain the natural water regime, in order to conserve the biological, physical and chemical diversity they support.

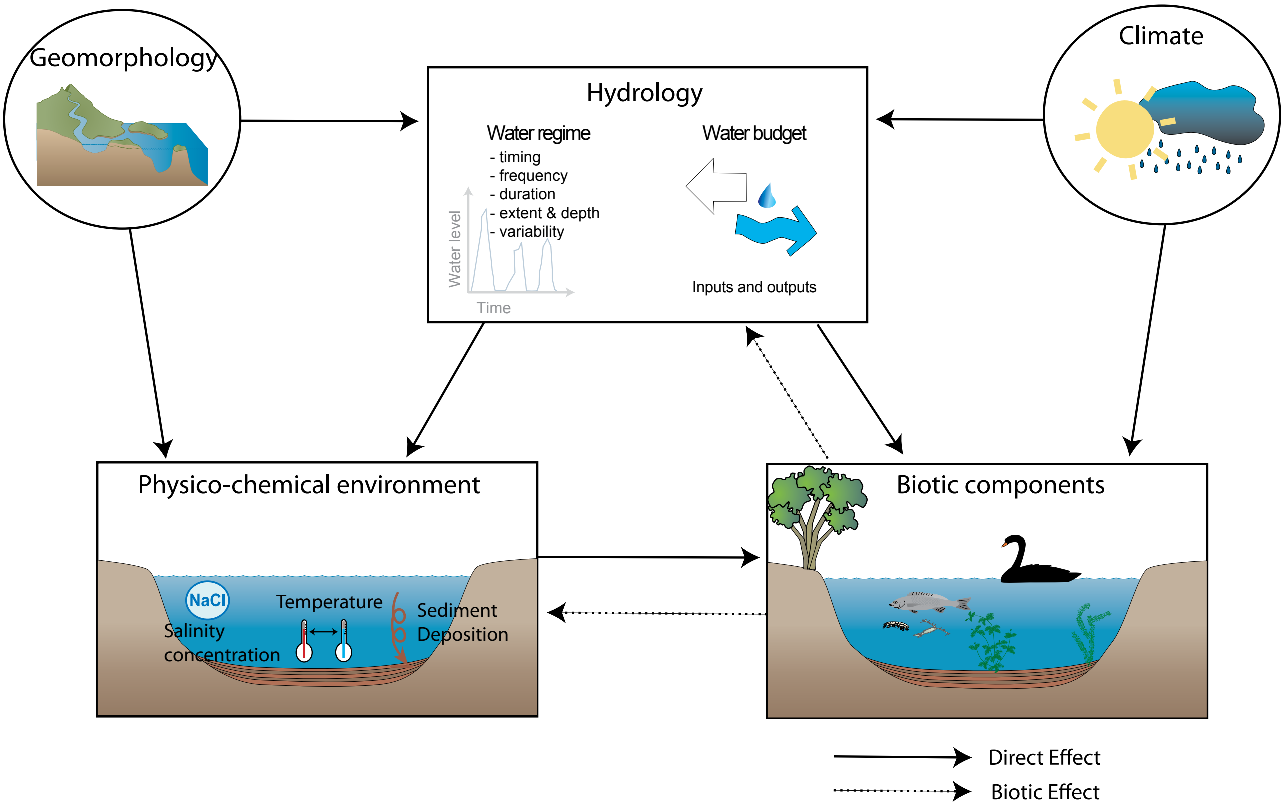

Figure 11. Conceptual model of wetland ecology, illustrating climate and geomorphology as the 'drivers' of wetland hydrology and the inter-relationship between wetland hydrology, physical and chemical components of wetlands and wetland plants and animals. Adapted from Mitsch and Gosselink (2007).[19]

Water availability

One of the most important effects of water regime is determining the availability of water for wetland species to live in, on or in proximity to. In this way, water affects the species composition, richness and abundance of organisms in a wetland.

The presence or absence of species at any given wetland can be explained, in part, by wetland water regime. This is because plant, animal, fungi, algae and bacteria species all have their own water requirements that dictate whether they can survive and flourish in a given water regime. As Jacques Cousteau (1910–1997) noted, the water cycle and life cycle are one.

At a basic level, WA's wetland organisms can be grouped into one of five extremely broad groups:

1. those that inhabit, or need permanent access to a wetland water column
2. those that inhabit, or need access to a wetland water column for a period sufficient

to fulfil part of their annual cycle or life cycle

3. those that inhabit, or need permanent access to saturated wetland soils (without an overlying water column)
4. those that inhabit, or need access to saturated wetland soils for a period sufficient to fulfil part of their annual cycle or life cycle
5. those that, due to an association with other wetland species, preferentially occur in wetlands

Some examples are shown in Figure 12.

Fish, such as Balston's pygmy perch, live in the water column and so require a permanent water column (with the exception of the salamanderfish and the black-stripe minnow).

Although rakali, *Hydromys chrysogaster*, can breathe air, they require permanent water and are highly adapted to a semi-aquatic life.

Almost all of WA's 81 species of frogs need surface water on a seasonal basis to breed and provide habitat for tadpoles. Some need access to a water column year-round and a few don't need it at all.

Verticordia plumosa subspecies *pleiobotrya* is just one of countless plants that live in seasonally inundated wetlands.

The ancient reedia, *Reedia spathacea*, inhabits permanently waterlogged areas in the South Coast. It is a relict from much wetter periods.

Burrowing crayfish, such as those in the genera *Engaewa*, inhabit seasonally inundated wetlands. As the water recedes, they burrow into the sediment and remain in the damp soil until the wetland is once again inundated.

The majestic modong, *Melaleuca preissiana*, inhabits seasonally waterlogged areas in the south-west.

Although they don't rely on them for a specific part of their life cycle, wetlands in the southern Kimberley and Pilbara are part of the habitat of bilbies, *Macrotis lagotis*.

Figure 12. Examples of broad water requirements of some wetland plants and animals.

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

Many organisms do not fit neatly into one of these groups; they are useful as broad generalisations only. In reality, each wetland species has specific **water requirements** that determine where and how it lives and reproduces. For example, burrowing crayfish require surface water for a period of the year, as well as saturated soils for the remaining period.

If the water regime of its habitat changes beyond its tolerance, an organism must move to a new habitat on either a temporary, seasonal or permanent basis, or it will die (Figure 13); many smaller animals and annual plants do, typically reproducing first.

Species water requirements explain, for example, why fish are not as prevalent in WA wetlands as in those of the eastern states. The majority of fish need a water column year-round for survival, yet a relatively small proportion of the state's wetlands are permanently inundated. In addition, many of WA's wetlands are not connected to waterways and therefore do not provide a route for fish migration when wetlands dry up.

Most of Western Australia's wetlands are not permanently wet. In response to this transience of water, wetland organisms have many adaptations for surviving or avoiding drought, and this is part of the reason for the uniqueness of our wetland flora and fauna. 'Boom and bust' cycles are a natural part of the population dynamics of many wetland species in Western Australia. When a dry wetland wets, water seeps through the soil and soaks the resting eggs, seeds, spores and cysts, which begin to develop.[20] The influx of water releases a pulse of nutrients from the soil that, together with light and water, provide the resources for germination and growth of algae and plants. Algae and bacteria proliferate, providing food for consumers. A succession of small animals hatch, grow, reproduce and die. Emergent plants flourish, and in inundated wetlands, aquatic plants grow in submerged or floating habits, and both types of plant provide habitats for other organisms. As water recedes, new plants germinate on the exposed soil, flourishing on the nutrients released by **anaerobic** bacteria on drying. If water recedes through evaporation, concentration of the salts may result in increases in salinity. The smaller water volume may also lead to increases in temperature. These types of cues trigger plants, algae, bacteria and animals to prepare for another dry period.[20] Those that cannot tolerate dryness leave, burrow down, or die, first replenishing seed or egg banks.

Figure 13. Tadpoles in a Holocene dune swale wetland near Mandurah, in the Peel region, perished when the water level receded before they had developed into adults.

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

The life history of an individual organism at any given wetland can also be explained, in part, by wetland water regime. Individuals are adapted to the specific wetting and drying conditions of that wetland. For example, the life history of a submerged plant living in a wetland that is permanently inundated with water is likely to be very different to that of a submerged plant living in a wetland that only holds water for a few months a year. The plant in the wetland that is permanently inundated can rely on the presence of water all year and can put its energy into growing leaves and stems, and becoming larger. The plant in the wetland that is seasonally inundated has strategies to survive dry periods and reproduces quickly before the wetland dries, leaving seeds that can tolerate drying and will grow when there is water in the wetland once more.

In these ways, the water regime influences the composition of the plants, animals, fungi, algae and bacteria found in a particular wetland, and if significant changes to the water regime occur, a change in species composition is likely to follow. [20] Unfortunately the knowledge of the water requirements of wetland species tends to be incompletely known.[18] Conserving all wetland species necessitates protecting the naturalness and diversity of the water regime of WA's wetlands.

Over time, some wetlands develop sediments that help to maintain the water regimes needed to maintain them. For example, the silica left behind in wetlands which support diatoms (a type of tiny algae with glass-like cell walls made of silica) can slowly build up in the sediment, over hundreds to thousands of years, when diatoms die. This diatomaceous earth has a high water holding capacity, which helps maintain soil wetness. Other wetland sediments, such as highly organic substrates like peat, as well as coffee rock and ironstone also serve this function.

➤ For more information on species water requirements, refer to the topic 'Wetland ecology' in Chapter 2.

Oxygen availability

One of the most fundamental differences between wet and dry environments is the availability of oxygen. Oxygen, which is essential to most forms of life, is available in very low concentrations in water. Despite this, a range of specialised plants, animals, fungi, algae and bacteria adapted to reduced oxygen conditions are able to flourish in inundated or waterlogged conditions. The water columns of permanently inundated wetlands tend to have relatively low oxygen levels, particularly deep lakes and those in which the water column develops layers with distinct physical and chemical properties (stratification). In contrast, intermittently inundated wetlands are dry a lot of the time, only intermittently supporting a water column, which may be present for periods of months to years. How deep a wetland is, and how long it is inundated or waterlogged for, influences how much oxygen is available, which in turn affects which species can inhabit it, from fish (which need about 30 per cent oxygen saturation[21]) and birds to bacteria.

Even in water, plants, algae and some bacteria need oxygen to survive. These life forms are known as primary producers because they create food and energy using sunlight, carbon dioxide and nutrients through the process of **photosynthesis**. Animals need the food and energy sources that primary producers make available. In this way, oxygen levels affect the composition, richness and abundance of life in wetlands, and oxygen levels are affected by wetland water regime.

Oxygen levels also affect the rates of organic matter accumulation in wetlands, as the **decomposition** of **detritus** is most efficient when carried out by **aerobic** (oxygen-dependent) bacteria. The alternative is decomposition by anaerobic bacteria, and it is under these conditions that peat and other organic-rich sediments develop most rapidly. The type of sediment present in turn affects the plants and animals and the water-holding capacity of the wetland.

➤ Refer to the topic 'Wetland ecology' for information on oxygen requirements of wetland species, and adaptations to low oxygen conditions.

Another critical function of oxygen availability is that it significantly affects the chemical characteristics of an environment. In particular, it influences nutrient availability, pH, and toxicity. For example, the availability of oxygen influences the availability of nutrients including nitrogen, phosphorus, iron and sulfur (via pH and redox potential).[19] Over the long term, the habitat and chemistry of intermittently and seasonally inundation/waterlogged wetlands varies much more than that of permanently inundated wetlands (Figure 14).

Significant changes in oxygen availability in a wetland can cause major shifts in the ecological character of a wetland, and this is an important reason to maintain natural water regimes. For example, the drying of wetlands that have been inundated for very long periods of time exposes their sediments to oxygen, which can lead to chemical reactions that result in the development of acid sulfate soils, which can have serious harmful effects to the ecosystem (Figure 15).

➤ For further information on oxygen in wetlands refer to the topic 'Conditions in wetland waters' in Chapter 2.

➤ For additional detail on altered water regimes and acid sulfate soils, see the topic 'Water quality' in Chapter 3.

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

Decomposition: the chemical breakdown of organic material mediated by bacteria and fungi; degradation refers to its physical breakdown.[18] Also known as mineralisation.

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

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

Figure 14. The availability of oxygen has a major influence upon wetland chemistry. In this wetland north of Wiluna, the cracking of clays allows for further diffusion of oxygen into the sediment during the dry phase. Photo – J Dunlop.

Figure 15. Oxygen availability determines many of the chemical properties of a wetland. In Gnangara Lake, drying of sediments that have been saturated over the long term has led to the exposure and oxidation of normally inert pyrite materials, causing harmful acid sulfate soils. Image – Google Earth™.

Light availability

Light availability in wetlands with a water column is quite different to that of drylands, because once sunlight reaches wetland waters it is rapidly altered and reduced, so that both the quality and quantity of light available is quite different to what first reached the surface of the water. This affects which organisms can inhabit wetland water columns. Wetland waters that are deep, heavily shaded, turbid or coloured (such as tannin-stained waters) tend to have reduced light levels compared to other wetlands.

Plants and algae are particularly affected by light availability. All plants and algae need light for photosynthesis and in wetlands with a water column they need to remain within the euphotic zone (also known as the photic zone). Put simply, this is the area of the water column penetrated by light of sufficient intensity and of suitable wavelength to enable photosynthesis by aquatic plants. In deep, permanently inundated wetlands, plants are generally limited to the lake margins; whereas algae that can remain suspended and cyanobacteria that can retain buoyancy in the water column can inhabit a much larger area of the wetland.

➤ For more information on the conditions that influence light levels in wetlands, refer to the topic 'Conditions in wetland waters' in Chapter 2.

➤ For more information on the light requirements of wetland species, see the topic 'Wetland ecology' in Chapter 2.

Salt availability

Water entering and leaving wetlands carries with it a range of materials, including salts. Sources of water, such as rainwater, surface water and groundwater can have very different amounts and types of salts.

Salts are compounds comprised of elements such as sodium, potassium, calcium and magnesium, combined with other elements such as chloride, sulfate and bicarbonate. Australian wetlands tend to be dominated by sodium and chloride, and sometimes bicarbonate, whereas in many other regions of the world calcium and bicarbonate dominate.

The availability and concentration of salt in a wetland helps to shape its ecological character. The type and concentration of salts in a wetland has a very strong bearing on the wetland, and particularly on the life forms which will inhabit it. Wetland species are adapted to particular ranges and types of salts in their environment; some saline wetland species may rely on a high level of salinity to function. Wetland species are physiologically adapted to particular ranges or concentrations of salinity meaning that if these concentrations change too much or too rapidly, this can cause a decline in health and even result in mortality. Salinity also affects water clarity, dissolved oxygen concentration, pH and other chemical equilibria in wetland waters.

In general, rainfall has low concentrations of dissolved materials, such as carbon, salts and nutrients. The water quality and chemical processes of a wetland with a rainfall-dominated water budget will reflect this relatively pure water source.[3,22] However, in WA where much of the rainfall is derived from water evaporated out of the Indian and Southern Oceans, rainfall closer to the coast contains significant amounts of salts derived mainly from ocean spray[23] (Figure 16).

The dominant salts in groundwater are sodium, potassium, calcium, magnesium, chloride, sulfate, bicarbonate and carbonate.[24] These salts come principally from rainfall, concentrated by evaporation and often further modified by soils and weathered rocks as the water percolates through these. The salinity of inflowing and outflowing waterways also affects the salinity of wetlands. Seawater intrusion is another potential source of salts to a wetland.

Figure 16. A wetland close to the coast near Preston Beach in south-west WA. Rainfall loaded with salts (due to the proximity to the ocean) combined with a direct input of seawater from seawater intrusion are a source of salts accumulating over a long period of time, resulting in high level of salts and a pH of around 8. Photo - M Morley/DEC.

The water regime of wetlands can have a significant influence on the concentration of salts. In drying wetlands, such as 'evaporative wetlands', the salinity increases due to a concentration of salts in the decreasing volume of water.[18]

Chemically and biologically diverse conditions arise when predominantly saline wetlands receive freshwater inflows at seepage points, which can create complex habitats within a wetland. Similarly a mosaic of saline and freshwater wetlands provide a complex range of habitats. Eatha Spring, for example, discharges fresh to brackish water on the eastern side of Leeman Lagoon near Leeman in the midwest of WA. In many saline intermittently inundated wetlands, smaller lunette wetlands occur that have a low enough salinity to support tadpoles and other species that would not normally be found in saline lakes.[25] In Lake MacLeod, seawater upwelling is responsible for maintaining saline, permanently inundated areas (described in the case study 'Hydrology of Lake MacLeod' near the end of this topic).

➤ For more information on the salt requirements and thresholds of wetland species, refer to the topics 'Wetland ecology' and 'Conditions in wetland waters' both in Chapter 2.

Nutrient availability

A 'nutrient' is any substance that provides essential nourishment for the maintenance of life'.[26] A whole range of substances are nutrients, but in wetlands nitrogen and phosphorus (with the chemical symbols 'N' and 'P'), are usually the two main nutrients of interest. The type and amount of nutrients available in a wetland influence which living things will inhabit it and how abundant those species will be.

Nutrients are carried into wetlands through rainfall as well as surface and groundwater flows. The export of nutrients from wetlands is also largely controlled by the outflow of water. Groundwater tends to have a higher concentration of most dissolved materials, which are picked up as the water moves across and through soils and rocks and delivered to wetlands. The greater the input of water, the higher the input potential of associated nutrients and carbon external to the wetland, which drive wetland productivity.[19]

Fluxes in water levels affect nutrient concentrations. For example, when water levels fall in an inundated wetland, nutrient concentrations increase. In such conditions, algae populations often flourish as do algae consumers such as water fleas including the *Daphnia* species.

The water regime also has an extremely significant effect on the transformations of nutrients into different chemical forms within a wetland.[19] The availability of nutrients to plants and other primary producers depends on their chemical form. The importance of water regime in this regard is related to associated conditions such as redox potential, oxygen availability and habitat for bacteria that are responsible for mediating most nutrient transformations in wetlands.

➤ For more information on the conditions that influence nutrient levels in wetlands, refer to the topic 'Conditions in wetland waters' in Chapter 2.

Organic carbon availability

All plants, animals and microbes must consume carbon in order to survive and grow. The movement of water can often be a major means of transporting carbon contained within organic material from one location to another. Other than mobile animals, there are two sources of organic carbon in wetlands: carbon generated by photosynthesis within the wetland (autochthonous carbon); and carbon imported into the wetland by wind or water movement, including groundwater transporting leached humic substances and overland flow transporting material such as leaf litter from the surrounding land. In practice, the carbon in most WA wetlands is a combination of both internal and external sources. Much of the export of organic matter from a wetland also occurs through outputs of water. If a wetland experiences a large volume of water moving though it (into and then out of it), it is likely to export organic matter at a higher rate.

➤ For further information on the organic carbon availability in wetland waters refer to the topic 'Conditions in wetland waters' in Chapter 2.

pH (acidity/alkalinity)

The pH of water sources to wetlands influences the pH of wetland waters. Rainwater is naturally slightly acidic (as low as pH 5.5), due to dissolved atmospheric carbon dioxide[18,27], but the pH may be rapidly modified by chemical and biological processes once the water enters the wetland (e.g. carbonate buffering, photosynthesis). In wetlands with little biological activity and few reactive minerals, the pH may remain mildly acidic.

The pH of inflowing surface water can be influenced by the characteristics of the catchment. For example, wetlands that receive surface water from granite-dominated catchments may be acidic.[18]

The natural pH of groundwaters in Western Australia is poorly known, due partly to a lack of data, and partly to high variability between sites. However, inflow of highly acidic or alkaline groundwater would have a major influence on the pH of wetland waters. Groundwater discharging from coastal dunes tends to be alkaline due to the carbonate minerals within the aquifer sediments, so wetlands that receive this groundwater are often alkaline. Groundwater in the valley floors of the Goldfields, eastern, central and southern Wheatbelt is thought to be naturally acidic (pH less than 4) and has resulted in the formation of naturally acidic wetlands.[28,29] Rising groundwater due to the clearing of Wheatbelt landscapes has resulted in increased discharge of this water to waterways and wetlands, resulting in the acidification of wetlands in some inland areas.[30]

Wetlands can also be acidified by acid sulfate soils.[31] These soils contain acidity stored as sulfide minerals in permanently waterlogged sediments that, if exposed to the air by falling water levels, can result in generation of strongly acidic soils and waters.[31,32,33]

Acid sulfate soils generally occur in coastal regions of WA in association with estuaries and groundwater systems in sand dunes. Wetlands in southern WA have been acidified by lowering of groundwater levels by decreased rainfall, pumping of groundwater and increased interception of rainfall by land uses such as plantations. Fires after drying can rapidly accelerate the release of acidify from these soils.

➤ For further information on pH of wetland waters refer to the topic 'Conditions in wetland waters' in Chapter 2.

The pH of groundwater can be determined by installing groundwater bores but the origin of the acidity may require further investigation of subsoil geology and historical events such as fires and drought.

extra information

Creating fluxes in the availability of materials

Wetlands that wet and dry tend to have more variation in water chemistry than permanently inundated wetlands. Extreme fluctuations in water chemistry can occur soon after wetting due to the first flush of dissolved material and release of chemicals from the sediment, and just before the water dries completely, due to concentration by evaporation and the reduction in water volume.[18] Changes in water quality during drying and wetting depend on:

1. sediment properties (sediment composition and structure, nutrient and organic content)
2. type of drawdown (gravity or evaporative)
3. extent and timing of drawdown (proportion of drying area, rate of drying, temperature, weathering, timing of drying
4. conditions on rewetting (origin of water, degree of sediment disruption).[18,34]

WHAT DETERMINES A WETLAND'S NATURAL HYDROLOGICAL CHARACTERISTICS?

Climate is the most important determinant of a wetland's hydrology, and it interacts with the landscape to determine where wetlands form and their hydrological characteristics.

The climate determines the incoming and outgoing water in natural landscapes, driving water gains due to rainfall and water losses due to evaporation and transpiration. How the water reaches, moves within, and leaves a wetland is influenced by the landscape which the wetland is part of, as well as the landform of the wetland. Figure 17 shows how climate and landscape shape the natural hydrological characteristics of a basin wetland situated low in the landscape, receiving both surface water and groundwater.

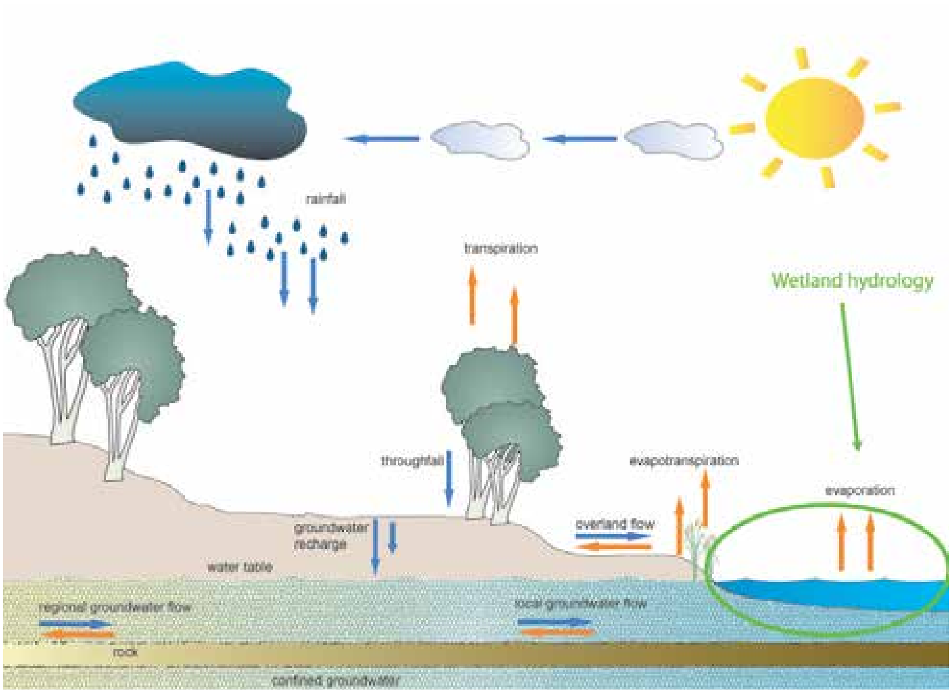

Figure 17. Aspects of wetland hydrology.

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

Transpiration: the process by which water (in the form of water vapour) is lost to the atmosphere by plants across the surfaces of leaves (through small openings called stomata). Transpiration drives the movement of water from the roots to the leaves and is the primary process by which water is lost from subsurface soils to the atmosphere

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

Climate

Climate has a primary influence on the development and characteristics of wetlands, through its effects on the availability of water.

A wetland's hydrological characteristics reflect the balance between gains of water from rainfall, run-off or groundwater inflows and losses of water via **evaporation**, **transpiration**, run-off and groundwater outflows, as shown in Figure 17. Collectively, these are known as components of the water balance. Climate determines the main driving components of wetland water balance—rainfall, evaporation and transpiration—and determines factors such as patterns of recharge to groundwater systems and therefore variation in groundwater discharge and run-off from catchments.

Rainfall provides a direct input of water to wetlands. It is also the source of surface water flows (such as waterways and other, non-channelised overland flow) that may enter wetlands, as well as groundwater that may enter wetlands. The processes of evaporation and transpiration (collectively '**evapotranspiration**') cause the loss of water from the land to the atmosphere. Temperature, wind and vegetation influence these processes.

When rain falls on vegetation, it has two possible fates:

- throughfall – which occurs when rain passes through the vegetation to the surface below
- interception – which occurs when rain is captured on the surfaces of the vegetation (foliage, stems, branches).

The amount of rainfall that is intercepted by the vegetation is dependent on a number of factors including the total amount of rainfall, the intensity of the rainfall and the characteristics of the vegetation (such as the type of vegetation and the strata (or levels)).[19] Rain that is intercepted by vegetation often evaporates to the atmosphere. Some water that reaches the ground infiltrates the soil, may be taken up by roots and returned to the atmosphere through evapotranspiration.[35] In these ways, vegetation can have a substantial effect on the natural hydrologic balance of a catchment.

Evapotranspiration is an important component of the hydrological balance across Australia, because almost 90 per cent of precipitation (rainfall, snow and hail) is returned to the atmosphere by this process.[36] The extent and rates of evaporative losses are highly variable according to season and latitude. Rates of transpiration and evaporative losses to the atmosphere vary greatly with different physical parameters including wind velocity, humidity, and temperature. Generally, evaporation and transpiration are enhanced by increased temperature and wind speed and lower humidity. The rate of transpiration may also affected by the structural and metabolic characteristics of the vegetation.[37]

Wetlands are more common in cool or wet climates than in hot or dry climates, because in cool climates less water is lost from the land via evapotranspiration and wet climates have excess rainfall (rainfall that exceeds evaporative losses[19]). Most of WA is dry and hot for at least part of the year. Rainfall ranges from more than 1,000 millimetres, with low variability, in the extreme south-west and northern areas to less than 250 millimetres per year, with high variability, over most of the interior (Figure 18). Temperatures can be very high (Figure 19) and evaporation rates reflect this, ranging from around 1,200 millimetres per year on the south west coast to over 4,000 millimetres per year in the Pilbara and exceeding average annual rainfall over most of the state. However, at times, rainfall rates exceed infiltration and evaporation, to generate surface run-off, which is a critically important source of water in wetlands as well as other ecosystems including waterways.

WA has three main climate regimes. In the south-west of WA, the regime is described as Mediterranean, with warm to hot dry summers and cool wetter winters. Many wetlands are wet in winter and spring, and dry during summer and autumn. However, major summer storm events can generate very high daily rainfall events.

In contrast, the north of the state is monsoonal with hot and wet summers known as the ‘wet season’ and warm dry winters known as the ‘dry season’. Many wetlands fill during the wet season from October to April and dry out through the dry season.

The rest of the state is characterised by hot dry summers and cool to warm dry winters. Wetlands are relatively less common in the central areas of the state, which are characterised by low rainfall, high temperatures and the highest evaporation rates. In the arid interior, rainfall and surface water flows can be highly unpredictable, and may not occur within the same season in consecutive years. Rainfall in these areas is highly variable and falls on very few days. However, when it does rain, large amounts can fall in a single event causing widespread flooding. For example, in February 1995, very heavy rainfall from a weakened Tropical Cyclone Bobby fell over the Goldfields region. Surface run-off inundated Lake Boondaroo to a depth of 12 metres, with water persisting for several years (Jim Lane pers comm).

Events such as cyclones, major floods and droughts play a major role in the determination of water regimes in some areas, particularly in the north-west and interior of the state, resulting in many wetlands in these areas have highly variable hydrology from year to year.

> *"When Europeans arrived in Australia… they called the dry times 'drought' and the wet times 'flood' and the times of perfect pasture growth 'normal'. The extremes were regarded as aberrations of the 'normal' conditions. However, as records show, extremes of wet and dry are not abnormal – they are part of the natural pattern."*
> – Brock *et al*. (2000).[20]

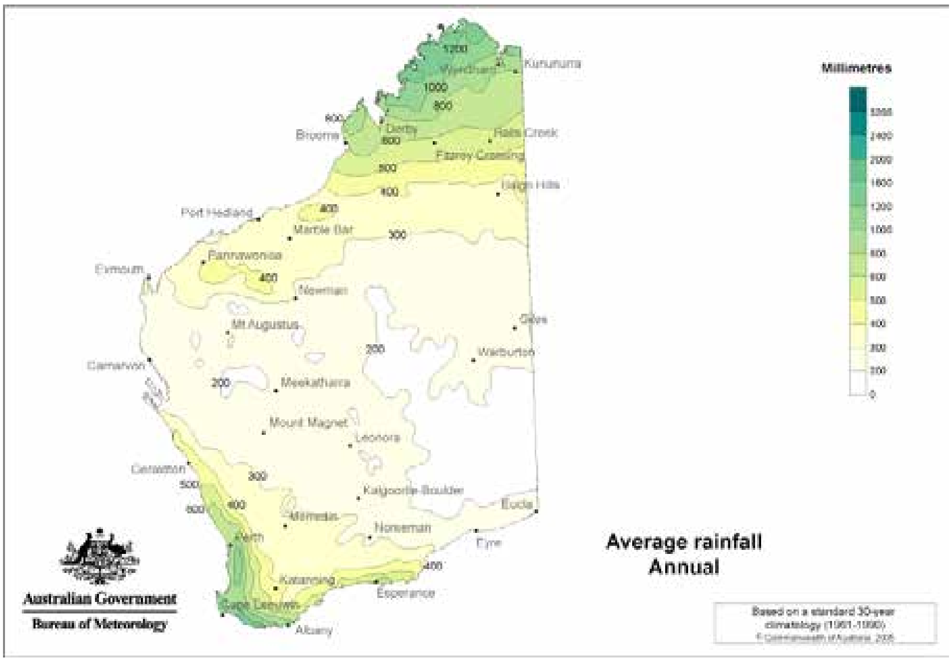

Figure 18. Average annual rainfall for Western Australia. Courtesy Bureau of Meteorology.

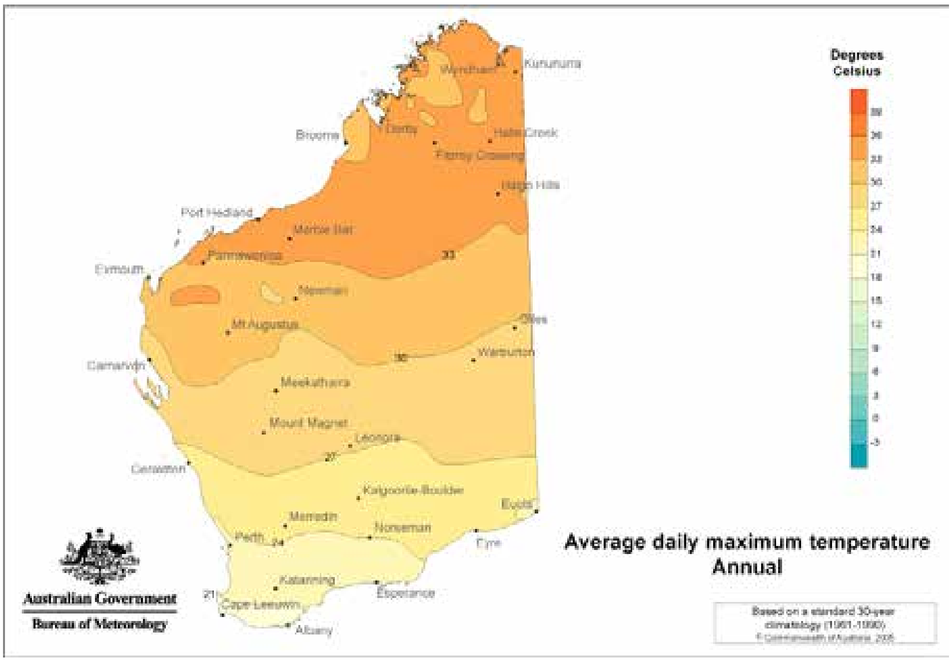

Figure 19. Average annual daily maximum temperature for Western Australia. Based on a standard 30-year climatology (1961–1990). Image - courtesy Bureau of Meteorology.

➤ The Bureau of Meteorology provides an extensive range of information and data about Western Australia's climate and weather: www.bom.gov.au

Water in the landscape - surface water and groundwater

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.

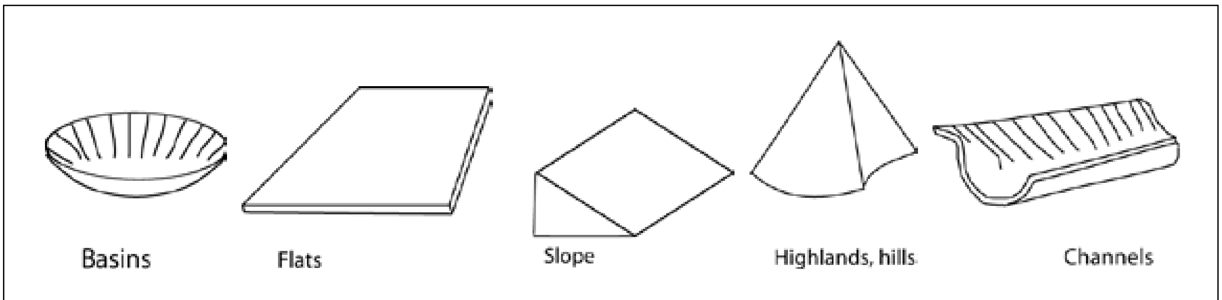

Figure 24. Landforms that become host to wetlands (basins, flats, slopes and highlands) and waterways (channels). Other wetlands, such as mound springs, are self emergent rather than developing in a host landform. Source: adapted from Hill et al. 1996.[5]

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').

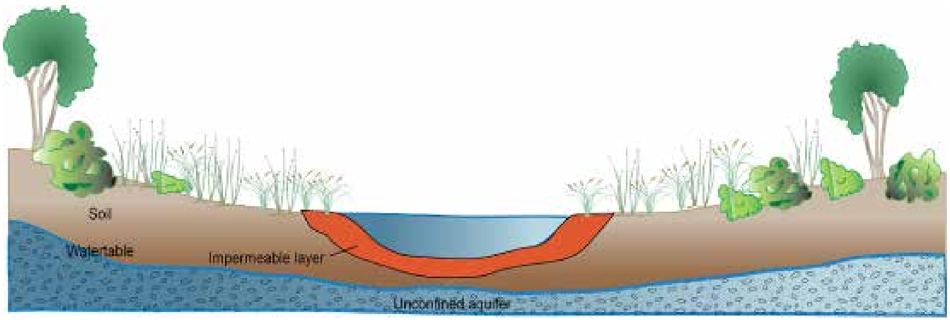

Figure 25. A perched wetland, which receives water from rainfall and overland flow. In this case, although there is groundwater in the vicinity of the base of the wetland, the thick impermeable sediment layer is a barrier between the wetland and the groundwater.

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).

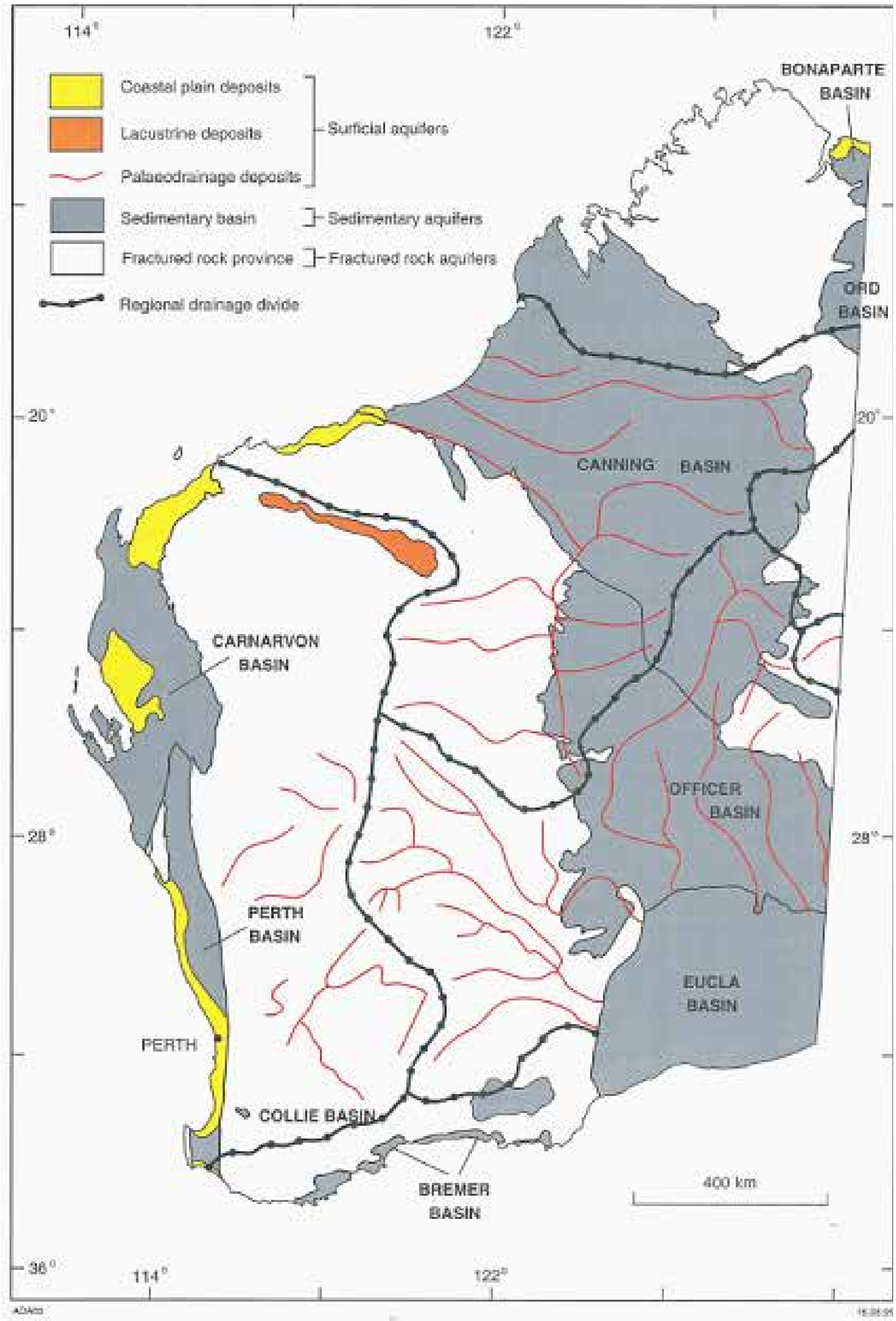

Figure 30. The general location of WA's surficial, sedimentary and fractured rock aquifers. Image – Allen (1997).[43]

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

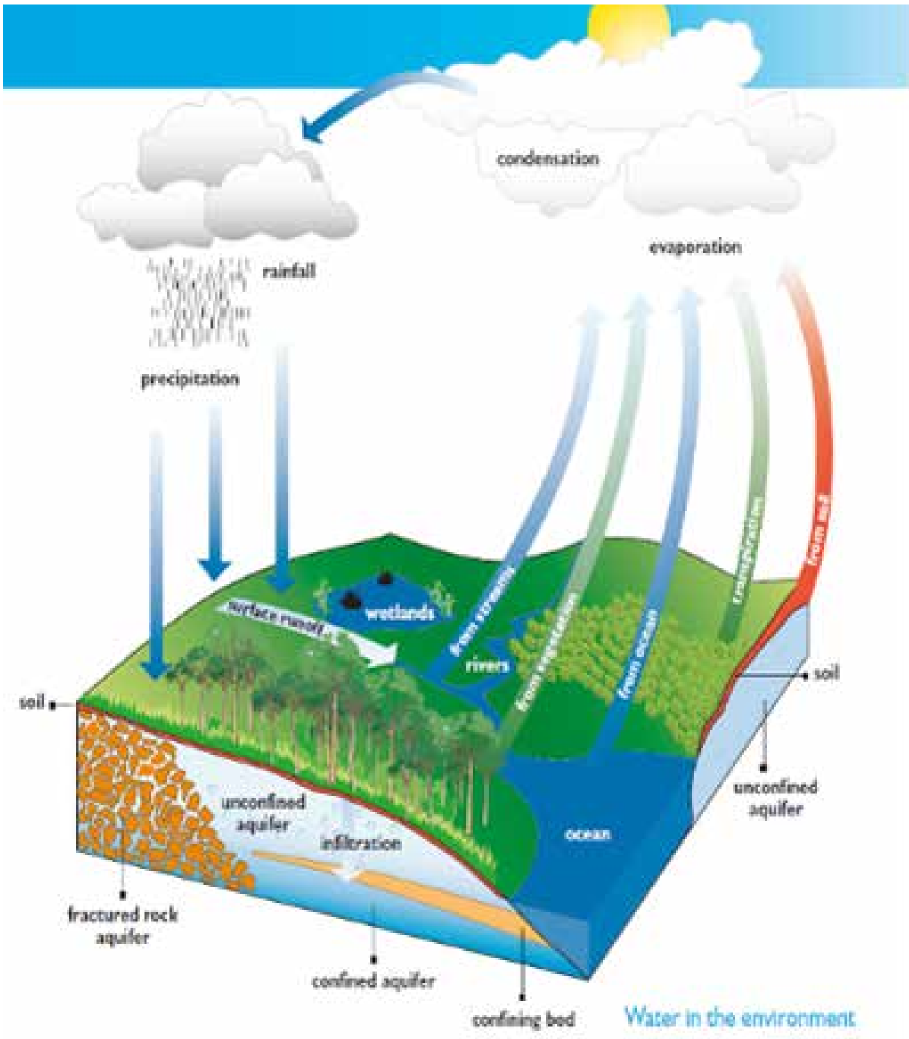

Figure 31. Confined and unconfined aquifers. Diagram – courtesy of Department of Water.[44]

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]).

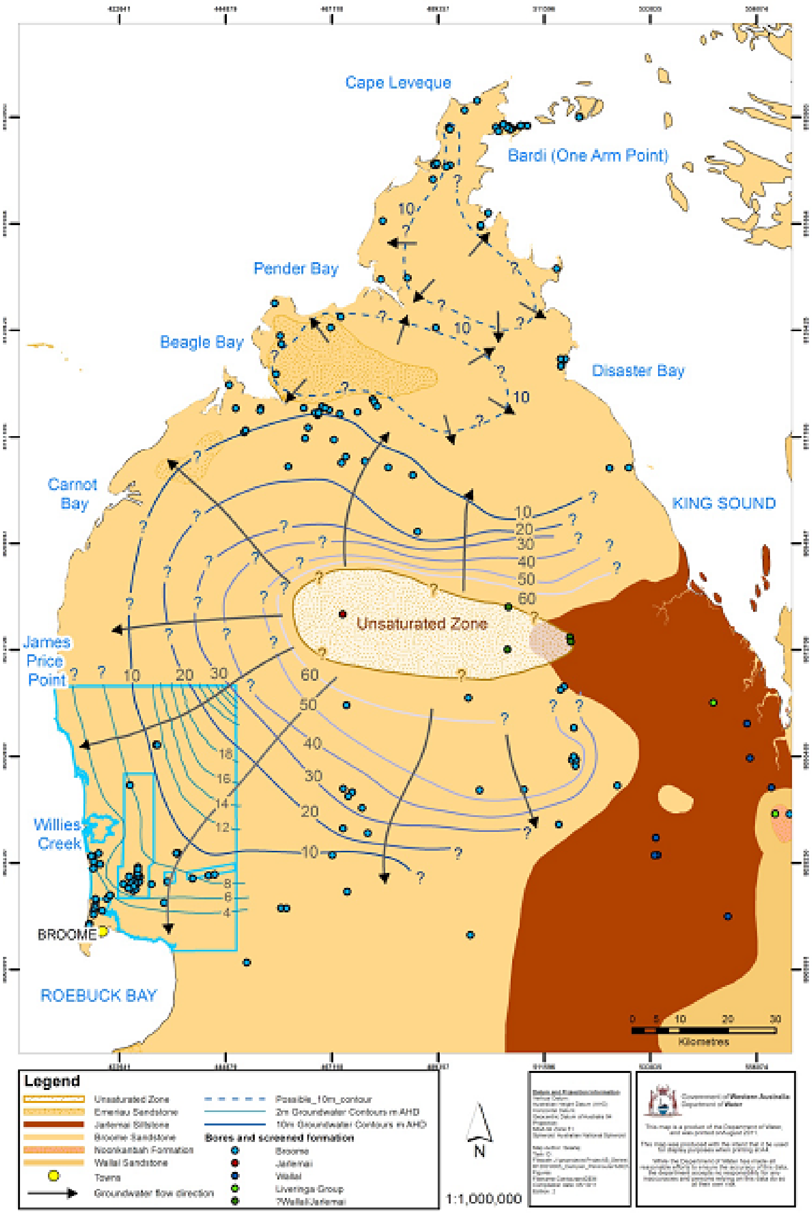

Figure 32. A map of the Broome area, showing multiple aquifers, inferred regional groundwater contours and groundwater flow direction. The circle in the centre represents the top of the mound, and the arrows indicate the inferred direction of groundwater flow. Source – courtesy of the Department of Water.[48]

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.

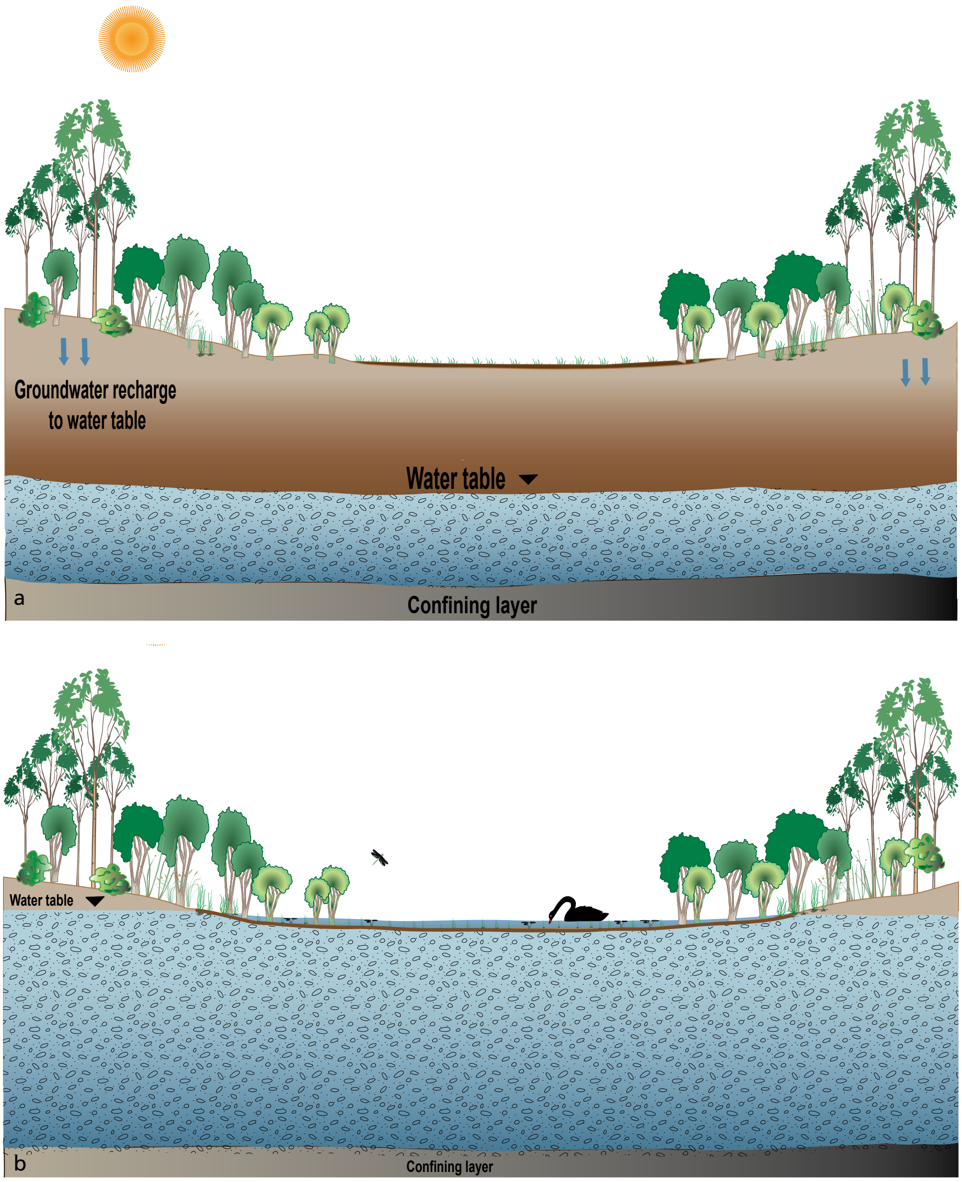

Figure 33. A simplified diagram of groundwater flux; (a) when the water table is far below the wetland, the wetland is disconnected from the groundwater; (b) when the water table is as high as the base of a wetland, water may flow into the wetland. Such wetlands are often said to be 'groundwater fed'.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

Paluslope: a seasonally waterlogged slope 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]

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]

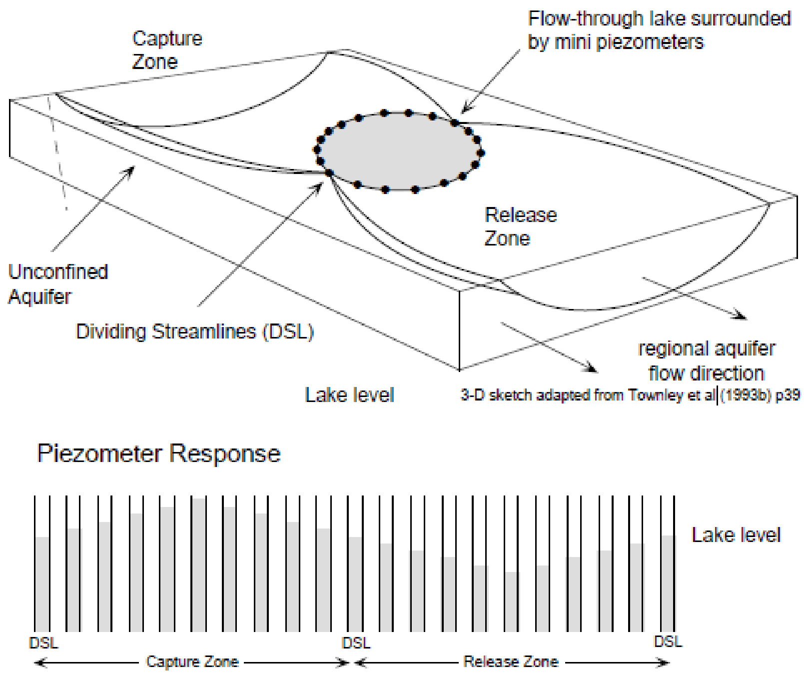

Figure 34. A schematic diagram showing the local capture and release zone of a flow-through wetland relative to the regional groundwater flow. Image - Integrated Mass, Solute, Isotopic & Thermal Balances of a Coastal Wetland: Wetland Research at Perry Lakes, Western Australia 1993-1998[52]

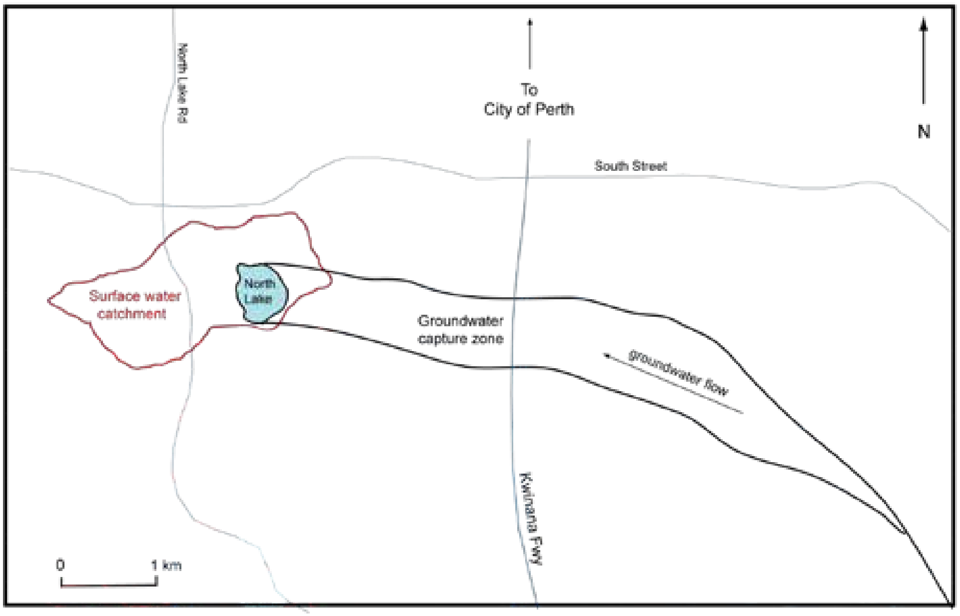

Figure 35. Schematic view of a wetland natural (prior to human modification) surface water catchment and groundwater capture zone, based on North Lake in Perth's southern suburbs.

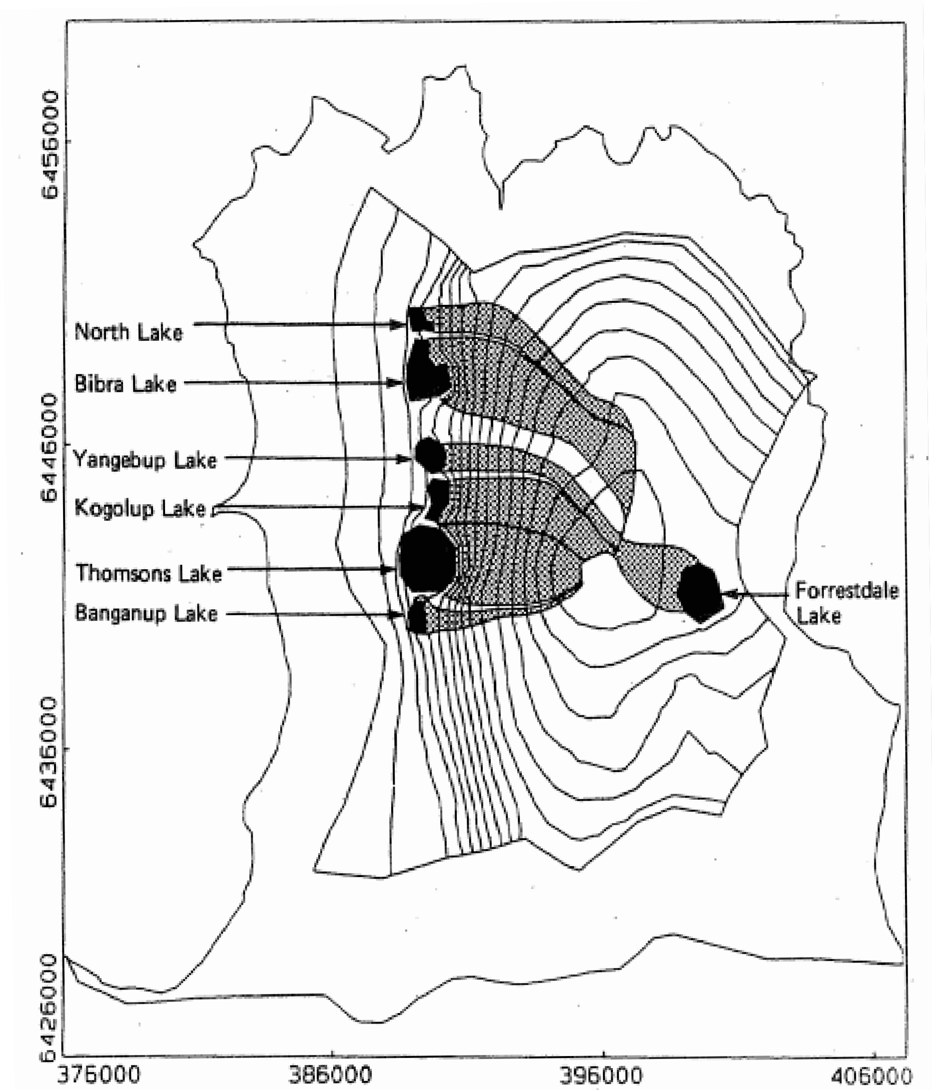

Figure 36. Predicted capture zones for seven lakes on the Jandakot Mound. Source – Townley et al.[52]

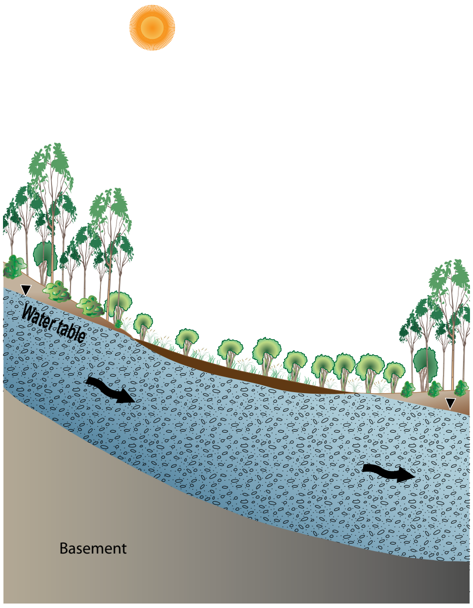

Figure 37. Wetlands can form on slopes, by seepages at the break of slope.

Figure 38. A paluslope in the south-west of WA. Photo – Wetlands Section/DEC.

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

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).

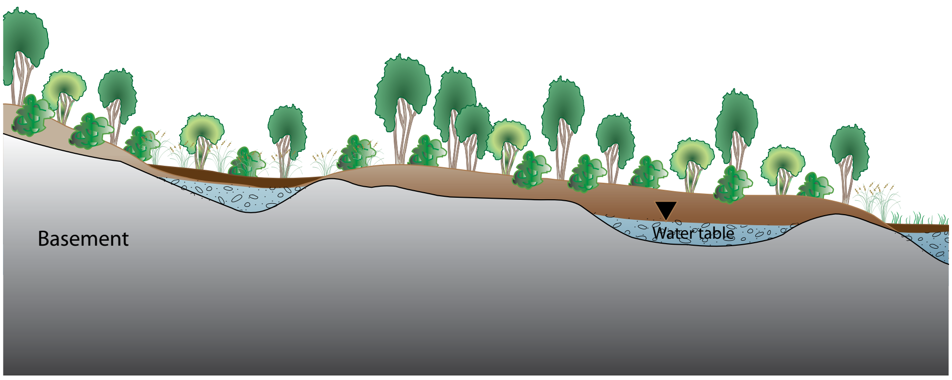

Figure 39. Bedrock highs trap water and force it to the surface, creating wetlands.

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.

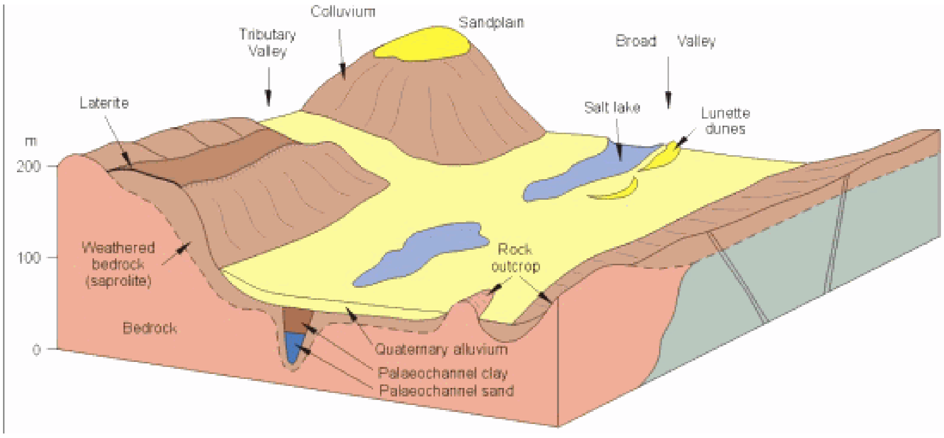

Figure 40. A stylised depiction of Wheatbelt valley geology including a palaeochannel. Image - Commander (2001).[54]

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.

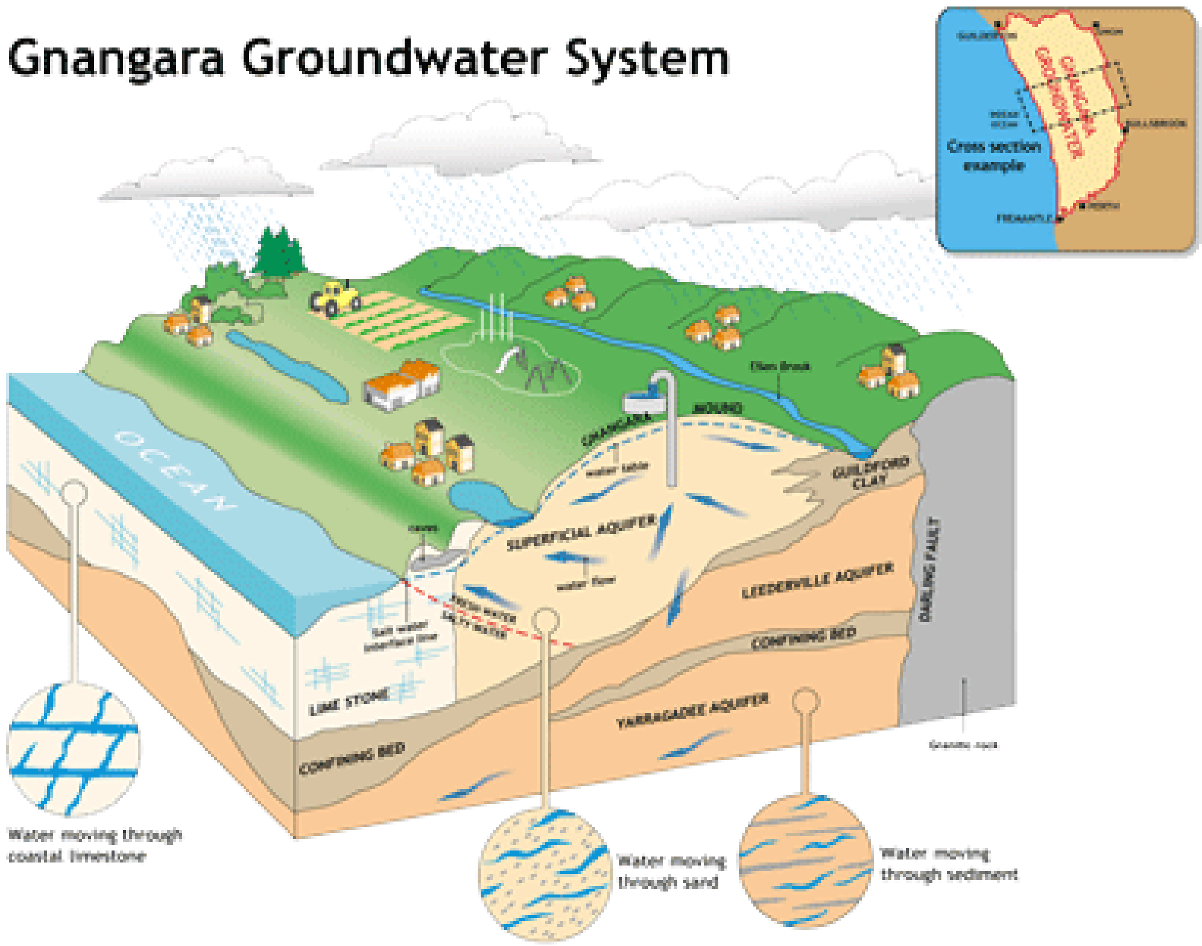

Figure 42. The Gnangara groundwater system in plan view. Image – courtesy of the Department of Water.

extra information

The Gnangara groundwater system (cont'd)

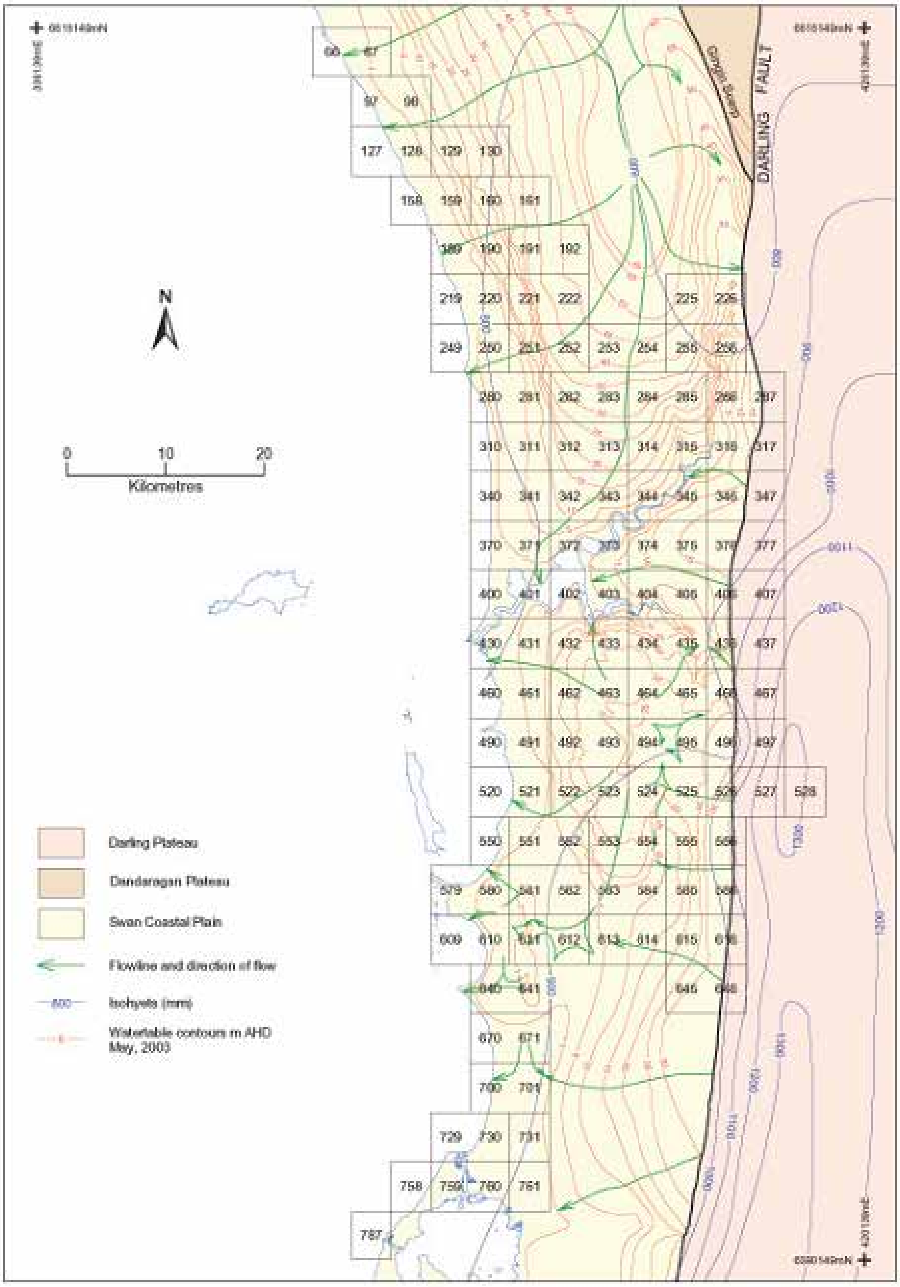

Figure 43. A map of the Gnangara (northern) and Jandakot (southern) groundwater mounds. Source – courtesy of the Department of Water.[56]

- 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

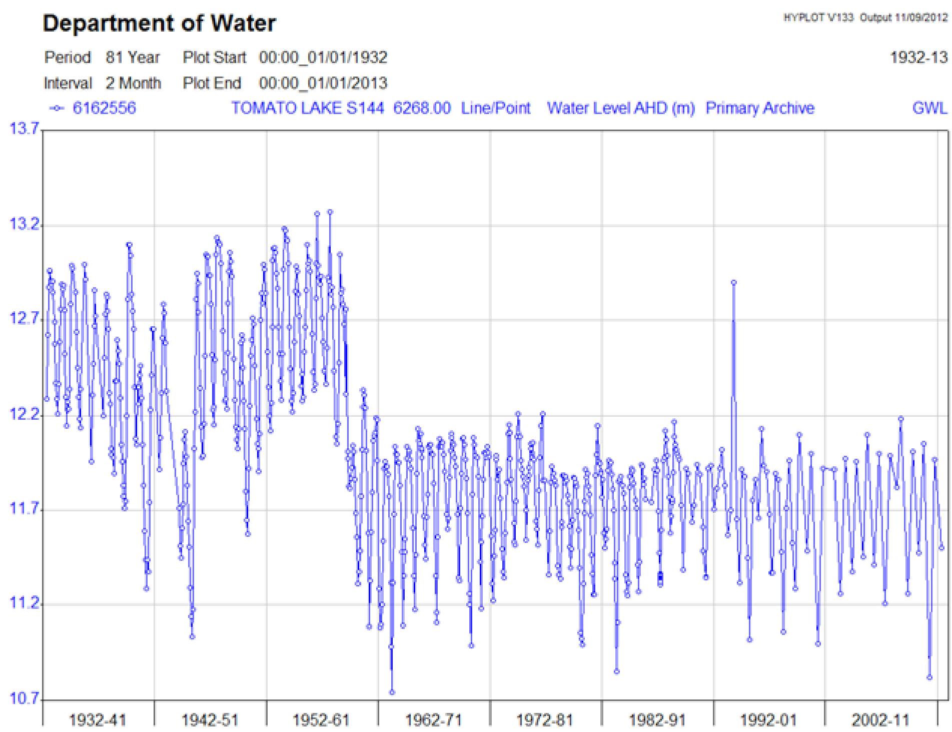

Figure 45. Groundwater measurements can be plotted in the form of hydrographs to show trends over time. Image – courtesy of Department of Water.[58]

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]

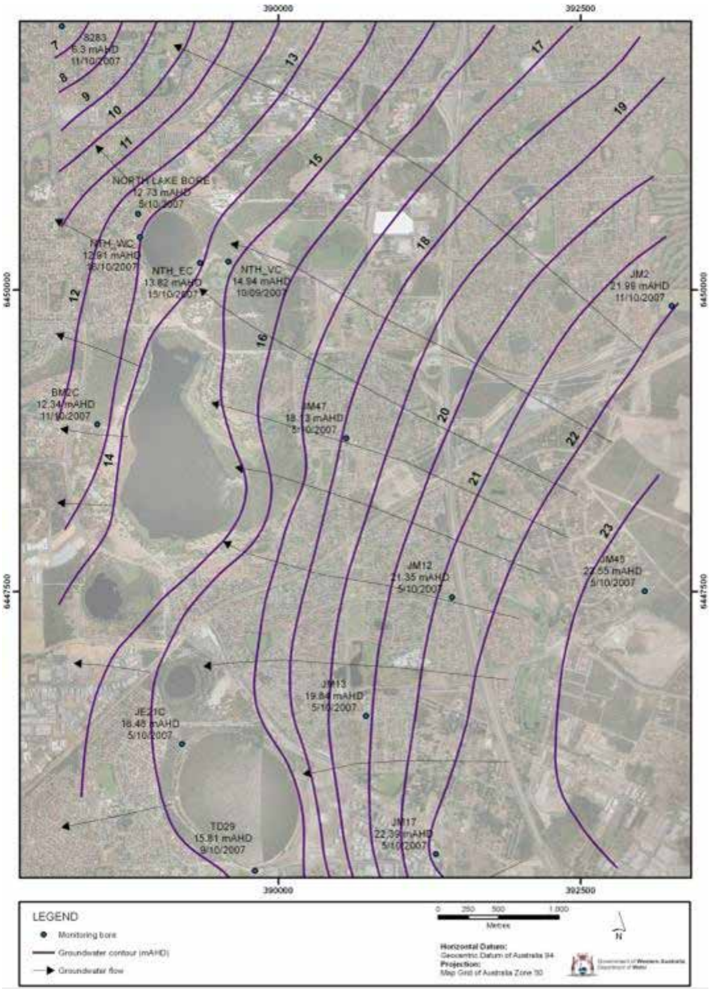

Figure 46. Mapping of the height of groundwater (contours) in the southern Perth area. The arrows indicate the direction of groundwater flow. Image – courtesy of Department of Water.

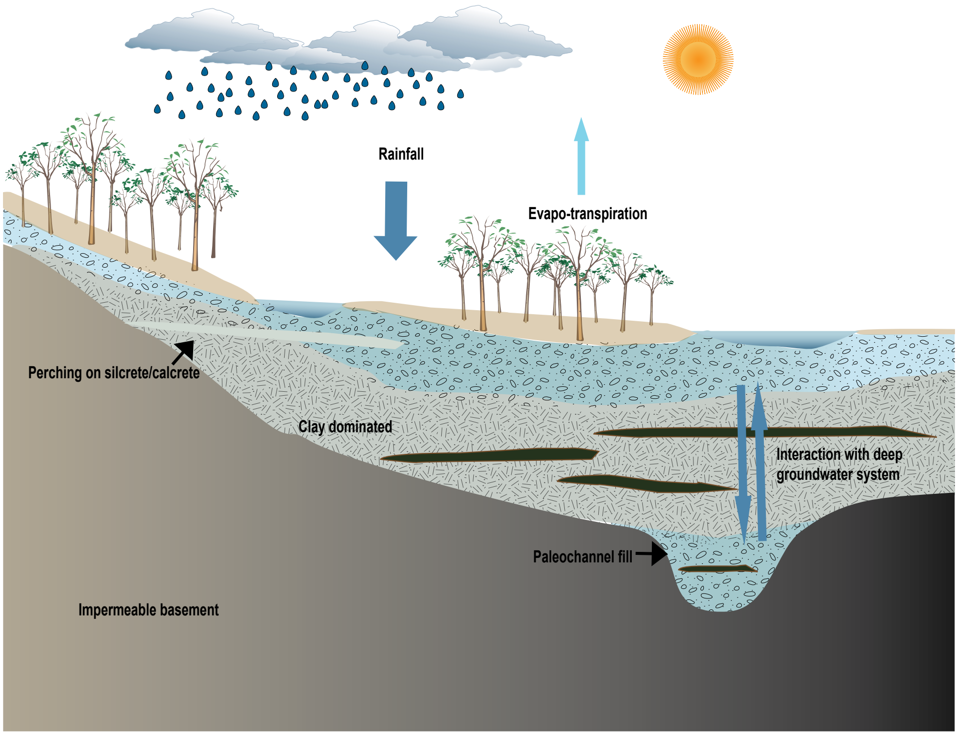

Figure 47. Complex below-ground layering can lead to complex groundwater conditions.

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]

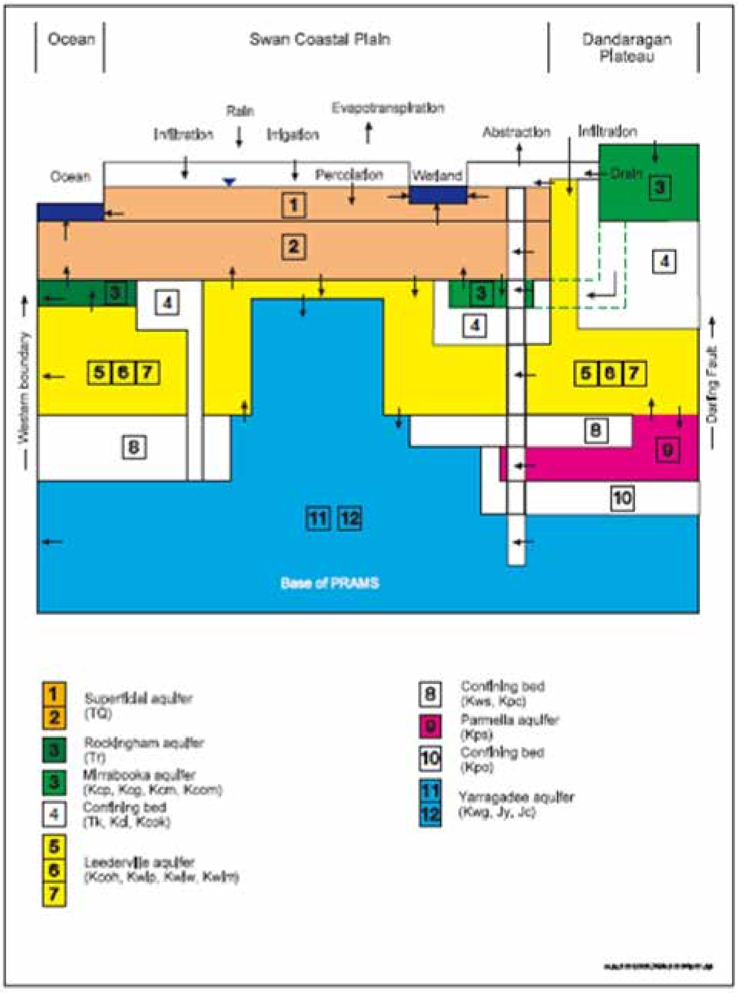

Figure 48. A conceptual hydrogeological model of the Perth groundwater system. Source – Department of Water. [62]

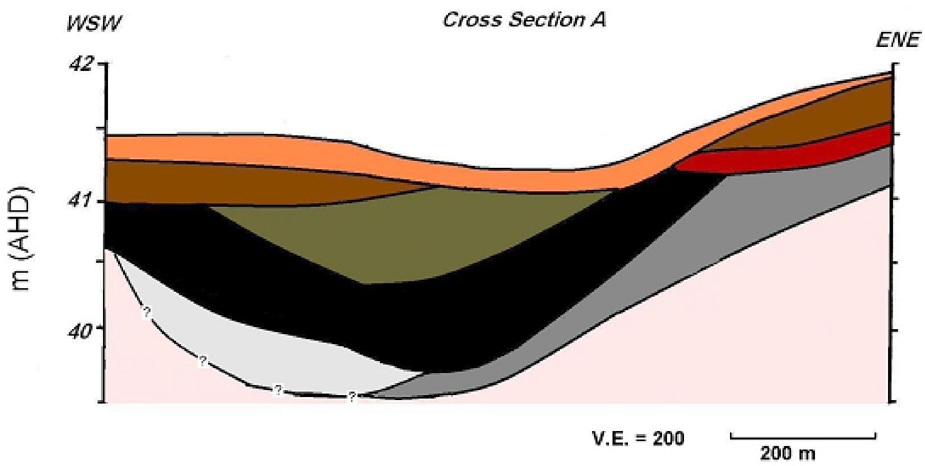

Figure 49. Many wetland sediments are not uniform across a wetland, such as those of Lake Mariginiup, represented here in cross-section. Image – Department of Water.[63]

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.

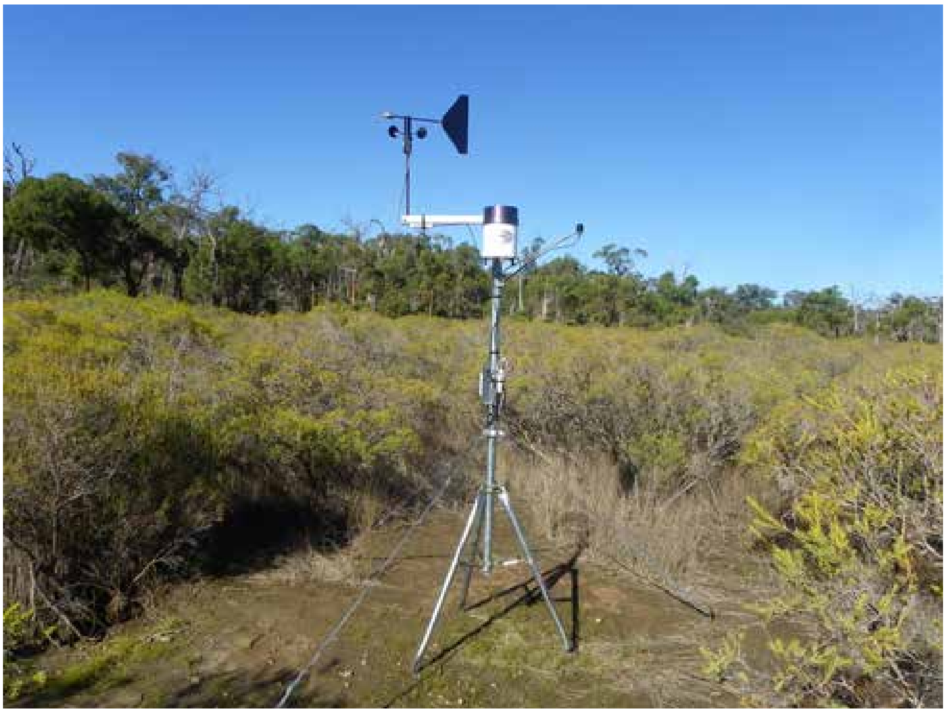

Figure 50. Understanding of the hydrology of a claypan in Drummond Nature Reserve, in the Northern Jarrah Forest region, is being aided by detailed field measurements. Photo – J Lawn/ DEC.

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.

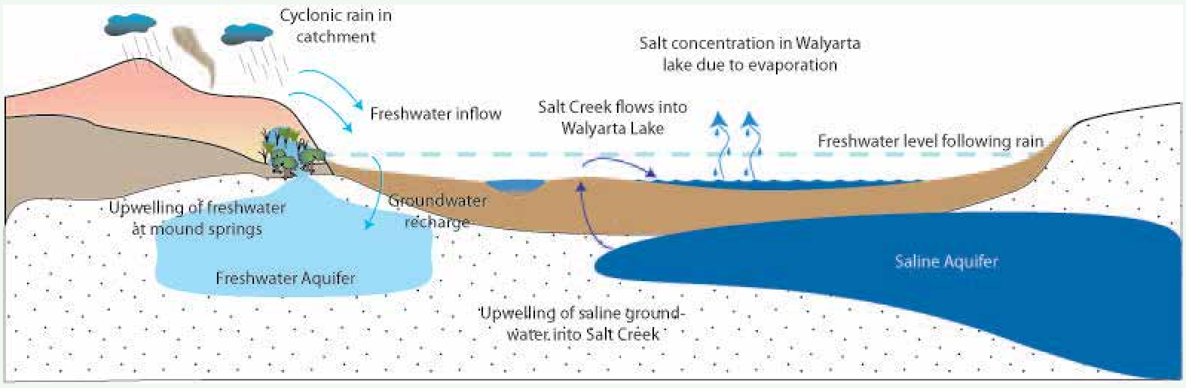

Figure 53. A conceptual model of the water inputs and outputs to Mandora Marsh.[69]

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.

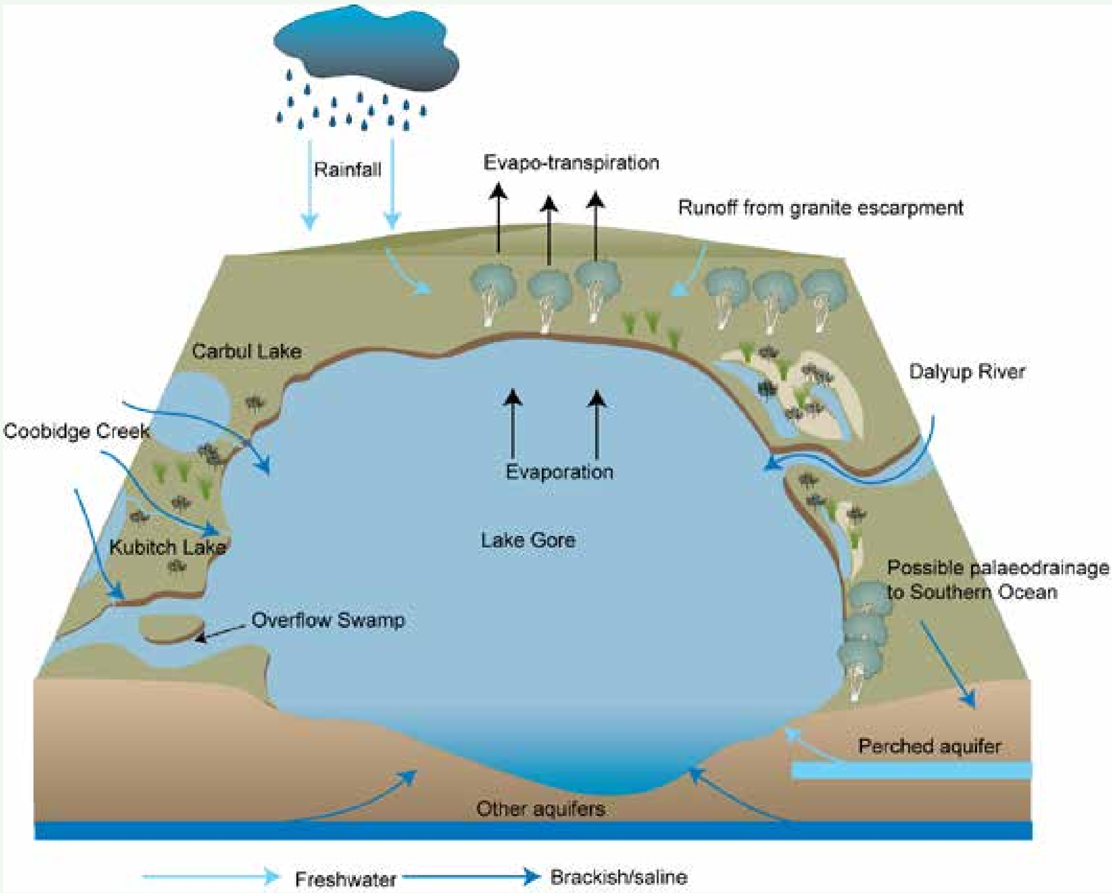

Figure 56. A conceptual model of inputs and outputs of Lake Gore. Image - Watkins (2008).[70]

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

Name	Date	Position	Organisation
Jim Lane		Principal Research Scientist	Department of Environment and Conservation

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