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NCCARF National Climate Change Adaptation Research Facility, Adaptation Research Network SETTLEMENTS AND INFRASTRUCTURE

Coastal Groundwater

and Climate Change

D J Anderson

WRL Technical Report 2017/04

Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

Groundwater and Climate Change

WRL Technical Report 2017/04

May 2017

by
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A technical monograph prepared for the
National Climate Change Adaptation Research Facility
'CoastAdapt' Programme

Project Details

Report Title	Coastal Groundwater and Climate Change
Report Author(s)	D J Anderson
Report No.	2017/04
Report Status	Final
Date of Issue	30/05/2017
WRL Project No.	2017003.01
Client Name	National Climate Change Adaptation Research Facility (NCCARF)
Client Address	Griffith University Gold Coast Qld 4222 Australia
Client Contact	Dr David Rissik

Document Status

Version	Reviewed By	Approved By	Date Issued
Draft	NCCARF Reviewer	G P Smith	03/03/2017
Final	W C Glamore, G C Rau	G P Smith	30/05/2017

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This document has been prepared by the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Australia for the National Climate Change Adaptation Research Facility (NCCARF) 'CoastAdapt' Programme. The material presented in this document updates and expands upon the introductory groundwater materials presented by Dr Ian Turner of WRL in the Saltwater Wetlands Rehabilitation Manual (Department of Environment and Climate Change NSW 2008). The document is designed to support stakeholders in understanding the influence of climate change on coastal groundwater.

This document should be cited as:
Anderson, D.J., 2017: Coastal Groundwater and Climate Change, WRL Technical Report 2017/04. A technical monograph prepared for the National Climate Change Adaptation Research Facility. Water Research Laboratory of the School of Civil and Environmental Engineering, UNSW, Sydney.

Acknowledgement:
This work was carried out with financial support from the Australian Government (Department of the Environment and Energy).

Preamble

Some 85% of Australia's population live within 50km of the coastline (ABS 2004) to exploit its natural assets. In 2005, Blackwell (2007) estimated that Australia's coastal zone generates upwards of $1,359 billion annually in ecosystem goods and services. With predictions of significant changes to the coastal zone from climate change and sea-level rise (Anon 2014) this is cause for concern and a prompt for timely action.

A sea-level rise of just one metre would put approximately 30,000 km of roads and $226 billion of infrastructure at direct risk from inundation (Department of Climate Change 2009). It would also put some 21,000 - 55,000 km^2 of valuable coastal land at risk from intrusion of saline groundwater (Ivkovic et al. 2012).

Groundwater is water that flows through the sediments and rocks beneath our feet. The study of groundwater is called hydrogeology and it is a complex discipline. Groundwater is hard to see, expensive to measure and, due to complexity and spatial variability in geology, difficult to understand and challenging to simulate.

Groundwater has many beneficial values including town and domestic water supply, irrigation of crops and pastures, ecological services, industrial usage, even as a fluid for heating and cooling. Groundwater can also be a nuisance. It can be salty, acidic, contaminated and sometimes too close to ground surface. It is subject to change associated with climate and land use.

To the best of our knowledge, estimates of the economic value of coastal groundwater in Australia are yet to be reported or compiled to support an economic assessment of the impacts of climate change on coastal groundwater resources. However, we do know more generally that groundwater in Australia is estimated to support approximately $34 billion in annual economic production and contribute directly to generating $6.7 billion of Gross Domestic Product (Deloitte Access Economics 2013).

This document provides a basic introduction to groundwater followed by a brief discussion of the possible range of groundwater related climate change impacts on coastal environs. While there is a distinct focus on such systems and impacts to them, where possible, these are discussed in general terms to make this report more relevant to readers from inland Australia.

This report seeks to educate stakeholders on potential future groundwater and climate change influences on the Australian landscape. A secondary objective is to stimulate debate regarding the groundwater impacts of climate change. A third objective is to encourage more timely, multidisciplinary investment in studies to better predict groundwater climate change impacts and to prepare methodology documents to assist stakeholders prepare and deliver considered, cost-effective and holistic climate-change adaptation strategies to Australian communities.

There are two overarching messages from this report, the first is to recognise the concept of 'feedback'; that the interactions between groundwater, hydrology, oceanography, ecology and human health are bidirectional and complex. The second is, since natural and anthropogenic systems influence groundwater and vice versa, there is a pressing need for multidisciplinary guidance in the Australian climate change and groundwater adaptation space.

Given the interlinked nature of groundwater systems, we encourage you to read this report on groundwater and climate change not in isolation but with consideration to all of the climate change impact sheets in the 'CoastAdapt' series listed below:

1. Beaches and estuary sediments (Hughes 2017)
2. **Settlements and infrastructure** (Ware 2017)
3. Emergency management (Jago 2017)
4. Freshwater ecosystems and biodiversity (Capon 2017)
5. **Human health** (Bambrick 2017)
6. Coastal tourism (Becken 2017)
7. **Fisheries and aquaculture** (Pearson and Connolly 2017)
8. **Ecosystems** (Paice and Chambers 2017)
9. Vulnerable communities (Hanson-Easy and Hansen 2017)
10. **Contaminated land** (Morton 2017)
11. **Coastal agriculture** (Williams 2017)
12. **Water supply and waste water management** (Ware 2017)
13. Communities (Smith 2017)
14. **Estuaries** (Glamore et al. 2016)

Those titles (systems) shown in bold above are systems that interact directly with groundwater. Development of effective groundwater management strategies for climate change will require a detailed understanding of the state of the science for all these disciplines and multidisciplinary collaboration.

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1. Introduction

Reports by the Intergovernmental Panel on Climate Change (IPCC) suggest that there will be rapid and extensive changes to global ecosystems with unknown consequences for human populations (e.g. Houghton et al. 2001). Within Australia, there is evidence to suggest that the Australian public, their coastal settlements, groundwater-supported ecosystems and groundwater users (farmers, factories and mines) will be significantly influenced by, and need to adapt to, natural and anthropogenic (human-induced) climate change.

Climate change is projected to result in higher, and more extreme, temperatures, more extreme weather events and sea-level rise. Some of the direct impacts of climate change in coastal zones are expected to include more hazardous storm surges, flood inundation, increased erosion and increased seasonality in groundwater recharge. This will have direct impacts on groundwater including rising groundwater levels, saline intrusion and enhanced mobilisation of contamination.

To provide introductory context to the social, human and economic challenges and disruption that sea-level rise may cause, the history of some early Australian coastal settlements provide good analogies. This includes the port city of Newcastle where, during the late 1800s, the export of coal and agricultural produce encouraged international imports and a booming economy.

At that time the majority of the settlements around the Port of Newcastle were situated within or below 1.2 m of mean sea level. This is a similar elevation to where many current Australian coastal settlements might find themselves in another 100 years. For these early settlers, being situated within 1.2 m of mean sea level meant that their homes and businesses were frequently inundated by high tides, storm surges and above average rainfall conditions. Newspaper reports from the period highlight considerable annoyance and social disruption extending from flooded roads and deep boggy soils to rising damp, bad smells, illness and disease.

In Newcastle, these issues were ultimately overcome by a costly capital works programs to raise the land surface of Carrington (then Bullock Island), Islington, Wickham and Civic by up to four feet (1.2 m). This was achieved over a period of approximately 80 years by the work of at least three dredges (the Juno, the Jupiter and the Castor) taking sand from the Hunter River. The reclamation work also included the opportunistic dumping of ballast reject from international shipping and the emplacement of slag and coal wash rejects from the Newcastle Steel Works.

Based on the available historical records it is likely that some 3 million cubic metres of fill was won to reclaim the port of Newcastle and the immediately surrounding suburbs. Assuming that sand dredging projects now cost some $30 per cubic metre, and excluding the costs of the land re-possession that took place, that is equivalent to some $90 million in today's dollars.

These historical experiences provide quite some insight into the nuisances associated with low-lying coastal land and the costs to protect just one settlement from tides, waves and storm surges. However, it does little to inform us of the risks and costs of climate change and sea-level rise on groundwater at a national scale.

Ivkovic et al. (2012) estimates that sea-level rise places 21,000 - 55,000 km^2 of valuable coastal land at risk from intrusion of saline groundwater and the Department of Climate Change (2009) estimates that a sea level-rise of just one metre places some 30,000 km of roads and $226 billion of infrastructure at direct risk from inundation. To help manage these assets under a changing climate, this report introduces basic groundwater concepts and describes how climate change may impact groundwater in the coastal zone.

1.1 Structure of this report

This report is structured into chapters as follows:

1. Introduction
2. Groundwater
3. Climate change
4. Summary
5. Further reading
6. References.

Chapter 2 of this report is dedicated to introducing basic groundwater concepts. This includes:

- the key components of groundwater systems
- the influence of tides, waves and salinity on groundwater movement
- surface water groundwater interactions in the coastal zone
- groundwater contamination
- coastal zone contaminant pathways
- the social, environmental and economic value of groundwater.

Readers familiar with these groundwater concepts may skip directly to Chapter 3 for a discussion of climate change observations and predictions, potential groundwater impacts and an overview of groundwater management options.

Chapter 4 is a three page summary of the content presented in Chapters 2 and 3.

References for further reading can be found in Chapters 5 and 6.

2. Groundwater

2.1 What is groundwater?

Groundwater can be defined as all subsurface water within soils and rocks that either fills the spaces between individual sediment grains (for example, sands and clays) or is located within fractures and other void spaces in underlying bedrock (Figure 2.1). Strictly speaking, the term 'groundwater' is used by professional hydrogeologists (scientists who study groundwater) to describe only that part of the subsurface water that occurs at or below the water table.

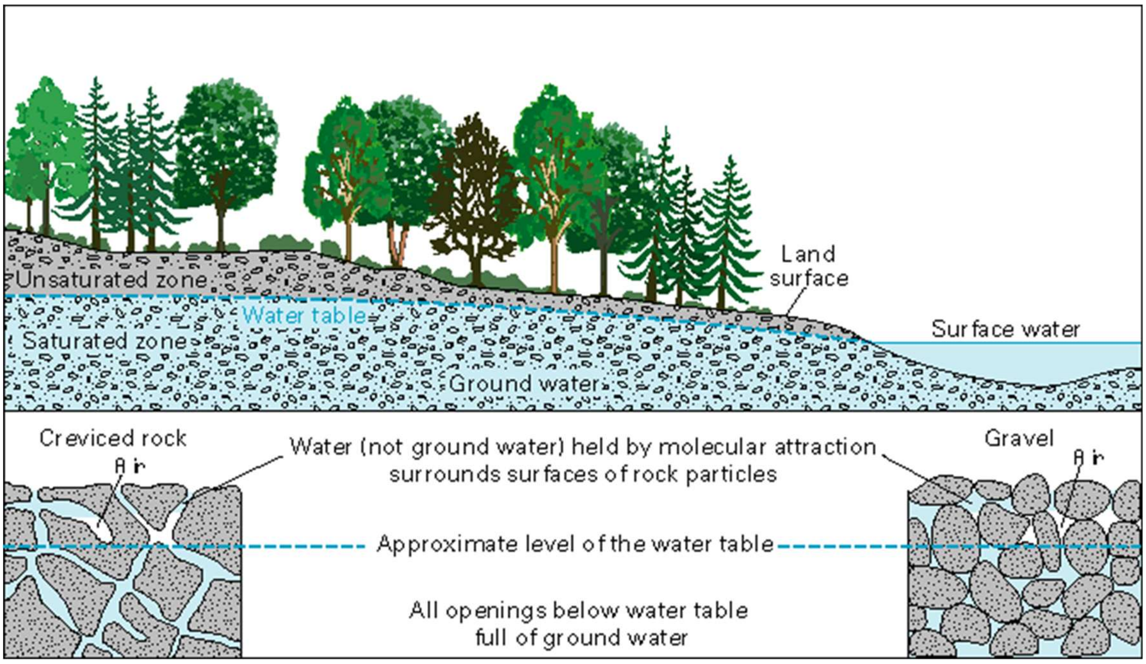

Figure 2.1: Groundwater is water that fills the spaces between soils and rocks**. Source:** Waller 1982. © U.S. Geological Survey.

On a global scale, groundwater is a fundamental component of the hydrological cycle, the endless circulation of the world's water resources between the oceans, atmosphere and land (Figure 2.2). Evaporation of water from vegetation, oceans and other water bodies and subsequent precipitation across the continents results in overland flow at the land surface and the infiltration of water into the subsurface where it becomes groundwater.

This groundwater then flows through the sub-surface under gravity. Groundwater may remain below the ground, however, in most cases it eventually finds its way back to the atmosphere. The residence time of water in the ground can range from days to millions or billions of years. Mechanisms that facilitate groundwater discharge back to the atmosphere include groundwater discharge to the ocean or land surface at lower elevations, pumping of shallow groundwater by vegetation (evapotranspiration) and pumping of shallow or deep groundwater by industry and agriculture.

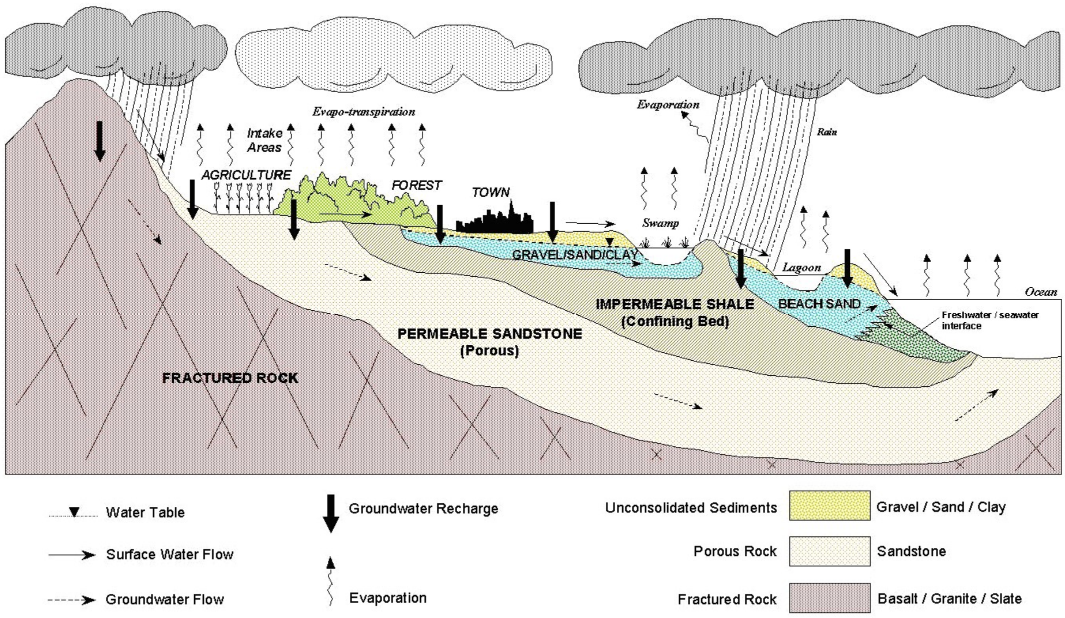

Figure 2.2: The hydrological cycle – groundwater is historical rainfall**. Source:** Adapted from NSW Government 1998.

2.2 Components of a groundwater system

Subsurface sediments and rocks can be classified as either water bearing aquifers or flow inhibiting aquitards (Figure 2.3). An aquifer is an underground (geologic) formation capable of holding and supporting (typically) a good quality water supply. An aquifer may consist of alluvial sediments, sedimentary rocks, fractured rocks or fissures in limestone (karst). Alluvial deposits are sediments composed of aquifer materials (such as gravel and sand) and aquitard materials (such as silt and clay) deposited in river channels or on floodplains.

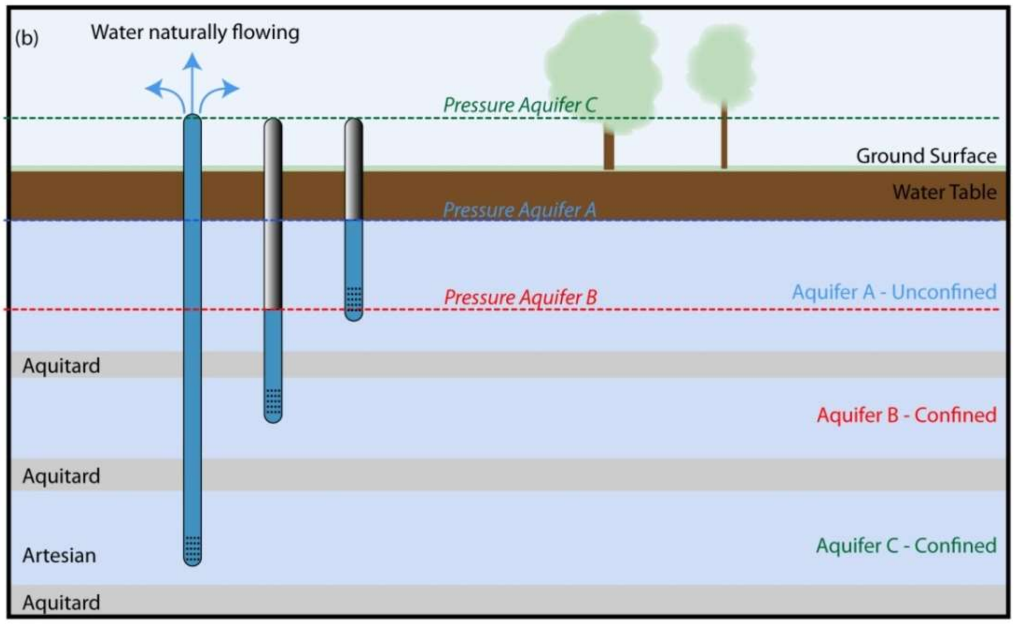

Figure 2.3: Components of a groundwater system. **Source:** Anderson et al. 2013. © Water Research Laboratory, UNSW.

The volume of water within the aquifer primarily relies on the volume of the pore spaces or porosity. Where groundwater is in direct contact with air from the atmosphere the aquifer is said to be unconfined. When the water (pressure) level in an aquifer is within or above the elevation of the overlying aquitard, the aquifer is said to be confined (under pressure). If this aquifer pressure level exceeds the elevation of the ground surface and this aquifer is tapped for a water supply, then groundwater will flow naturally out of the well. A water supply of this nature is said to be flowing artesian. Groundwater within aquifers can be classified as unconfined, confined or artesian.

An aquitard is a geologic layer (or strata) through which water percolates extremely slowly (relative to adjacent geological strata). Due to the geologic nature of the rock or sediments, an aquitard may contain water but this groundwater is difficult to extract. Single or multiple aquitard layers may exist and these layers can be regionally continuous, segmented or angled with spatially variable properties. An example of an aquitard would be a saturated siltstone, clay, silt or indurated 'coffee rock' layer overlying a saturated sandy layer (aquifer).

2.3 Groundwater movement

The movement of water within the ground results primarily from the force of gravity. Groundwater will flow from a region of higher pressure (higher water table elevation) to a region of lower pressure (lower water table elevation). This is illustrated in Figure 2.4. As the pumping well operates, water and soluble nutrients and contaminants begin to move laterally within Aquifer C towards the pumping well. Water also starts to leak from Aquifer B through the aquitard into Aquifer C (and similarly for Aquifer A to Aquifer B).

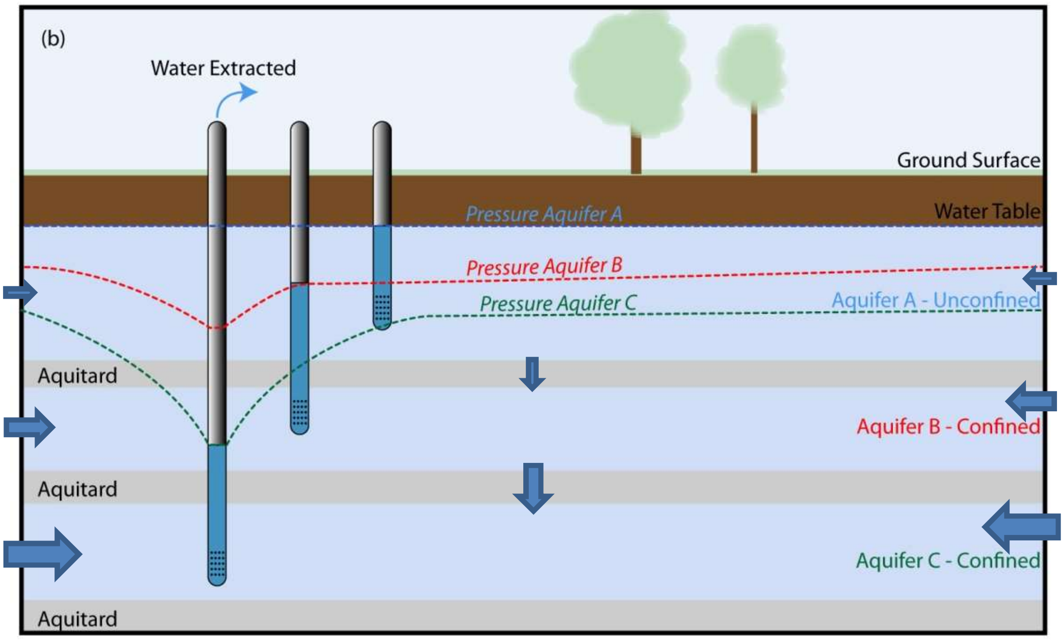

Figure 2.4: Groundwater movement. **Source:** Anderson et al. 2013. © Water Research Laboratory, UNSW.

The rate of groundwater flow (or leakage) is essentially determined by the difference in groundwater elevation between two points and the characteristics of the material through which the water is moving. The term 'permeability' or 'hydraulic conductivity' is used to describe the rate at which groundwater can flow within differing soils and rocks. Hydraulic conductivity is determined by soil texture, organic matter content and structure. Generally soils with coarse textures (e.g. coastal sands) or fractured rocks and many interconnected pores have a relatively high hydraulic conductivity of the order of tens of metres per day or more. In contrast, some estuarine mud and clays have a hydraulic conductivity of <1 mm per day. However, some clay soils have a relatively high hydraulic conductivity: for example, macropores (possibly relic root channels from previous vegetation) can raise hydraulic conductivity.

Groundwater flow can be considered at a number of scales. At the regional scale, fresh groundwater tends to discharge at the coast via several natural mechanisms. These include evapotranspiration, mixing with saline groundwater to form a subsurface region of brackish water; and direct seepage through wetlands, springs, tidal rivers and the ocean floor. At the local scale, the flow of groundwater near a waterbody may vary. Groundwater levels and resulting groundwater flow vary in response to natural factors such as rainfall and the rise and fall of the tides, waves, and human factors such as groundwater pumping and irrigation. Where groundwater interacts with brackish waters, such as within a wetland, the density difference between fresh and saline waters will also help to drive groundwater flow, with fresher water tending to move over the top of more saline waters.

2.3.1 The influence of tides and waves

A groundwater system and its connected water bodies can be somewhat influenced by the action of ocean tides and waves, similar to an estuary or tidal creek. The action of tides and waves tends to cause cyclic and irregular flows of water through the groundwater system and any other connected inland water bodies. In addition, tides and waves act like a pump to elevate the water table in the groundwater system above the mean water level of the ocean or estuary (Figure 2.5).

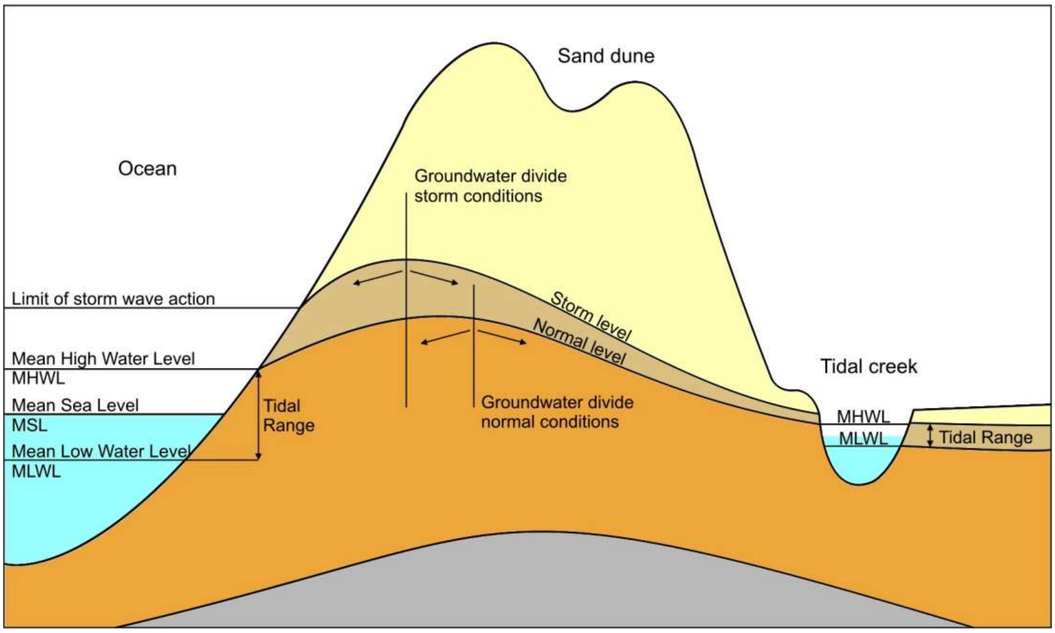

Figure 2.5: Elevation of coastal groundwater by tide and wave action. **Source:** © Water Research Laboratory, UNSW.

At low tide, the water table within the surrounding groundwater system may be higher than the water level within the connected water bodies, and therefore groundwater will discharge into and through the banks and base of the water body. At high tide, the water level within the water body may exceed the surrounding groundwater elevation, resulting in the recharge of waters back into the groundwater system.

For this reason, the groundwater elevation in the immediate vicinity of a tidal water body can often be observed to fluctuate at the same frequency as the tides or respond to coastal storm events (Figure 2.6). Owing to the relatively slow rate at which water flows through the ground, the magnitude of tidally driven groundwater fluctuations will tend to decrease rapidly with increasing distance from the tidal water body. Away from the side bank, the tide and water table fluctuations may show a time-lag of several hours. To determine the average groundwater level surrounding a tidal water body, it is therefore necessary to monitor at several different stages of the tide, and preferably during both neap and spring tide cycles.

Monitoring wells and computer modelling studies have shown that tidal signals alone with an amplitude of between 1.0 m and 2.5 m will increase groundwater levels within 100 m of a tidal estuary or ocean by between 0.2 m to 1.8 m above mean sea level, depending on the aquifer characteristics (Ataie-Ashtiani et al. 2001). Wave action (coastal storms) and groundwater recharge temporarily raise groundwater levels even higher (Turner et al. 1996).

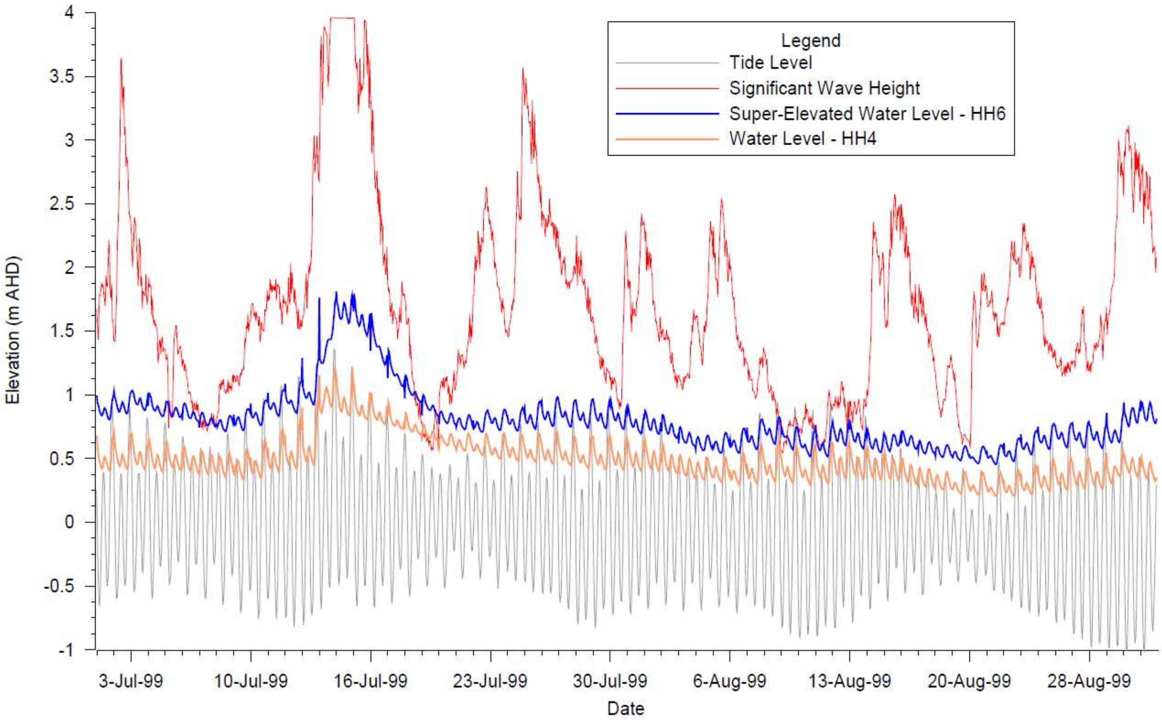

Figure 2.6: Tide and wave effects on groundwater, Hat Head, NSW. **Source:** Anderson et al. 2002. © Water Research Laboratory, UNSW.

The blue and brown lines in Figure 2.6 show the groundwater elevation recorded at two groundwater monitoring wells at Hat Head on the New South Wales (NSW) coast during 1999. The HH6 well is located closer to the ocean while the HH4 well is located closer to a tidal creek. In this example there is about a 0.2 m groundwater level response to the diurnal tide signal. Note also the elevation of groundwater levels by tides and variations in the wave run-up. The latter are represented by the red line showing off-shore significant wave height. At this site groundwater levels are between 0.5 m and 1.0 m Australian Height Datum (AHD) during calm conditions and around 1.8 m AHD following storm events.

2.3.2 The influence of salt water

The regular rise and fall of the water level within a water body, such as an ocean, estuary or saltwater wetland, is important to the surrounding groundwater system, as this process may influence the rate of exchange of nutrients and contaminants between surface and subsurface waters. It is likely that the tidal rise and fall of the water level within a coastal water body will assist the mixing between fresher groundwater discharging towards the coast and saline or brackish waters entering the groundwater from the water body. Without tides, the fresh groundwater would flow over the denser saline groundwater, which would occur at a considerable depth below the ground surface.

In theory, if the water table adjacent to a coastal water body was elevated 1 m above the base of the water body, in the absence of tides the fresh–saline groundwater interface would stabilise at a depth of about 40 m (Figure 2.7). However, the action of tides and waves means there is considerable mixing across the saline–fresh interface, and brackish groundwater may be detected at much shallower depths. This tidal mixing process results in a potential increase in groundwater salinity adjacent to the water body, but also means that any contaminant present can enter or leave the groundwater system by the process of tidal mixing.

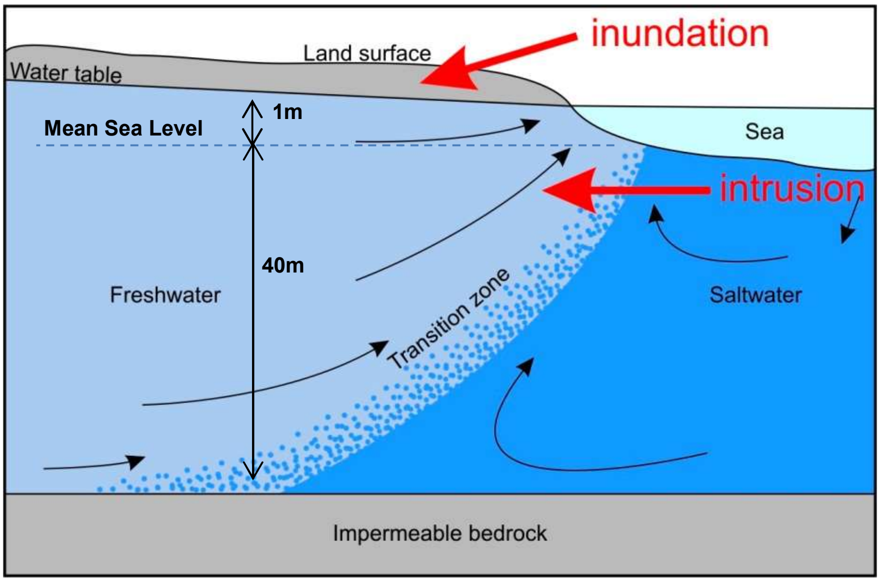

Figure 2.7: Idealised theoretical position of the salt water interface. **Source:** Timms et al. 2008. © Water Research Laboratory, UNSW.

Under natural conditions, the regional flow of fresh water towards the ocean limits the landward encroachment of sea water. When groundwater is pumped from an aquifer that is hydraulically connected with a source of salt water, such as that in a saltwater wetland system, the resulting flow regime may induce salt water encroachment into the aquifer. This migration of salt water into fresh water is known as saltwater intrusion.

As noted earlier, in theory, for every 1 m that the water table adjacent to a wetland is raised above the water level within the wetland, the fresh–saltwater interface will stabilise at a depth of approximately 40 m. For the same reason, for every 1 m that the water table is pumped down for irrigation, domestic, mining or industrial use, the fresh–saltwater interface will rise by approximately 40 m. Therefore, pumping must be carefully managed adjacent to saltwater bodies. Even though the fresh–saltwater interface may be known to be well below the ground surface, a relatively minor lowering of the water table by pumping can result in a large rise of salt water into the upper freshwater aquifer.

2.4 Surface water – groundwater interactions

On the scale of an individual lake, river, estuary or wetland, groundwater comprises one component of the water cycle (see Figure 2.2). Groundwater may be a source or sink of water within the surface water body. Poor groundwater quality may degrade surface water quality, and similarly, poor surface water quality may reduce the quality of the surrounding groundwater.

Generally, groundwater flow in the vicinity of a saltwater wetland can be categorised into one of three flow regimes; discharge, recharge and flow-through. At some sites the exchange of water between a surface water body and the surrounding groundwater system may be significant; at other locations, the prevailing hydraulic and geological conditions may reduce the significance of the volumes of water involved in this exchange.

2.4.1 Discharge regimes

Discharge regimes exist where the net direction of groundwater flow is from the surrounding groundwater system into the surface water body. In other words, the groundwater system is discharging water into the lake, stream or wetland (Figure 2.8). Seepage into the surface water body will typically occur through the base and banks following rainfall. The flow of groundwater into and out of many water bodies can decrease significantly with increasing distance, as the creek / stream / wetland bed may be relatively impermeable owing to fine sediments.

A discharge regime will tend to occur when the ground surface surrounding the water body is elevated, and the water table elevation surrounding the water body is above the level of the wetland. Under such conditions, the groundwater is a source of water to the wetland, stream or lake and any contaminants present in the local groundwater system should be assumed to be entering the surface water system.

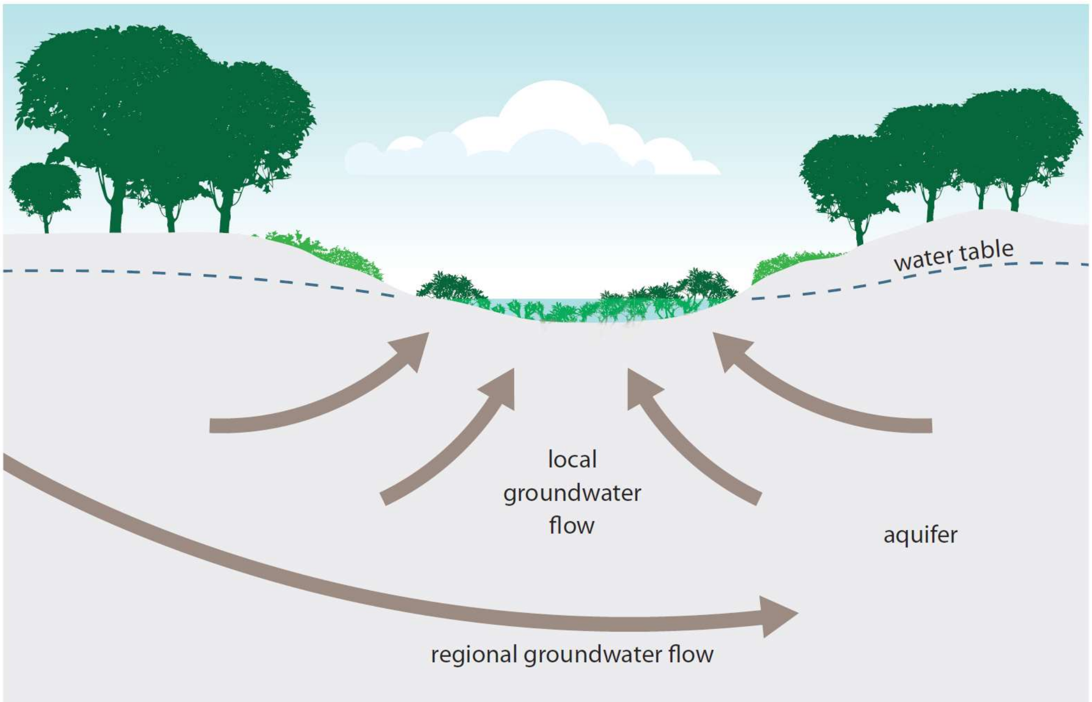

Figure 2.8: Groundwater discharge regime. **Source:** Campbell 2008. © Commonwealth of Australia (Department of Climate Change) 2017.

2.4.2 Recharge regimes

Recharge regimes exist where the net direction of flow is from a surface water body into the groundwater system. In other words, water from the surface water body is infiltrating to and increasing the volume of the surrounding groundwater system (Figure 2.9). This is less likely to occur in saltwater wetland systems on the coast, but it may occur in areas where groundwater extraction has lowered the water table. For example, near a golf course, mine or field where groundwater is pumped from a bore for irrigation, dewatering or cropping.

Under recharge conditions, water will flow from the surface water body into the groundwater system, transporting any contaminants from within the surface water body. This may have a detrimental impact on the surrounding groundwater system.

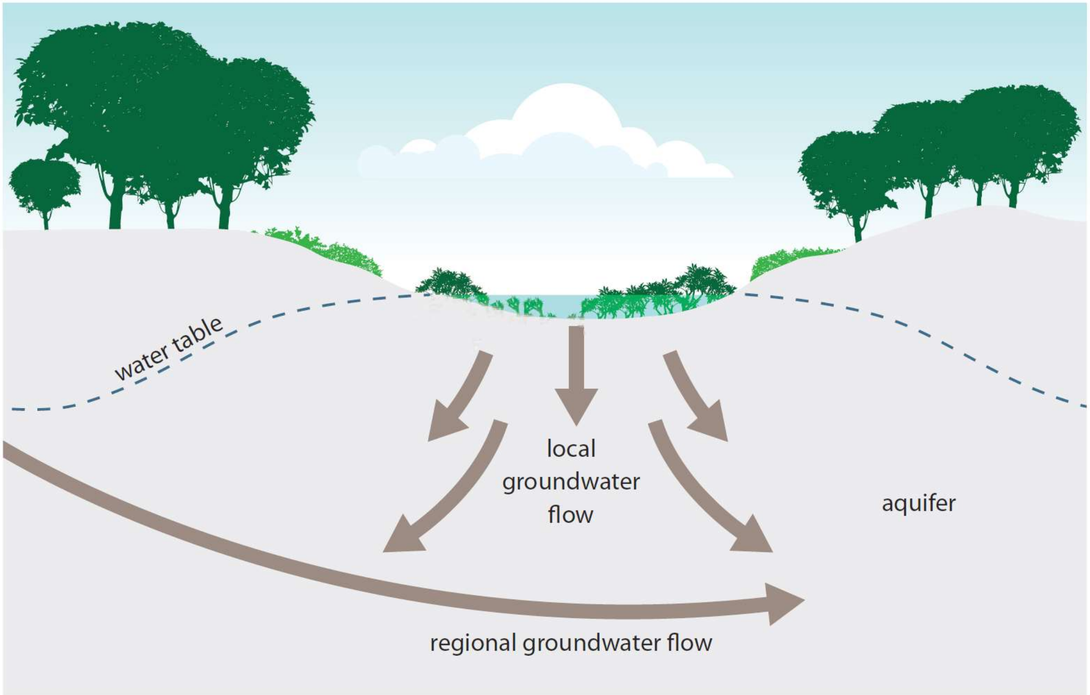

Figure 2.9: Groundwater recharge regime. **Source:** Campbell 2008. © Commonwealth of Australia (Department of Climate Change) 2017**.**

2.4.3 Flow-through regimes

Flow-through regimes exist where the water table adjacent to one region of the surface water body is higher than that at another location. Under such conditions, groundwater flows into and then out of the surface water feature, from the region of higher water table elevation to the region of lower water table elevation (Figure 2.10). Such conditions are likely to be rare in coastal settings, but could occur in response to either localised irrigation or groundwater extraction on one side of a wetland only.

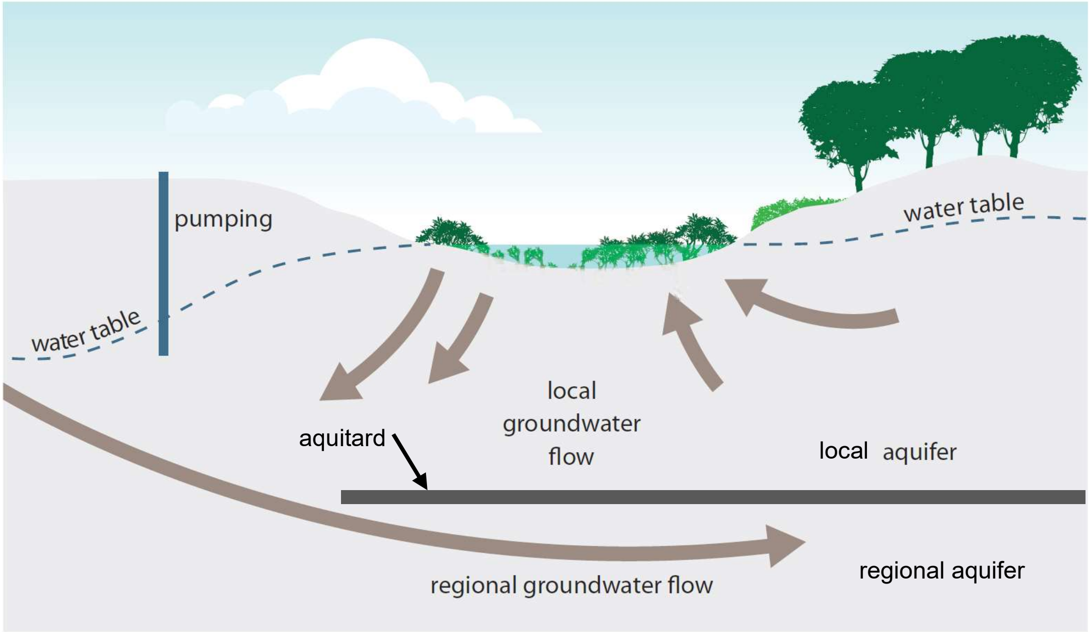

Figure 2.10: Groundwater flow-through regime. **Source:** Modified from Campbell 2008. © Commonwealth of Australia (Department of Climate Change) 2017.

2.4.4 Groundwater 'capture' zone

It is important to recognise that surface water bodies interacting with groundwater can have a relatively large capture zone, meaning that the region from which groundwater may discharge from one to the other is likely to be significantly larger than the surface area and depth of the surface water body itself. As illustrated in Figure 2.11, for inland (freshwater) wetlands the horizontal capture zone may typically be twice the width of the wetland. Similarly, as illustrated in Figure 2.12, the vertical capture zone is typically twice the depth of the wetland.

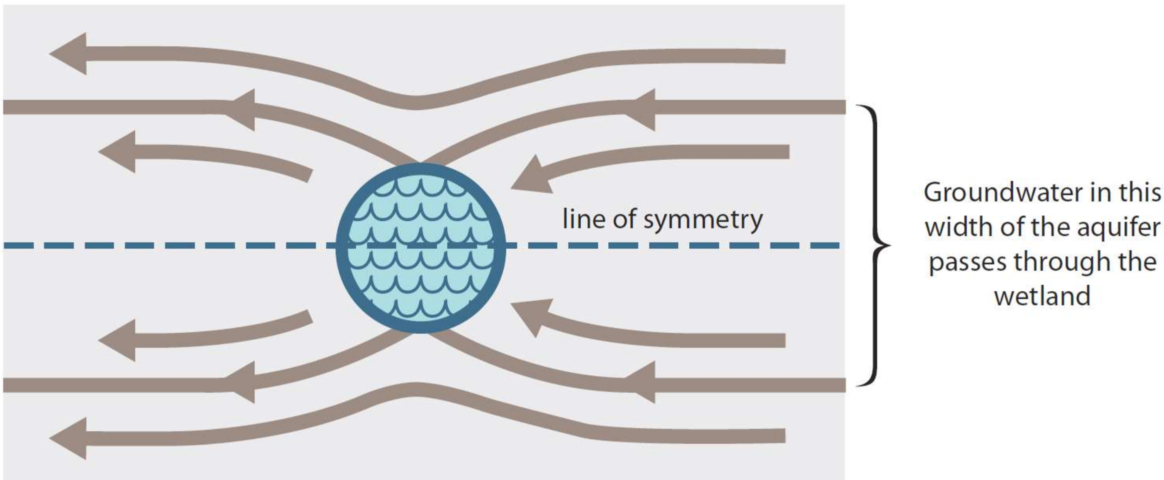

Figure 2.11: Horizontal groundwater capture zone (plan view). **Source:** Campbell 2008. © Commonwealth of Australia (Department of Climate Change) 2017.

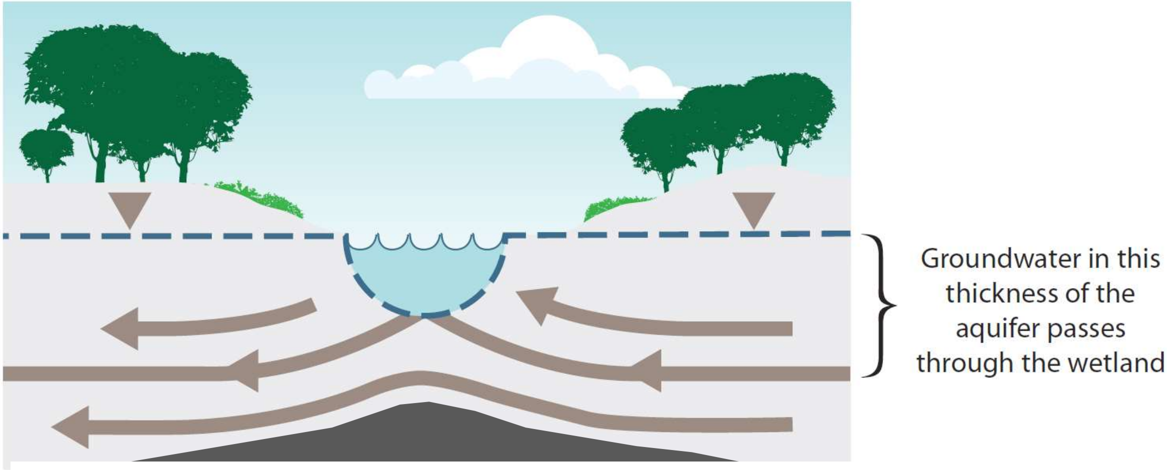

Figure 2.12: Vertical groundwater capture zone. **Source:** Modified from Campbell 2008. © Commonwealth of Australia (Department of Climate Change) 2017.

Note that the capture zone for saltwater wetland systems is likely to be significantly greater on account of the mixing action of the tides. The existence of a relatively large capture zone is significant because it means that any human-induced changes to a surface water body or groundwater system can affect both systems over an area that significantly exceeds the area of the water body alone.

2.5 Groundwater contamination

Groundwater can be degraded by several types of contaminant that may enter the surrounding aquifer from surface waters or overlying land use activity, for example, where liquid wastes from stormwater, agriculture, mining or industry are directed to a water body or when fertilizers, pesticides or other chemicals (such as firefighting foams) leach directly into the ground. Unconfined shallow aquifers with high permeability are most susceptible to pollution. Indirect groundwater contamination contact scenarios include inhalation of volatile groundwater gases in enclosed spaces such as basements, ingestion from drinking groundwater or eating crops grown in gardens, and adsorption from primary or secondary contact. Primary contact is where the body is fully immersed in water and there is a potential to swallow water (e.g. surfing, diving, swimming and water skiing). Secondary contact includes activities such as paddling, wading, boating and fishing where there is a chance of skin contact but swallowing water is unlikely.

2.5.1 Metals

Metals in groundwater can cause environmental, ecological and human health problems. Groundwater contamination by metals can affect the potential human use of the resource, but it can also affect aquatic organisms when the contaminated groundwater discharges to surface waters or is taken up by vegetation and crops.

The metals of principle concern include lead, copper, nickel, chromium, zinc and also arsenic (a metalloid). Research has shown that most metals are likely to accumulate within the soils close to their source, such as the base of a wetland. However, in sandy and loamy soils there is significant downward movement of copper and iron. Therefore, if the groundwater adjacent to a water body is acidic, these and other metals can be mobilised and move into the surrounding groundwater system. As the solubility of most metals increases with decreasing pH, the risk of acidification and metal release following oxidation could be greatly increased in Acid Sulfate Soils (ASS).

2.5.2 Nutrients

Nitrates are among the most frequently found contaminants in groundwater. Whenever nitrogen-containing compounds come into contact with soil, there is the potential for nitrate to leach into groundwater. Nitrates are highly soluble, and so are easily transferred from a water body into the surrounding aquifer (or from the aquifer to the surface water body).

Phosphorus adsorption is limited in porous soils which are prone to considerable groundwater movement. Phosphorus in its dissolved form (orthophosphate) can move freely from a wetland into the surrounding groundwater system and vice versa.

Excessive nutrient concentrations can cause both environmental and human health problems. The enrichment of a water body with nutrients is called eutrophication. This process induces the growth of plants and algae, which depletes dissolved oxygen. Changes in the dissolved oxygen concentration of groundwater can mobilise or immobilise certain contaminants. A change from discharge of oxygenated to de-oxygenated groundwater in the coastal zone has the potential to significantly alter and disrupt the functioning of benthic communities.

2.5.3 Pathogens

Pathogens may enter the groundwater via a wetland from sewage, septic systems, stormwater and agricultural runoff. Pathogenic organisms can harm human health. There have been cases in Canada, New Zealand and elsewhere where people have been hospitalised, and even died, from drinking town water sourced from contaminated pumping wells after heavy rain.

Several factors influence the movement of viruses and bacteria into the surrounding groundwater system. Viral survival time increase with increasing pH (more alkaline) and decreasing temperature. Higher groundwater flow rates also decrease the rate of virus adsorption in soils, and hence increases the potential area that may be contaminated away from the viral source. Bacterial and viral survival times are also increased by the presence of organic matter within the soil. Higher clay content is associated with a decrease in the extent to which viruses can move to or from an aquifer system.

2.5.4 Pesticides

Pesticides that enter a waterbody, usually as a result of agricultural practices, may subsequently pass through the banks or base of a water body and thereby enter the adjacent groundwater system. Pesticides decompose in soil and water, but the total decomposition time can range from days to years.

2.5.5 Coastal zone contaminant pathways

Contaminant pathways in coastal systems are often sensitive to variations in climate, land and water use. This sensitivity stems from the complex interactions of variable land and water use, rainfall and runoff, tide and wave action, and fresh and salt water interactions with the coastal geological materials. For sensitive systems, a small change in one of the inputs can significantly change the contaminant migration pathway and the environmental outcomes.

For example, consider the conceptual flow model shown in Figure 2.13 for a case study completed at Hat Head in NSW by Anderson et al. (2002) to assess the fate of viruses from a hypothetical waste-water disposal system.

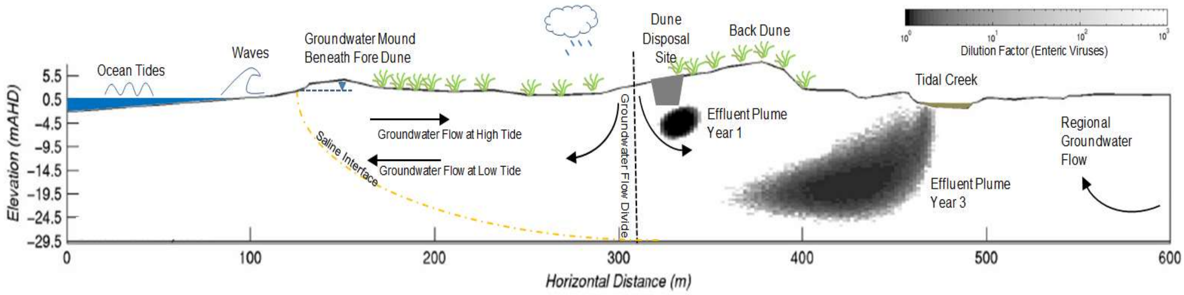

Figure 2.13: A conceptual flow model showing one scenario for migration of treated effluent disposed of into a coastal aquifer. **Source:** Anderson et al. 2002. © Water Research Laboratory, UNSW.

It seems intuitive to expect that waste-water discharged to the back dunes of a beach would discharge directly to the ocean through the beach face, however, this is not always the case. The dotted vertical line on Figure 2.13 shows the location of the groundwater flow divide within the shallow aquifer system predicted by a numerical groundwater flow model. If the waste-water disposal site is located landward of the divide, the waste-water will migrate to the tidal creek rather than the ocean with potential health implications for humans, fisheries and the estuary.

The system shown in Figure 2.13 is also sensitive to changes in climate. With changes in rainfall, ocean levels, storm events and creek flows the location of the groundwater flow divide may migrate landward and/or seaward with time. This in turn may change the directions of waste-water plume migration.

Note also that the conceptual model in Figure 2.13 shows the development of a broad plume extending over a depth of about 15 m. This assumes a homogeneous distribution of uniform sand in the coastal aquifer. However, in many coastal systems the geological materials are highly heterogeneous (spatially variable) with, for example, thin layers of indurated sand and organic material (sometimes called coffee rock). This heterogeneity can have a significant impact and make contamination and contaminant pathways even more difficult to measure and predict.

2.6 The value of groundwater

Over 98% of the world’s available freshwater resource occurs as groundwater, with the remaining (more visible) 2% being found in lakes, rivers and ice-sheets. Freshwater in aquifers is therefore a strategic water resource with many beneficial uses including town water supply, domestic supply, irrigation of crops and pastures, stock use and industrial usage. Globally, irrigation has accounted for approximately 70% of total freshwater transfers and approximately 90% of consumptive water use. Alluvial and fractured rock systems account for approximately 60% and 33% respectively of Australia’s groundwater extraction (Geoscience Australia 2013).

One example of coastal groundwater use for town water supply is the coastal Tomago aquifer near Newcastle in NSW. This aquifer typically supplies 10 - 15 ML/day for the Hunter Valley scheme or approximately $12 million worth of water annually. The sustainable yield of this groundwater source is currently 45 ML/yr. The potential for climate change impacts on this aquifer are recognised and are being investigated but have not yet been fully assessed.

Total groundwater use in Australia is estimated to be approximately 3500 GL/yr across several industries (Deloitte Access Economics 2013). The 2013 breakdown for use was estimated as: agriculture (60%), manufacturing and other industries (17%), mining and other extraction (12%), potable town water supply (9%) and household water supply (5%).

Groundwater is best known as being a reliable source of town water supply or irrigation water (Figure 2.14) in parts of inland or arid / semi-arid Australia where surface water is scarce or absent, or of poor quality. However, groundwater systems provide many additional services. For example, long after rainfall has subsided, groundwater supports a diverse array of native vegetation and ecological communities in addition to base flows to streams (Figure 2.15).

Figure 2.14: Irrigation of cotton with groundwater and monitoring of levels in a well. **Source:** © Water Research Laboratory, UNSW.

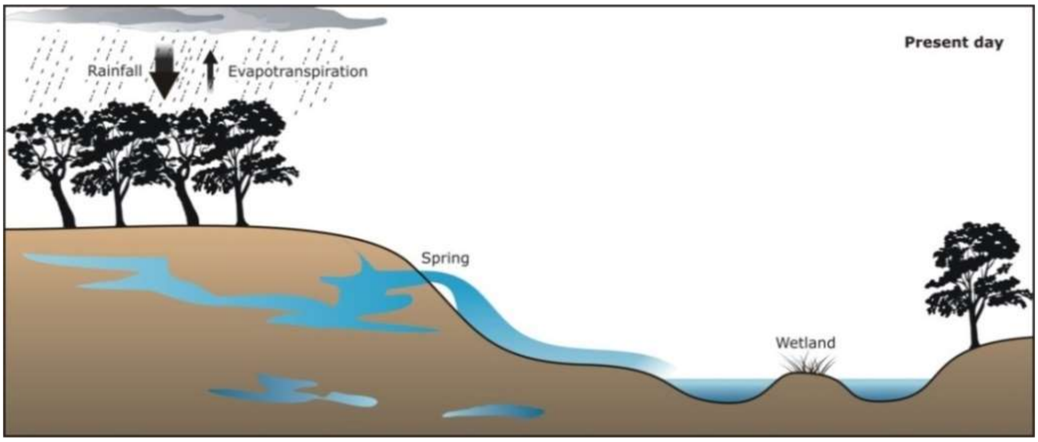

Figure 2.15: Groundwater provides ecosystem services. **Source:** Developed by the author. © Water Research Laboratory, UNSW.

Groundwater systems can also be managed with artificial recharge to maximise water supplies when surface water is scarce (Figure 2.16). This is called managed aquifer recharge (MAR). A MAR system stores excess runoff and treated waste-water in the ground without any of the evaporative losses associated with surface water storages. This water is then recovered during drought and treated for use. This is called aquifer storage, treatment and recovery (ASTR).

In locations that experience climatic extremes, the energy stored in groundwater and the Earth's sub-surface can be used as a heat-exchanger to provide low-cost heating in winter and cooling in summer (Figure 2.17). Several companies in Australia provide geothermal heating and cooling solutions.

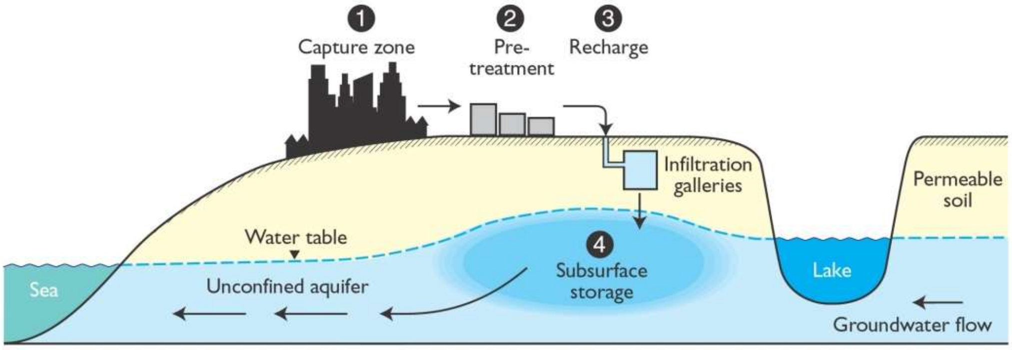

Figure 2.16: Managed Aquifer Recharge. **Source:** Page et al. 2010. © Copyright CSIRO Australia.

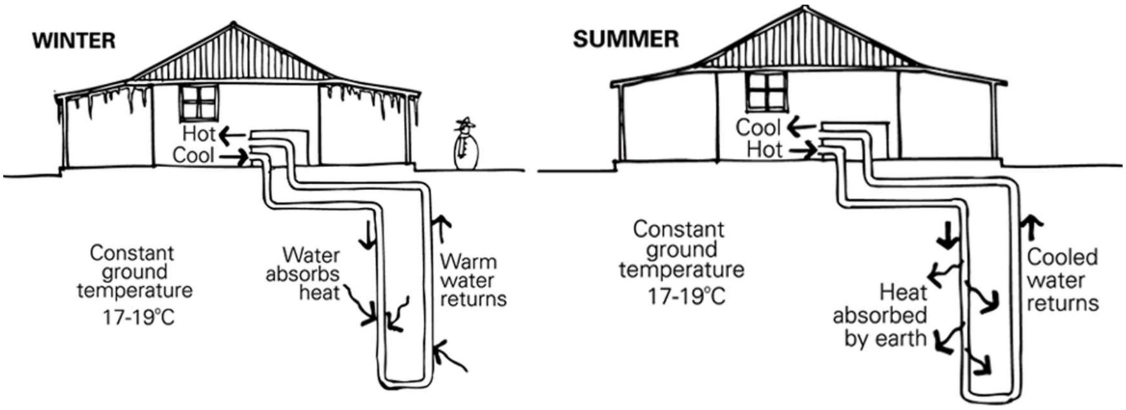

Figure 2.17: Geothermal heating and cooling. **Source:** Milne and Reardon 2013. © Commonwealth of Australia (Department of the Environment and Energy) 2017.

Groundwater can also be a nuisance. It must be pumped away (dewatered) to allow for the safe extraction of mineral resources and the construction of foundations and basements (Figure 2.18). In many low-lying coastal and estuarine areas groundwater is also drained away to reclaim land for agricultural, urban and industrial development (Figure 2.19).

Figure 2.18: Groundwater dewatering in construction – Botany Sands aquifer. **Source:** Wendy Timms © Water Research Laboratory, UNSW.

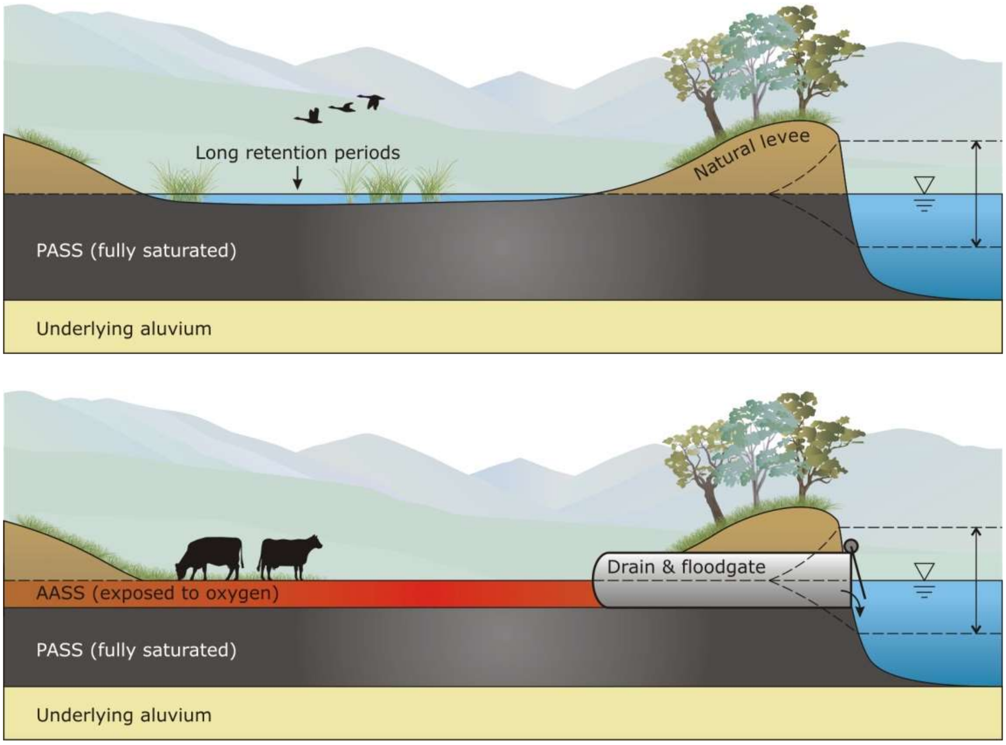

Figure 2.19: Acid sulphate soils and reclamation of land for agriculture. **Source:** Glamore et al. 2016. © Water Research Laboratory, UNSW.

Without careful management, groundwater dewatering and land reclamation may expose potential acid sulphate soils (PASS) to oxygen. PASS (or ASS) contain reduced sulphate compounds. These compounds may oxidise to sulphuric acid following rainfall, irrigation or overland flooding. The resulting acid drainage can cause a variety of problems including the mobilisation of toxic metals which can devastate marine life such as fish, crabs and oysters (Figure 2.20).

Various combinations of land clearing, irrigation, rainfall, increased sea level and decreased pumping can also create problems such as rising groundwater levels that result in water logging. Elevated extreme temperatures and higher atmospheric carbon dioxide concentrations may force the stomata of some plant leaves to close more often causing increased mortality, reduced evapotranspiration and rising water tables. Elevated groundwater levels can cause mortality of vegetation and crops, mobilisation of toxic industrial contaminants in soil and groundwater (e.g. BTEX, petroleum hydrocarbons, PFAS, vapours), rising damp in buildings, growth of mould and changes in ecological communities (e.g. more mosquitoes).

Also, when soil or groundwater is saline, elevated groundwater levels can kill vegetation (Figure 2.21), render groundwater wells unusable, agricultural land unproductive and cause urban salinity (Figure 2.22). Management of groundwater to minimise the social, economic and human health effects is discussed further in Section 3.4.

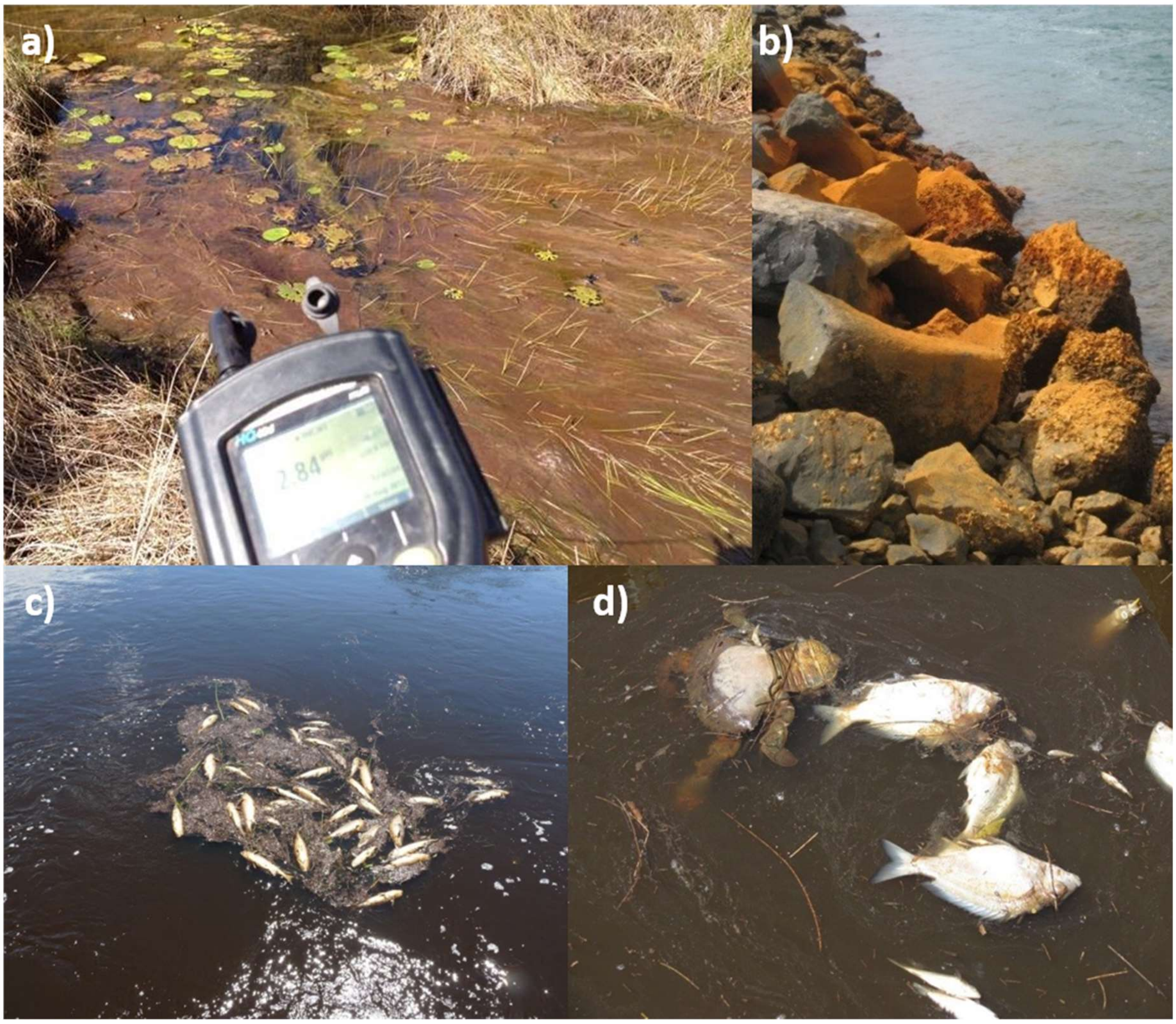

Photo credits: (a) Acid drainage (pH 2.84) from reclaimed agricultural coastal land at Cattai Creek (D. Rayner. © Water Research Laboratory, UNSW.), **(b)** Deposition of iron from acid drainage on an engineered river bank (Wendy Timms © Water Research Laboratory, UNSW.), **(c)** Fish kill in Clybucca Creek, NSW (Max Osborne, North Coast Local Land Services), **(d)** Fish kill in Clybucca Creek, NSW (Penny Kendall).

Figure 2.20: Problems caused by acid drainage in NSW.

Figure 2.21: Dryland salinity in Western Australia. **Source:** © Western Australian Agriculture Authority (Department of Primary Industries and Regional Development, WA). Photo: Arjen Ryder.

Figure 2.22 shows some of the different types of damage that can be cause by shallow, saline groundwater. The top left panel shows salt efflorescence and damage to brick work. Salt efflorescence is the migration of salt to the surface of a porous material where it forms a coating. The top right panel shows salt efflorescence and damage to a road pavement. The lower left panel shows a salt scald on a playing field where grass no longer grows. The lower right panel shows salt efflorescence and damage to a gyprock wall caused by rising damp.

Photo credits: Top and Lower Left - Slinger and Tenison 2007, in Podmore 2009 © State of New South Wales through NSW Department of Industry, Lower Right: © State of New South Wales through NSW Department of Industry.

Figure 2.22: Urban salinity in NSW.

2.7 The economic value of groundwater

A report by Deloitte Access Economics (2013) found a lack of understanding of the economic value of groundwater use in Australia and compiled disparate research on groundwater uses and values into a centralised economic value description and estimate. The report estimated that the direct value of groundwater extraction in Australia was $1.8 to $7.2 billion per year and that it was directly responsible for generating $3.0 to $11.1 billion in Gross Domestic Product (GDP). The total value of production where groundwater was a significant input into production was estimated at $33.8 billion.

Table 1 and 2 provide a breakdown of the estimated economic values of groundwater quantified by sector from 2006 – 2012 data. Note that the numbers do not represent non-extractive groundwater and option values (e.g. the value of groundwater to the forestry and horticulture industries that require groundwater either for production or as an option for production). Refer to Deloitte Access Economics (2013) for further details, including limitations and assumptions.

Table 1: Economic value of groundwater use to Australia
Source: Deloitte Access Economics (2013).

Sector	Direct value range and central estimate ($ per ML)1	Groundwater volumes (ML)	Direct value-add ($ m)	Ratio of direct to total value add	Total groundwater contribution to GDP ($ m)
Agriculture - irrigation	$30-500 $200	2,050,634	$410	2.00	$820
Agriculture - drinking water for livestock	–	–	$393	2.08	$818
Mining	$500 – 5,000 $2,750	410,615	$1,129	1.45	$1,637
Urban water supply	$1,000 – 3,000 $2,000	303,230	$606	1.89	$1,146
Households	$1,400 – 6,400 $2,500	167,638	$419	NA	NA
Manufacturing and other industries	$1,000 – 3,000 $2,000	588,726	$1,177	2.00	$2,355
TOTAL		**3,520,843**	**$4,136**		**$6,777**

Table 2: Total value of economic production that is dependent on groundwater
Source: Deloitte Access Economics (2013).

Sector	Proportion (%) of sector that is groundwater dependent	Total value of production ($ billion)	Total value of production dependent on groundwater ($ billion)
Agriculture			
Agriculture – Irrigation	29	12.9	3.7
Agriculture – Drinking water for livestock	7	13.8	1.0
Mining			
Metal ore mining	37.6	65	24.4
Coal mining	0.1	62	0.1
Manufacturing			
Food production	0.9	68.8	0.6
Beverage production	1.6	9.2	0.1
Petroleum and coal production	0.9	28.6	0.2
Basic chemical and chemical production	1.2	17.6	0.2
Primary metal and metal production	3.2	99.2	3.2
Fabricated metal	1.8	6.8	0.1
TOTAL		383.8	33.8

3. Climate change

3.1 Climate observations

Several scientific studies have linked changing rainfall (Figure 3.1), sea level (Figure 3.2), temperature, rainfall and evaporation measurements) to anthropogenic activity, in particular increases in global carbon emissions and changes in land use, such as clearing of natural vegetation for irrigated agriculture and construction of cities. Increased greenhouse gas emissions have trapped more heat in the Earth's atmosphere and this has increased the rates of sea-level rise. Historical data also highlights significant correlations between land use change and changes in terrestrial hydrology that are much greater than those that might be caused by climate change.

Case Study – Hunter and Central Coast Region
Historical observations for the Hunter and Central Coast region of NSW reported by Blackmore and Goodwin (2009) show that average temperatures increased by 0.5ºC to 1.5ºC from 1970 to 2007 and (from 1948 to 1977) summers and winters become drier (46mm and 52 mm decrease in rainfall, respectively), and springs become wetter (4 mm increase).

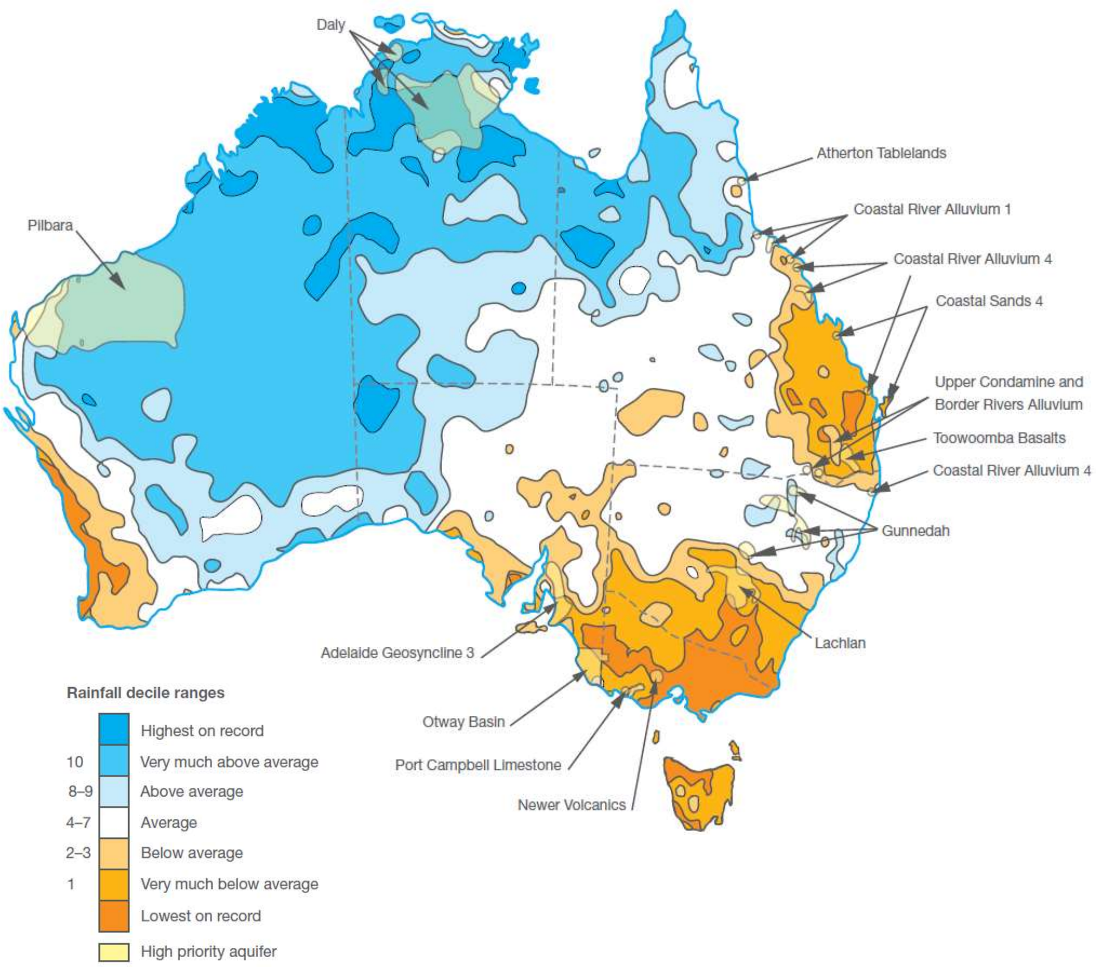

Figure 3.1: Rainfall conditions for 1997 – 2009 compared to 1900 – 2009. **Source:** Harrington and Cook 2014 (from Chiew and Prosser 2011). Reproduced with permission from CSIRO (2010).

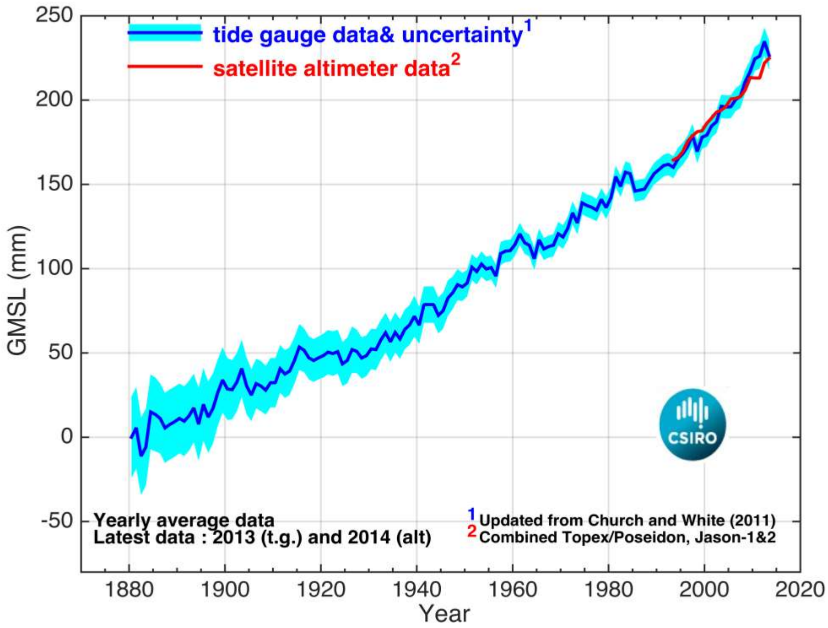

Figure 3.2: Sea-level rise records in Australia. **Source:** CSIRO 2015. © Copyright CSIRO Australia.

Sea-level rise has been measured around the world for many years, providing evidence that the rate of rise is increasing (Church and White 2011). Global sea levels have risen on average by about 2 mm/year with a total rise of 0.2 m over the last century (Figure 3.2). The average sea-level rise that is evident in tide gauges around Australia is approximately 1.2 mm/year.

3.2 Climate Predictions

Scientists use computer models, called General Circulation Models (GCMs), to predict changes to future climate caused by changing land use practices and changing concentrations of atmospheric gases such as carbon dioxide, methane and CFCs. These models are both complex and simplistic because it is challenging to mathematically represent the movement of water, gases and energy across the entire planet. Many scientific studies make use of sixteen or more different GCMs with differing assumptions and complexity to appreciate the likelihood or uncertainty associated with any prediction of future climatic conditions. The representation of groundwater processes in these models is highly simplified.

In general, while there is substantial uncertainty in the predictions of changes to mean rainfall and groundwater recharge from GCMs (**Figure 3.3**), there is consensus from these models concerning the influence of land use change and greenhouse gases on rainfall and temperature extremes, changing seasonal rainfall patterns and sea-level rise. For example, it is generally acknowledged that:

- There will be a 0.38 m to 0.66 m median rise in sea level by 2090 (relative to 1990).
- These estimates of sea-level rise do not account for the melting of the Antarctic and Greenland icesheets. The total melting of the Greenland ice sheet might elevate global sea levels by a further seven metres over a very long time period (Houghton et al. 2001).
- Mean recharge across Australia is more likely to decrease across the west, central and southern portions of the continent and increase in the north (Crosbie et al. 2013).
- Many regions will experience long droughts and periods of more frequent and intense rainfall associated with either a decrease or increase in mean rainfall.

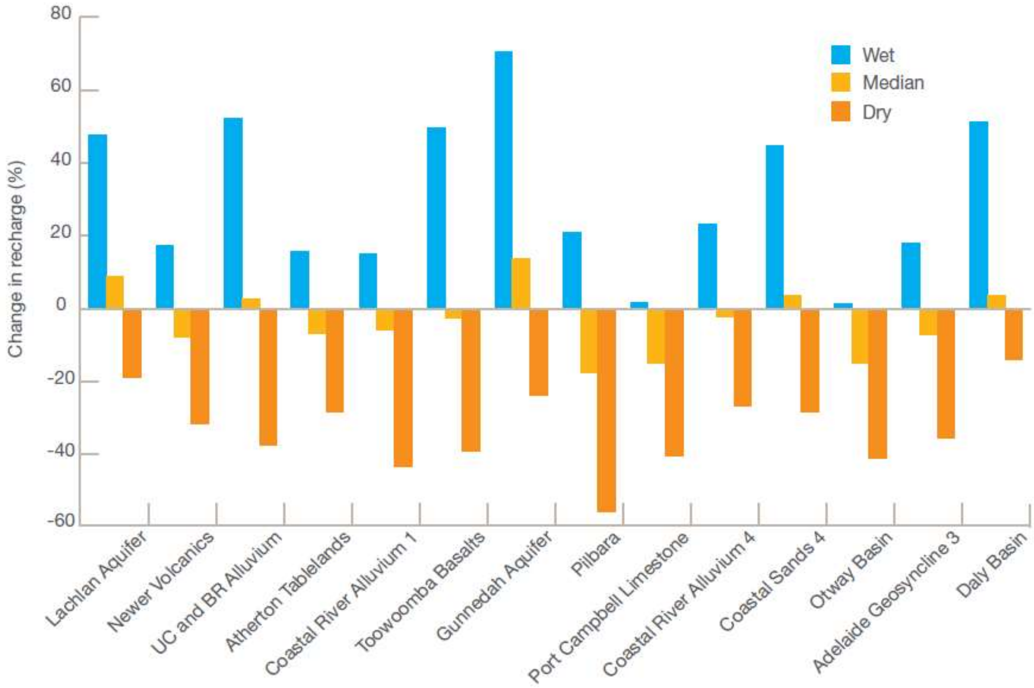

Figure 3.3: Predicted percentage change in groundwater recharge under wet, median and dry climate change scenarios in 2050 for the fourteen priority aquifers listed in Barron et al. (2011). **Source:** Harrington and Cook 2014 (from Chiew and Prosser 2011). © Copyright CSIRO Australia.

Case Study – Hunter and Central Coast Region
Blackmore and Goodwin (2009) suggest that:

- Winters will become even more dry (180 mm decrease in rainfall) while springs will become even wetter (210 mm increase in rainfall).
- Autumns and winters are predicted to become a further 0.5ºC to 1.4ºC warmer while springs and summers will experience lower minimum (0.2ºC and 0.9ºC) and larger maximum (0.9ºC to 1.4ºC) temperatures;
- In the absence of extreme events, groundwater recharge potential (rainfall less evaporation) is predicted to decrease marginally in autumn and increase slightly in winter and spring;
- More high intensity rainfall and heat wave events are predicted for summer and autumn, fewer high intensity rainfall events in winter and spring, and more extreme coastal storm surge events in autumn and winter.

3.3 Expected impacts on groundwater

Predicting the impacts of climate change on groundwater involves the reconciliation of numerous future changes to climatic, oceanic, hydrological, biological and geological processes and parameters. It also requires consideration of the anthropogenic responses to these changes, in particular adaptations that alter land use. This complexity makes it challenging to predict the exact impacts of climate change on groundwater at any one location. One study by Döll (2009) suggests that by the 2050s some 20% to 30% of the world's population may be impacted by a more than 10% increase in groundwater recharge, 19% may be affected by at least a 10% decrease. Of this 19% some 6% will be particularly vulnerable to decreases in recharge.

Climate change can impact groundwater (Figure 3.4) by one or more mechanisms:

1. Increased intra or inter annual variability causing larger fluctuations in groundwater recharge, groundwater level and groundwater-surface water interactions.
2. Drought, sea-level rise, extreme rainfall and coastal storms causing increased groundwater abstraction, saline intrusion and inundation.
3. Declining groundwater levels and storage in dry areas due to increased groundwater consumption (e.g. town-water supply and groundwater-fed irrigation).
4. Rising groundwater levels from changing land cover and/or increases in surface-water-fed irrigation to offset increased evapotranspiration.

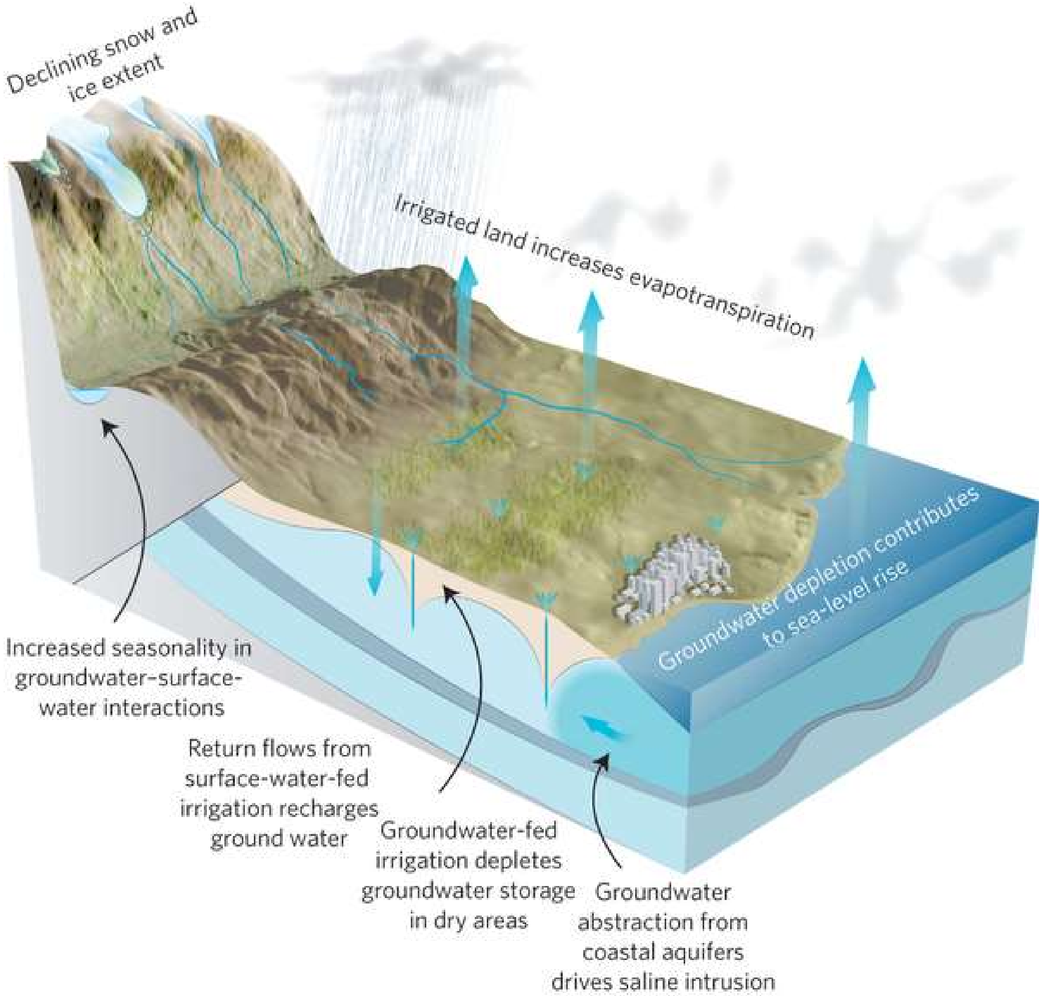

Figure 3.4: Potential impacts of climate change on groundwater. **Source:** Reprinted by permission from Macmillan Publishers Ltd: [NATURE CLIMATE CHANGE] (Taylor et al. 2013), copyright (2012).

In coastal areas and further inland, the links between climate change and groundwater are complicated by land use change which includes the expansion or contraction of rain and groundwater-fed and irrigated agriculture. Taylor et al. (2013) note that in southeast Australia conversion of natural ecosystems to rain-fed cropland increased recharge rates by one to two orders of magnitude in addition to degrading groundwater quality through mobilisation of accumulated salinity in the unsaturated zone (i.e. dry land salinity). Thus, the impacts of climate change on groundwater levels in coastal and inland Australia will also be strongly dependent on future land use and land use management practice.

In 2011, the Australian National Water Commission (now abolished) published a report entitled "Climate change impact on groundwater resources in Australia" (Barron et al. 2011). The report includes an aquifer characterisation tool to assess which Australian groundwater systems are likely to be sensitive to climate change, and of those, which are nationally important based on economic, social and environmental criteria. Key findings included the following (Barron et al. 2011):

- Diffuse recharge is likely to become more variable and, since this variability is yet to be precisely quantified with current tools (e.g. Cuthbert et al. 2015; Shanafield and Cook 2014), planners and decision makers will need to consider this uncertainty and variability in addition to further field investigations and research in the water balances underpinning their water management plans
- *"Current knowledge of groundwater systems (both monitoring data and conceptualisation) is inadequate to allow informed climate change adaptation and management decisions in most of Australia. Models currently in use for management should undergo an audit to establish if they are fit for purpose for proposing climate change adaption strategies"*
- *"Not all groundwater systems are equally sensitive to climate change"*
- *"Groundwater/surface water interactions with rivers are highly sensitive to climate change and could have a profound effect on water availability"*
- *"Various climate models yield different results from similar initial scenarios – however, projections are consistent for south-west Western Australia and the southern Murray–Darling Basin, where all global climate models project a decrease in rainfall"*
- *"Of 14 aquifer areas identified as sensitive and important, 11 are dependent on groundwater (that is, groundwater comprises greater than 60 per cent of all water extraction)"*
- *"Adaption to climate change is predicted to incur significant costs for groundwater users and managers"*

3.3.1 Declining groundwater levels

Longer droughts will have a substantial impact upon populations that rely on groundwater for drinking water and for agricultural production and food security. This is a particular problem for Australia since many groundwater sources are already over-allocated. It is also possible that subsidence of the land surface (from historical or future dewatering or underground mining) may exacerbate the potential impacts of climate change and sea-level rise.

This is because there is not always a one to one correspondence between rainfall and groundwater recharge or between rising sea levels and rising groundwater levels. This ratio has been found to vary by as much as two (McCallum et al. 2010) to four (Harrington and Cook 2014) depending on the site and its unique combination of climate, hydrology, geology and land use. Site specific investigation, monitoring data and modelling data are needed to predict changes in groundwater levels and availability at every location.

Case studies

In the last decade Western Australia has experienced unprecedented population and economic growth in addition to dwindling water availability. Rainfall in Perth has declined by 12% since 1990, runoff to dams has fallen by more than 50% and groundwater levels have steadily declined. The coastal Gnangara Mound aquifer which previously supplied about 60% of Perth's water now supplies around 45% or 220 ML/d.

During the recent multi-annual Millennium Drought in Australia, groundwater storage in the Murray–Darling basin declined substantially and continuously by approximately 65 – 135 km^3 from 2000 to 2007 in response to a sharp reduction in recharge (Leblanc et al. 2009). This is equivalent to the loss of 18 to 38 Sydney Harbours of groundwater every year!

3.3.2 Rising groundwater levels

Section 1.3 of this report introduced many of the problems associated with elevated groundwater levels. Additional problems may include leakage of water into basements and instability of swimming pools, tanks and other subsurface structures that are not anchored.

Many coastal cities in Australia have billions of dollars of assets and infrastructure situated on low lying land below 3-5 m AHD which is at significant risk from climate change. These climate change impacts are discussed in more detail in Section 3.3.4.

3.3.3 Increased seasonality in groundwater recharge, levels and discharge

Most historical observations of climate and land use change, and numerical model predictions of future climate, point to a future with more frequent and severe temperature and rainfall extremes. Given that groundwater recharge is strongly linked to rainfall frequency, intensity and duration, ground cover and evaporative demand, these changes in climate will drive increased variability in groundwater recharge, increased variability in groundwater discharge and hence increased seasonality in groundwater levels.

This increased seasonality will be further exacerbated by changes in groundwater consumptive demand (e.g. less pumping during wet periods and more pumping during dry periods). The larger variability will place increasingly larger stresses on natural ecosystems, such as those supported by spring discharge (Figure 3.5), in addition to town water supplies and irrigated agriculture.

This increased variability will alter the makeup of ecological communities in favour of species that are more tolerant to extremes in temperature and water availability. Town water supply restrictions may become the norm. In addition, groundwater may no longer be available (or economically accessible) to support irrigated agriculture during key growth periods or drought. All of these changes have the potential to threaten water quality and quantity, cause serious impacts upon the global food chain and threaten food security. These ecosystems, agricultural, water supplies and waste-water infrastructure are discussed in more detailed in 'CoastAdapt' Impact Sheets 8, 11 and 12.

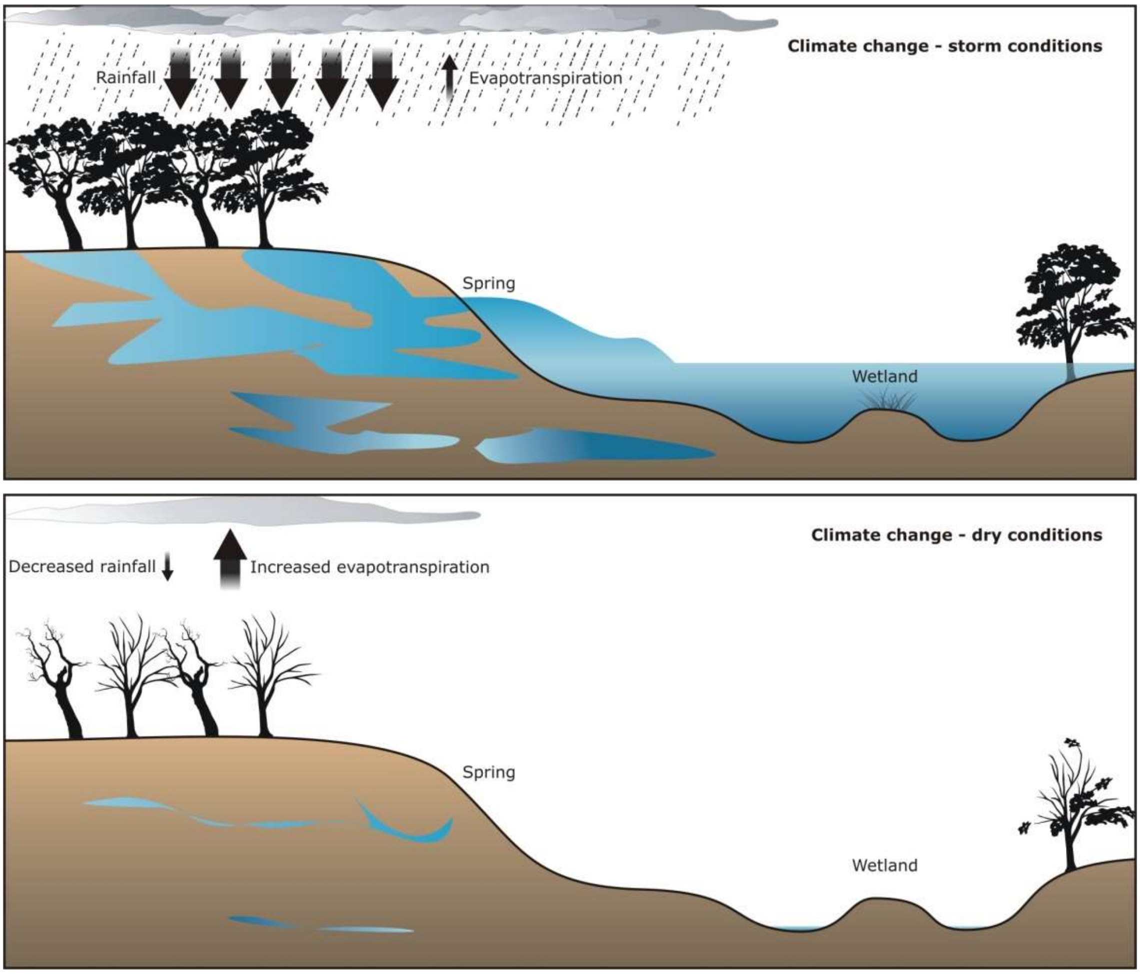

Figure 3.5: Impacts of increased seasonality on groundwater. **Source:** Developed by the author. © Water Research Laboratory, UNSW.

3.3.4 Inundation and saline intrusion

Increased frequency and severity of inundation and saline intrusion are the most likely impacts of climate change, particularly for shallow sandy aquifers in low-lying coastal areas. Inundation (Figure 3.6) is surface flow into and across low-lying areas from (possibly) more frequent and severe coastal storms. This water may be saline or brackish, resulting in the recharge of saltwater into freshwater aquifers thereby degrading the beneficial use category of the resource. Saline intrusion (Figure 3.7) is the progressive encroachment of saltwater through the subsurface. It is caused by higher sea levels and increased groundwater pumping.

Case study
The Water Research Laboratory at UNSW Sydney has reviewed sea level risks at a number of locations in Australia including in Tasmania and NSW. An analytical model study by Anderson et al. (2015) for one suburb predicted that groundwater levels might rise at twice the rate of sea-level rise. The ratio varied as a function of aquifer structure, properties, recharge and distance inland. Given typical variability in coastal soil types and ground surface elevation, a sea-level rise of 0.4 to 0.8 m might cause intermittent to permanent waterlogging of 20% to 45% of coastal land below 3 m AHD. Numerical and analytical models can be used to predict the amount of groundwater that would need to be pumped to lower the water table.

Fresh water contaminated with only 5% of seawater makes it is unusable for many beneficial purposes, including supplies for drinking, irrigation of crops, parks, gardens, golf courses and for groundwater dependent ecosystems (Timms et al. 2008). Under a contamination scenario these groundwater users would need to replace or supplement their groundwater supplies with town water and/or large rain tanks. To account for the increased seasonality in rainfall, these tanks would need to be considerably larger than current designs.

By itself, sea-level rise may only contribute a 5 m to 100 m inland encroachment of the salt water interface. However, when compounded by increased seasonality (longer droughts and elevated groundwater levels from more frequent extreme rainfall and inundation), adaptation strategies may cause increased rates of groundwater pumping and dewatering. Increased rates of groundwater pumping cause significantly greater saline intrusion problems. This is shown clearly by Ferguson and Gleeson (2012) from their numerical modelling case study from the United States (Figure 3.8). The lower panel provides, for the study site in America, the expected saline intrusion as a function of geology and population. The upper panel shows the saline intrusion caused by sea-level rise and groundwater pumping for select numbers of groundwater users for different hydraulic gradients. For coastal aquifers with steep hydraulic gradients, the impacts from coastal storms and saltwater inundation will be more costly than saline intrusion.

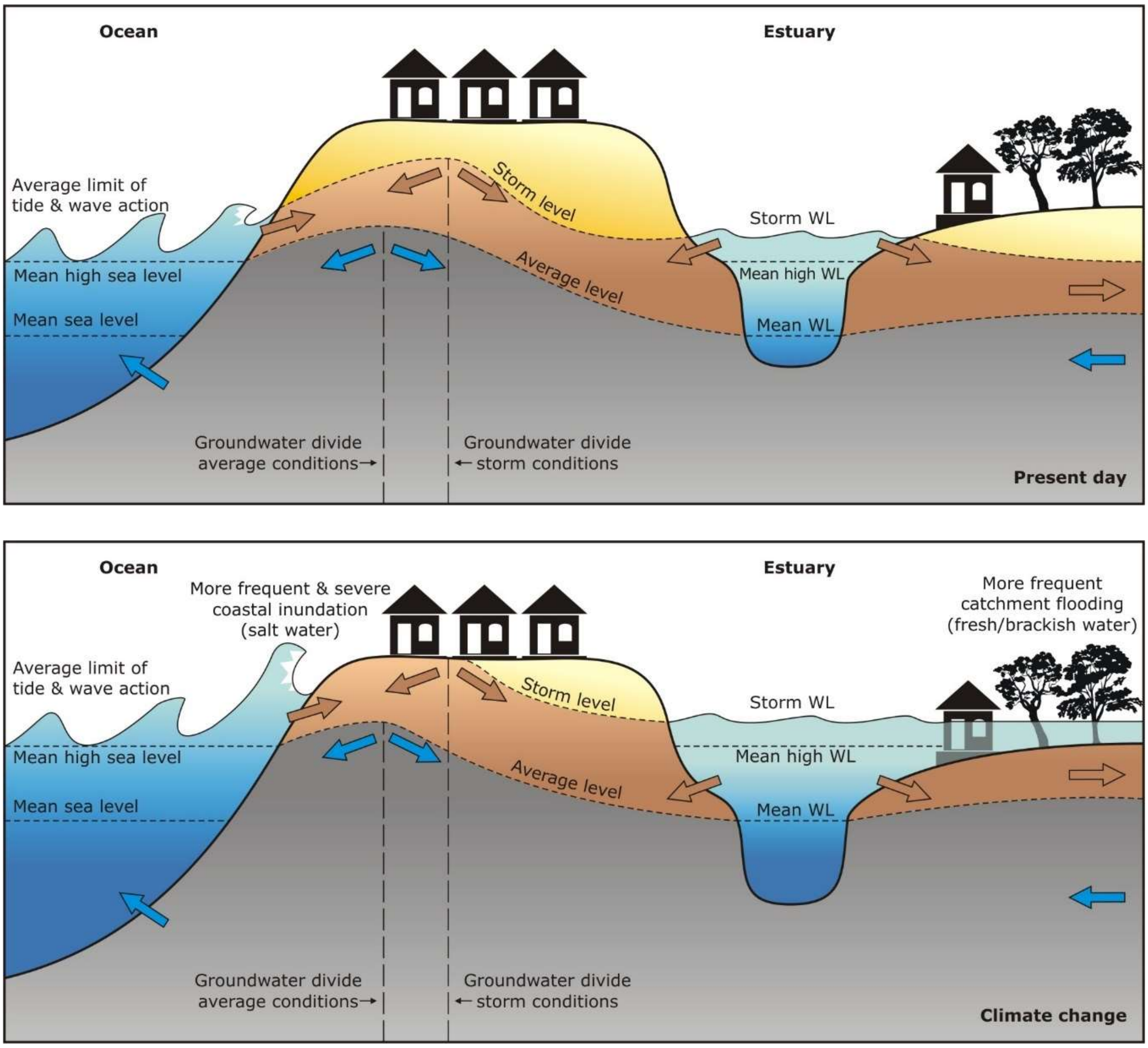

Figure 3.6: Increased sea level, more extreme rainfall events and more frequent and severe coastal storms will elevate coastal groundwater levels. **Source:** Developed by the author. © Water Research Laboratory, UNSW.

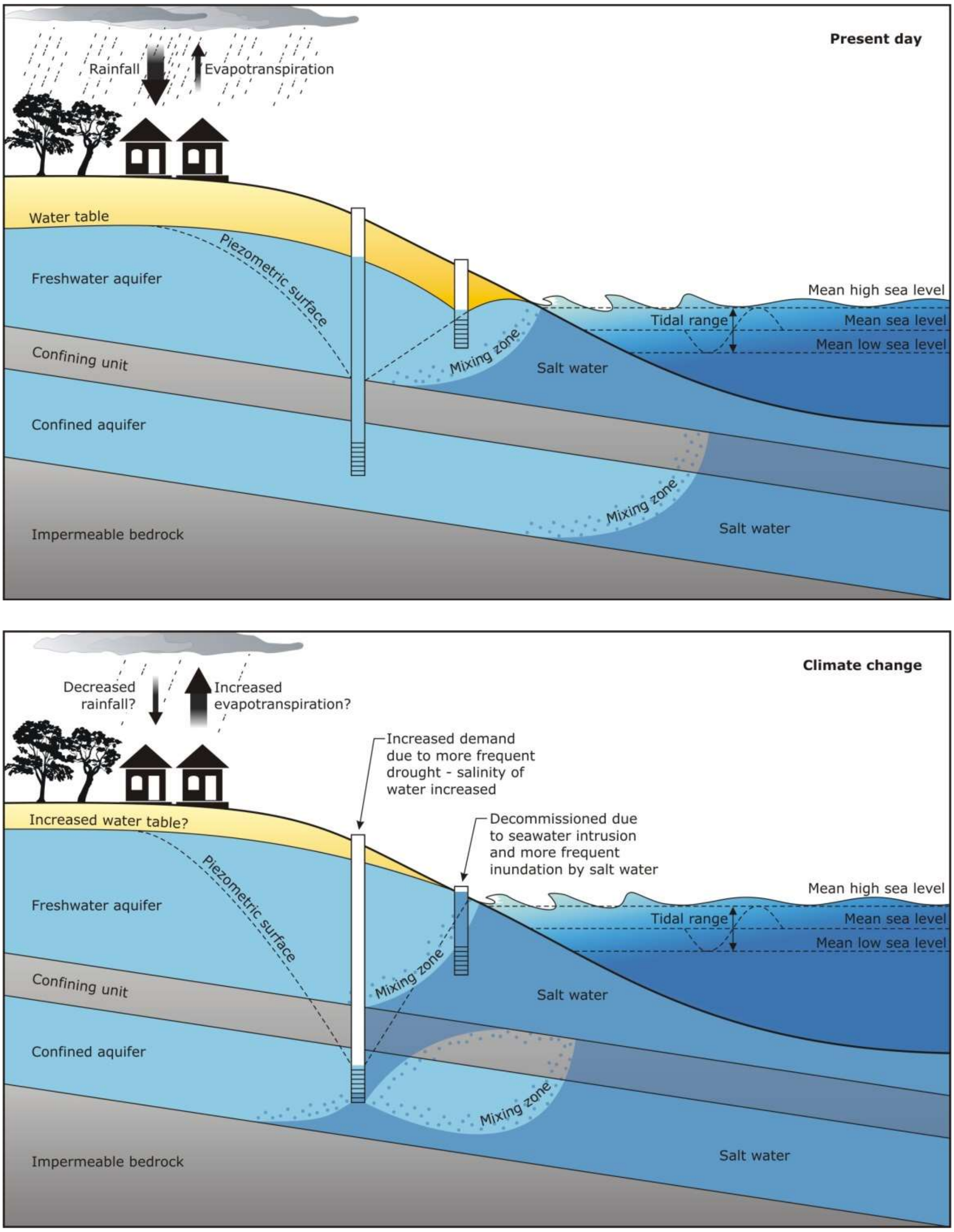

Figure 3.7: Increases in sea level, more frequent and severe coastal storms, decreases in mean rainfall, increases in evaporative demand and increases in groundwater pumping will result in a landward shift in the position of the saltwater interface. **Source:** Developed by the author. © Water Research Laboratory, UNSW.

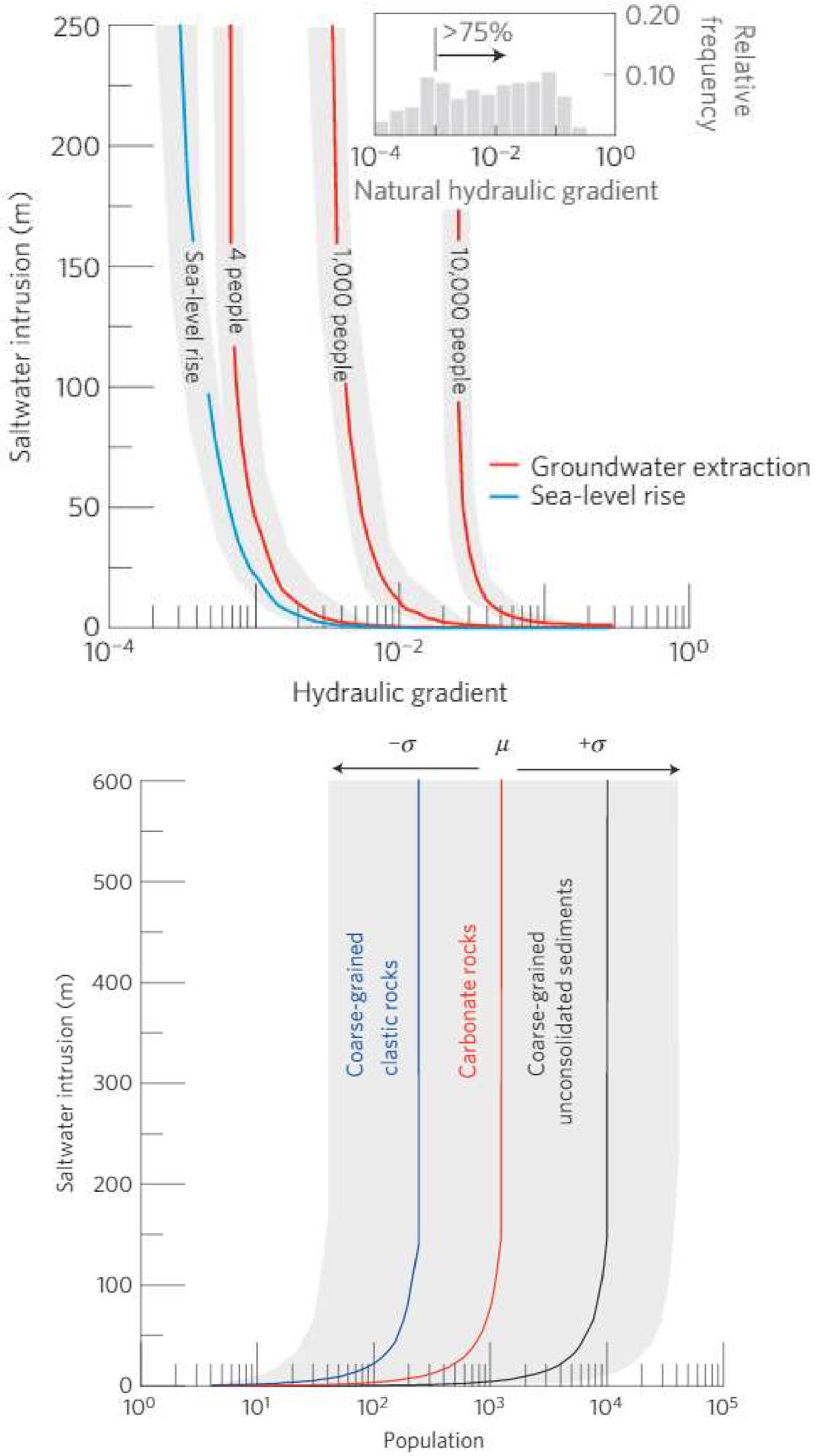

Figure 3.8: Influence of sea-level rise, groundwater extraction and geology on extent of sea-water intrusion for coastal watersheds in the United States (excludes inundation). **Source:** Reprinted by permission from Macmillan Publishers Ltd: [NATURE CLIMATE CHANGE] (Ferguson and Gleeson 2012), copyright (2012).

Inundation and seawater intrusion risks in Australia
Comprehensive investigations of seawater intrusion (SWI) in Australia are relatively uncommon (Werner 2010) because of our relatively short history of coastal groundwater exploitation. Thus far, only a few SWI hotspots have been noted. In more developed aquifers overseas, saline intrusion has already occurred, for example in Los Angeles, Spain and the Mediterranean coast.

Irrigation areas between 0 and 5 m AHD that are potentially at threat from seawater salinisation cover an estimated 46,060 hectares or 1.4% of Australia's irrigation area (Werner et al. 2008). Nation et al. (2008) reported that Queensland's more extensive irrigation areas were most vulnerable to SWI along with some smaller areas in Victoria, South Australia and Western Australia. New South Wales, Tasmania and the Northern Territory were also flagged for further assessment because there were signs indicating a vulnerability to SWI, such as lowered groundwater elevations, but no documented evidence of any SWI investigation.

Preliminary mapping of coastal inundation risks areas across Australia were prepared by the Commonwealth of Australia (2010) to show the predicted extents of inundation at Highest Astronomical Tide (HAT) in 2100 as low (0.5 m), moderate (0.8 m) and high (1.1 m) sea-level rise scenarios, exclusive of any local flooding. These maps can provide an initial indication of aquifers, groundwater resources and groundwater nuisances that might need to be managed more carefully into the future (e.g. Figure 3.9).

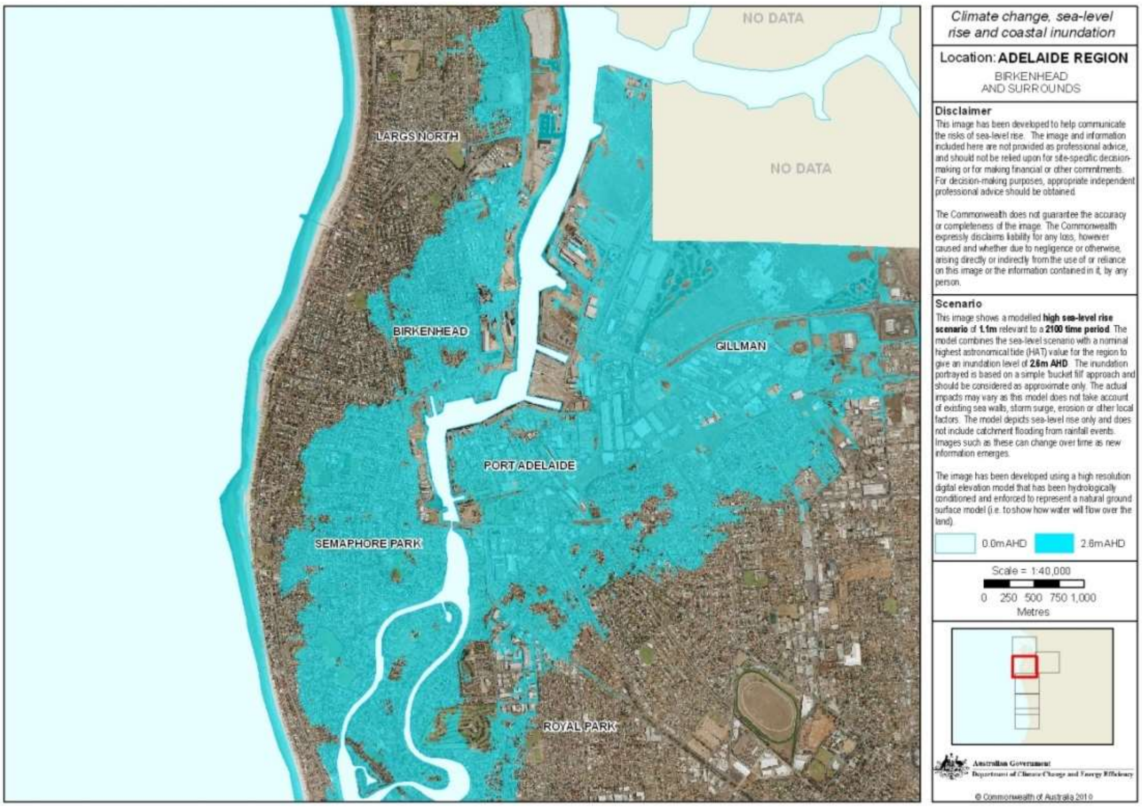

Figure 3.9: Climate change, sea-level rise and coastal inundation modelling for Port Adelaide. **Source:** © OzCoasts (Geoscience Australia) 2012.

In 2012, Geoscience Australia (GA) and the National Centre for Groundwater Research and Training (NCGRT), in collaboration with state and territory water agencies, reported a literature review and national-scale assessment of the vulnerability of coastal aquifers to inundation and SWI (Ivkovic et al. 2012). While there was insufficient data at both the national and local scales to complete a full assessment, the threats of SWI excluding inundation (Figure 3.10) and inundation (Figure 3.11) were assessed at a number of locations along the Australian coast line.

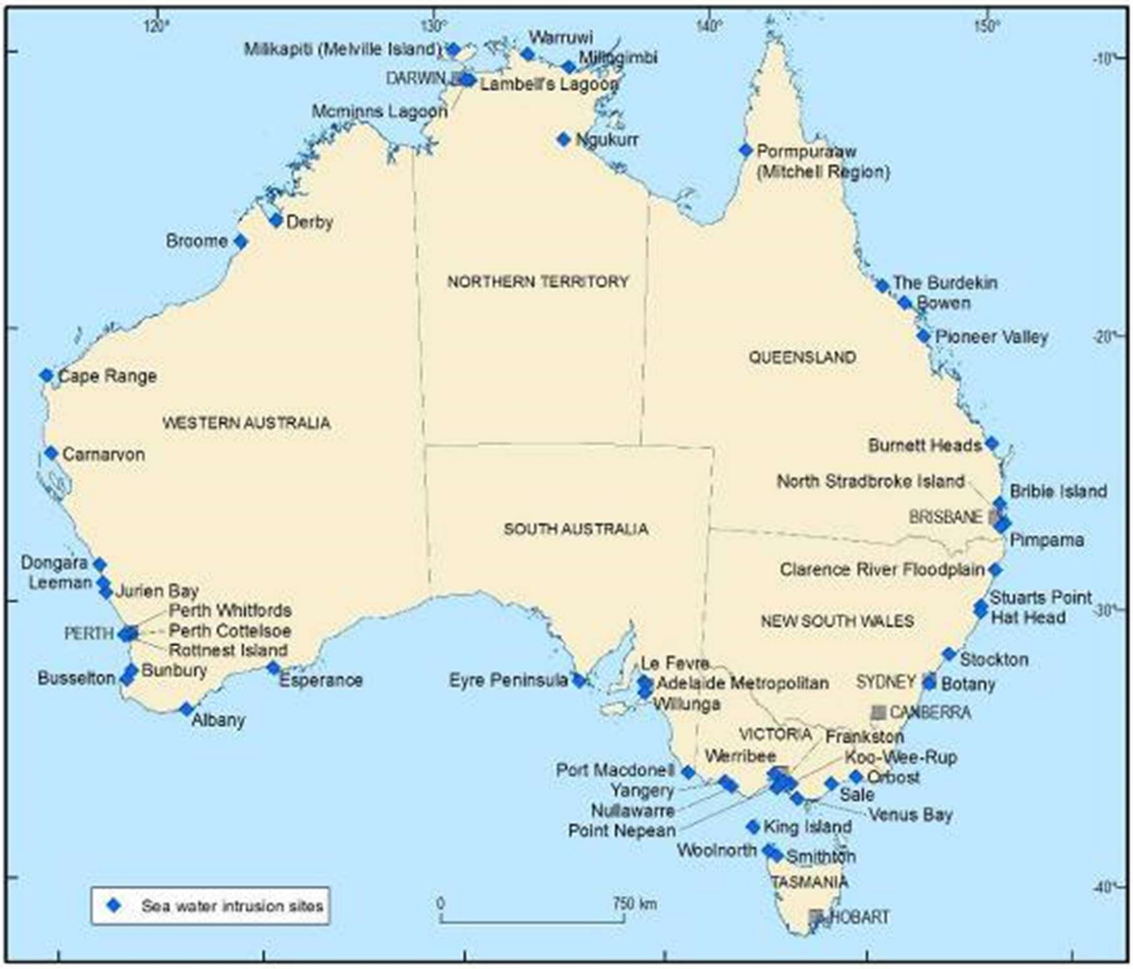

Figure 3.10: Seawater intrusion threats assessed in Australia. **Source:** Ivkovic et al. 2012. © Commonwealth of Australia (Geoscience Australia) and National Centre for Groundwater Research and Training 2013.

The study mapped areas in each state at risk of inundation due to sea-level rise and storm surges based upon the following criteria:

- land less than 1m AHD at risk of inundation based on IPCC sea level predictions
- land between 1 m AHD and 5 m AHD at risk of inundation by storm surges based upon storm surges of 5 m AHD recorded in Australia
- land between 5 m AHD and 10 m AHD at risk of inundation by storm surges based on predictions for extreme storm events.

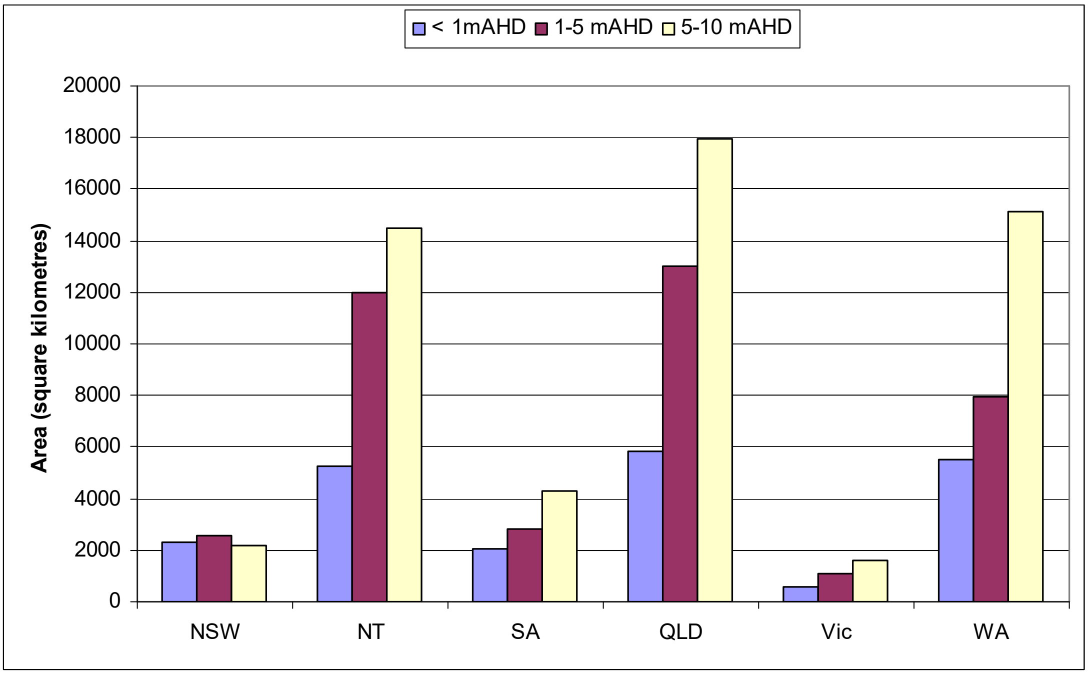

Figure 3.11: Seawater intrusion threats in Australia from limited national scale mapping. **Source:** Ivkovic et al. 2012. © Commonwealth of Australia (Geoscience Australia) and National Centre for Groundwater Research and Training 2013.

Other issues associated with saline intrusion, inundation and elevated groundwater in coastal areas are likely to include:

- accelerated corrosion of surface and sub-surface fittings including essential services (gas, water, electricity, communications, sewer)
- ingress of saltwater into sewer systems and impacts upon wastewater treatment
- saline water-logging of soils resulting in urban salinity and death of vegetation
- migration of noxious chemicals and gases from industrial contamination towards the land surface where they might be inhaled, ingested or adsorbed by humans.

3.3.5 Increases in groundwater temperature

Groundwater temperatures respond to changes in atmospheric temperature. Green (2016) notes: "*Soil water content and temperature are important factors in terrestrial biogeochemical reactions, land atmosphere interactions, and a critical determinant of terrestrial climate. Variability in vadose-zone hydrology, shallow water tables that support SWC, and ultimately infiltration that feeds aquifers are also affected by SWC and temperature…The combination of the heat-island effect from urbanisation and global warming on subsurface temperatures has implications for groundwater quality because of changes to subsurface biogeochemical reactions … Additional research is needed to understand and predict the full range of effects on groundwater quality from changes in the subsurface thermal regime and various biogeochemical reactions.*".

3.3.6 Water quality

The potential for enhanced migration of contaminants in soils and groundwater through increases in temperature and changes in salinity and level is particularly concerning with the potential for significantly increased costs for land and water management. Green (2016) suggests that "*nutrient transport rates beneath agricultural lands may also be sensitive to climate change*" and that "*relatively few studies have explored climate-change effects on pesticide fate and transport in the subsurface*".

Operation of landfills, contamination containment cells and other engineered facilities to contain waste or contaminants may be irreversibly altered by changes in groundwater levels, recharge and temperature. Design criteria and guidelines for these facilities will need to be updated to accommodate greater variability. There will be a shift towards more expensive contaminated land studies. New land and groundwater remediation projects may be required and the success rates of existing remediation techniques may decline. The impacts of climate change on land contamination are discussed in more detail in 'CoastAdapt' Impact Sheet 10.

3.3.7 Impacts summary

The interactions between climate change, Earth systems and groundwater may have a number of undesirable consequences including:

- dryland salinity (loss of productive land, vegetation mortality, ecosystem impacts)
- urban salinity (degradation to roads, road bases, footpaths, buildings, pipes, cabling)
- mobilisation of noxious gases from contaminated sites into basements, buildings, confined spaces or the land surface posing a risk to human health
- enhanced migration or mobilisation of soluble industrial contaminants in land, groundwater and waste containment facilities to the land surface or surface waters with flow on impacts for water quality, fisheries, agriculture, gardens and human health
- increased cost of managing (potentially salty or contaminated) groundwater ingress into basements, storage tanks, pipes (e.g. sewer, stormwater) with potential implications for human health and waste-water management
- instability of pools, tanks and other subsurface structures that are not anchored
- rising damp due to inadequate damp courses leading to mould issues and health risks
- increased salinity in coastal groundwater wells due to saline intrusion making water unusable for some (or all) purposes with consequential impacts for town water demand and/or economic viability of coastal agricultural and industrial producers
- waterlogging of coastal land including roads, residences, businesses and parks with consequential impacts for human health, recreation and economic productivity
- evolution of ecological systems in favour of species that are more tolerant to extremes in temperature and groundwater baseflow conditions
- more frequent town water use restrictions in locations with groundwater dependency
- inability to secure water supplies for irrigated agriculture during droughts and/or key crop growth periods with follow on impacts for food security and economic production
- increased groundwater extraction costs (drilling new groundwater wells, pumping from greater depths and treating water to an appropriate standard for beneficial use)
- more frequent problems with acid drainage in acid sulphate soil risk areas.

3.4 Groundwater management

The Australian national and regional governments, and its agencies, have many legal instruments, economic instruments, policy documents and guidelines for managing Australian groundwater water resources. Australian water supply authorities all possess forward looking water supply strategies that consider climate change to some degree. In relation to climate change many of these instruments are still in their infancy, however, they are gradually being revised and updated to facilitate the management of groundwater under more uncertain and variable future climates.

Groundwater related adaptation strategies may need to involve some combination of:

- retreat to higher ground
- reduced and more efficient water use and recycling
- remediation of contaminated soils and groundwater
- managed aquifer recharge to minimise seawater intrusion
- managed aquifer recharge to restore depleted aquifers
- reduced groundwater pumping to prevent saline intrusion
- improved design and management of underground waste storage facilities
- groundwater-surface water dewatering networks to minimise water logging
- introduction of more salt tolerant vegetation and urban structures / assets
- raising the ground surface and surface infrastructure to prevent inundation
- upgraded stormwater drainage and waste water infrastructure to facilitate drainage
- construction of surface water and groundwater barrier defences to minimise saline intrusion and waterlogging.

The cost to develop and implement adaptation strategies will be significant and efficient implementation will require many decades of planning and forethought. Options assessment planning may require field investigations, monitoring and data analysis programs to better characterise and predict response of the groundwater resource and its interlinked systems. The costs of this work will be reflected in tax rates, Council rates and costs of services, food and utilities.

3.4.1 Coastal Zone Adaptation

Early plans for coastal climate change adaptation in some NSW towns have focussed on surface water issues such as examining and costing options to prevent more frequent flooding and inundation. Options that are typically included in these assessments include coastal defences, land raising, improved storm-water drainage infrastructure (including pumps) and retreat. Very few of these studies have considered the groundwater risks or the costs of managing groundwater issues and quite often these are listed as an afterthought and an unknown.

This is not surprising given the complex interactions between groundwater, surface water, ecology and land use management practice. No individual town planner, consultant or scientist will be an expert in all of these inter-related disciplines. Therefore, ecosystems and groundwater users across Australia (and town planners, water managers and policy experts in particular) would benefit greatly from further coordinated and multi-disciplinary investment in the development of more detailed guidance documentation to support decision makers in local and state government.

3.4.2 Water supply security

Recent decades have seen considerable planning and development work to secure town water supplies for population growth and future climatic variability. For further details on climate change and management of water security refer to 'CoastAdapt Impact' Sheet 12.

Case study
The Western Australia Government (2012) recognises climate change.

Water efficiency measures introduced in Perth between 2001 and 2013 reduced water consumption by 29% per person saving 100 GL/yr. With the successful completion of the Perth Groundwater Replenishment trial system, WA Water Corporation is already recycling 13% of water inflows in WA and providing 21 GL of recycled water annually (Figure 3.12).

Future water supplies will be secured through further water use efficiency measures and the potential identification of new water source options. The Western Australia Water Corporation (2013) plan for 2030 targets a further 8% reduction in per capita water use in addition to recycling 30% of all waste-water flows to provide a further 46 GL/yr of recycled water.

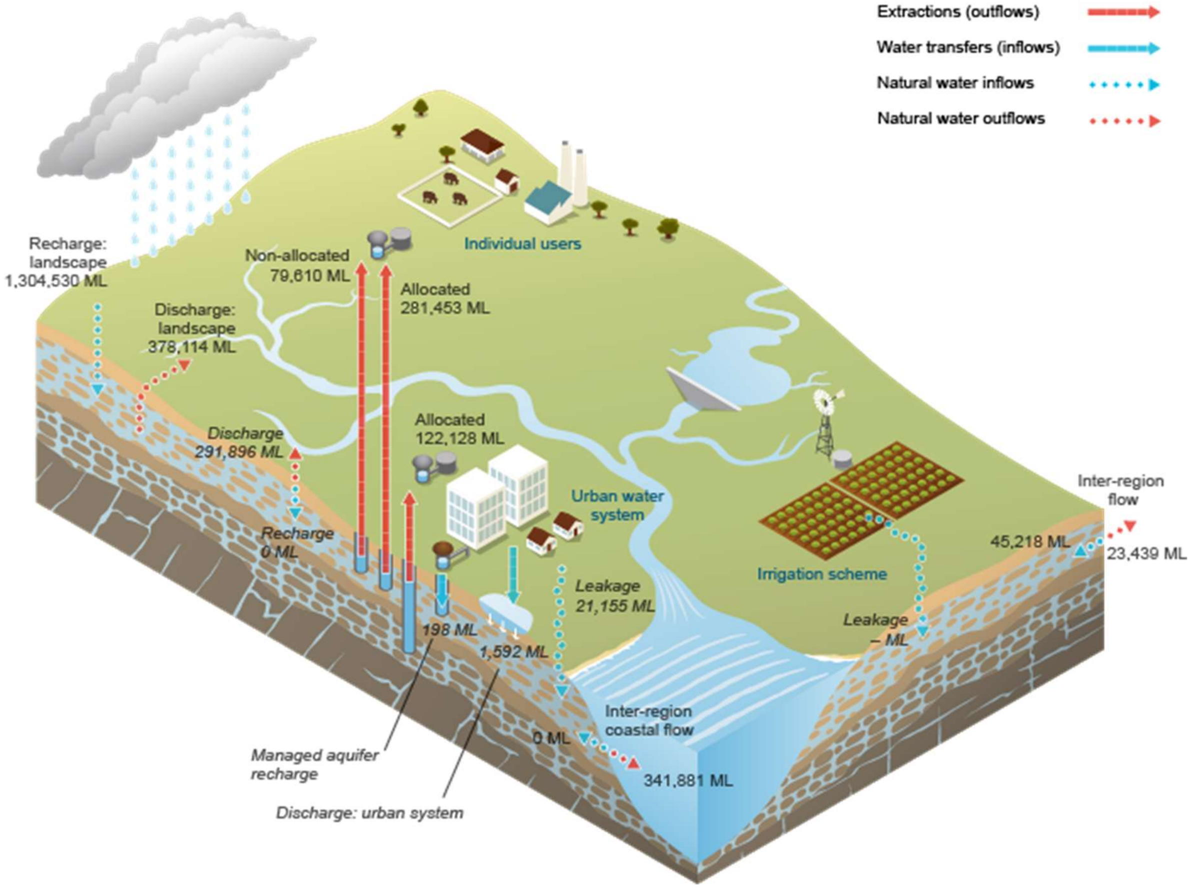

Figure 3.12: Managed aquifer recharge in Perth (2014-2015). **Source:** Bureau of Meteorology 2015. © Commonwealth of Australia 2017.

4. Summary

In 2005, Blackwell (2007) estimated that Australia's coastal zone generates upwards of $1,359 billion annually in ecosystem goods and services. With predictions of significant changes to the coastal zone from climate change and sea-level rise (Anon 2014) this is cause for great concern. Some 85% of Australia's population live within 50 km of the coastline (ABS 2004) to exploit these natural assets. A sea-level rise of just one metre would put some 30,000 km of roads and $226 billion of infrastructure at direct risk from inundation (Department of Climate Change 2009). It would also put some 21,000 - 55,000 km^2 of valuable coastal land at risk from rising groundwater tables and saline groundwater intrusion (Ivkovic et al. 2012).

Groundwater is water that flows through the sediments and rocks beneath our feet. The study of groundwater is called hydrogeology and it is a complex discipline. Groundwater is hard to see, expensive to measure and, due to complexity and spatial variability in geology, difficult to understand and challenging to simulate. Groundwater flows in response to gravity, pumping and infiltration of surface water into the ground. This infiltration (groundwater recharge) is a function of land cover, land use management practice (e.g. land clearing, irrigation and mining), evapotranspiration, flood frequency and severity, and rainfall intensity, frequency and duration.

Groundwater has many beneficial values in addition to ecological services including town and domestic water supply, irrigation of crops and pastures, industrial usage, even as a fluid for heating and cooling. Groundwater in Australia is thought to support some $34 billion in annual economic production and contribute directly to generating $6.7 billion of Gross Domestic Product (Deloitte Access Economics 2013).

Groundwater can also be a nuisance. It can be salty, acidic, contaminated and sometimes too close to the ground surface. Near ground surface it may interact with and damage urban structures, surface water bodies (e.g. estuaries, rivers, wetlands), ecological systems and human health. The cost of nuisance groundwater issues has, to the best of our knowledge, not been estimated.

Australia has many policies, guideline documents and various economic and legal instruments to maximise the benefits of Australian groundwater and to minimise the nuisance. In relation to climate change, however, many of these instruments are relatively new and being developed in different states at all levels of government.

Previous sections have discussed the potential movement of contaminants between water bodies and adjacent groundwater systems, as water bodies and groundwater cannot be considered in isolation. To successfully manage both resources, it is important that surface water and groundwater systems be considered in conjunction, as a whole (Winter et al. 1998). If a groundwater discharge regime prevails, then groundwater should be managed to prevent a corresponding degradation within adjacent surface water bodies. If a groundwater recharge regime prevails, then land use and surface water should be managed to prevent a corresponding degradation of the groundwater system. Practices such as dewatering and excavation in acid-sulfate-prone coastal regions must be managed to ensure that groundwater is not contaminated, so avoiding contamination of the adjacent creeks, rivers, lakes and wetlands.

Climate change poses a great many risks to the security of coastal and inland groundwater supplies supporting agricultural production, drinking water and ecological systems. In some locations there may be a decrease in groundwater levels and/or quality. Water supplies may no longer be available when needed or may be more expensive. In other locations groundwater levels will rise and groundwater quality will deteriorate due to the pervasive nature of many anthropogenic contaminants. Elevated groundwater levels and more mobile pollutants may degrade or sterilise farmland, damage urban infrastructure and alter ecological communities, which will affect the natural food chain. This will cause a range of damaging social, environmental, economic and human health outcomes.

Adapting to the groundwater impacts of climate change will require a multi-pronged approach. It may require retreat to higher ground and more efficient water use through recycling, water saving devices and changes to land use management practice. It may also involve reduced groundwater use, managed aquifer recharge and construction of barrier defences to minimise saline intrusion and inundation. The design and management of underground waste storage facilities will need to be considered, and more extensive and expensive remediation of contaminated soils and groundwater may be required. Stormwater drainage and waste water infrastructure may need to be updated to improve drainage, minimise corrosion and contamination. Groundwater and surface water dewatering networks may be needed to minimise water logging but would cause saline intrusion. More salt tolerant vegetation and urban structures / assets may need to be introduced and ground surface and infrastructure might need to be raised. This list is not exhaustive.

The linked nature of Earth systems means that predicting the exact impacts of climate change on groundwater and its users requires broad knowledge and complex simulation. Close interdisciplinary collaboration will be required to minimise the nuisance of groundwater and maximise groundwater availability under a changing climate.

Systems with feedback are challenging to simulate but not impossible. Predicting impacts requires baseline knowledge of climate, geology, hydrology, oceanography, ecology, hydrogeology and prevailing land use: the more detail the better. It also requires reliable predictions of the impacts of changing climate parameters which influence and interact with the hydrological, anthropogenic, physical and ecological systems that influence groundwater flow. In turn, changes in the properties and behaviour of the groundwater system will influence the functioning of each of these interlinked complex systems.

Our ability to make precise predictions of climate change has limitations. This uncertainty can be reduced through continued, ongoing investment. With appropriate data, funding and time, climate scientists, hydrologists, hydrogeologists and engineers can prepare more reliable and informed estimates of the uncertainty in predictions of future climate for informing adaptation decisions.

Without further investment in prediction, adaptation to groundwater changes will need to be informed by adaptive, reactionary management based solely upon observation. These observations should consist of continuous long monitoring data supplemented by the reconstruction of historical groundwater conditions from physical and biological analogues. As with any form of reactionary management, however, the outcomes may be sub-optimal and the costs of remediation more expensive than prevention. The best way to minimise the impacts of climate change on planetary systems will only be achieved through careful planning and visionary forethought. This is best achieved when there are observations and modelling simulations to consider.

The objectives of future work in the groundwater and climate change management space would be greatly facilitated by the following:

- Continued investment in GCMs to minimise the limitations, including improved simulation of groundwater and surface-water groundwater interactions to underpin management decisions
- Long-term ongoing monitoring of groundwater resources and reconstruction of past groundwater conditions from historical physical and biological analogues so managers can better plan and decide when to act
- Documentation and training materials that provide detailed technical and methodology guidance for best-practice predictions of groundwater related climate change impacts
- Multidisciplinary framework documents at the national or state-wide level to guide water practitioners towards implementing practical, consistent economically efficient and holistic (groundwater inclusive) climate change adaptation strategies.

Understanding groundwater, and planning for its efficient use and future management is harder than for surface water, takes a considerably longer periods of time and requires considerably more investment. Historically, investment in groundwater research and resource management in Australia, similar to elsewhere, has been provided in response to crises in surface water or groundwater availability. Several authors have referred to this process as the 'hydro-illogical' cycle. The issues surrounding climate change will not be managed practically or efficiently if investment in groundwater related climate change adaptation studies are managed in a similar fashion.

5. Further reading

All links accessed 24 November 2017:

Groundwater fact sheet:

- http://www.wrl.unsw.edu.au/sites/wrl/files/uploads/PDF/Groundwater-Facts.pdf

International climate change predictions and water accounting:

- Intergovernmental Panel on Climate Change (IPCC): http://www.ipcc.ch/
- NASA: https://climate.nasa.gov/

National resources on groundwater and climate change:

- Australian Government:
  https://www.environment.gov.au/climate-change/climate-science/impacts
  https://www.climatechangeinaustralia.gov.au/en/
  https://search.csiro.au/search
- National Climate Change Adaptation Research Facility
  Coast Adapt: https://coastadapt.com.au/likely-impacts-sector
  Adaptation Library: https://www.nccarf.edu.au/adaptation-library
- The National Centre for Groundwater Research and Training:
  http://groundwater.com.au/documents/groundwater-in-australia_final-for-web.pdf
  http://www.groundwater.com.au/fact_sheets
- Australian Academy of Sciences:
  https://www.science.org.au/learning/general-audience/science-booklets-0/science-climate-change
- UNSW Connected Waters Initiative:
  http://www.connectedwaters.unsw.edu.au/articles/2009/01/potential-impacts-sea-level-rise-and-climate-change-coastal-aquifers

National climate and water accounting:

- Australian Government, Bureau of Meteorology:
  Annual Climate Summaries: http://www.bom.gov.au/climate/annual_sum/2015/
  National Water Accounts: http://www.bom.gov.au/water/nwa/2015/
- Commonwealth Scientific Industrial Research Organisation (CSIRO):
  State of the Climate: https://www.csiro.au/en/state-of-the-climate

State resources on groundwater and climate change:

- QLD: https://www.qld.gov.au/environment/climate/climate-change/
- NSW: http://climatechange.environment.nsw.gov.au/Impacts-of-climate-change/
- VIC: http://www.climatechange.vic.gov.au/action/water
  http://www.depi.vic.gov.au/environment-and-wildlife/climate-change
  http://www.depi.vic.gov.au/water/groundwater
- TAS: http://www.dpac.tas.gov.au/divisions/climatechange
- SA: http://www.climatechange.sa.gov.au/
  https://data.environment.sa.gov.au/Climate/SA-Climate-Ready/
  http://www.environment.sa.gov.au/Science/Science_research/climate-change
- WA: https://www.der.wa.gov.au/your-environment/climate-change
- NT: http://www.darwin.nt.gov.au/climate-change/climate-change

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