

Coastal Groundwater

Water Research Laboratory
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School of Civil and Environmental Engineering

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WRL Technical Report 2017/04

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by
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National Climate Change Adaptation Research Facility
'CoastAdapt' Programme**

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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. [GYhiYa Yblp'UbX'lbZUel'fi Wi fy](#) (Ware 2017)
3. [Emergency management](#) (Jago 2017)
4. [Freshwater ecosystems and biodiversity](#) (Capon 2017)
5. [< i a Ub \ YUH](#) (Bambrick 2017)
6. [Coastal tourism](#) (Becken 2017)
7. [: lg\ YfiYg'UbXUei UW'hi fy](#) (Pearson and Connolly 2017)
8. [9W'gnghYa g](#) (Paice and Chambers 2017)
9. [Vulnerable communities](#) (Hanson-Easy and Hansen 2017)
10. [7cbHLa lbUH'X'UbX](#) (Morton 2017)
11. [7cUelU'U'fiW'hi fy](#) (Williams 2017)
12. [K UMF'gi dd'mUbX'k UglY'k UMF'a UbU Ya Ybh](#)(Ware 2017)
13. [Communities](#) (Smith 2017)
14. [9ghi UfiYg](#) (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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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.

**:][i fY &% 'Groundwater is water that fills the spaces between soils and rocks''Gci fW. Waller 1982. ©
U.S. Geological Survey.'**



: || i fY&'& The hydrological cycle – groundwater is historical rainfall" Gci fW. 'Adapted from NSW Government 1998

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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.



: || i fY&' . 'Components of a groundwater system' Gci fW. '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

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

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.

: || i fY &%. Idealised theoretical position of the salt water interface. 'Cci fW. Timms et al. 2008 © Water Research Laboratory, UNSW'

Under natural conditions, the regional flow of fresh water towards the ocean

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: || i fY'&%'& Vertical groundwater capture zone. 'Gci fW. 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

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).

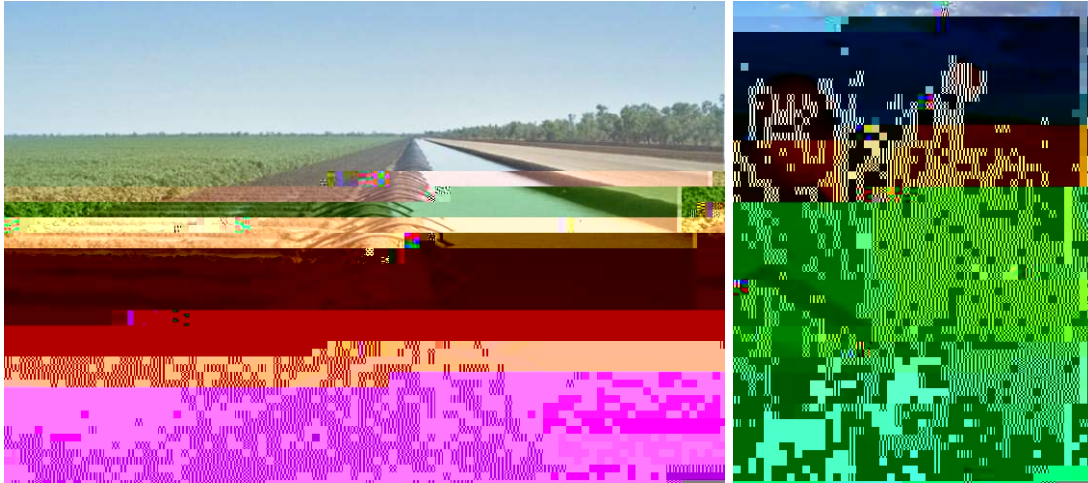


Figure 2.14. Irrigation of cotton with groundwater and monitoring of levels in a well. © Water Research Laboratory, UNSW

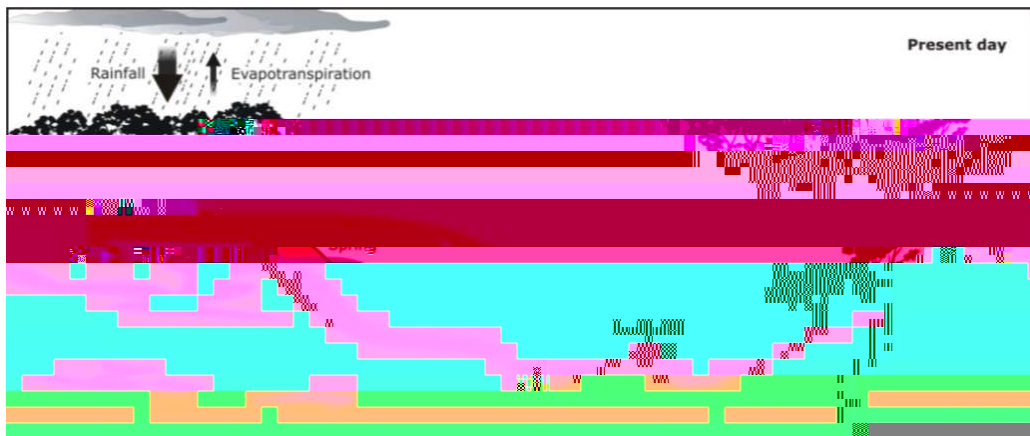


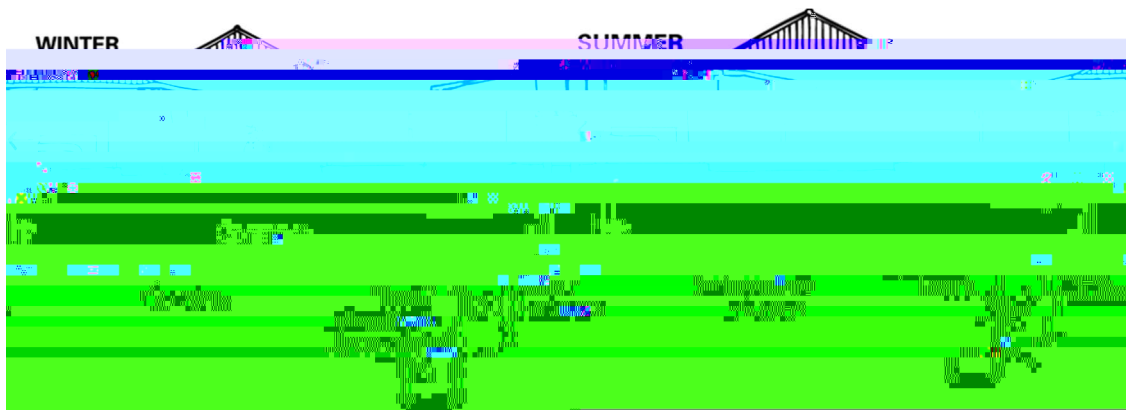
Figure 2.15. Groundwater provides ecosystem services. © Water Research Laboratory, UNSW

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.



: || i fY & % . 'Managed Aquifer Recharge.' Gci fW. Page et al. 2010. © Copyright CSIRO Australia. '



: || i fY & % . 'Geothermal heating and cooling.' Gci fW. Mine 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).

: || i fY & % . 'Groundwater dewatering in construction – Botany Sands aquifer.' Gci fW. Wendy Timms © Water Research Laboratory, UNSW. '



: || i FY&% . 'Acid sulphate soils and reclamation of land for agriculture.' Gci fW. '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

Figure 1. Acid drainage (pH 2.84) from reclaimed agricultural coastal land at Cattai Creek (D. Rayner © Water Research Laboratory, UNSW), Figure 2. Deposition of iron from acid drainage on an engineered river bank (Wendy Timms © Water Research Laboratory, UNSW), Figure 3. Fish kill in Clybucca Creek, NSW (Max Osborne, North Coast Local Land Services), Figure 4. Fish kill in Clybucca Creek, NSW (Penny Kendall).

Figure 5. Problems caused by acid drainage in NSW

Figure 6. Dryland salinity in Western Australia. © 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 caused 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.

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: || i fY' " . 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). Gci fW. Hamington and Cook 2014 (from Chiew and Prosser 2011). © Copyright CSIRO Australia.

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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

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.**

: [i fY' '(. Potential impacts of climate change on groundwater: Gci fW. 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] lion na ~ 013) m m es the ! expansion or cont

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):

x 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; Sharafeld 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

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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.

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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.

Fresh water contaminated with only 5% of seawater makes it 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

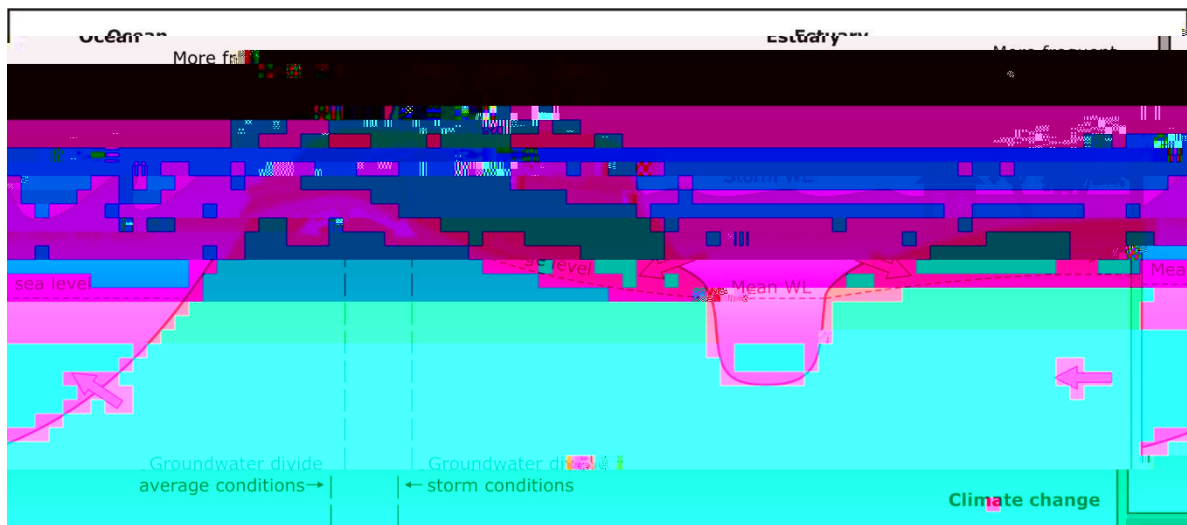
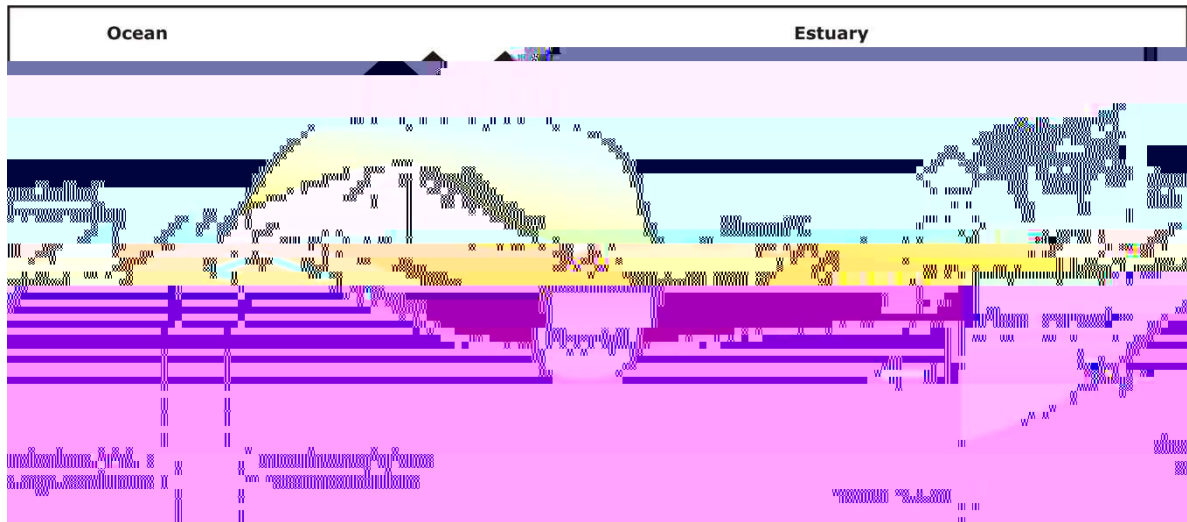


Figure 1. Increased sea level, more extreme rainfall events and more frequent and severe coastal storms will elevate coastal groundwater levels. Developed by the author. © Water Research Laboratory, UNSW

:] [i fY' "4. Increases in sea level, more frequent and severe coastal storms, decreases in mean rainfall,

Figure 1. Influence of sea level rise, groundwater extraction and geology on extent of sea water intrusion
for coastal watersheds in the United States (excludes inundation). Citi FW. Reprinted by permission

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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 3.11: Seawater intrusion threats assessed in Australia. Givoni 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:

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

: [[i fY" "% Seawater intrusion threats in Australia from limited national scale mapping 'Gci fW. Tvlovic 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:

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

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Groundwater temperatures respond to changes in atmospheric temperature. Green (2016) notes:

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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

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- x Continued investment in GCMs to minimise the limitations, including improved simulation of groundwater and surface-water groundwater interactions to underpin management decisions
- x 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
- x Documentation and training materials that provide detailed technical and methodology guidance for best-practice predictions of groundwater related climate change impacts
- x 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.

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Harrington, S. and Cook, P. (2014), Groundwater in Australia, National Centre for Groundwater

