Groundwater in Australia

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Contents

Groundwater is one of Australia's most important natural resources. It is a major source of water for urban areas, agriculture and industry. It is used throughout the country, and for many regions is the only source of water available – numerous townships, farms and mines are totally reliant on groundwater.

The importance of groundwater is most pronounced in Australia, which is the driest inhabited continent on Earth and where surface-water resources are limited over vast areas.

Despite its importance, groundwater is often undervalued and poorly understood.

This may in part be due to its nature as a complex, hidden resource that is difficult to conceptualise. Many myths and misconceptions surround groundwater and its availability.

It often plays a crucial role in sustaining stream flows, particularly during droughts when it can also be used as an alternative water source. Many ecosystems, including some of our most iconic, depend on groundwater discharge or access to it.

For instance, aquifers are often wrongly thought of as 'underground streams' or 'underground lakes'.

As more and more pressure is placed on groundwater resources through increased pumping and a changing climate, declines in groundwater levels are causing a growing awareness of groundwater as a critical natural resource.

This document briefly summarises the current state of knowledge on groundwater in Australia, and discusses some of the major groundwater issues.

Overview of Australia's groundwater resources

The nature of Australian groundwater resources

A simplified map of Australia's groundwater resources is shown in Figure 1, with the darker shades of blue and green corresponding to the most productive groundwater regions. Some iconic groundwater resources in Australia include: the Great Artesian Basin, which covers one fifth of the continent; the major alluvial aquifers of the Murray–Darling Basin, which support Australia's major food bowl; the Perth Basin, which supplies much of Perth's water demands; the Canning Basin in northern Western Australia; the Daly Basin of the Northern Territory; and the Otway Basin aquifers of south-east South Australia and south-west Victoria. Although it gives a broad national overview of Australia's major groundwater resources, Figure 1 does not show the many other crucial groundwater resources that occur over smaller areas and are equally important for sustaining communities, agriculture and the Australian economy.

Figure 1 separates groundwater resources into two broad categories. The dark and light blue regions correspond to sedimentary aquifers, where groundwater is stored in and flows through the pore spaces of rocks and sediments. The dark and light green regions correspond to fractured rock aquifers, where groundwater flows primarily through fractures and fissures in the rocks. Early groundwater development mainly occurred in sedimentary aquifers, and most groundwater extraction is still focused in these systems. This is because sedimentary aquifers generally underlie the best arable lands and tend to have higher groundwater yields, whereas fractured rock aquifers typically outcrop in upland areas, where water tables are usually deeper and extraction costs are higher.

Sedimentary aquifers develop in permeable layers of gravel and sand and usually occur in the flatter low-lying landscapes of Australia, beneath riverine floodplains and within geological basins. They can be consolidated (e.g. sandstone) or unconsolidated (e.g. sand). The coastal sands aquifers of New South Wales and Queensland, and Albany and Esperance of Western Australia (Figure 1), typically cover small areas in shallow sedimentary deposits and are influenced by their close proximity to the ocean. Alluvial aquifers, for example the Pioneer Valley in Queensland (Figure 1), form within the sediments deposited by streams and are often in close connection to those streams. Sedimentary basins, such as the Great Artesian Basin (Qld, NT, NSW and SA), the Canning Basin in northern Western Australia and the Perth Basin (WA), contain extensive and deep aquifers with considerable storage. Karstic aquifers, which may be part of sedimentary basins, have unique features such as caves and sinkholes which can rapidly transmit water. Examples of Karstic aquifers occur in the Daly Basin (NT) and the Otway Basin (SA, Vic) (Figure 1).

Fractured rock aquifers are prevalent throughout much of the Great Dividing Range of eastern Australia, Tasmania, the Flinders Ranges, and the ancient hills and ranges of Western Australia and the Northern Territory (Figure 1). Basalt aquifers, such as those in the Atherton Tablelands of Queensland, have a high degree of brittle fractures and tend to be more productive than fractured metamorphic and intrusive igneous rock aquifers, such as those found in the Mount Lofty Ranges, located near Adelaide in South Australia.

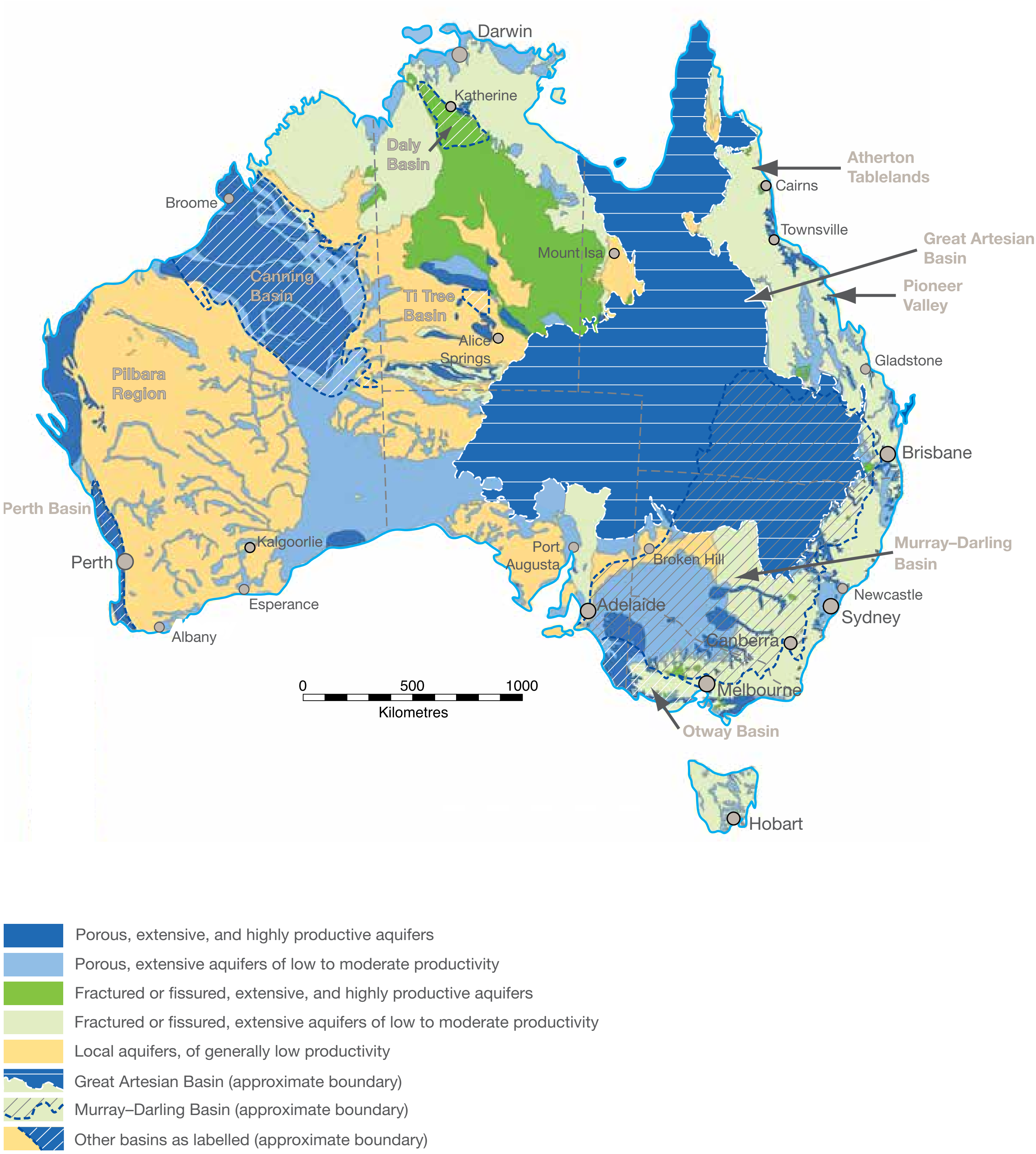


Figure 1. Map of Australia's groundwater resources, showing generalised hydrogeology and the locations of some iconic groundwater basins (modified from Jacobsen and Lau, 1997). Note: the base hydrogeology map was produced in 1997 and the basin boundaries shown are the most recent available. Hence the relationships between basin boundaries and geological boundaries should be considered to be approximate only.

Groundwater salinity

Whilst groundwater is present throughout Australia, much of it is too saline for drinking or agricultural purposes. This is particularly the case in internally draining arid and semi-arid regions where evaporation considerably exceeds rainfall. Here, the low levels of salts that are naturally present in rainfall become concentrated during recharge through the processes of evaporation and transpiration, leading to low recharge rates and the gradual accumulation of salt in the landscape. Ancient groundwater resources that have long flow paths are also often salty. Here, the groundwater picks up salts from the dissolution of minerals as it passes through the aquifers.

Detailed groundwater salinity maps are available for many local regions and aquifer systems of Australia (e.g University of Ballarat, 2012; Department of Environment, Water and Natural Resources, 2012 and 2013; Department of Water, 2013). However, Figure 2 provides a simplified overview of groundwater salinity in Australia, showing the proportion of each groundwater province with groundwater salinity (total dissolved salts) greater than 1,500 mg/L. This number is relevant because it is the salinity threshold for irrigation of most crops, although some crops can tolerate higher salinities.

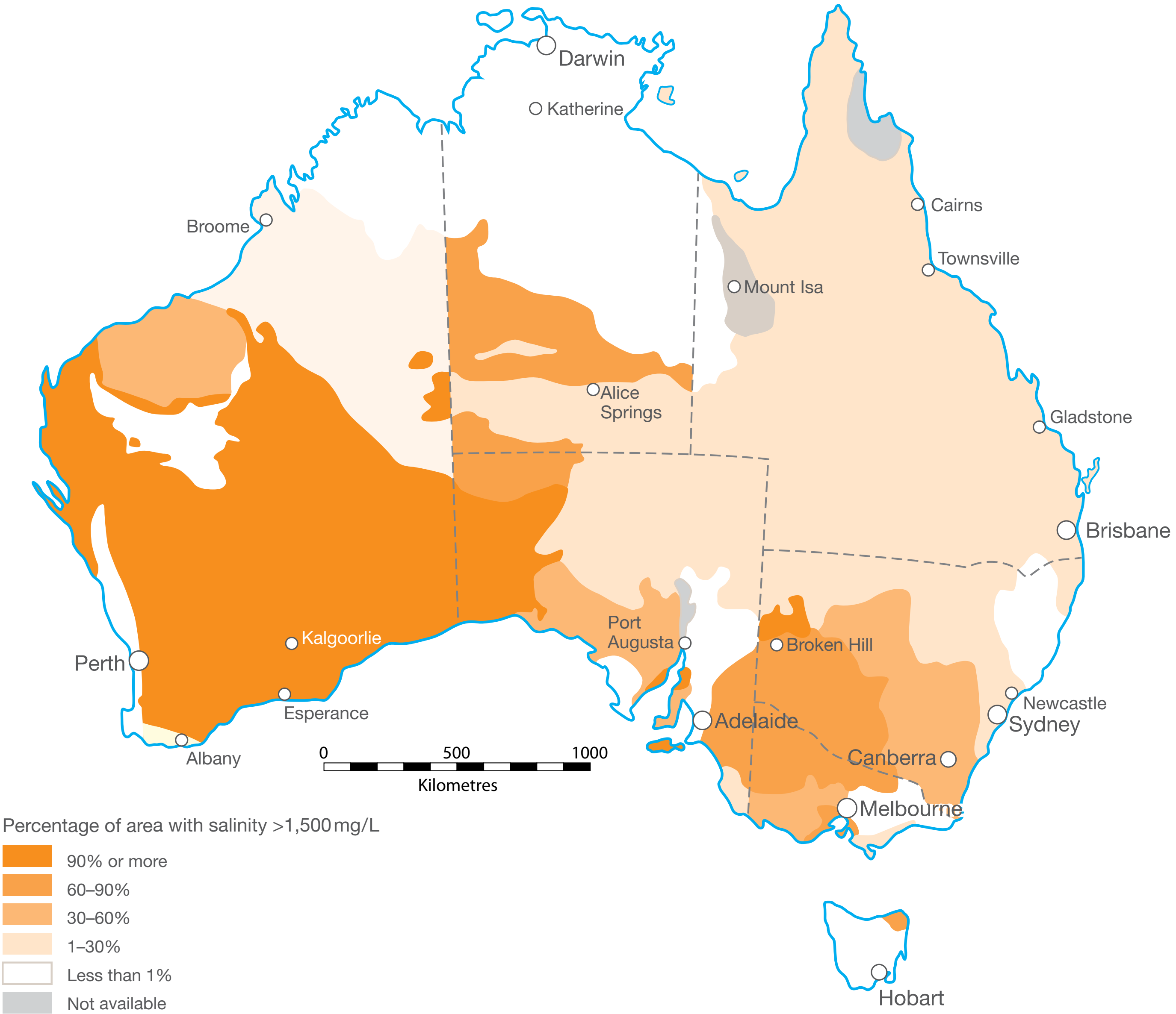


Figure 2. Map showing the proportions of each groundwater province that contains saline groundwater, where total dissolved salts (TDS) exceed 1,500 mg/L (ABS, 2005; Primary Industries and Resources SA, 2009; CSIRO, 2009a–c; Department of Environment, Water and Natural Resources, 2011b, 2012 and 2013; University of Ballarat, 2012; Department of Water, 2013)[1].

[1]The groundwater provinces shown in this figure are based on data provided to the ABS in 2000 by the various state and territory governments. The figure is based on that of the ABS (2005) and modified where additional data is available as per the references provided.

Consumptive groundwater use

Accurate statistics on groundwater abstraction and use in Australia are difficult to obtain due to limited monitoring infrastructure and inconsistent national reporting procedures, including inconsistencies in water accounting methods and what is reported as 'groundwater use' both between jurisdictions and reporting periods. In addition, only a small proportion of abstraction wells are metered. Some statistics are provided below to give an indication of historical trends in groundwater use in Australia, although these are considered to be very approximate for the above reasons. Moving into the future, more consistent and comparable data are expected to become available through the Australian Water Resource Information System (AWRIS), which is being developed by the Bureau of Meteorology under the National Water Initiative (Bureau of Meteorology, 2013). In general, the implementation of the National Water Initiative (see page 11) means that water accounting systems should become more comparable across the country and that national-scale changes to groundwater use will be easier to quantify in the future.

In recent years, the estimated total water consumption in Australia has been of the order of 15,000 GL per annum. Approximately one third of this water, roughly 5,000 GL per annum, has been reported to be sourced from groundwater (ABS, 2005), with the remainder derived mostly from surface-water sources (desalination accounts for a small but growing proportion, approximately 300 GL per annum in 2012). Many in the groundwater sector consider that actual groundwater use may be approximately double this. Notably, reported groundwater use in Australia increased by approximately 60% between 1983–84 and 1996–97, from 2,600 GL/yr to 4,200 GL/yr (NLWRA, 2001) (Figure 3). This was caused not only by an increase in population, but by people switching to groundwater from surface-water sources that had become more limited and more tightly regulated. Figure 3 also shows an increase in groundwater use between 1996–97 and 2009–10 for some states, but a decrease for others. The apparent decrease may be a misrepresentation in some cases, due to the inconsistencies in data as described above. However, decreases in use over this time frame are plausible for those jurisdictions in the south-east of the Australian continent, where irrigation is a major use of groundwater (e.g. SA and Victoria). During the millennium drought, which affected much of the 2000s, rainfall was below average across much of the south-east and south-west and, in particular, across the Murray–Darling system, reducing the availability of groundwater supplies (ABS, 2010).

As an example of the differences in methods used for water accounting over time and the difficulty in obtaining comparable data, the Western Australian Department of Water considers the 1983–84 estimate of groundwater use for that state to be too low, as this included only consumptive use. The 1996–97 estimate is derived from information on groundwater entitlements, providing an upper bound for potential groundwater use[2]. Having now moved towards a system of metered groundwater abstractions (although many wells are still not metered, including 170,000 domestic wells in Perth), the 2009–10 estimate for Western Australia is 1,714 GL. Despite the inconsistencies in the data reported for Western Australia, the overall trend of increasing groundwater use, with Western Australia also being the highest groundwater user, is considered to be correct[3]. These inconsistencies are common across all states. For New South Wales, the groundwater use reported is that recorded when meters fitted to bores were visited by the New South Wales state water department or its representatives. Additionally, the reported use for New South Wales is for access license holders in the major groundwater sources only and there can be significant use of groundwater resources that are not fully metered[4]. In the case of South Australia, estimates of groundwater use for irrigation (the dominant groundwater use in SA) in 1983–84 and 1996–97 were made using crop area-based approaches, which generally overestimate actual use. The lower value for 2009–10 probably reflects the more universal application of meters in prescribed areas, as well as the effects of the millennium drought on available groundwater resources[5].

Figure 4a shows that Western Australia, New South Wales and Queensland are the highest groundwater users of the Australian states and territories. Again, these figures should be considered to be indicative. The states and territories with the most reliance on groundwater are Western Australia, the Northern Territory, and New South Wales (Figures 4b,c). The Northern Territory sources 90% of its water from aquifers and Figure 4b suggests that New South Wales and Victoria have also significantly increased their reliance on groundwater over the past two decades. The highest concentration of groundwater use is in the Murray–Darling Basin, which covers parts of South Australia, Victoria, New South Wales and Queensland, where an average of 1,795 GL of groundwater is abstracted annually, primarily to support irrigated agriculture (Murray–Darling Basin Authority, 2012). Here, groundwater use represents 16% of total water use in the basin (CSIRO, 2008).

[2] WA Department of Water, pers. comm., 2 May 2013.
[3] WA Department of Water, pers. comm., 3 Sept 2013
[4] NSW Office of Water, pers. comm., 2 Sept 2013
[5] SA Department of Environment, Water and Natural Resources, pers. comm., 2 Sept 2013

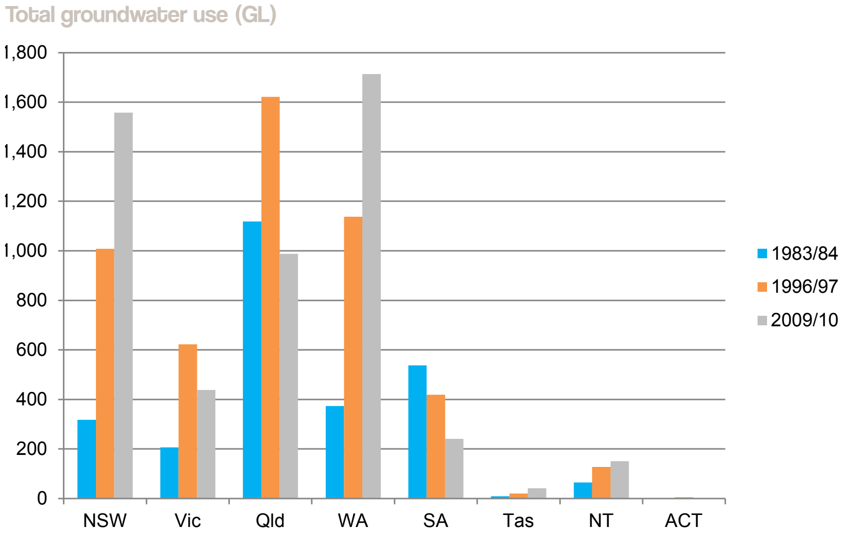


Figure 3. Change in annual groundwater use (GL) between 1983–84, 1996–97 and 2009–10 (National Land and Water Resources Audit, 2001; the Victorian Department of Sustainability and Environment, 2011; ABS, 2011).

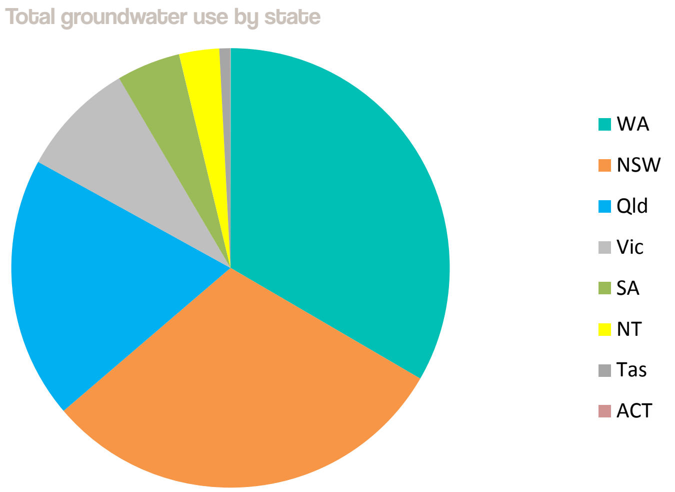


Figure 4a. Groundwater use for each state or territory as a proportion of total national groundwater use in 2009–10 (ABS, 2011; Department of Water, 2010).

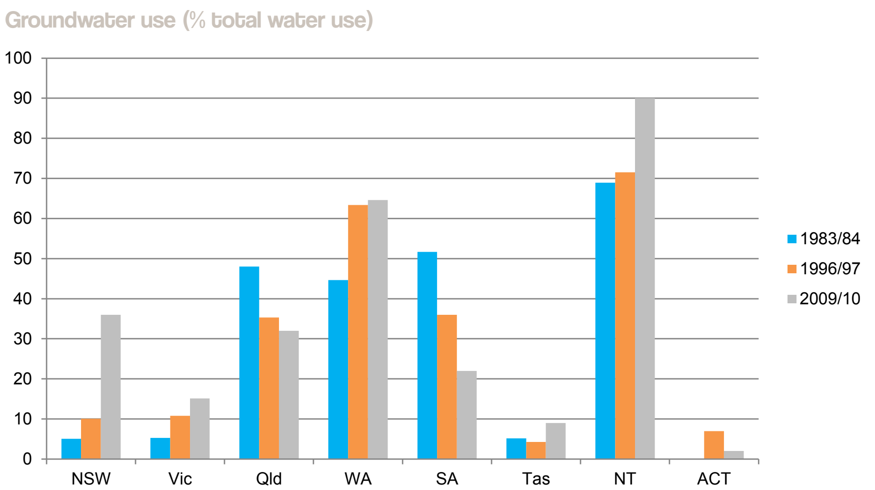


Figure 4b. Groundwater use for each state and territory as a proportion of total water use from all sources for 1983–84, 1996–97 and 2009–10 (NWC, 2005; Department of Water, 2010; ABS, 2011).

Figure 4c. Groundwater use at a national scale as a percentage of total water use (AWRC, 1981; CSIRO, 2008; CSIRO, 2009a–e; Barron et al., 2011; NT Department of Land Resource Management, pers. comm., 4 Sept 2013; WA Department of Water, pers. comm., 23 Oct 2013)[6].

[6]Note: this figure is based upon the original AWRC map from 1981, with more recent data added where available as per the references provided. The divisions used in the original map were based upon drainage divisions, and extra detail has been added to this based upon the references provided.

Of the groundwater used in Australia in 1996–97, approximately 70% was used for agricultural and/or pastoral purposes such as irrigation and stock water. The remainder was used for domestic and town water supplies, and for industrial purposes such as mining (Figure 5). With the exception of Western Australia, the greatest proportion of use is for agriculture. In Western Australia, agriculture accounts for approximately 21% of groundwater use and there is also a considerable amount of groundwater used to support mining activities (38% of groundwater use), including mine dewatering (included in the urban and industrial use category). Groundwater now accounts for more than 50% of Perth's water supply (National Water Commission, 2011).

Recent data for total water use (all sources) shows that, at a national scale, water use in the urban centres was 1,497 GL in 2009–10, decreasing from 1,719 GL in 2005–06, and residential water consumption accounted for 68% of this (Bureau of Meteorology, 2010). The decrease probably reflects the effects of water restrictions implemented in some capital cities as a result of the drought and is not necessarily indicative of a long-term trend. Annual agricultural irrigation water use (all sources) in Australia in 2009–10 was approximately 6,600 GL, up 1% from 2008–09 (Bureau of Meteorology, 2010).

Uses of groundwater by each state and territory

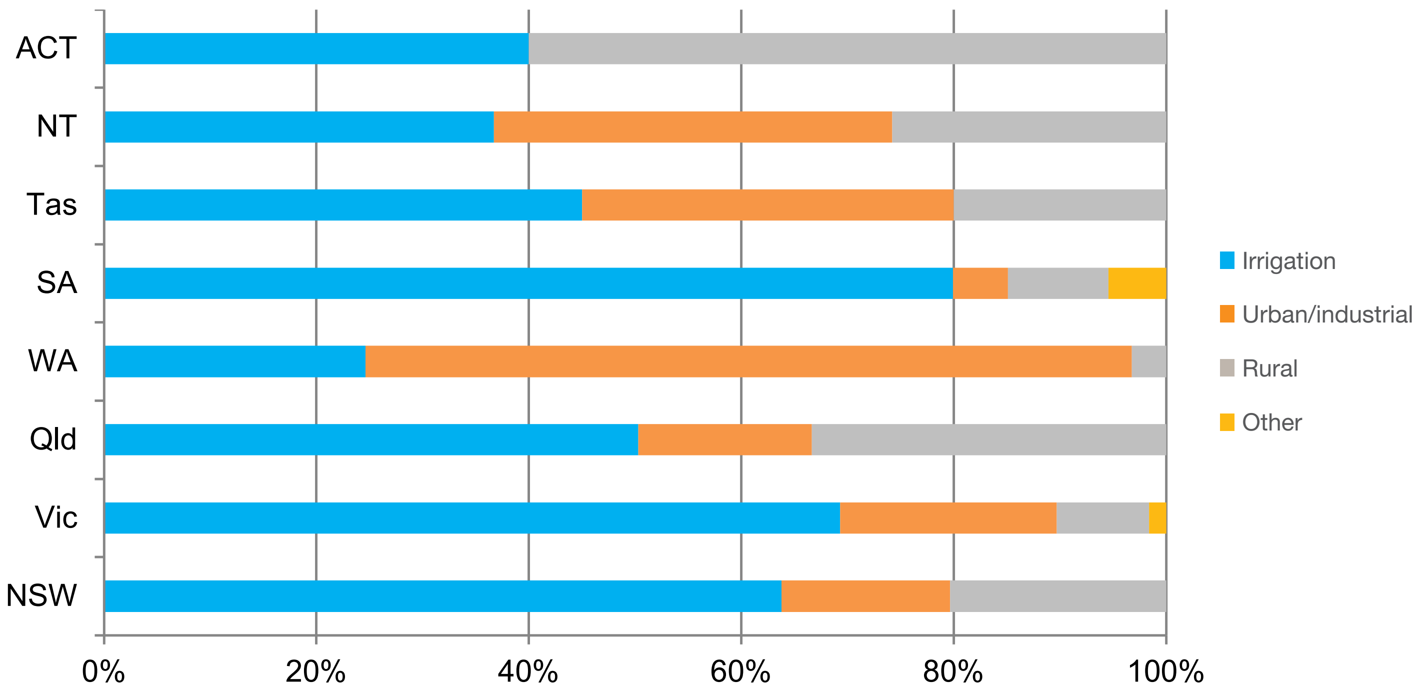


Figure 5. Uses of groundwater by each state and territory in 1996–1997 (NLWRA, 2001).

Groundwater management and sustainable use

Groundwater in Australia is a public resource and the rights to use and control groundwater rest with the Crown (NRMSC, 2002). Water authorities have been granting groundwater allocations (or entitlements) in Australia for a long time and groundwater users are granted an entitlement to use the resource, normally in the form of a water property right (often called a licence). Groundwater entitlements have traditionally been tied to land property rights; however, under the National Water Initiative (see below), this is gradually changing so that in some parts of Australia groundwater entitlements are becoming separate from land property rights to allow trading of the two separately. The licence associated with a groundwater entitlement generally specifies matters such as the conditions of use, length of tenure, and volume permitted to be extracted. Although most entitlements are automatically renewed, governments can alter the conditions of use on a water entitlement with a licensee's agreement, or in accordance with a water management plan.

Sustainability issues occur because extraction of groundwater creates a change in the water resource, which, in turn creates an impact on users or systems dependent on that resource. The question is not whether an impact will occur, but of the location, magnitude and timing of the impact. This has long been recognised in Australia as an issue that crosses jurisdictional (state and territory) boundaries, and a strong national policy framework now exists for water resources management. Two pivotal events in the progression of water reform in Australia have been:

- the Council of Australian Governments (COAG) adopting a Water Reform Framework in 1994
- COAG establishing the National Water Commission (NWC) and an Intergovernmental Agreement on a National Water Initiative (NWI) in 2004.

The National Water Initiative is described as Australia's enduring blueprint for water reform. Through it, governments across Australia have agreed on actions to achieve a more cohesive national approach to the way Australia manages, measures, plans for, prices, and trades water (NWC, 2013). Under the National Water Initiative, the federal, state and territory governments have also acknowledged the importance of groundwater and are committed to a 'whole of water cycle' approach. Importantly, they have committed to returning currently over-allocated or overused systems to environmentally sustainable levels of extraction, improving the understanding of sustainable extraction rates and regimes, and developing common approaches to achieving sustainability. This includes preparing water management plans with provisions for the environment, and particularly dealing with over-allocated or stressed water systems. Two major cross-jurisditional examples are the Murray–Darling Basin Plan (Murray–Darling Basin Authority, 2013) and the Great Artesian Basin Strategic Management Plan (Great Artesian Basin Consultative Council, 2000).

Management of groundwater use to minimise undesirable impacts revolves around determination of a 'sustainable yield'. Sustainable yield is defined in the National Water Initiative as:

> *the level of water extraction from a particular system that, if exceeded, would compromise key environmental assets, or ecosystem functions and the productive base of the resource.*

Even within this definition, there is a great deal of flexibility in how sustainable yield could be estimated, and there is no standardised method across Australia. Methods of estimating sustainable yield vary with the characteristics of each groundwater system and the environmental and socioeconomic factors that must be considered. In many cases, the methodology is evolving with the scientific understanding of the systems, and water management plans are developed in a way that allows for incorporation of new knowledge.

The total sustainable yield of Australian groundwater resources across all salinity classes is estimated to be 29,173 GL per annum, of which 18,310 GL per annum is of potable quality (a salinity of less than 1,000 mg/L) (ABS, 2005; Table 1). Table 1 presents a breakdown of these estimates by salinity class and by jurisdiction (noting once again that there is inconsistency between states and territories on how sustainable yield is calculated).

Groundwater availability and use reporting is based on groundwater management units (GMUs), recommended and used by the states and territories in their management and reporting practices. This approach allows geographical reporting of groundwater resource issues in Australia. GMUs have been defined based on natural aquifer boundaries, as well as administrative and management boundaries. For this reason, some boundaries apparently follow natural features of groundwater systems whilst others are straight, aligning with jurisdictional boundaries. *The Australian Water Resources Assessment 2000* used 538 GMUs and these areas were amended slightly for *Australian Water Resources 2005* to better reflect the management areas of states and territories and therefore be more relevant to NWI initiatives and reforms. GMUs can vary greatly in size and in the level of data available, and therefore estimates of groundwater resource condition and use can vary greatly in accuracy.

Figure 6 shows the ratio of groundwater use to sustainable yield for a modified set of GMUs developed by Currie et al. (2010). This provides a visual indication of the level to which groundwater resources are developed, with the highest levels of development apparent in Queensland (38%), South Australia (33%), New South Wales (26%) and Western Australia (20%) (Table 1). These statistics should be used cautiously as they suggest there is scope for significant development of groundwater resources throughout Australia, which may be true in some regions, but many major aquifers throughout Australia have been developed to the point where use is equivalent to or even exceeds the sustainable yield. These very high and possibly unsustainable levels of use may lead to a diminishing resource base and adverse environmental impacts.

Aquifers where groundwater is most highly developed (shown in orange and red shades in Figure 6) include the Great Artesian Basin and some alluvial aquifers of the Murray–Darling Basin. Figure 6 presents data collated as part of the *Australian Water Resources Assessment 2005*, updated with more recent data, where available, by Currie et al. (2010). This figure does not demonstrate the effects of the management changes that have been made in the Murray–Darling Basin since then. As a result, a number of the Murray–Darling Basin high use systems in New South Wales would be no longer be as red[7].

	NSW	Vic	Qld	SA	WA	Tas	NT	Aust
Salinity class and potential uses	**GL/yr**	**GL/yr**	**GL/yr**	**GL/yr**	**GL/yr**	**GL/yr**	**GL/yr**	**GL/yr**
Less than 1,000 mg/L (most purposes including drinking)	4,626	1,021	2,368	285	2,960	2,352	4,699	18,310
1,000–1,500 mg/L (irrigation – most crops)	34	386	119	679	995	-	455	2,670
1,500–3,000 mg/L (irrigation – salt-tolerant crops)	812	244	113	253	1,468	178	139	3,208
3,000–5,000 mg/L (stock watering)	2	707	30	-	588	-	183	1,510
5,000–14,000 mg/L (stock watering – sheep only)	440	201	63	762	841	-	-	2,307
More than 14,000 mg/L (industrial purposes)	-	797	-	-	371	-	-	1,168
Total groundwater sustainable yield	**5,914**	**3,356**	**2,693**	**1,979**	**7,223**	**2,530**	**5,476**	**29,173**
Groundwater use	1,524	499	1,017	644	1,422	41	124	5,271

Table 1. Groundwater sustainable yield by salinity class, with groundwater use for each state and territory. Sustainable yield data obtained from ABS (2005) and groundwater use data from Currie et al. (2010). Empty cells (-) signify data that is unavailable; there are significant supplies of saline water available that are not captured in table.

[7] Murray–Darling Basin Authority, pers. comm., 15 Aug 2013

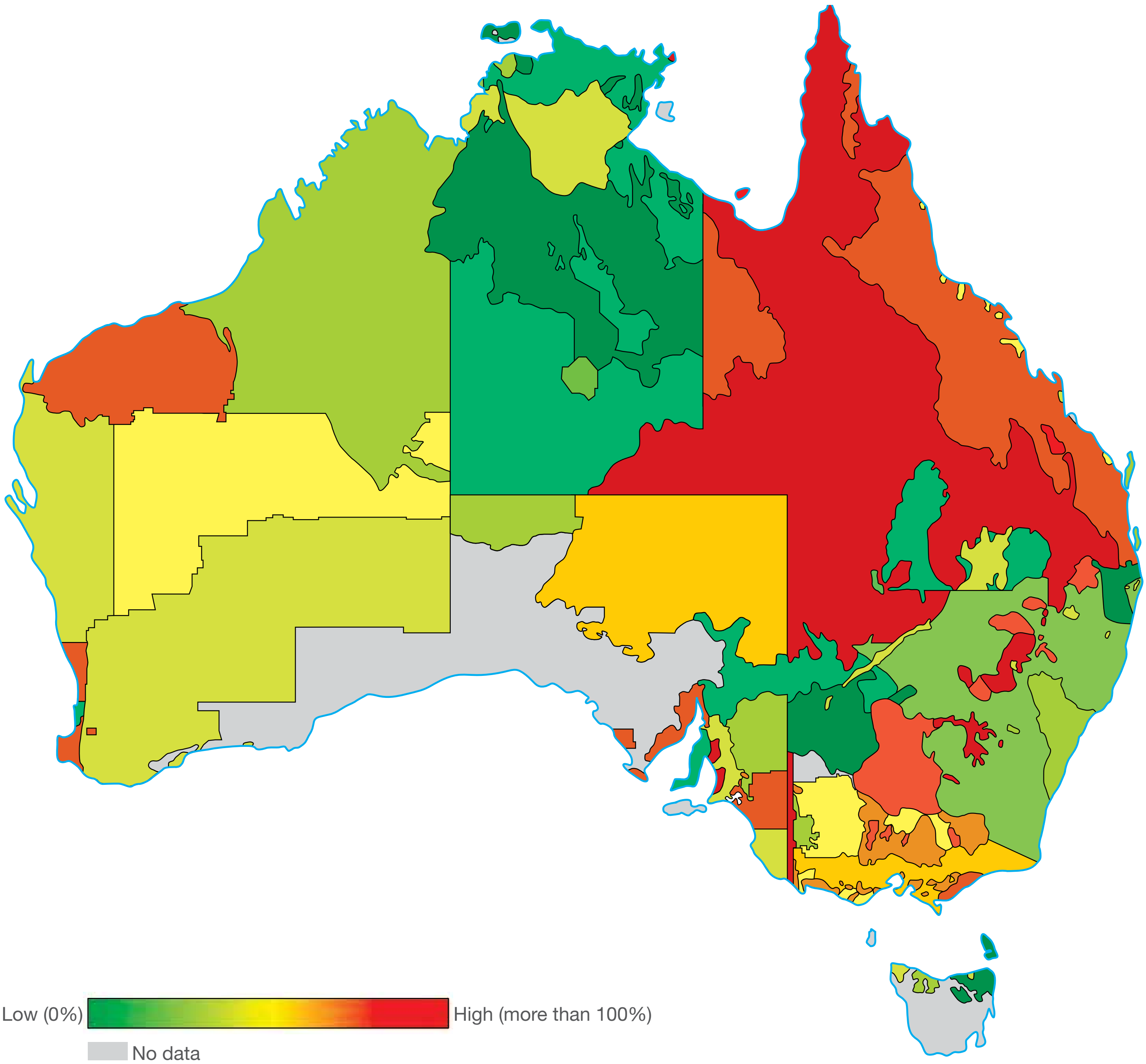


Figure 6. Ratio of use to sustainable yield for Australian groundwater management units (Currie et al., 2010). This figure is based upon data obtained from the National Water Commission (2005) dataset and updated by Currie et al. (2010), with more recent data provided for the purpose of this report by the relevant jurisdictions and from the CSIRO Sustainable Yields projects. References are provided in Currie et al. (2010).

Key issues for groundwater management in Australia

Overallocation and overuse of groundwater

Groundwater is too often seen as a resource that can be drawn on when surface water is scarce. However, groundwater is not an infinite resource, and its connectivity with surface-water resources means that care must be taken to ensure that both groundwater and surface-water supplies are used sustainably (NWC, 2012). A historial lack of resourcing for the management, measurement and monitoring of a number of groundwater systems in Australia has led to too many licences being issued in the past (overallocation) and in some cases too much groundwater being extracted (overuse) (NWC, 2012). This was made worse by:

- licensed groundwater usage not being metered in many parts of Australia
- provision of free or under-priced groundwater
- failure of management plans to recognise the connectivity of groundwater and surface water.

The primary impact of groundwater overuse is an unacceptable decline in groundwater levels. The timeframe and magnitude of groundwater level decline depends upon the properties of the aquifer, other components of the water balance (e.g. recharge), and the groundwater pumping regime. The immediate result of declining levels is often a loss of access to groundwater by users, including groundwater-dependent ecosystems (GDEs), or at least a need to deepen bores or lower pumps, with the associated infrastructure and pumping costs. Secondary impacts include changes in water regimes of streams, lakes and wetlands that are connected to the groundwater system; seawater intrusion; and contamination of aquifers through inter-aquifer leakage driven by changed groundwater flow conditions. These secondary impacts are discussed in subsequent sections. Some examples of overused groundwater systems in Australia and the management responses that have been implemented are discussed further here (NRMSC, 2002).

In the **Lower Namoi aquifer system (NSW)**, where the sustainable yield was estimated to be 95,000 ML/yr, total allocations were 213,264 ML/yr and use was 118,849 ML/yr (NRMSC, 2002). Forty years of monitoring groundwater levels throughout the Lower Namoi showed water levels to be consistently falling, a clear sign that groundwater use was above the sustainable yield for the aquifer system. A new framework for managing groundwater in the Lower Namoi commenced in 2006 with the implementation of the Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources. The water sharing plan gradually reduces extraction limits to 86,000 ML, the estimated average annual recharge for the Lower Namoi, by 2015–16 (Department of Water and Energy, 2008). The Lower Namoi aquifer system is also included in the recently developed Murray–Darling Basin Plan and this is likely to further influence groundwater extraction from this aquifer system (Murray–Darling Basin Authority, 2012).

The **Lockyer Valley (Qld)** covers around one quarter of the Brisbane River catchment. The main watercourses are the Lockyer Creek and its tributaries. The area is well known for production of vegetables and lucerne and is often described as the 'salad bowl of south-east Queensland'. Groundwater extracted from alluvial aquifers is the primary source of water for irrigation in the valley. In the past, only the Central Lockyer Valley was a declared water resource area, being the only part of the valley where groundwater use was licenced and metered. Here, the sustainable yield was estimated to be 15,000 ML/yr and annual extraction for irrigation of horticulture and fodder crops was between 8,000 ML/yr and 18,000 ML/yr (NRMSC, 2002). Overdevelopment resulted in depleted groundwater levels in some areas and reduced access to groundwater. In some areas, leakage of saline groundwater from underlying bedrock aquifers occurred and a small number of surface-water storages were also impacted. Management approaches included use of surface water from off-stream supplies, both as a water resource and to supplement stream recharge. Weirs were instealled to improve recharge, meters were installed to monitor use, and allocation limits were implemented.

The alluvial aquifers of the entire Lockyer Valley are now recognised as being under stress, with groundwater use continuing to exceed the estimated sustainable yield. In October 2004, 87% of monitoring bores recorded groundwater levels within 2 m of the lowest recorded value. Underlying sandstone aquifers have also experienced major stress insome areas (Queensland Department of Natural Resources and Mines, 2005). To improve groundwater management, the entire Lockyer Valley has now been divided into groundwater implementation areas to allow implementation of a progressive management approach. In 2005, the Moreton Moratorium Notice came into effect, prohibiting drilling of any new bores (other than for stock or domestic use) throughout the whole Moreton area, which includes the Lockyer Valley. In March 2006 and March 2007, the Great Artesian Basin Water Resource Plan and the Moreton Water Resource Plan were released. Under these plans, all groundwater in the Lockyer Valley can now be managed under a water resource plan.

In the **Pioneer Valley (Qld)**, total allocations were 61,879 ML/yr (WQA, 2010) but extractions were only between 17,000 ML/yr and 40,000 ML/yr for irrigation, town water supply and some industrial purposes. This level of extraction resulted in a loss of access to groundwater during drought periods in some areas, and seawater intrusion in coastal areas. Without management intervention, many users would lose access to groundwater for most of the time and seawater intrusion and related impacts on groundwater-dependent ecosystems would expand. The management response to this was developed in consultation with water users and involved implementation of pumping restrictions over much of the Pioneer River valley, with most stringent restrictions near the coast. Meters were also installed and a long-term water resource plan has been developed, supported by extensive monitoring of water levels and seawater intrusion indicators. The result of the reduced levels of use has been that most users have maintained access to some water during peak demand periods and seawater encroachment has been arrested in most areas; however, in areas already impacted by seawater intrusion, water quality is expected to take many years to return to acceptable levels.

In the **Northern Adelaide Plains (SA)**, the current allocation limit is 26,500 ML, and total metered groundwater extractions in 2009–10 were 14,713 ML. Extractions occur primarily from two Tertiary limestone aquifers, each with long-standing cones of depression in aquifer pressures that have been relatively stable for the past 20 years (DFW, 2011). Under natural, pre-irrigation conditions, the main aquifers were artesian (10–15 m above ground surface) in the western portion of the plains. Artesian conditions were lost by the 1940s due to irrigation extraction and by the 1960s the cones of depression had formed (NABCWMB, 2000). Although water levels experience slight recoveries when rainfall is above average, declines continue to occur when rainfall is below average and extractions increase (DFW, 2011). The Northern Adelaide Plains area is managed through a water management plan adopted in 2000, including the use of recycled water obtained from the Bolivar Aquifer Storage and Recovery Scheme. However, a new Adelaide Plains water management plan (including the northern and central plains) is currently being developed, which will respond to the risks associated with increasing groundwater demand.

Impacts of groundwater extraction on surface-water systems

Groundwater and surface water are often connected. They are part of the one hydrologic cycle, and surface-water resources can be significantly impacted by groundwater abstraction. Groundwater recharge can also be impacted by surface-water extraction or river regulation; however, this has received little attention to date in Australia. Although hydrologists and hydrogeologists have long recognised the interconnection between surface-water and groundwater resources, the impact of groundwater abstraction on surface-water systems has only been translated into policy and management to a limited extent. Conversely, the impact of surface-water diversion and use on groundwater resources has generally not been acknowledged in water management policy at all in Australia.

The time lag from the commencement of groundwater pumping until the impact on a surface-water system is realised can vary from days to decades or longer. Historically, groundwater and surface-water resources have been managed separately and this was not a problem where water resources were abundant and demands were low (Evans, 2007). However, when increases in demand and low rainfall levels caused regulators to cap the use of many surface-water resources, this had the unintentional result of shifting the pressure to groundwater resources. The impacts of this on surface-water flows then became apparent in some of Australia's more heavily developed catchments. Reductions in baseflow to rivers and streams caused reductions in surface-water flows or complete drying out of streams (Evans, 2007).

One of the best examples of this was in the Murray–Darling Basin (the Basin; see Figure 1), where there is usually a close hydraulic connection between the streams and the underlying alluvial aquifers. Much of the growth in groundwater use in south-eastern Australia between 1983–84 and 1996–97 was attributed to irrigation in the Basin. Increased pressures on surface-water resources in the Basin resulted in a cap on surface-water diversions from the Murray–Darling river system in 1997, with diversions limited to around 1993–94 levels. However, groundwater use was not capped and continued to increase. Addressing groundwater impacts on streamflow was quickly recognised as an immediate priority (Craik, 2005). In 2008, groundwater use represented 16% of total water use in the Basin, and it was expected that this could increase to over 25% by 2030 under the prevailing water management arrangements (CSIRO, 2008). It was estimated that one quarter of the groundwater use would eventually be sourced directly from induced streamflow leakage (CSIRO, 2008). The environmental impact of this was potentially very great during periods of low river flow, times when the river obtains much of its flow from groundwater baseflow.

The development of the Murray–Darling Basin Plan (Commonwealth of Australia, 2012) is Australia's most prominent example of government intervention to achieve conjunctive management of surface-water and groundwater resources. The Basin Plan is a legislative instrument developed by the Murray–Darling Basin Authority to achieve a balance between the water needs of communities, industries and the environment in the Basin (Murray–Darling Basin Authority, 2012). It aims to do this through the establishment of long-term average Sustainable Diversion Limits (SDLs), which will come into effect in 2019, along with a range of other measures to improve water management in the Basin. The SDLs are limits on the volumes of water that can be taken for human uses (domestic, urban and agricultural uses) from both surface-water and groundwater systems across the Basin.

The Basin Plan is the first time that:

- a limit on groundwater use is being established across the Murray-Darling Basin, in contrast to surface-water use, which has been capped since the mid-90s
- a consistent management arrangement will be applied across all of the Basin's groundwater resources.

In developing the SDLs for each of the catchments, the Murray–Darling Basin Authority has used a consistent approach to assess the risk of groundwater extraction on:

- the ability of aquifers to continue to be productive over time
- groundwater-dependent ecosystems
- surface-water resources that are fed from groundwater
- water quality (salinity) of groundwater.

Like the Murray–Darling Basin Plan, many jurisdictions are now developing integrated water resources management plans that recognise the movement of water between surface-water and groundwater systems. However, policies and management practices to deal with surface water – groundwater interactions still vary across the country and are usually more advanced for highly developed resources. A major limitation to the successful management of connected surface-water and groundwater systems is the fact that data on surface water – groundwater interactions are often limited or unreliable. Where good quality data is available, estimates of flows between surface-water and groundwater systems can be used to assess the importance of groundwater – surface water interactions in the overall water balance of a catchment.

Analyses for the Australian Water Resources assessment (NWC, 2005) showed that groundwater – surface water interactions were significant across most of the priority areas analysed in that study. Of the 51 water management areas investigated, 17 had surface water – groundwater interconnectivity of more than 10% of the total runoff and recharge. Some examples of these are:

- the Macquarie (15%), Lachlan (21%) and Murrumbidgee (13%) rivers (NSW). These are all regulated rivers located within the Murray–Darling Basin.
- the Hunter River (NSW) (17%). The alluvial aquifer systems of the Hunter Valley are highly connected to both the unregulated river systems and the regulated Hunter River. In the Hunter Valley, the major pressure on groundwater is coal mining, which has the potential to alter both the quality and availability of groundwater.
- the Moorabool River (Vic) (23%), which is one of Victoria's most flow-stressed rivers. Changing volume, timing and duration of flows affects ecosystems depending on the river for survival. During the past decade, dry conditions have placed

additional strain on populations of native fish species in the river. The river is an important habitat for native animals and plants, and environmental flows have a key role in their survival.

- the Roper River (NT) (31%), one of the largest rivers in the Northern Territory.
- the watercourses of the Lower Limestone Coast (SA) (22%). Here, winter rainfall-derived surface water moves slowly north-west across the landscape through a series of swamps and wetlands that are connected by a man-made drainage network. In summer, ecosystems in many of these swamps and wetlands are sustained by inflows from the shallow groundwater system.
- South West Yarragadee (WA) (13%). Here, groundwater discharge from the Leederville and Yarragadee aquifers sustains baseflow within the Blackwood River and several tributaries throughout summer.

These statistics are useful as preliminary indicators of the importance of groundwater to surface water flows and ecosystems; however, they can understate this importance. Australia's extreme and spatially variable climate means that some regions may have very high annual rainfall and runoff, but this is concentrated in only a few months of the year, followed by very dry periods where groundwater inputs are crucial to maintain stream flows and ecosystem health. In these systems, groundwater inputs may be very small but important components of the annual water budget. Groundwater inputs are also crucial to sustain surface-water systems through periods of low rainfall or drought and this importance is not conveyed in snapshot data or annual averages.

Surface water – groundwater exchange is a very active area of research, both in Australia and internationally. Because of the prioritisation of conjunctive management of surface-water and groundwater resources in the National Water Initiative, new knowledge and data on this is being obtained at a rapid rate for Australian systems.

Glenn Harrington

Blanche Cup Mound Spring, Great Artesian Basin.

Groundwater as a source of water for ecosystems

A number of ecosystems rely on groundwater discharge or access to groundwater. They are called groundwater-dependent ecosystems (GDEs) and occur in a wide range of forms throughout Australia. There are three main types of GDEs; these are (Murray et al., 2003; Eamus et al., 2006; Eamus, 2009):

- ecosystems reliant on the surface expression of groundwater: springs, waterways, wetlands and lakes in which groundwater discharge is crucial to maintaining habitat or providing flows during summer or dry periods. Estuarine and coastal groundwater discharge can also support unique marine life or life cycles of marine species due to differences in the salinity, nutrients and temperature of water in the discharge zones.
- ecosystems reliant on access to groundwater in the subsurface: vegetation that accesses groundwater through roots, drawing on moisture derived from the water table. Many of Australia's iconic river red gum forests derive much of their water needs in this way. Some animals also rely on access to groundwater in the subsurface. In Tasmania, burrowing crayfish dig down to the water table and rely on the proximity of groundwater for their habitat.
- aquifer and cave ecosystems: these occur within the aquifer itself. A diverse array of groundwater-dwelling fauna (stygofauna) have been found throughout Australian aquifers, particularly in Karst systems.

Groundwater-dependent ecosystems require the input of groundwater to maintain their current composition and functioning. Some ecosystems, such as stygofauna (the fauna of cave and aquifer ecosystems) and artesian mound springs, are entirely dependent on groundwater, whilst others, such as paperbark swamps in the Northern Territory and river red gum stands in South Australia, are partially dependent (Hatton and Evans, 1997). The quality (e.g. salinity, heavy metal concentrations), quantity (e.g. groundwater depth) and timing of groundwater availability (e.g. during dry season and extreme drought years), can also be important. Removal of groundwater from these ecosystems, or a change in the quality, quantity, timing or distribution of groundwater can affect ecosystems and change flora and fauna assemblages. Some ecosystems will change gradually as water availability is reduced, whilst others have a threshold response, with little obvious change in ecosystem health occurring until a threshold value is reached, below which the ecosystem becomes seriously impacted. Responses to changes in groundwater availability vary with organism age, species and ecosystem type. Although GDEs cover only a small area of the vegetated land surface, they contribute significantly to social, economic, biodiversity and spiritual values (Murray et al., 2003), and GDEs must now be considered when managing groundwater resources.

A great deal of progress has been made in the identification of GDEs. In 2007, Land and Water Australia commissioned a practical tool to assist in the identification of GDEs and the management of their environmental water requirements (Clifton et al. 2007). That tool, *A Framework for Assessing the Environmental Water Requirements of Groundwater Dependent Ecosystems*, became known as the 'GDE toolbox'. Significant advances were then made in the years following the development of the first GDE toolbox in the understanding of GDEs and their environmental water requirements. In 2011, the National Water Commission (NWC) undertook a revision of the toolbox to update the scientific tools it outlined in light of feedback from the target users and to facilitate its adoption at a national scale. The updated toolbox contains two parts: an assessment framework and assessment tools (Richardson et al., 2011a,b).

Another key advance in the management of water resources towards GDE health has been the commissioning of a web-based GDE atlas for Australia, which is hosted on the Bureau of Meteorology's website (http://www.bom.gov.au/water/groundwater/gde/index.shtml). The atlas displays ecological and hydrogeological information on GDEs across Australia, collated from a number of sources, including published research and remote sensing data. It incorporates information from previous fieldwork, literature and mapping studies and national-scale layers of remote sensing data to provide searchable information on GDE locations and attributes. The atlas also includes an 'inflow dependent landscapes layer', which is interpreted at a 30 m resolution from remotely sensed data such as MODIS and Landsat. These datasets are interpreted into a likelihood that ecosystems are accessing water other than rainfall. The additional water may be soil water, surface water or groundwater.

The presence of GDEs was recently used in the prioritisation of aquifers for inclusion in a national-scale investigation of the impacts of climate change on groundwater resources (Currie et al., 2010). Knowledge of the specific requirements of GDEs, as described above, is required for water management plans to be effective, and despite the advances described above, this remains a priority area of research. Table 2 presents a summary of the groundwater dependence, threats, vulnerability and risk of some key groundwater-dependent ecosystems in Australia.

ECOSYSTEM	THREAT To ecosystem process	VULNERABILITY Impact if threat realised	RISK Likelihood of threat being realised	VALUE Conservation value of ecosystem
Entirely dependent on groundwater				
Great Artesian Basin spring ecosystems	WR	High	High	High
Karstic groundwater ecosystems	WR, A, M	High	High	High
Permanent lakes and wetlands of Swan Coastal Plain	UC, WR	High	High	Moderate
Pilbara spring ecosystems	M, WR	High	Moderate	High
Inland mangrove near 80 Mile Beach in Western Australia	No major current threat	High	Low	High
Arid zone groundwater calcrete ecosystems	WR, M	High	Moderate	High
Riverine aquifer ecosystems	WR, A, UC, CD	High	High	Moderate
Marine tide influenced cave (or anchialine) ecosystems	WR, M	High	Moderate	High
Highly dependent on groundwater				
Pilbara river pool ecosystems	WR, M	High	Moderate	Moderate
Coastal lake stromatolites of WA	UC, WR	High	Moderate	High
Groundwater-dependent wetlands of basalt plains of Western Victoria	WR, A, F	Moderate	High	Moderate
Damplands of Swan Coastal Plain	WR, UC,	High	High	Moderate
Proportionally dependent ecosystems				
Permanent coastal lake, dune and beachridge plain ecosystems of coastal NSW and coastal sand islands of NSW and Qld	UC, WR, AS	High	High	Moderate
Phragmites and *Typha* communities of permanently flooded swamps and lakes of inland areas of the south-eastern uplands	WR, A	High	High	Moderate
Permanent base flow dependent swamps and river pools of Kangaroo Island	WR, A	Moderate	High	Moderate
Riparian swampland communities of Mount Lofty Ranges	WR, A	Moderate	High	Moderate
Swan Coastal Plain damplands and sumplands with paperbark, and *Banksia* woodlands	WR, UC	High	High	Moderate
Coastal swamp scrub sedgeland communities in the near-coastal dune systems of the Upper South East of SA	A	High	Moderate	Moderate
Ecosystems with opportunistic groundwater dependence				
Ecosystems of the Coorong	A, WR	Moderate	High	High
Ecosystems of permanent lakes and swamps at termini of inland rivers in the Central Lowlands and South Australian Ranges	A, WR	High	Moderate	Moderate
Major ocean embayments such as Port Phillip Bay	A, UC, AS	Moderate	High	Moderate

WR = Water resource, **A** = Agriculture, **M** = Mining, **UC** = Urban and commercial, **CD** = Commercial development, **F** = Forestry, **AS** = Acid sulphate soils

Table 2. Summary of groundwater dependence, threats, vulnerability and risk of some key groundwater-dependent ecosystems in Australia (SKM, 2001).

Effect of climate change on availability and quality of groundwater resources

Over the past few decades, large areas of Australia have experienced a drier climate and reductions in surface-water resources, causing increasing pressure on groundwater resources. Analysis of the climate over the past 80 years shows warming over most of Australia (except in the inland north-west); increasing rainfall over northern, central and north-western Australia; and decreasing rainfall in eastern, south-eastern and south-western Australia (Barron et al., 2011).

From 1997 to 2009, large areas of southern Australia, particularly the southern Murray–Darling Basin, experienced prolonged drought, often referred to as the millennium drought (Figure 7). Although there have been other multi-year droughts, such as the Federation drought of 1895 to 1903, and the Depression drought of the late 1930s and early 1940s, none have been as severe as the millennium drought in the 110 years of recorded rainfall history (Chiew and Prosser, 2011). In places, runoff was less than half the long-term average, even though average rainfall had decreased by less than 20%.

The south-west region of Western Australia has experienced a longer trend of gradually declining rainfall than the rest of the country (Bates et al., 2010). The average runoff to Perth reservoirs between 1975 and 2009 was 55% lower than prior to 1975, a result of a 16% fall in average annual rainfall. This led the Western Australian government to develop additional water supplies for Perth, leading to a greater reliance on groundwater and commissioning of the first desalination plant to supply an Australian city.

Climate modelling indicates that the persistent dry conditions in the far south-west and the millennium drought have been at least in part due to climate change (CSIRO, 2010; Bates et al., 2008; Cai and Cowan, 2006).

There is considerable variability in predictions of the future climate in Australia, depending on the amounts of greenhouse gas emissions and the global climate model selected to estimate future rainfall. Most models predict that southern Australia is likely to be drier in the future, consistent with recent observations (Barron et al., 2011). This includes the Murray–Darling Basin, although averaged across the Basin, the extreme estimates range from a 13% decrease to an 8% increase in mean annual rainfall (Chiew et al., 2008). This has significant implications for the future availability of groundwater resources. The reason for this is that variability in groundwater recharge can be two to four times greater than rainfall variability with the effect of this being particularly obvious in areas of low recharge (Barron et al., 2011).

Predictions of future changes in recharge have been made using 16 global climate models and these results have been scaled according to three global warming scenarios (low, medium and high) for both 2030 and 2050 (Barron et al., 2011). The uncertainties associated with modelling the trend and magnitude of regional rainfall changes have caused considerable uncertainty in the projected impacts of climate change on groundwater resources for many regions of Australia (see Figure 8). Application of the median future climate at 2030 and 2050 causes predictions of decreases in diffuse recharge across most of the west, centre and south-east of Australia, and increases across northern Australia and a small area of eastern Australia. However, for many regions, the full range of predictions can vary from a decrease in recharge to an increase.

Fourteen priority aquifers have been identified as being both sensitive to climate change and regionally important (Barron et al., 2011; Figure 7). These aquifers occur across all climate types and cover most aquifer types. Groundwater as a percentage of total water use is above 80% in six of these high priority aquifers, and between 60% and 80% in a further five, highlighting the importance of these groundwater resources. The outputs of the 16 global climate models have been simplified into three future climate scenarios (wet, median and dry), for the purposes of assessing the range of climate impacts on groundwater resources. A future wet scenario would see little or no impact to groundwater users or the environment in these aquifers (Figure 8). Seven of the fourteen priority aquifers might expect to be affected under a median scenario and most would experience water shortages under a dry scenario. Figure 8 highlights the sensitivity of groundwater recharge to changes in rainfall, with 12 of the 14 aquifers predicted to incur a reduction in recharge of more than 20% under future dry scenarios.

As well as reducing the availability of water resources, climate change may increase the demand for water resources from irrigated agriculture, cities, wetlands and other water-dependent ecosystems. Hence, climate change intensifies the water scarcity challenge facing cities and rural catchments and provides an even greater challenge in achieving environmentally sustainable levels of usage.

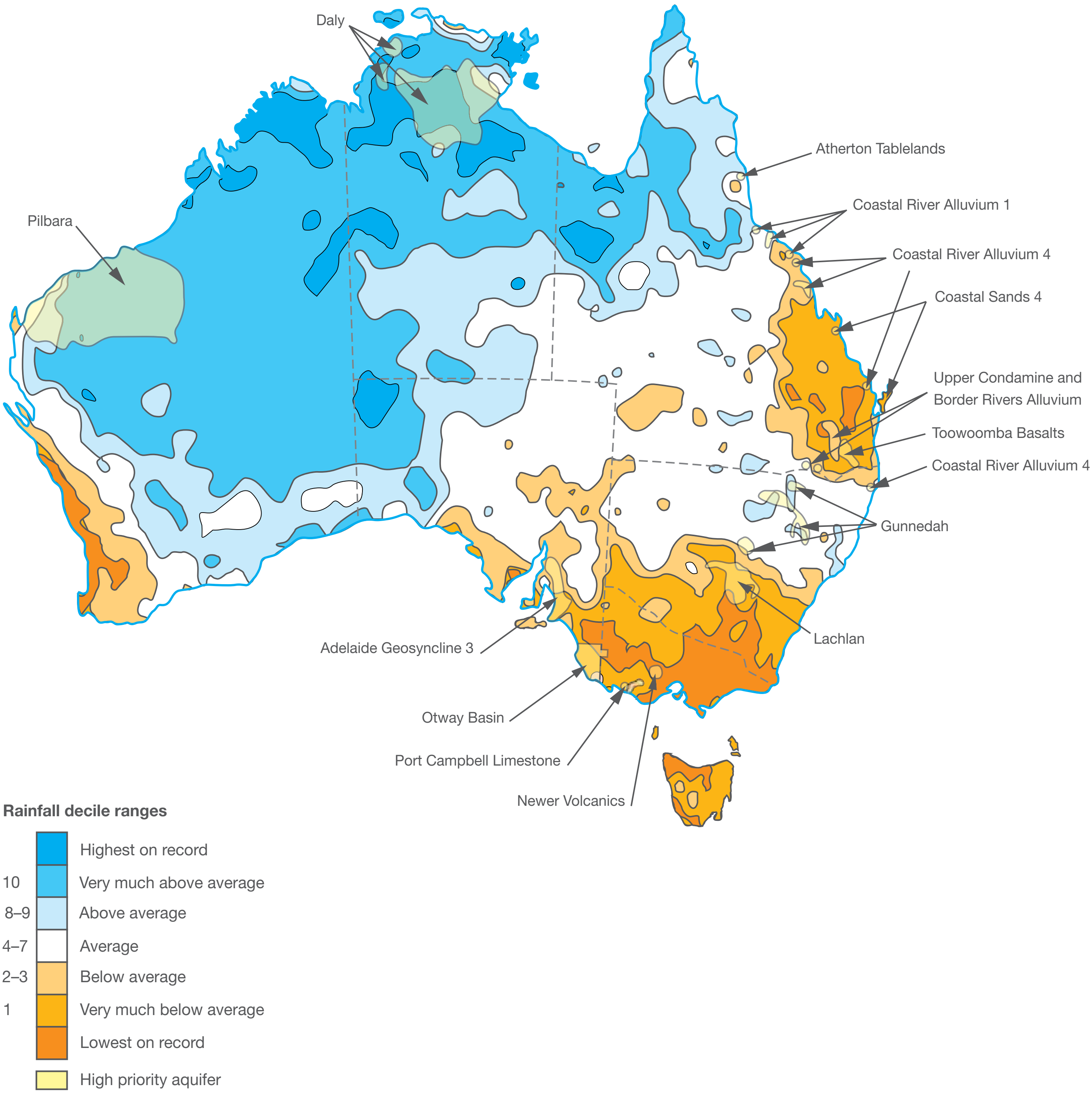
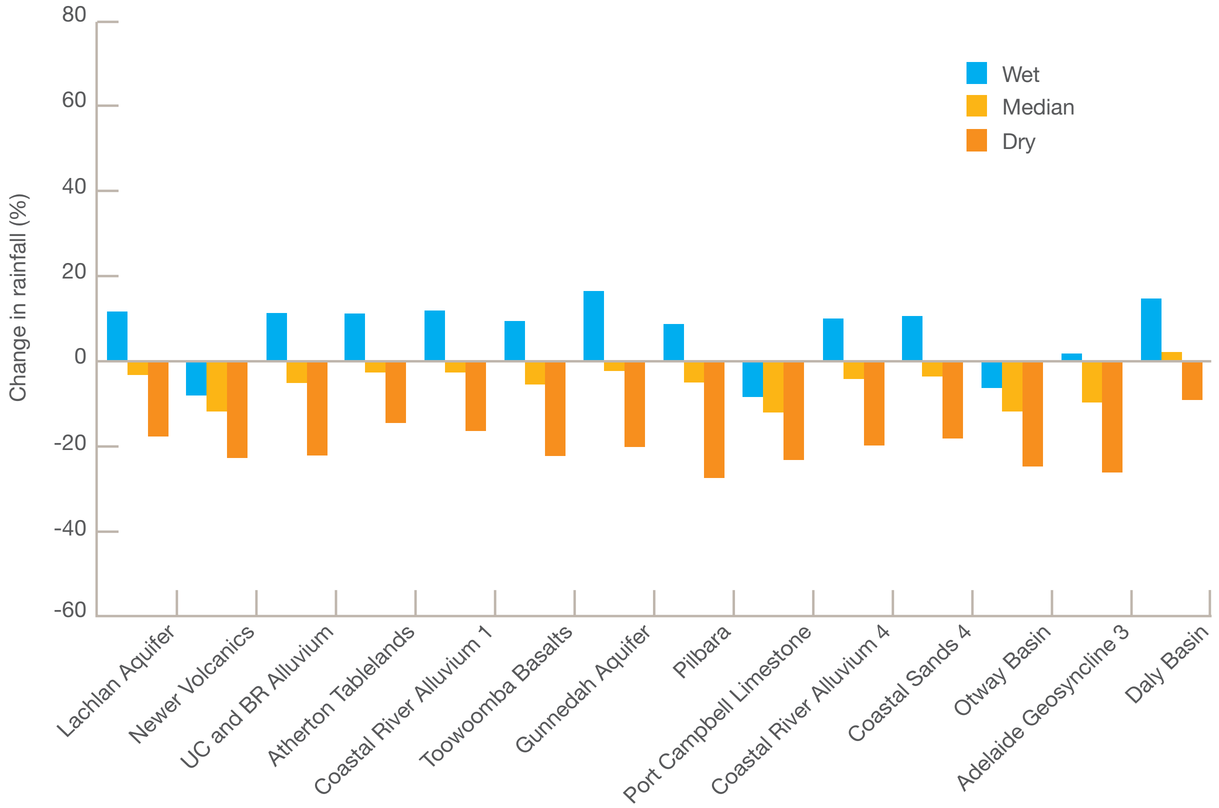


Figure 7. Rainfall conditions across Australia for the period 1 Jan 1997 to 31 Dec 2009 compared with the 1900–2009 climate, showing the extreme dry conditions across the south-east, the far south-west and south-east Queensland (from Chiew and Prosser, 2011).



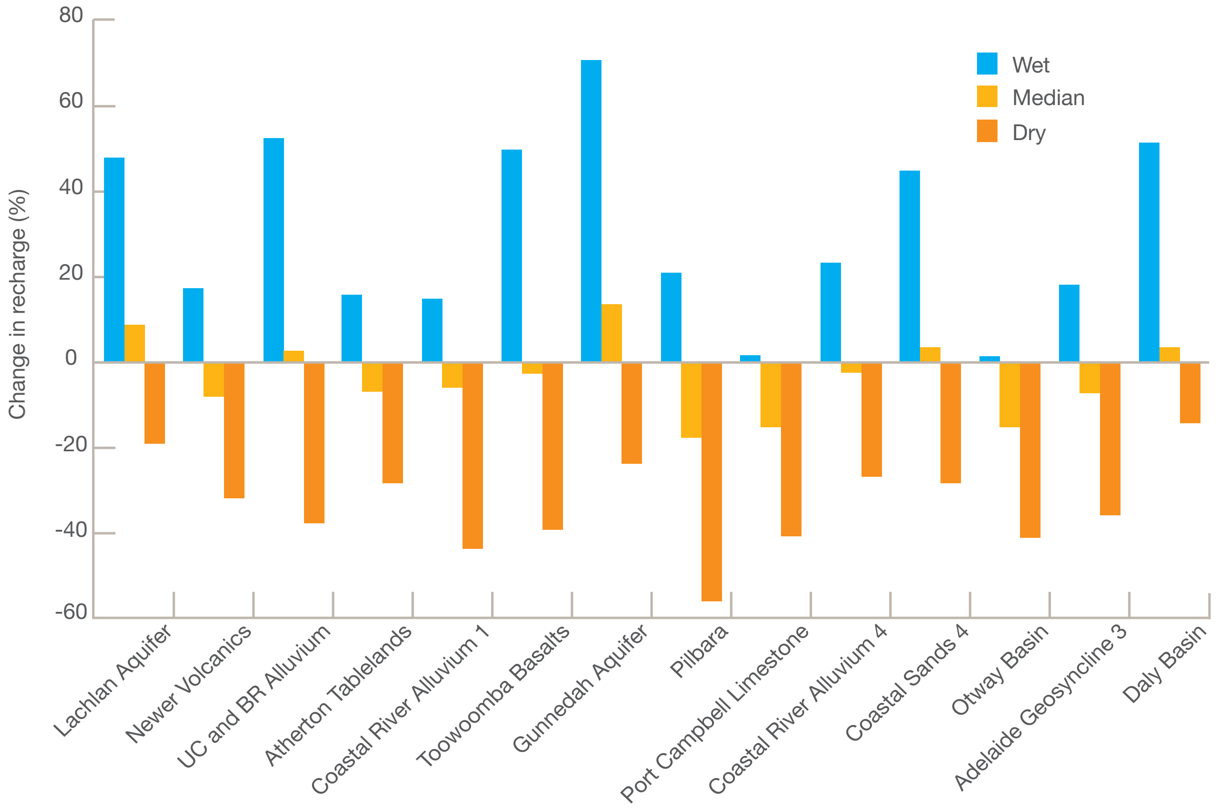


Figure 8. Percentage change in (a) rainfall and (b) recharge under the wet, median and dry climate change scenarios at 2050 for the fourteen priority aquifers of Barron et al. (from Barron et al., 2011).

Impacts of mining on groundwater systems

The mining sector is a large industrial user of water that is growing rapidly. Mining (including mineral, coal, petroleum and gas extraction) and quarrying tend to have a high gross value added per gigalitre of water consumed compared with agricultural uses. Despite an exponential increase in production, reported water use by the mining industry has historically been relatively steady, consuming 592 GL in 1993–94 and 508 GL in 2008–09, (Australian Bureau of Statistics, 2010; Prosser et al., 2011). It is believed that the stable trend is due to improvements in water use efficiency in the mining industry since 1994, but also possibly to under-reporting of water use (some enterprises are not required to report all forms of water use, such as, for example, water used in tailings dams).

Most water used for mining is in arid or semi-arid regions where water is scarce and there are few competing users. In these regions, the mining industry provides its own infrastructure, so water provisions tend to be part of the mining development approval process and are not always counted as a licenced extraction under a water management plan with other users. There are exceptions to this, for example in New South Wales, where all extraction for mining requires a water access entitlement, and so falls under the water planning process. However, mining is increasingly occurring in systems that are already developed for agriculture, such as the Hunter Valley, the Murray–Darling Basin and parts of the south-west of Western Australia. In such cases, the potential impacts of this on other water users can be controversial.

Water uses in the mining industry include:

- transport of ore and waste in slurries and suspension
- separation of minerals through chemical processes
- physical separation of material such as in flotation or centrifugal separation
- cooling systems around power generation
- dust suppression
- washing equipment
- incidental take, such as mine dewatering for access or safety.

The by-product of these uses can be water that is acidic or polluted and may be discharged to the environment, under strict controls, or disposed of in evaporation ponds. The major water management issues around the mining industry are therefore the discharge of waste water to the environment and the impacts of reduced groundwater pressures on other water users.

A boom in coal seam gas (CSG) developments in Queensland and New South Wales presents major challenges in understanding and managing impacts of mining on other water users and the environment. New technology to extract methane from deep lying coal beds has led to unprecedented CSG production in areas previously considered to be economically non-viable.

Here, the gas extracted from coal seams is cooled and compressed to produce liquefied natural gas, which has about 1/600th the volume of natural gas and is ideal for export (Asia Pacific Economic Corporation, 2004).

Queensland has exceptionally large reserves of coal seam gas (Prosser et al., 2011). Coal seam gas has been produced from the Bowen Basin in Queensland since 1996 and production started growing in the Surat Basin in 2006 (Figure 9). At the end of 2011, there were more than 50 commercially producing CSG fields in Queensland, with more than 1,100 wells extracting gas from coal seams in the Bowen Basin (the Bandanna, Baralaba and Moranbah Coal Measures) and the Surat Basin (Walloon Coal Measures) (Sydney Catchment Authority, 2012). Limited gas production also occurs in New South Wales, from the Illawarra Coal Measures at the Camden Gas Project, south-west of Sydney (Sydney Catchment Authority, 2012). The Camden CSG field contains approximately 89 producing wells (Roy, 2012). Exploration is occurring in other Queensland basins, northern New South Wales, and Western Australia where there are known coal deposits.

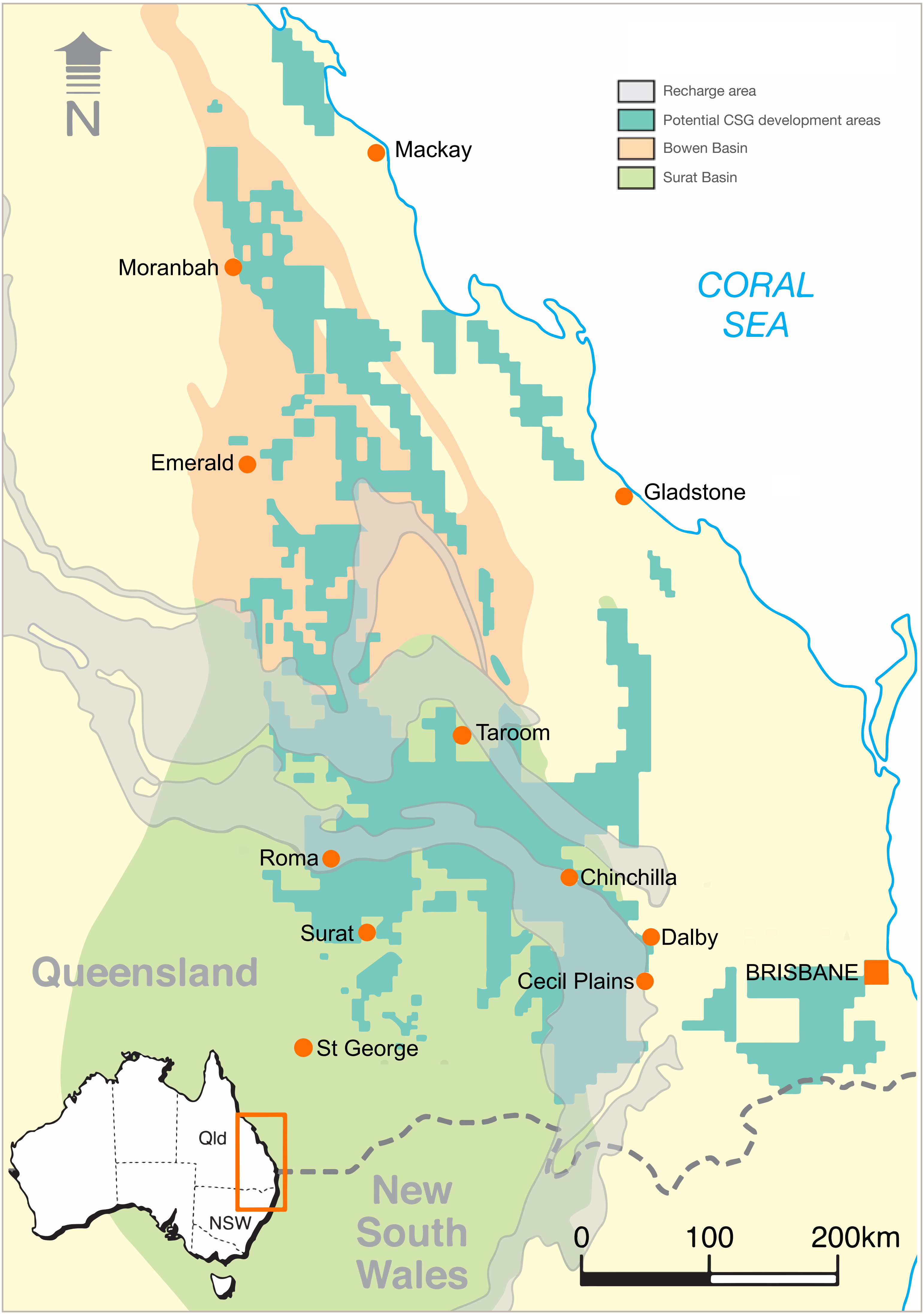
Coal seam gas extraction affects groundwater resources because the gas is bound to the coal by the pressure of the surrounding water and is released by extracting large volumes of water to lower the water pressure. Extraction of gas and water occurs across many wells within a few hundred metres of each other, in each gas field. The highest quantities of gas and water produced to date in Australia have been from the Walloon Coal Measures (Surat Basin, Queensland). Here, up to 10,000 ML/yr of water has been produced over the period 2005–11, with a predicted total of 95,000 ML (Queensland Water Commission, 2012). The Sydney Basin lies at the lower end of the scale, with produced water volumes of around 2.5 ML/yr to 4 ML/yr over the period 2009–11 (Sydney Catchment Authority, 2012). The developments in the Bowen Basin lie between these two extremes.

Some key water management challenges in the current coal seam gas boom are (a) the effect of depressurisation on surrounding aquifers, (b) the likelihood and impacts of inter-aquifer leakage caused by aquifer depressurisation and hydraulic fracturing, and (c) chemical processes affecting the quality and safe disposal of the released water. In Queensland, there are concerns over possible interactions of the CSG developments with usable aquifers in the Great Artesian Basin, the Bowen Basin and the Surat Basin (Figure 9) (Prosser et al., 2011). Usable aquifers can occur above or below the coal seams, and removing water from the coal seams induces leakage from the surrounding aquifers. The extent of the leakage would depend upon the amount of water removed, the distance between the aquifers and whether there are any low permeability layers in between to inhibit leakage.

In some CSG developments, hydraulic fracturing of the coal beds is carried out to increase gas output (a process known as fracking). Fracking involves pumping large volumes of fluid into a well under high pressure and opening the fractures in the surrounding coal seam to increase hydraulic conductivity. Fracking fluid consists of water, sand and a small amount (<2%) of additives that provide a variety of functions, including making the fluid more gel-like to suspend the sand. The sand keeps the fractures open once the injection pressure is removed and allows the gas to flow out. The major issue with fracking is that fractures can extend beyond the coal seam if not executed properly and induce leakage between aquifers. This can be a water quality issue as saline groundwater from adjacent aquifers can leak through aquitards into aquifers where good quality groundwater is present. It can also be a groundwater quantity and access issue as leakage can cause a reduction in aquifer pressures. A minor but controversial issue is that some of the additives that have been known to be used in CSG developments can be toxic at high concentrations (Batley and Kookana, 2012), leading to concern over pollution of aquifers. However, in Australia, the use of fracking is not widespread and tight regulation has led to a rapid change towards more environmentally-friendly chemical additives (Batley and Kookana, 2012). The potential environmental impacts from fracking, including inter-aquifer leakage and mobilisation of naturally occurring elements in the gas-bearing formations, are currently areas of active research.

An overarching issue for the management of water resources around coal seam gas and mining developments in general is the uncertainty about the cumulative regional impacts of multiple developments on, for example, groundwater levels and pressures, and inter-aquifer leakage. Groundwater flow velocities are slow in many of the basins of interest, and any unforeseen consequences of the mining process can take decades or centuries to become apparent. Groundwater models are often desirable in this kind of analysis and these require a good characterisation of basin geology and how it controls groundwater pressures, flows, and quality (Prosser et al., 2011). This sort of information is often not readily available for regional and remote groundwater basins because groundwater data can be scarce. However, as a result of the recent CSG boom, there has also been an increase in the amount of groundwater data collected in these areas. Groundwater flow models are increasingly being used to assist with the assessment of the likely impacts of single and multiple CSG developments, for example, in (a) the Surat and Southern Bowen Basin Cumulative Management Area (Queensland Water Commission, 2012), and (b) the Namoi catchment in north-eastern New South Wales (Schlumberger Water Services (Australia) Pty Ltd, 2012).

Figure 9, right. Potential coal seam gas production areas in relation to the Surat and Bowen basins and the recharge areas for the Great Artesian Basin (from Prosser et al., 2011).


N
Recharge area
Potential CSG development areas
Bowen Basin
Surat Basin
CORAL SEA
Mackay
Moranbah
Emerald
Gladstone
Taroom
Roma
Chinchilla
Dalby
Surat
Cecil Plains
BRISBANE
St George
Queensland
New South Wales
Qld
NSW
0
100
200km

Seawater intrusion

Seawater intrusion is the landward encroachment of seawater into fresh coastal aquifers. Typically, a wedge of saline groundwater underlies the coastal zone (Figure 10) and this can move inland in response to hydrological changes, such as groundwater extraction, reductions in groundwater recharge, construction of canals and sea level rise.

The threat of seawater intrusion has been enhanced in Australia by an increased use of coastal groundwater, caused by increasing populations of coastal areas, and below-average rainfall (Werner, 2010). Unfortunately, in many coastal areas, most groundwater use is from un-monitored domestic bores, meaning that the total extraction of coastal groundwater is unknown (Werner, 2010). The risk of seawater intrusion has been identified to be greatest in Queensland, although smaller but significant areas of Victoria, South Australia and Western Australia have also been identified as being at risk (Nation et al., 2008) (Figure 11). In some areas, the identified risk has already led to the installation of monitoring networks. However, to date, targeted investigations into seawater intrusion to support water management have been mostly limited to the high value groundwater resources in the sugarcane agricultural areas of Queensland, e.g. the Bundaberg area (Liu et al., 2006), the Pioneer Valley (Werner and Gallagher, 2006) and the Burdekin Delta (Narayan et al., 2007) and high-value aquifers used for urban water supplies (e.g. the southern Eyre Peninsula, SA; and the Darwin peri-urban area, NT; Werner, 2010).

A recent study, completed in 2012, by Geoscience Australia and the National Centre for Groundwater Research and Training, undertook a national-scale assessment of the vulnerability of coastal aquifers to seawater intrusion (Ivkovic et al., 2012).

The study incorporated literature and data reviews of coastal aquifers around the country and technical and mathematical assessments of 27 case study areas. The project aimed to identify the coastal groundwater resources that are most vulnerable to seawater intrusion, including future consequences of over-extraction, sea-level rise, and climate change. Through the analysis of the case study areas, for which a reasonable amount of data was available, a first-pass method was developed for assessing the risk of seawater intrusion for the remainder of the Australian coastline as data becomes available.

Despite nearly 50 years of research, a number of fundamental knowledge gaps still exist that have serious implications for managing seawater intrusion (Werner et al., 2013). In particular, one of the greatest shortfalls in the understanding of seawater intrusion is considered to be the lack of intensive monitoring studies, where comprehensive measurements of changes in the mixing zone between fresh groundwater and seawater are reconciled with methods of prediction (Werner et al., 2013).

Other specific challenges include:

- understanding the factors affecting the thickness of the seawater wedge at the field scale. Most of the current understanding of the behaviour of the seawater interface is based upon laboratory-scale experiments. However, it is known that these cannot always be directly up-scaled to field-scale problems.
- a better understanding of local-scale coastal fringe processes, e.g. pumping in the tidal zone, and their interactions with the seawater wedge.

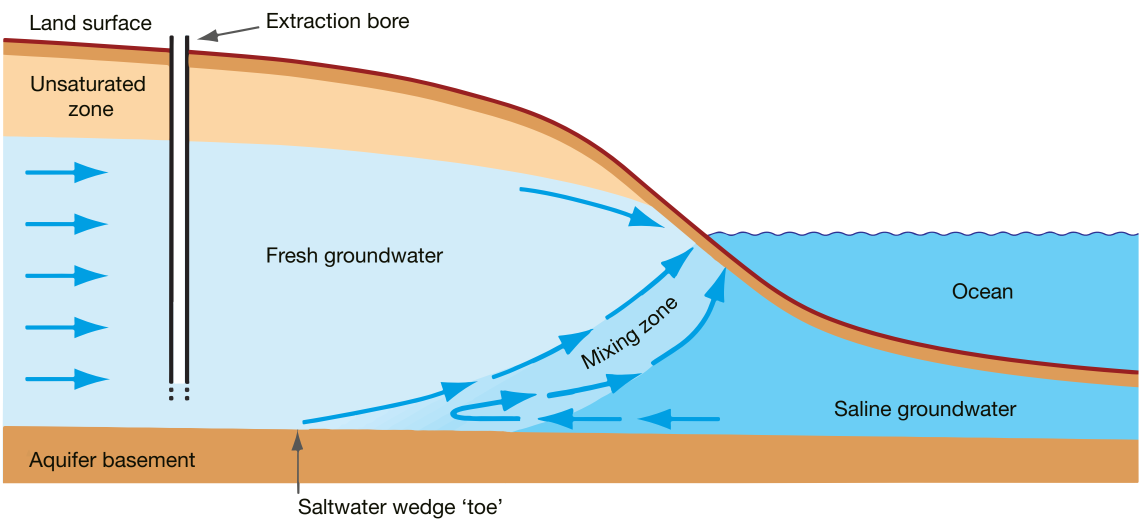


Figure 10. Simplified conceptual diagram of seawater intrusion. Seawater naturally occurs in aquifers in the coastal zone, forming a wedge of saline groundwater that thins inland. The extent and thickness of this wedge is controlled by aquifer characteristics and groundwater hydraulic heads. The thin edge of this wedge is known as the 'saline wedge toe'. A mixing zone occurs between the seawater wedge and the fresher groundwater. Here, groundwater salinities are in between those of these two end members. The position of the seawater wedge is usually stable but it can move inland in response to hydrological changes, a process known as seawater intrusion.

- quantifying and reducing uncertainty in basin-scale modelling assessments of seawater intrusion. This uncertainty is caused by large data requirements of the models and the inability to quantify impacts of small-scale processes, such as tidal fluctuations, chemical reactions and small-scale variations in aquifer properites.
- measuring or estimating groundwater ouflows at the coast and including this in groundwater models.
- predicting changes in the extent of seawater intrusion in response to water management practices, e.g. changes to pumping patterns in response to groundwater management plans.

Because the mechanics of seawater intrusion vary across different coastal aquifer systems and climatic settings, monitoring, investigation and management have to be individually tailored to each system. It can also be important to understand other sources of groundwater salinity, such as mobilisation of relic seawater or hypersaline brines, and concentration of salts through irrigation water recycling. Where groundwater salinity is of seawater origin, the salinity observed in production bores can be due either to the lateral movement or 'up-coning' of the seawater wedge. Distinguishing between these mechanisms is important for management of the problem, but there is currently no clear guidance for how this should be done (Werner, 2010).

Possible management responses to seawater intrusion include operational controls (e.g. restrictions on pumping and well construction) and engineering works. An example of an operational control is 'trigger-level management', whereby the pumping restrictions enforced are set based on a measured condition in the aquifer, e.g. groundwater level or salinity. This is also known as 'adaptive management' and is applied in the Pioneer Valley, Queensland, where the trigger is tidal overheight (the hydraulic head in the aquifer above mean sea level; Werner and Gallagher, 2006). Groundwater trading, with rules established to reduce groundwater use from areas under threat of seawater intrusion, is another operational control that has been used in the Pioneer Valley (Werner, 2010).

Engineering works to mitigate seawater intrusion usually involve managed aquifer recharge (see page 30). These have been implemented in the Lower Burdekin area, the Pioneer Valley and Bribie Island in Queensland. Detailed investigations of the Perth coastal aquifers have also been carried out to explore options for the artificial recharge of recycled wastewater to mitigate seawater intrusion.

Figure 11. The distribution of places where the threat of seawater intrusion has been identified by previous Australian studies (after Nation et al., 2008; Werner, 2010; Ivkovic et al., 2012).

Salinisation of groundwater resources and groundwater as an agent for salinisation

Groundwater salinity and land salinisation are major Australian natural resource management issues and together are one of our most significant environmental problems. Salts are naturally distributed across the Australian landscape. They originate mainly from deposits of oceanic salt from rain and wind and are concentrated in soil water through evaporation and transpiration by plants. In a healthy catchment, where the water and solute systems are in balance, salt is slowly leached downwards by rainfall and is stored in the soil below the root zone of the vegetation.

European farming practices, which replaced deeper-rooted native vegetation with shallow-rooted crops and pastures, have caused dramatic increases in the salinity of our land and water resources. In many cases, groundwater recharge rates have been increased (e.g. by clearing rain-fed native vegetation for irrigated broad-acre farming or grazing). Such an increase in recharge can flush salts from the soil into groundwater systems. It can also cause the watertable to rise, bringing salts into the root zones of plants and even to the surface. The resulting salinity and waterlogging reduce plant yields. Where saline groundwater sits close to the ground surface, evaporation will also increase the groundwater salinity, further impacting upon vegetation.

Increased recharge can increase hydraulic gradients towards surface-water bodies. This increases the flow of saline groundwater into rivers and streams, increasing river salinity (Figure 12). Surface runoff from areas of land salinisation can also contribute to stream salinity. Rising watertables also affect rural infrastructure including buildings, roads, pipes and underground cables, causing significant infrastructure costs.

Two broad forms of salinity are recognised in Australia.

- Primary or naturally occurring salinity, which is part of the Australian landscape, reflects the development of this landscape over time. Examples are the marine plains found around the coastline of Australia, and the salt lakes in central and western Australia, and in the Murray-Darling Basin.
- Secondary salinity is the salinisation of land and water resources due to land-use impacts by humans. It includes salinity that results from dryland management systems (dryland salinity) and from irrigation systems (irrigation salinity). Dryland salinity occurs due to increased recharge under cleared land and the resulting rising watertables mobilising salt in the soil. Irrigation salinity (or irrigation recycling) occurs where groundwater is applied to crops at the surface as irrigation water, salts in the irrigation water are concentrated by evapotranspiration, and the residual, saltier water returns to the groundwater system by infiltration below the root zone. Over time, the repetition of this process causes a gradual increase in groundwater salinity.

State	1998–2000
New South Wales	181,000
Victoria	670,000
Queensland	not assessed
South Australia	390,000
Western Australia	4,363,000
Tasmania	54,000
Total	**5,658,000**

Table 4. Areas (ha) with a high potential to develop dryland salinity in Australia (National Land and Water Resources Audit, 2001). Note: the Northern Territory and the Australian Capital Territory were not included as the dryland salinity problem was considered to be very minor or of moderate to low risk.

The extent and likely costs associated with groundwater and land salinisation in Australia have led to significant investment in research in this area over the past two decades. The extent, causes and management options for irrigation salinity are now well understood, as this formed an important part of the Murray–Darling Basin Commission's activities for more than twenty years. The National Dryland Salinity Program also operated between 1993 and 2004, with an investment of $40 million, most of which was spent on research and development into the causes, costs, consequences, solutions and management of dryland salinity in Australia.

A focus was placed on dryland salinity by the National Land and Water Resources Audit's Australian Dryland Salinity Assessment 2000 (National Land and Water Resources Audit, 2001), which, in collaboration with the states and territories, defined the distribution and impacts of dryland salinity across Australia. Table 4 shows the best available estimates of areas affected by or at risk from dryland salinity at the time (1998–2000) (National Land and Water Resources Audit, 2001). At the time of the assessment, 5.7 million hectares were affected or had a high potential for the development of dryland salinity. It was estimated at the time that this area at risk could approximately triple by 2050, although this was a relatively coarse estimate that did not take into account severe climate processes such as drought and flood, or the effects of remediation actions already underway. The areas assessed to be 'at risk' were based upon locations of shallow or rising water tables. Some 20,000 km of major roads, 1,600 km of railways and 630,000 ha of remnant native vegetation and associated ecosystems occur in regions that were mapped as being high risk. The accuracy of these estimates was within the limits of the methods and data used by the states and research agencies that undertook this risk assessment.

Groundwater systems can be slow to respond to changes in land and water management practices (see Figure 12), meaning that, while Australia's salinity problem was already significant in 2001, it was expected to increase as a result of past and present practices. The predicted expansion of areas affected by dryland salinity has created a major challenge for governments, industry and the community to develop management approaches that protect environmental and human assets, address the problem of rising water tables, and make productive use of saline resources.

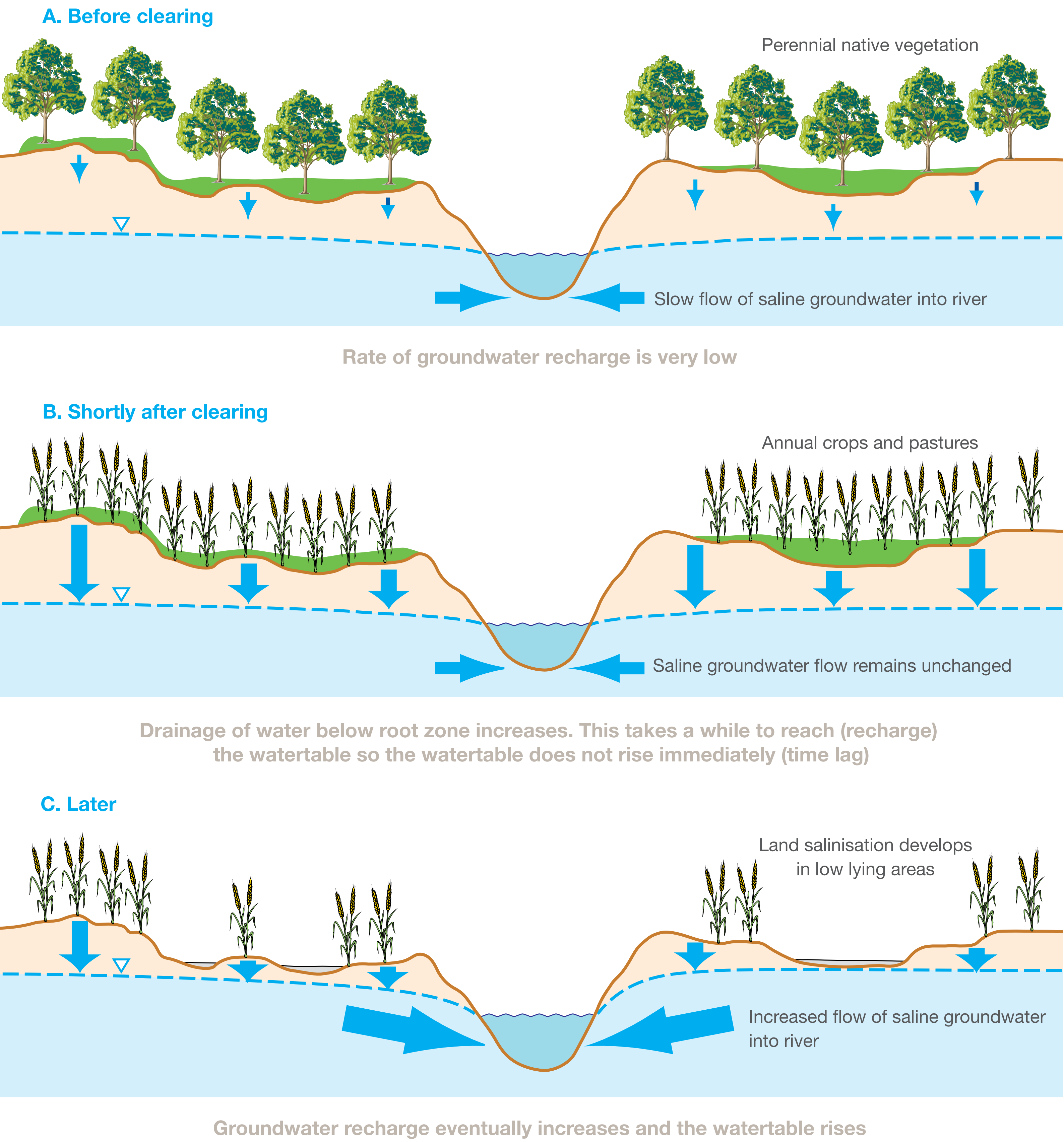


Figure 12. Processes leading to dryland salinity.

Managed aquifer recharge

Increasing pressure on water resources from climate change, population growth and increasing urbanisation means that Australia needs to diversify water sources to meet demand. Desalination of seawater, water recycling, increased use of groundwater, and stormwater and rainwater harvesting are all becoming more common practices in Australian urban centres. Managed aquifer recharge (MAR) is a less established but growing alternative available to water resource managers.

A comprehensive overview of managed aquifer recharge is provided by Dillon et al. (2009). Managed aquifer recharge is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. Aquifer recharge occurs naturally by rain soaking through soil and rock to the aquifer below or by infiltration from streams. Human activities that can enhance aquifer recharge may be unintentional (e.g. clearing deep-rooted vegetation, leaks from water pipes and sewers) and unmanaged (e.g. creation of stormwater drainage wells). However, managed aquifer recharge intentionally enhances recharge through mechanisms such as injection wells, infiltration basins and galleries for rainwater, stormwater, reclaimed water, mains water and water from other aquifers that can be subsequently recovered for all types of uses. The recovered water may be used for drinking water supplies, industrial water, irrigation or toilet flushing, with the appropriate levels of pre-treatment before recharge and post-treatment on recovery. Managed aquifer recharge can also be used to benefit the environment by leaving the stored water in the aquifer to sustain groundwater-dependant ecosystems or provide a barrier against seawater intrusion.

Common objectives for managed aquifer recharge include:

- securing and enhancing water supplies
- improving groundwater quality
- preventing seawater intrusion into coastal aquifers
- reducing evaporation of stored water
- maintaining environmental flows and groundwater-dependent ecosystems.

There can also be additional benefits, which include:

- improving coastal water quality by reducing discharge of contaminated groundwater
- mitigating floods and flood damage
- facilitating urban landscape improvements that increase land value.

Managed aquifer recharge can play a role in increasing storage capacity to help city water supplies cope with the runoff variability in Australian catchments exacerbated by climate change. Harvesting and recycling abundant urban stormwater and sewage effluent/wastewater, which are currently underutilised water sources, can also help to reduce the negative impacts of these discharging to coastal environments.

There is a growing variety of methods used for managed aquifer recharge internationally. Well injection techniques generally target deeper confined aquifers, whereas infiltration techniques can be used for unconfined aquifers. Those currently in use in Australia are (Dillon et al., 2009):

- **aquifer storage and recovery:** water is injected into a well for storage and recovery from the same well. This is useful in brackish aquifers, where storage is the primary goal and water treatment is a smaller consideration (e.g. for watering golf courses).
- **aquifer storage, transfer and recovery:** water is injected into a well for storage, and recovered from a different well. This is used to achieve additional water treatment by extending residence time in the aquifer (e.g. Parafield, SA).
- **infiltration ponds:** surface water is diverted into offstream basins and channels that allow it to soak through an unsaturated zone to the underlying unconfined aquifer (e.g. Burdekin Delta, Qld).
- **infiltration galleries:** buried trenches (containing polythene cells or slotted pipes) in permeable soils are built that allow infiltration through the unsaturated zone to an unconfined aquifer (e.g. trials conducted at Floreat Park, WA).
- **soil aquifer treatment:** treated sewage effluent is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal as it passes through the unsaturated zone for recovery by wells after residence in the unconfined aquifer (e.g. Alice Springs, NT).
- **percolation tanks or recharge weirs:** dams built in ephemeral streams detain water which infiltrates through the bed to be stored in unconfined aquifers and is extracted down-valley (e.g. Callide Valley, Qld).
- **rainwater harvesting for aquifer storage:** roof runoff is diverted into a well, sump or caisson, often filled with sand or gravel and allowed to percolate into the watertable where it is collected by pumping from wells (e.g. metropolitan Perth, WA).
- **recharge releases:** dams on ephemeral streams are used to detain flood water and uses may include slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge (e.g. Little Para River, SA).

Figure 13 shows the processes common to all types of managed aquifer recharge projects (Dillon et al., 2009). Where water is to be stored in confined aquifers, managed aquifer recharge requires injecting water via a well (Figure 13a). Where aquifers are unconfined and allow water to infiltrate through permeable soils, recharge can be enhanced by basins and galleries (Figure 13b).

The occurrence and diversity of managed aquifer recharge in Australia has increased in recent years. In 2011, five states and territories had operational managed aquifer recharge projects and two states had investigations underway (Figure 14).

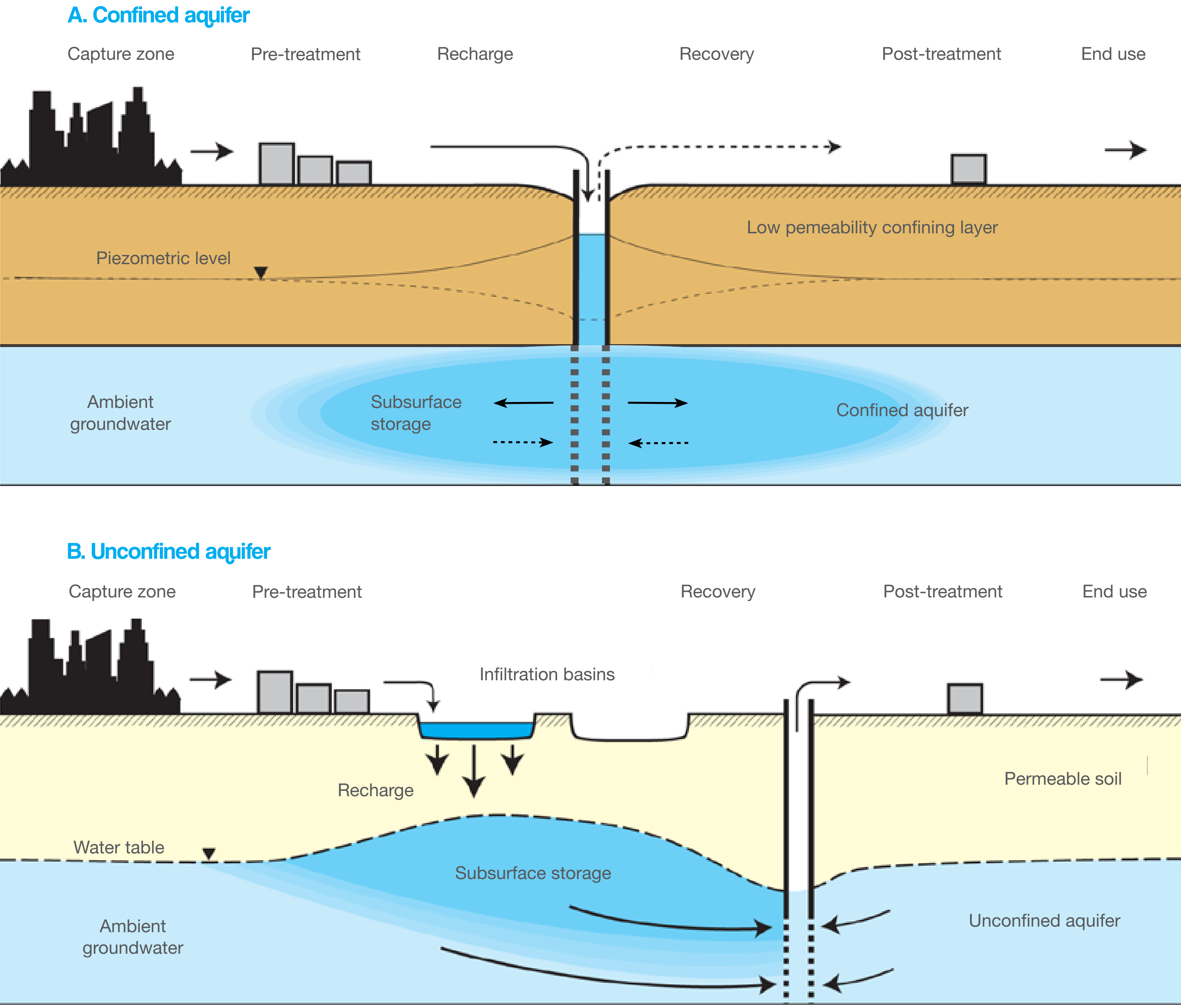


Figure 13. Two examples of managed aquifer recharge, (a) aquifer storage and recovery in a confined aquifer, and (b) soil aquifer treatment in an unconfined aquifer (modified from Dillon et al., 2009).

In 2011, managed aquifer recharge contributed 45 GL/yr to irrigation supplies and 15 GL/yr to urban water supplies across Queensland, South Australia, Western Australia and the Northern Territory (Parsons et al., 2012).

In December 2012 the Western Australian Water Corporation completed a comprehensive three-year trial of groundwater replenishment to the confined Leederville aquifer at a purpose-built facility near Perth. More than 2.5 GL of recycled water was recharged during the three year trial and it has been estimated that groundwater replenishment of 28 GL/yr could be achieved by 2023. Additionally, Parsons et al. (2012) conservatively estimated that 80 GL/yr of recharge occurred to the surficial aquifers across the greater Perth area from stormwater diverted to sumps with no monitoring or treatment. However, until simplified assessment criteria are adopted by local authorities this is not classified as 'managed' recharge under the Australian managed aquifer recharge guidelines (NRMMC, EPHC and NHMRC, 2009). Parsons et al. (2012) pointed out that engineered stormwater recharge is likely to already be a significant part of aquifer water balances in many locations and should be recognised as managed aquifer recharge through implementation of risk-based assessments and management plans where appropriate.

The feasibility of managed aquifer recharge as a water supply depends greatly on its costs and benefits in relation to other water supply options, including improved water conservation, tapping new surface-water supplies or aquifers, rainwater tanks, and groundwater or seawater desalination. The cost effectiveness of each option is governed by local conditions and therefore varies greatly between localities (Dillon et al., 2009). In a comparison of direct costs of water supply enhancement and demand reduction options carried out for four Australian cities (Sydney, Adelaide, Perth and Newcastle), three options were assessed that potentially include managed aquifer recharge among other approaches: stormwater reuse, indirect potable reuse and nonpotable water recycling (Marsden and Pickering, 2006). The analysis showed that, under certain circumstances, the costs of these three options can be less than seawater desalination and rainwater tanks.

There are some potential issues that need to be recognised and managed in the development of managed aquifer recharge schemes. Managed aquifer recharge in Australia normally involves the recharge of aquifers with stormwater or recycled water. The source water introduced into the aquifer may interact with the ambient groundwater or aquifer sediments, which can result in changes to water quality or aquifer permeability. Therefore the source water may require treatment to an appropriate level prior to recharge to prevent any risk to human health and the environment, including rendering an aquifer unsuitable for certain beneficial uses (e.g. drinking or irrigation).

Drainage or injection and subsequent extraction of water can also cause mobilisation of existing contaminated or saline groundwater. In some cases, mixing of injected water with ambient groundwater can lead to chemical reactions within the aquifer that affect water quality.

The National Water Quality Management Strategy provides a framework for ensuring that managed aquifer recharge projects protect human and environmental health. Specific guidelines for managed aquifer recharge were developed in 2009 and form part of the Australian guidelines for water recycling along with other relevant guidelines for end uses of recycled water (NRMMC, EPHC and NHMRC, 2009). A policy framework for entitlements in managed aquifer recharge has also been prepared (Ward and Dillon, 2011) and has been implemented in regulations in Victoria and Western Australia. Other states are expected to follow.

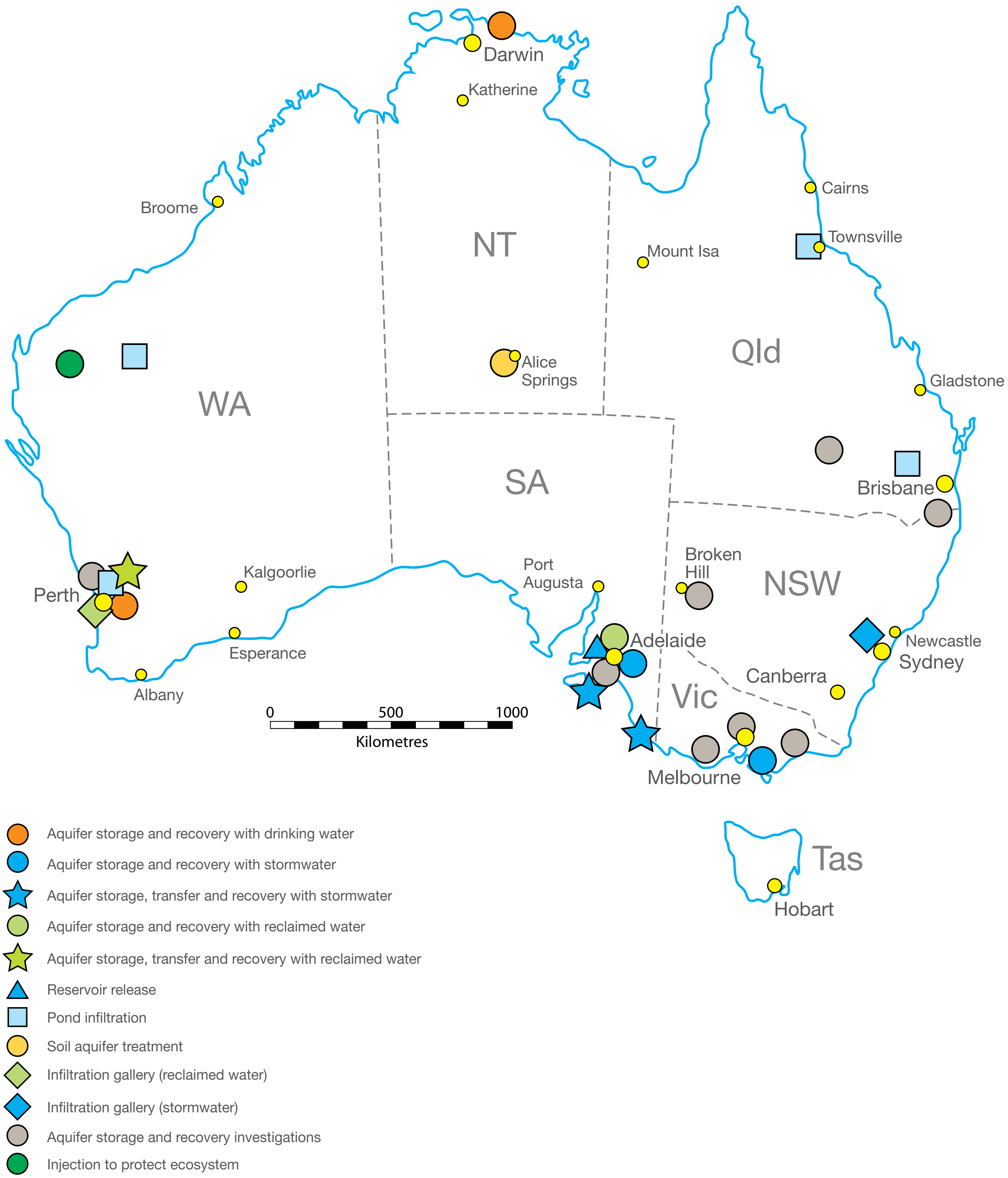


Figure 14. Locations and types of managed aquifer recharge in use in 2011 (Parsons et al., 2012).

Water planning and establishing sustainable groundwater extraction regimes

Water planning is required to ensure that groundwater is managed sustainably. This requires addressing issues such as increasing water demand, decreasing and less certain water supplies in some areas due to climate change, and historical poor management approaches that have led to overallocation of water resources. Through the water planning process, there should be certainty for consumptive users (e.g. irrigators, industry and the environment) about the availability and terms of access to water resources. Determining the best approaches for allocating water resources, and managing trade-offs between economic, environmental and cultural water needs is a major challenge that is currently facing water resource managers when every system to be managed is different. The challenge is made greater by the fact that Australia is at a turning point, where the concept of an infinite free water resource is no longer valid, and it is rapidly becoming a highly valued tradeable commodity.

In 2004, the Council of Australian Governments (COAG) agreed to the National Water Initiative (NWI), formalising a national commitment to establish clear pathways to return all systems to environmentally sustainable levels of extraction. This had become a priority due to prolonged and severe drought in southern Australia, uncertainty associated with climate change, growing demand and a legacy of past decisions. All of these things would clearly place a severe strain on future available water resources. To facilitate the development and implementation of NWI-consistent water management plans, in 2008 COAG commissioned the development of the *NWI Policy Guidelines for Water Planning and Management* (Australian Government, 2010), herein described as 'the Water Planning Guidelines'. The Guidelines were developed by officers from federal, state and territory water agencies, including the Murray–Darling Basin Authority and the National Water Commission. The guidelines highlight good practice approaches to planning and management, providing a number of case studies as supplementary material.

Water planning is essentially the process of setting sustainable environmental, social and economic objectives for the management of water resources. Effective water planning establishes the rules to meet environmental objectives and to share water resources between users by providing certainty of access to a share of water over an agreed timeframe. According to the Water Planning Guidelines, the planning process should aim to meet environmental and consumptive needs within an evidence-based, participatory and transparent process (Australian Government, 2010). Potential and emerging threats to the resource, including climate change, need to be taken into account. The ultimate result of the water planning process is a water plan (also known as a water management plan). This is defined in the Water Planning Guidelines as '*a legally enforceable plan … that defines the allowable level of diversion or take of water from a defined water resource that is environmentally sustainable, and sets out the arrangements for sharing the water available for consumptive use among competing users.*'

Underlying the water planning process is the fundamental knowledge that any extraction of water will create an impact somewhere in the hydrologic system. This means that, if water is to be extracted, decisions must be made about the acceptable level of impact. The standard approach to managing groundwater in the past had been to manage extractions to a volumetric sustainable yield, defined for a particular groundwater management unit. In many cases, the sustainable yield was determined as a percentage of the long-term average recharge for the groundwater management unit, but the percentage chosen often had little scientific basis. Additionally, the use of a long-term average recharge has little applicability in a variable climate. In an environment of water scarcity, and competing stakeholders, it was recognised that a more robust approach was needed.

A more rigorous approach, which forms the basis of many recent water management plans (see, for example, Richardson et al., 2011c), involves managing extractions so that the impacts fall within a set of agreed resource condition limits. Frameworks are developed so that groundwater extraction can be varied if certain resource condition trigger levels are reached (e.g. a certain drop in groundwater levels or increase in groundwater salinity is measured). Of course, because groundwater systems can respond slowly to changes in land use and groundwater extraction, adverse impacts (particularly contamination and seawater intrusion) can be difficult to reverse. It is therefore important to use predictive models, which attempt to foresee impacts, as part of this adaptive management type approach. This forms one element of the suggested framework for establishing a sustainable water extraction regime in the Water Planning Guidelines.

The water planning process, as described in the Water Planning Guidelines, is complex, with a large number of principles and considerations to be incorporated. The water planning process includes a number of stakeholder consultation steps (summarised in Figure 15).

Other key features of the water planning process are:

- incorporation of all available knowledge of the water system into a description of the water resource and its use within the planning area, including identifying future risks. This provides an informed position from which to set objectives for water management.
- resulting water plans should have a statutory base, i.e. they contain legally enforceable management arrangements, rules, entitlements or licence conditions.
- water plans contain explicit monitoring and review arrangements. They require that the condition of the resource be monitored, and there may be prescribed indicators of declining resource conditions that trigger either remedial action or an early review of the plan.
- regardless of the condition of the resource or status of resource condition triggers, water plans are reviewed at regular intervals to incorporate new knowledge, emerging issues or requirements for changes to planning objectives.

Developing effective water plans and implementing them into the future is critical to Australia's agriculture, industry, environmental assets and culture, which depend so heavily on groundwater.

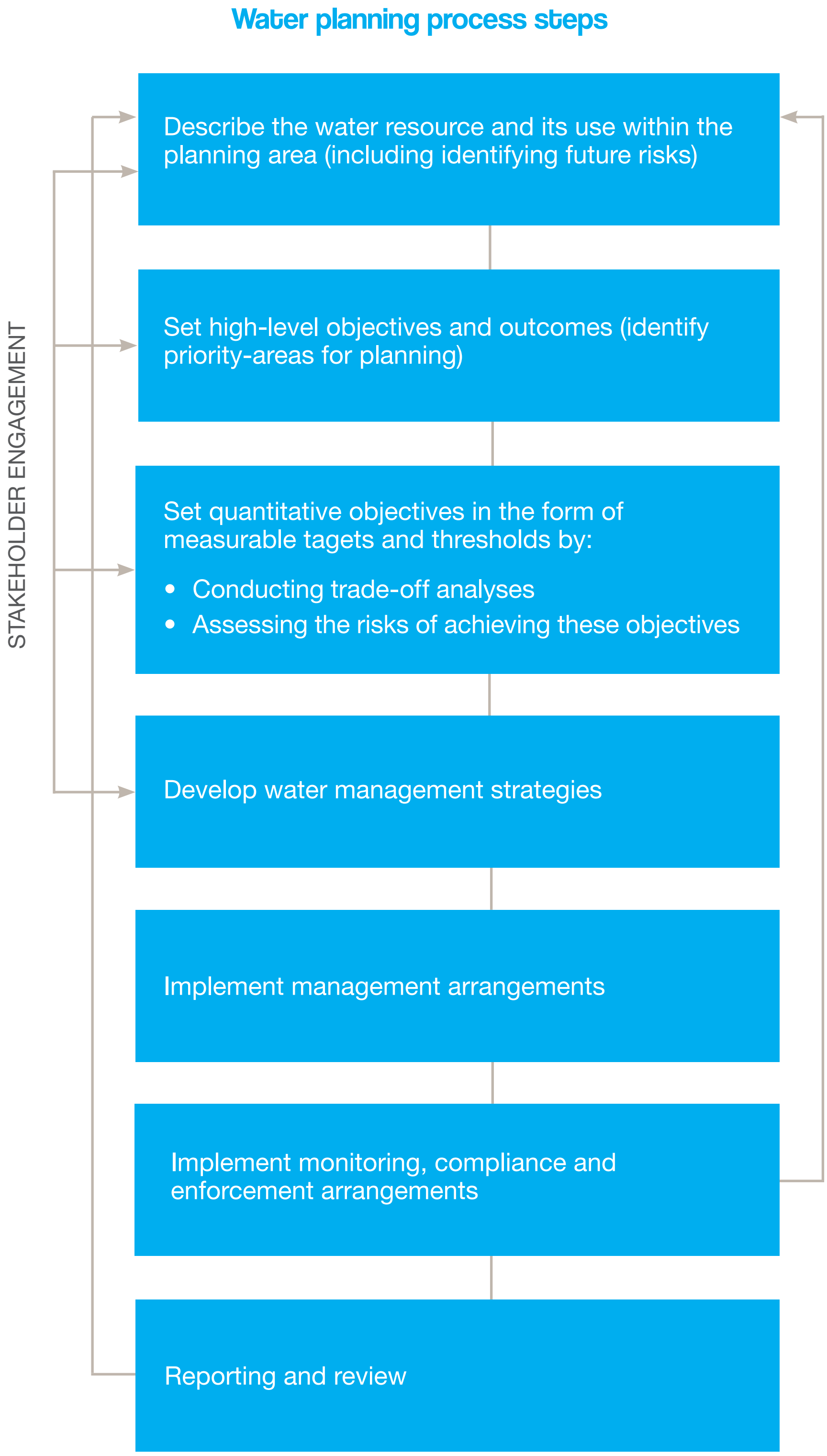


Figure 15. The water planning process (Australian Government, 2010).

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WQA — see Water Quality and Accounting

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