Conclusions

Relatively small changes in rainfall are amplified to much larger changes in runoff and groundwater recharge, which make Australia's water resources the most variable in the world. Water management is highly adapted to this variability, but the millennium drought in south-east Australia and the sharp drop in runoff in the South West of Western Australia since 1975 have tested the effectiveness of these adaptations. New measures are being introduced such as urban water supplies that are less dependent on runoff and the return of water to the environment to make it more sustainable. Climate change is occurring on top of that variability and in southern Australia it is likely to further reduce water resources. For the moderate climate change predicted to occur by 2030, the adaptation to droughts and floods can be effective, because the worst consequences are likely to be more intense droughts and less frequent but more intense floods. For further climate change, projected to occur by 2050 or 2070, the conditions of the millennium drought might become the average future water availability, which would have profound consequences for the way water is used and for ecosystems. The understanding of how climate influences water can help make water management more adaptable, such as through improved seasonal forecasts, and it can help communities plan how they will respond to reduced water availability in future.

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Groundwater

Andrew Herczeg

Key messages

- Groundwater use is increasing and it is the main source of water for much of Australia's dry interior.
- Groundwater shares many of the same sustainability issues as surface water, with the added complication that over-use may not be detected for several decades because of slow renewal and movement of the resource.
- Groundwater resources are strongly connected to surface water supplies, and many of Australia's ecosystems, plants, and animals depend upon groundwater for their survival.
- The sustainable extraction limit of an aquifer is usually much less than the rate of annual recharge, or renewal. Pumping aquifers causes groundwater levels to fall, affecting ecosystems and river discharge, and increasing salinity.

Groundwater use is increasing as surface water resources become fully allocated, and as demand grows for water in drier regions in which groundwater is the predominant resource. Groundwater is ubiquitously found beneath the surface but it is only usable where the water is not too deep, where the rock or soil is permeable, and where it has suitable quality. Much groundwater in Australia is unusable because of its natural salinity.

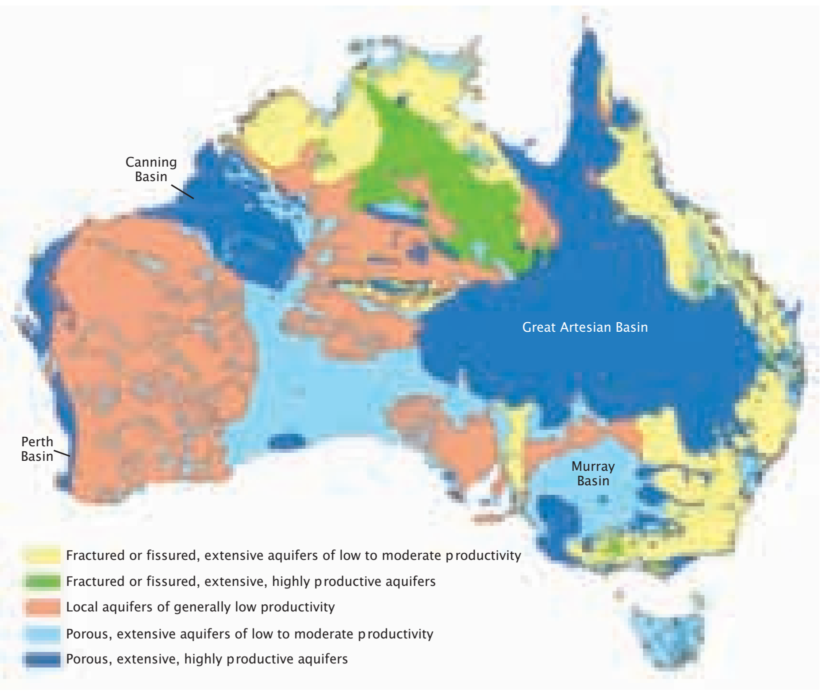
Groundwater was regarded as a resource to be mined, much like the rocks in which it lies, but it is now generally managed as a renewable resource, recognising that it is recharged from rainfall and discharges into rivers, lakes, the oceans, and through vegetation. Consequently, groundwater management faces many of the same sustainability issues as surface water. Ecosystems depend on the discharging groundwater, and over-extraction of groundwater can lower water tables or the pressure of water, which impacts upon the dependent ecosystems and on other users.

There are added difficulties of groundwater being hidden below the surface and moving slowly so that over-use may take many years to detect. The complex movement and interactions of different layers of water can be hard to detect but they have a direct effect on the sustainable use of the resource, such as by protecting fresh groundwater from being polluted by nearby saline layers. Many groundwater systems are poorly understood, as are their connections to ecosystems, so we do not know the full potential for groundwater in Australia even though pressures on the resource are growing.

Australia's groundwater resources

The amount of water that can be pumped over a reasonable time without causing a well to dry up is called 'groundwater yield'. It is a major factor in determining whether groundwater can be put to beneficial use. Salinity is the other major factor limiting groundwater use. About 30% of Australia's groundwater is potable (containing less than 1500 mg/L of total dissolved solids). The remainder varies from brackish to highly saline, and can be saltier than sea water.

High water yields occur in aquifers where rocks or sediments are highly porous and the pores, or holes, are well connected. Aquifers are often separated by impermeable low water-yielding rocks, termed aquitards, where the pores are small or disconnected, where the rocks effectively act as a barrier to water flow.



◂ ***Figure 4.1**: The variety of aquifer types and their productivity across Australia. The most productive aquifers are shown in dark blue and green.*[1]

The aquifers of Australia's sedimentary basins can cover thousands of square kilometres and contain several layers of variable quality, separated by aquitards. Highly productive basins include the Perth Basin, the Murray–Darling Basin (straddling the South Australia–Victoria border) and the Gippsland Basin in Victoria (Figure 4.1). Where aquifers are confined between aquitards, the water can be held under pressure and flow freely to the surface if penetrated by a bore. These are termed artesian basins, where bores continue to flow without any pumping, the best example of which is the Great Artesian Basin, which provides water to much of Australia's arid interior.

Very productive aquifers are also found in the alluvial plains of Australia's river systems, and the coastal plains. The sediments in these areas have porous, permeable layers and give good yields of fresh, quality water – up to 0.8 ML/day – at a shallow depth that can be easily pumped.

Analysing a sample of groundwater, Perth. Photo: David McClenaghan, CSIRO.

Much of the Australian continent overlies hard rock geology (areas coloured yellow, green, and pink in Figure 4.1). These areas provide limited groundwater resources, because water can only refill the aquifers through cracks and fractures in the rock. Although groundwater is present, it is only usable where the fractures are connected. The uplands of the Murray–Darling Basin, the Mount Lofty Ranges (including the Adelaide Hills), the Darling Range of the South West of Western Australia and the Sydney Basin would all have high demand for groundwater, but the geology makes them largely unproductive.

Groundwater use

Groundwater use is increasing across Australia but the total use is difficult to estimate. Most groundwater is extracted by individual users and is rarely metered, and only a small fraction is managed through distribution networks. In 2004–05, licences for groundwater use were about 4700 GL/year, or 25% of the total amount of water consumed in Australia.[2,3] Unlicensed use of groundwater – mainly for stock and domestic uses – is estimated to consume an additional 1100 GL/year.[4] The amount of groundwater used is estimated to have almost doubled since the mid 1980s. Increased use of groundwater has been facilitated by recent drilling technologies and cheap submersible pumps that can lift water from considerable depths.

In the drier parts of Australia, groundwater is the predominant water source because surface water resources are so scarce. Perth and Alice Springs, for example, rely on groundwater for about 80 and 100% of their water supply, respectively. When surface water resources become scarce, users turn to groundwater to meet their needs. Declines in surface water availability during the millennium drought in the southern Murray–Darling Basin led to a modest rise in groundwater use (1240 GL in 2000–01 to 1531 GL in 2007–08), but a sharp rise in the proportion of water supplied from groundwater (11% to 37%).[5] Given the reliability of supply and convenience of self supply, the use of groundwater may not return to previous levels, even when surface water availability does.

Groundwater as a renewable resource

Groundwater is recharged, or replenished, over timescales ranging from years to millennia and eventually all recharged water discharges back to the surface (Figure 4.2). Thus, in some ways, groundwater is complementary to surface water – it is a very large reservoir of water that is renewed slowly. The large reservoir effectively smooths annual and even decade to decade variations in rainfall to provide a highly reliable supply of water, provided it is used within limits that do not have unacceptable impacts on storage or ecosystems.

Different types of aquifers have very different reservoir effects. The deep, large sedimentary basins have enormous stores of water equivalent to thousands to millions of years of recharge, although extraction can cause changes to pressure (see below). By contrast, the small alluvial aquifers of river floodplains are renewed in a matter of years and, like dams, the amount stored is much more variable and sensitive to the levels of use.

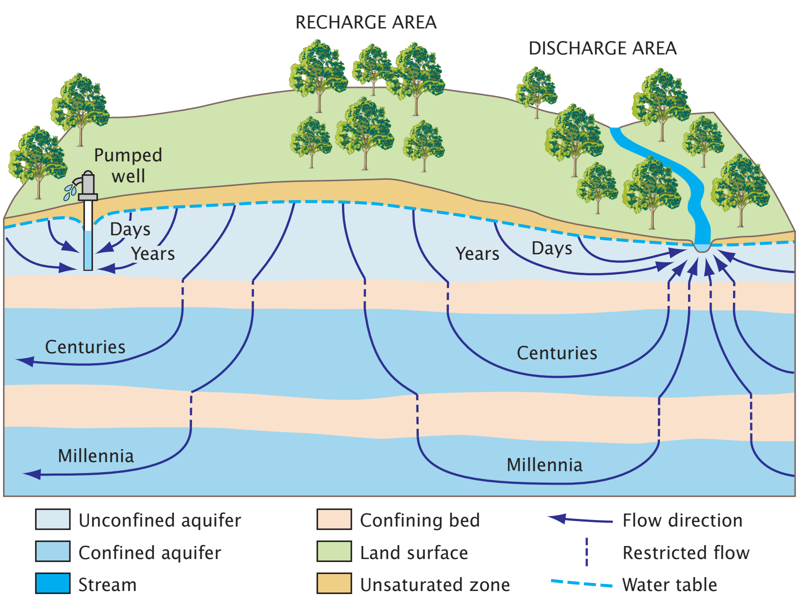
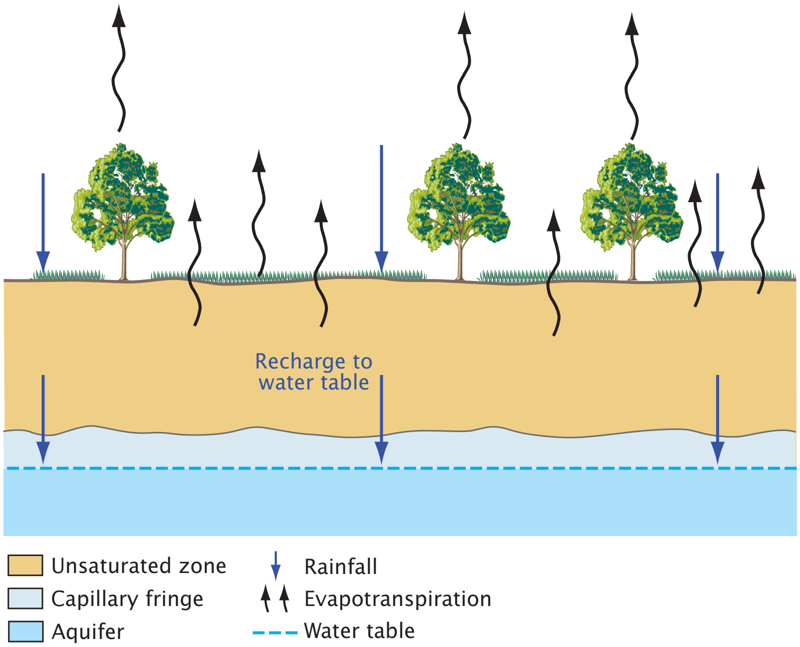


***Figure 4.2**: Idealised cross-section showing two types of aquifers. An unconfined aquifer below the water table flows into a stream and is also drawn down into a well. Below that, two confined aquifers are renewed over much longer time scales.[6] (Courtesy of the U.S. Geological Survey.)*

Diffuse recharge occurs when infiltrating rainfall percolates through the soil, beyond the reach of plant roots, and into the underlying water table (Figure 4.3). Floodwaters also recharge groundwater, especially in parts of northern and inland Australia that are affected by monsoonal rainfall, where vast floodplains are inundated by water. The floodwaters percolate through the soils and into underlying aquifers.

A map of groundwater recharge across Australia consolidated from more than 4400 recharge estimates[7,8] is shown in Figure 4.4. For much of Australia, less than 5 mm of rainfall recharges aquifers per year on average. This is an even lower proportion of total rainfall that becomes surface runoff. Recharge exceeds 30 mm/year in some of the wettest parts of the tropics, along

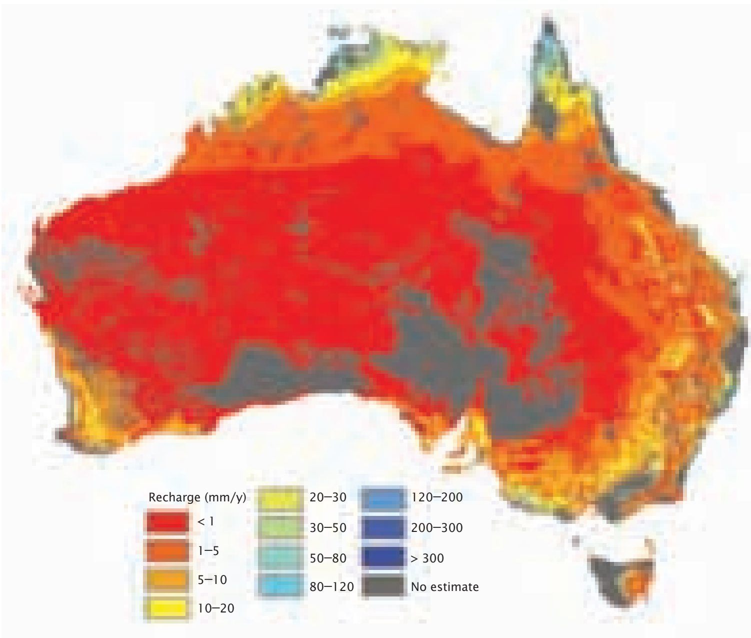


▸ ***Figure 4.3***: *Conceptual diagram of water fluxes beneath the land surface to the water table. The amount of rainfall that reaches the water table depends upon rainfall, evaporation through soil and vegetation and the amount of water stored in the soil.*[6]

sandy coastal plains, and in the wetter highlands. Not all of the recharge is usable, because much of it contributes to saline, low yielding or deep aquifers.

It is important to know the amount of recharge, as it (not the volume of water stored) determines the maximum level of renewable resource. However, recharge is notoriously difficult to measure or estimate. In the long term, diffuse recharge is the amount of rainfall that is not lost to evaporation and runoff. Potential evaporation exceeds rainfall across much of Australia, but, during sporadic wet periods and large storms, rainfall exceeds evaporation and recharge occurs. Recharge is often calculated from the difference between rainfall and evaporation rates, but it only takes small errors in either of these large terms (measured in hundreds of millimetres) for there to be very large errors in the recharge estimate (which is just a few millimetres per year). A more reliable method uses soil measurements of the chloride ions that accumulate during evaporation of rainfall. The difficulty with this technique is how to scale up those measurements to represent the whole aquifer across a range of soils, rocks, and vegetation. Alternatively, the age of groundwater can be measured using chemical and isotopic techniques, which, combined with data on the aquifer's volume, can be used to estimate recharge rate. But these techniques are very sensitive to assumptions about leakage from aquifers and the sources of recharge. The best estimates are obtained by combining multiple techniques in a single groundwater model to best reconcile recharge estimates to the different sources of information.

Eventually, all of the water recharging a groundwater system is discharged. Groundwater can discharge directly into the ocean, rivers, lakes, and springs. In areas with shallow water tables, it can also discharge back to the atmosphere via evaporation through vegetation and the



◂ ***Figure 4.4**: Groundwater recharge rates across Australia, showing very low values throughout much of the interior (less than 1 mm/year). These are approximate estimates of recharge based upon extrapolation from limited measurements.*[8]

soil. Discharge occurs in many subtle ways and it too is hard to measure it directly. In general, discharge balances recharge over the long term; however, this may not be true for groundwater aged over tens of thousands of years in very large aquifers where discharge rates reflect recharge under past climates and not the current rate. Discharge of groundwater is a key component maintaining many ecosystems, including keeping trees alive in times of soil water stress.

Groundwater to surface water connections

Surface water and groundwater are strongly connected – particularly alluvial aquifers adjacent to rivers and the aquifers that support lakes. Many rivers flow long after runoff from tributaries has receded, because flow is maintained from groundwater discharge. The Daly River in the Northern Territory, for example, receives virtually no runoff during the three driest months of the year, but groundwater discharge lets it flows all year round. Except in the wettest parts of Australia, a good indicator that a river is maintained by groundwater discharge is that it flows throughout the year.

The connections between groundwater and rivers mean that the use of one resource can have negative impacts on the other. Rivers can be termed as 'gaining', 'losing', 'disconnected' or 'throughflow', depending on the interactions between groundwater and the river (Figure 4.5). In a gaining river reach, groundwater pumping may eventually reduce river flows by the amount pumped (Figure 4.6), because this water would have otherwise discharged to the river.[9] In a losing river reach, groundwater pumping can draw down the water table and induce additional recharge

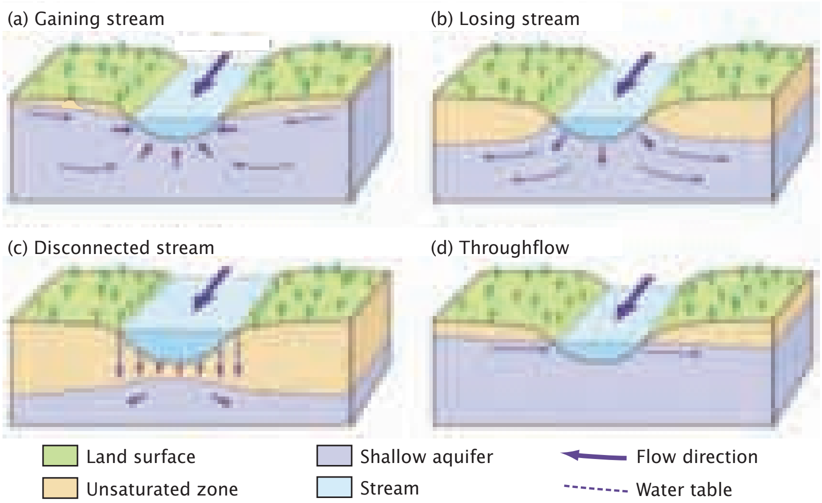
Permanent wetland supported by groundwater inflow. Photo: Bill van Aken, CSIRO.

from the river. When groundwater and rivers are managed as separate resources these interactions are neglected, leading to overestimates of the amount of water that can be used – a problem known as double accounting.

The low gradients and low flow rates through aquifers can cause considerable time lags before the consequences of pumping are realised. For example, the recent expansion of groundwater use in many alluvial aquifers will not be experienced for several decades in some cases.

Groundwater contributions to streams can be estimated from dry season discharge, but more recent methods use a combination of chemical and isotopic properties of streams to reveal the groundwater source. This provides a relatively easy and accurate way to estimate the location and amount of groundwater discharge. Water losses from 'losing rivers' to groundwater are far harder to estimate.

▸ ***Figure 4.5****: The types of connection between groundwater and streams. In a gaining stream, the water table is higher than the stream, and the stream gains groundwater. If the water table is below the stream, the stream loses water to the aquifer. In extreme cases, the stream is disconnected if the water table is below the bottom of a stream, but the water table still receives water from seepage through the stream bed. In a throughflow system, groundwater passes across the stream.[6] (Courtesy of the U.S. Geological Survey.)*



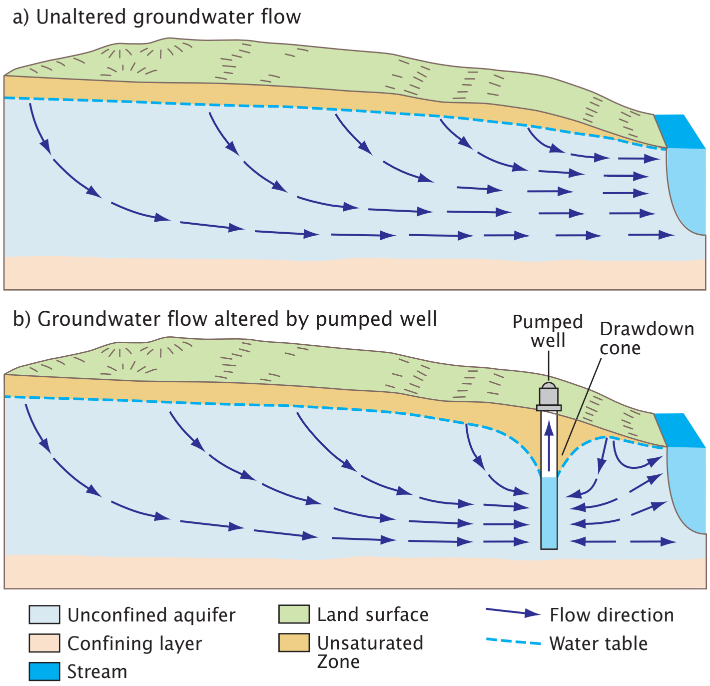


Figure 4.6: *Comparison between an unaltered groundwater flow system (a) and a system with a pumped well installed near a stream (b). Water withdrawal from the pump becomes another component of total discharge, intercepting groundwater that would otherwise discharge to the stream.*[6] *(Courtesy of the U.S. Geological Survey.)*

Groundwater-dependent ecosystems

Because many rivers, lakes, and wetlands are supported by groundwater, their associated ecosystems, plant, and animal species depend on groundwater discharge to survive. Australian examples include lowland forests, fauna in northern rivers such as the Daly River in the Northern Territory, springs and wetlands in the Great Artesian Basin, floodplain red gum forests near the Murray River, refuge pools in ephemeral rivers, and lakes of the Perth Basin.[10]

Some marine organisms rely on marine discharge of groundwater to support their habitats. Aquifers also contain distinctive, diverse communities of microorganisms known as stygofauna, which include bacteria that metabolise some contaminants.

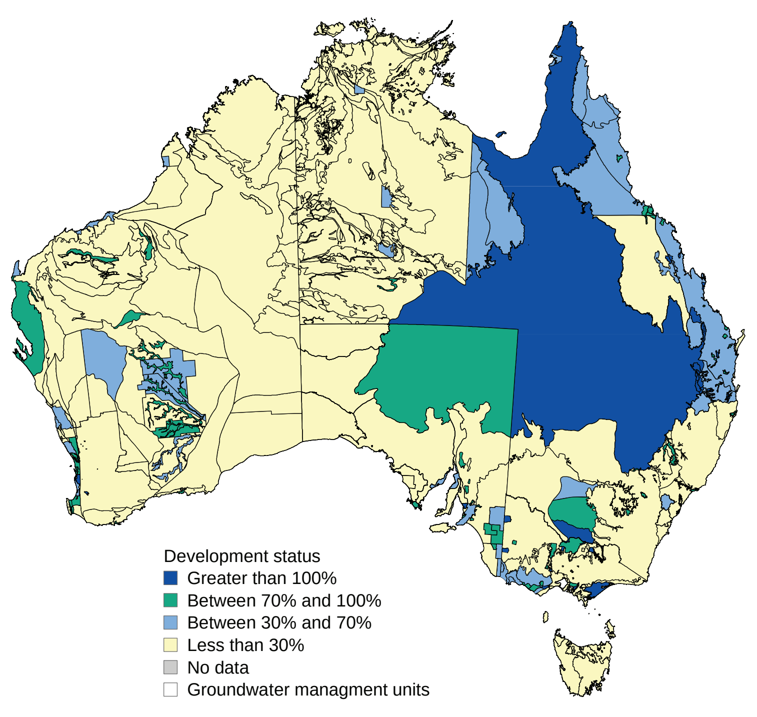
A subtle form of groundwater dependence is that of trees which can persist for long periods without rainfall in the dry season or extended drought, such as red gums across the drier regions. Most vegetation thrives where a high level of soil moisture is available close to the land surface. If soil conditions become dry and salinity levels become high, trees survive by sending tap roots to the water table and lift water from great depth.

Ecosystems may be entirely or partly dependent on groundwater, and their needs are a key part of determining sustainable groundwater extraction rates. The extent and nature of groundwater-dependent ecosystems are only now being mapped across Australia. A variety of techniques is used to estimate groundwater fluxes, but assessing how an ecosystem will respond to reduced discharge or lower water tables is a bigger challenge, involving ecological and hydrological assessments (see Chapter 9).

Sustainable groundwater extraction

The recharge rate of the aquifer is the absolute maximum amount of groundwater that could be used sustainably, but, in reality, only a fraction of the recharge can be used in the long-term or without impacts. This is because any extraction of groundwater can alter recharge, reduce discharge elsewhere, lower water levels or change the flow paths and water pressure through an aquifer. These changes may affect other users of the resource, including groundwater dependent ecosystems.

Extraction of groundwater will be sustainable if water use can be maintained long into the future by recharge and if use has no unacceptable impacts on other users (including surface water users) or the environment. Determination of sustainable yield is always a compromise between different demands for the resource as any extraction will have some impacts. Regulators can sometimes decide to allow mining of fossil groundwater reservoirs in remote areas as part of a fixed-term mining development, or consciously enable greater exploitation of groundwater during times of limited surface water supply.



▸ ***Figure 4.7****: Australia's major aquifer systems have been developed to varying degrees.[11] The development status shown is the level of use compared to the estimated long-term level of use that could be sustained. (Source: National Land and Water Resources Audit. Department of the Environment, Water, Heritage and the Arts.)*

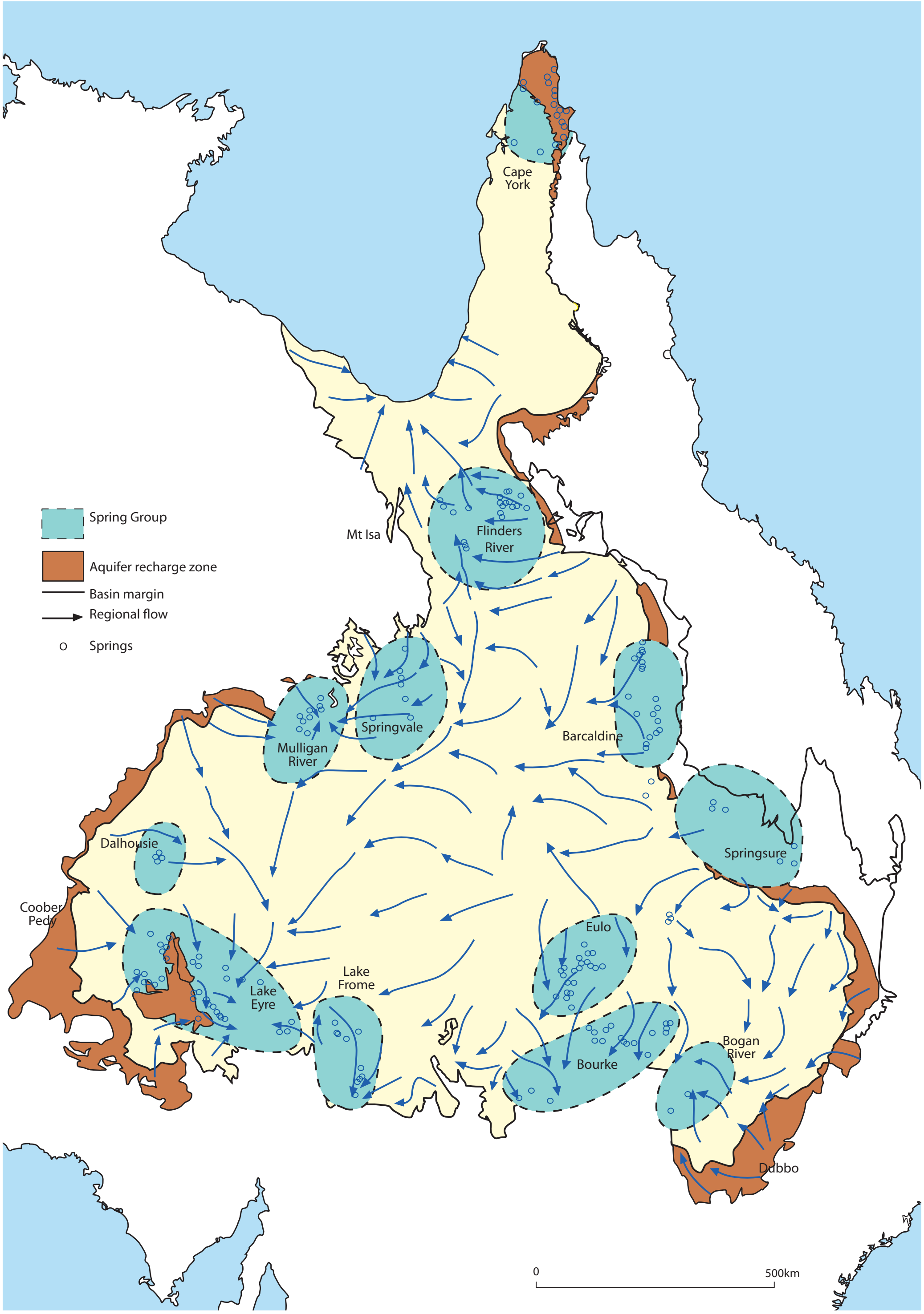
It is useful as a reference point to express the sustainable rate of extraction as a percentage of recharge. As a simple rule of thumb extraction should not exceed 50–70% of recharge without very careful assessment. This precaution is required because rates of recharge are highly uncertain and the actual rate may be lower than estimated. The sustainable level of use may also be a lower fraction of recharge than first thought when local hydrogeology, induced salinity, or impacts on groundwater dependent ecosystems are considered. The National Land and Water Resources Audit[11] (Figure 4.7) and the CSIRO's Murray–Darling Sustainable Yields project[12] have revealed several highly stressed Australian groundwater systems.

Aquifers typically have hundreds to thousands of wells. Extraction from each well will create a drawdown halo around each well (Figure 4.2); the extent and severity of the drawdown depends upon the rate of pumping and local hydrogeology. Extraction can also induce vertical leakage between aquifers. This may cause saline water to enter from adjacent poor quality aquifers, or extraction from coastal aquifers can result in sea water intrusion as the aquifer's water levels fall below sea level, as has occurred in Perth.

It may take several decades for the water table or water pressure response to spread across the whole aquifer, so consequences of pumping may not be detected until long after its use has been established. Eventually, a new lower water level will be reached where recharge is balanced with extraction and discharge. This lower water level will have a lower discharge to rivers and lakes, and may be low enough to dry the wells of other users.

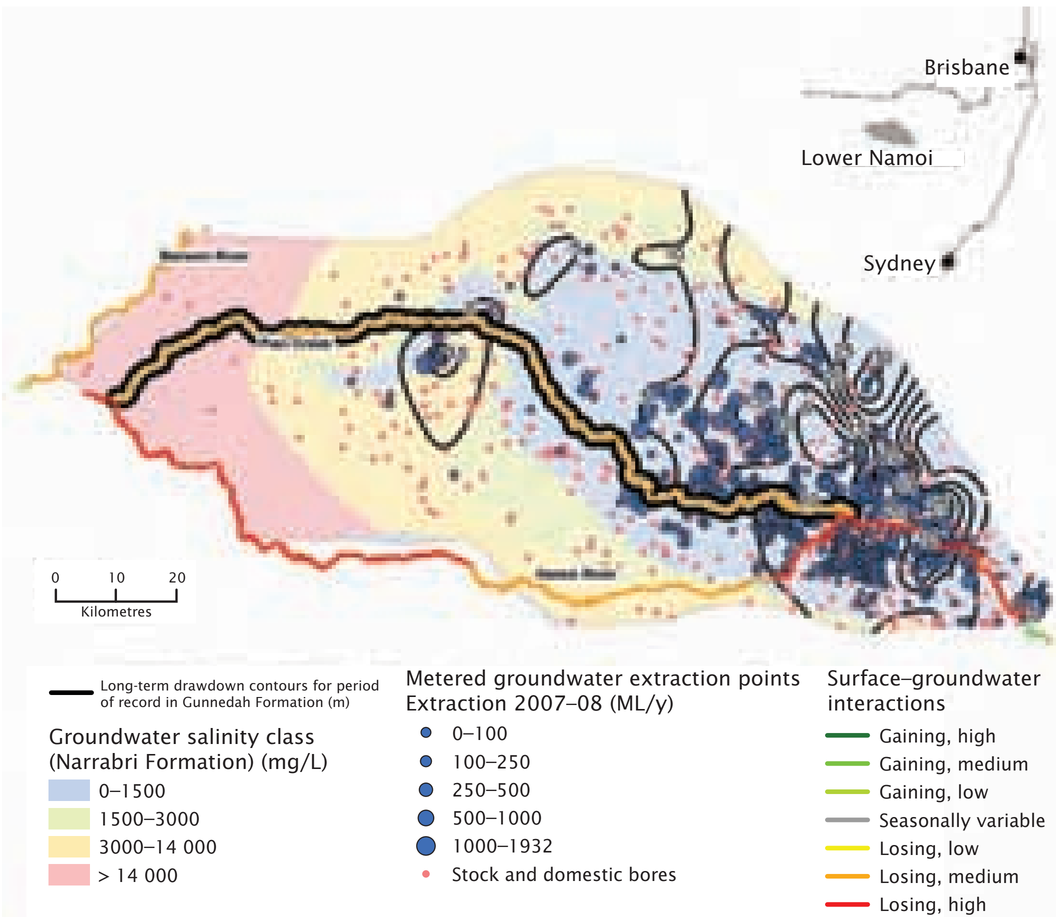
The Great Artesian Basin is a good example of the consequences of over-use. It is one of the world's largest continuous groundwater systems (Figure 4.8) and supports hundreds of springs and wetlands, many of which are listed as significant by the Ramsar Convention on Wetlands of International Importance. The typical age of water as it discharges is 1 to 2 million years, having travelled up to 1500 km from recharge areas. Thousands of wells have been drilled into the Basin's highly productive confined aquifers, and many have been left to flow, lowering aquifer pressure and encouraging feral animals and weeds that otherwise would not have an available water supply. A program of well capping is restoring pressure to the system to enable sustainable use and maintenance of dependent ecosystems. Most of the 500 GL/year used from the Great Artesian Basin is for stock watering, but there are new demands from the mining and resource sector – particularly from companies seeking to develop the abundant coal seam gas resources in Queensland's Surat and Bowen Basins, which may have an impact on existing users (see Chapter 10).

The Namoi region of northern New South Wales (Figure 4.9) has one of the most intensely exploited groundwater resources in Australia. It is a stressed system in which it was realised too late that rates of groundwater pumping were too high. Approximately 250 GL/year (2004–05) are used from the Namoi, equivalent to half the estimated annual extraction from the entire Great Artesian Basin. High levels of groundwater use over small areas in the Namoi region have lowered groundwater levels by several metres, and the alluvial aquifers now essentially receive most of their recharge from the losing streams in the area. The Murray–Darling Basin Sustainable Yields



▲ ***Figure 4.8**: The Great Artesian Basin stretches from the Gulf of Carpentaria across much of western Queensland to the north western part of the Murray–Darling Basin, and into the Northern Territory and South Australia. This map shows the general direction of groundwater flow (arrows) and main areas of groundwater springs. The main recharge zones are on the western slopes of the Great Dividing Range and some recharge occurs on the western margin.[13] (Source: ABARES.)*

project[14] suggests that groundwater use in the Namoi exceeds recharge; the water balance shows that increased groundwater use corresponds almost entirely to induced leakage from streams, reducing access to river water in dry times and increasing salinity and land subsidence caused by the declining groundwater levels.



▲ ***Figure 4.9****: An example of a report card assessment of the Lower Namoi region of New South Wales, showing distribution of wells, salinity and assessment of losing (to groundwater) streams and gaining (from groundwater) streams.[13] Groundwater levels are falling in the east and salinity of groundwater is rising in the west. The Namoi River loses water to groundwater, and Plan Creek gains water from discharging groundwater.*

Conclusions

Many aquifers with high historical rates of use are showing symptoms of over-use, such as falling water tables and lower aquifer pressures and subsequent impacts on future use, groundwater salinity, river flows, and ecosystems. The level of over-use was not recognised for decades because of the lags inherent in large, flat, and slow moving groundwater systems. Remediation of these systems is expensive and difficult because salinity and ecological damage are hard to reverse, and because of the historical expectation of reliable water supplies. Inadvertent impacts of recent strong growth in groundwater use have not been felt yet and, given that the consequences of present use are in many cases still to be felt, some caution should be exercised around future groundwater development, by putting effective risk assessment and management processes in place.

Groundwater systems are hard to understand, being hidden below the surface and involving complex geological patterns. The principles are well understood, but applying those to characterise the unique situation of each aquifer is fraught with difficulty. To properly understand a groundwater aquifer relies on information about aquifer dimensions, structure, and permeability, as well as the timescales of recharge, discharge, and groundwater flow. It requires many bore holes

Blue Lake, Mount Gambier, South Australia, fed by groundwater. Photo: Bill van Aken, CSIRO.

to be drilled and pump tests to be undertaken. Laboratory analyses of the chemical and isotopic properties of groundwater provide a complementary picture of an aquifer's history, and new remote sensing techniques to map salinity and water content are emerging. All of the information can be interpreted and integrated in detailed groundwater models, where predictions can be made of the consequence of current and future extraction.

The best groundwater assessments come from a combination of all these techniques, and research is continually improving their accuracy, but detailed groundwater assessment is expensive and time-consuming and cannot be undertaken for all aquifers. A risk assessment approach is appropriate, where the level of investigation is matched against the possible consequences of use. For large aquifers with little prospect of use, reconnaissance assessments and local experience are appropriate levels of assessment. As the rate of use starts to approach a reasonable proportion of the rate of recharge, and where other users and environmental impacts need to be considered, more detailed assessments are required. The challenge is to ensure that additional investigations and regulations keep pace with growing use. Groundwater monitoring and adaptive management complement thorough planning by detecting and responding to early symptoms of over-use. A better understanding of groundwater would lead to less precaution needing to be applied to future use, or less frequent occurrence of the impacts of over-use.

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Water quality

Simon Apte and Graeme Batley

Key messages

- Strict water quality controls are in place to protect human health and aquatic ecosystems from chemical, and biological pollutants.
- In general, control of pollutants at their source is more effective than remediation because of their persistence in the environment and concentration through the food chain.
- Elevated levels of salinity, nutrients, metals, pathogens, and organic contaminants (e.g. pesticides) are the main causes of poor water quality in Australia. Pollutants are derived from a wide range of sources including agriculture, industry, and urban areas.
- Sediment layers at the bottom of waterways are a major sink for nutrients and contaminants, which can be released into waters and become toxic under certain conditions.
- New contaminants, for example pharmaceuticals, are continually emerging and much monitoring and research is focussed on detecting their presence and toxicity in aquatic environments.

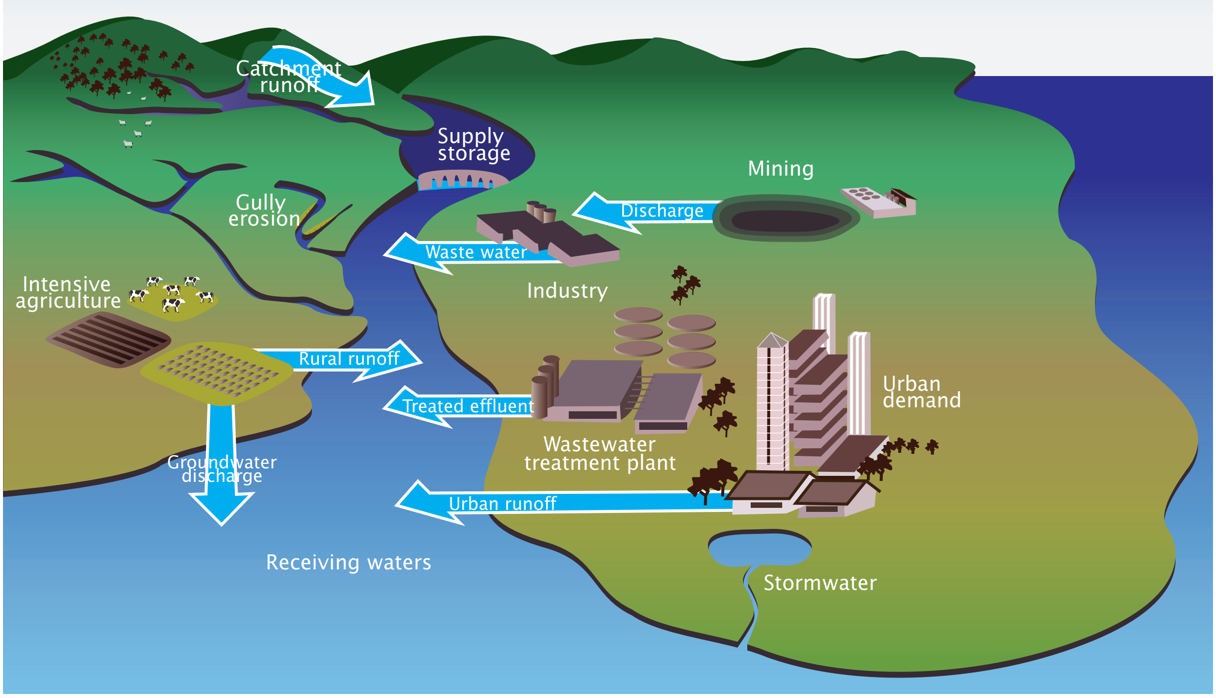
It is not only the quantity of water that matters, but the quality of the water has to be maintained for it to be useful. Maintaining supplies of potable quality water for human health is of paramount concern, either through water treatment or the protection of sources such as the largely pristine water supply catchments that provide for much of Sydney, Melbourne and Perth. Pollutants such as metals and pathogens may also enter the food chain, so the quality of irrigated water and that of fisheries have long been of concern. Poor quality irrigation and stock water can also reduce agricultural productivity. Finally, natural organisms are quite sensitive to some contaminants, so to conserve aquatic ecosystems the highest water quality needs to be maintained. For example, the pollution criteria for copper in the Australia and New Zealand water quality guidelines[1] is 0.0013 mg/L for freshwater ecosystems, compared with 2 mg/L for drinking water.

Streams, rivers, lakes, and groundwater naturally contain chemical and biological constituents. Natural waters contain essential nutrients of phosphorus, nitrogen, cations and trace metals and biological constituents, such as algae, which are essential requirements for fish and invertebrates. The physical properties of water, including its temperature and the degree of light penetration, also influence aquatic organisms. Water released into rivers from the depths of large dams can be so cold and deprived of oxygen as to be lethal to organisms for tens of kilometres downstream. Consequently, dam release valves have been re-engineered to take water from higher up in the dam.

Native ecosystems have become adapted to an enormous range of natural water quality across Australia, from the clear waters of rainforest streams to the naturally turbid waters of Cooper Creek in western Queensland or the hypersaline lakes of the arid regions. It is the changes to natural water quality, through the pollution of water, which threatens human health and other life. Pollution can result from changes in the naturally occurring concentration of some components in waters, such as when nutrient levels become too high and trigger the toxic growth of algae, or when oxygen levels become too low. Of course, pollution also occurs from manufactured constituents, such as pharmaceuticals, which are not normally found in water.

Managing pollutants in a river basin or groundwater system involves several steps.[2] The first is to define the uses and environmental values of water and risks to them from pollution. Then the sources of pollution and transport pathways should be identified. In large catchments with multiple land uses, there can be many possible sources, and for chemical and biological pollutants, the pollutants can be transformed as they pass through the environment. For example, herbicides can degrade into harmless constituents, so they may only be pollutants close to the source. Targets for improved water quality are then set, along with management actions to achieve them. Monitoring of water quality is used to identify new pollution risks and to help evaluate the effectiveness of the management strategies.

Water quality from point source pollution has improved in recent decades as a result of strong regulations that control pollution at its source from industrial plants, hospitals, sewage treatment



▲ ***Figure 5.1***: *There are many potential sources and pathways of pollutants to waterbodies.*

plants, and mine sites. Diffuse pollution of waters from catchment land use is much harder to tackle, and poses the most extensive pollution problems today. Salt, nitrogen, phosphorus, and suspended sediment are diffuse pollutants resulting from a wide range of agricultural and urban land uses that have degraded water quality across much of Australia. There are many possible sources of these pollutants in each catchment (Figure 5.1), making them hard to control. Being natural constituents of water, the levels required to prevent ecological damage are hard to determine and highly variable, although much progress has been made.

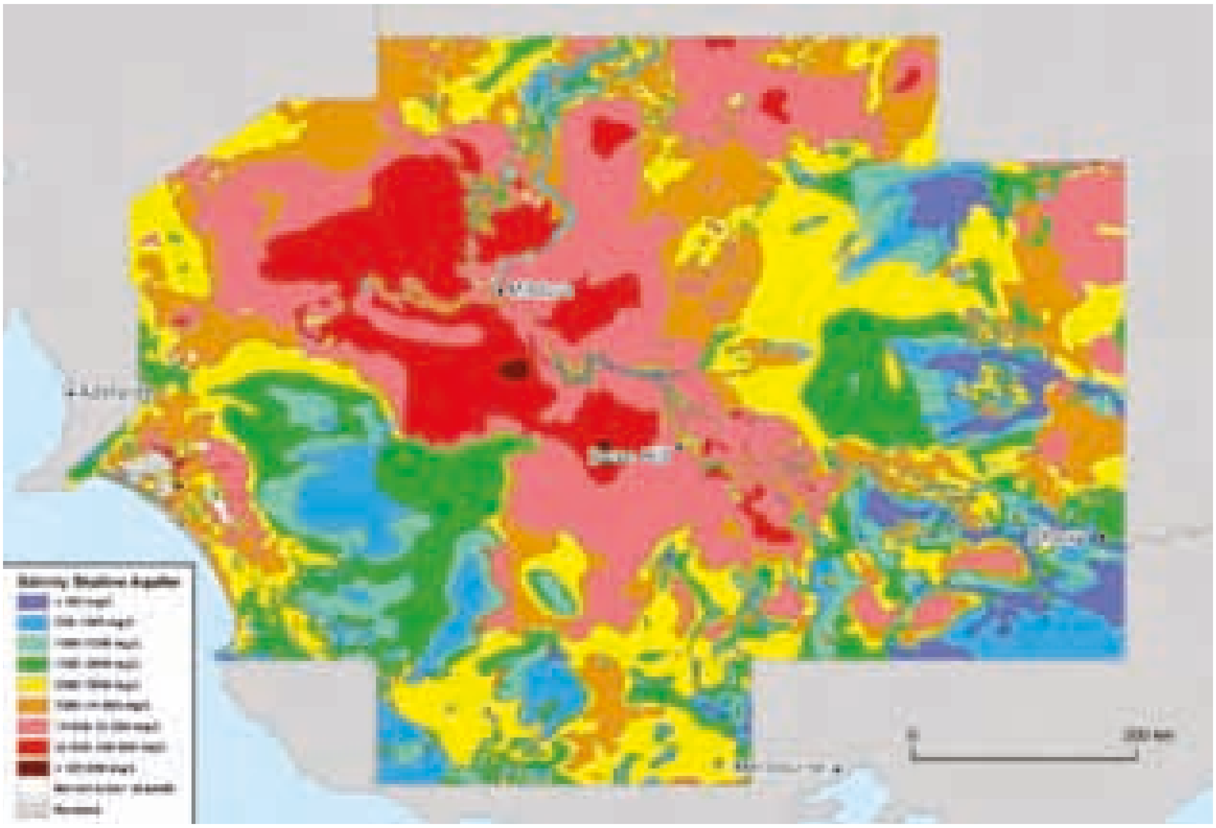
Salinity

Land use-induced increases in salinity affect about one-third of rivers in agricultural regions and cost about $3.5 billion a year in lost production and treatment.[3,4] Salinity has an impact on the potable use of water, including supplies for Adelaide obtained from the Murray River, and the use of water for irrigation and stock (Table 5.1). Although most adult Australian fish can tolerate salinity, juvenile fish (such as Murray cod), are particularly sensitive to salt.[5]

Table 5.1 Indicative salt concentrations above which agricultural production or quality of use declines. Sea water has a concentration of about 30 000 mg/L.

Water use	Salt concentration (mg/L)
Drinking water	500
Irrigation of fruit and vegetables	500–1500
Irrigated pastures	800–3000
Dairy cattle	3000
Sheep	6000

The ultimate source of salt is from rainfall, which contains small amounts of ocean spray, even far inland. The salt accumulates deep in soil over many millennia, especially in regions where rainfall is fairly low (300 to 600 mm/year). Geochemical and isotopic evidence is unequivocal that the source of salt is from marine aerosols and rainfall, even though some rocks were deposited under the sea. That salt is being mobilised and transported to rivers with the rise in groundwater levels under current land use regimes. Under the natural cover of forest and woodland there was very little groundwater recharge (0.1% to 1–2% of the annual rainfall) and correspondingly little discharge of groundwater into rivers. Clearing of trees reduced evaporation, increased recharge up to 10 times, causing groundwater levels to rise. This mobilised the salt stored in soils and



▲ ***Figure 5.2****: Map of groundwater salinity in the shallow aquifers of the Murray Basin, south-east Australia. Large areas of very saline groundwater in the central Murray Basin leak slowly into the Murray River.*[6]

increased its discharge into rivers. Salinity is also a result of rising saline water tables under irrigation areas and mining can directly discharge saline water into rivers. Much of the salinity in the lower Murray River comes from naturally saline groundwater that has risen in level as a result of clearing of the mallee woodlands and introduction of irrigation (Figure 5.2).

Salinity loads in rivers can be reduced by revegetation of catchments and promoting pastures with deep roots that use more water, but very large areas need to be revegetated.[5] Salt interception schemes are used to pump highly saline groundwater or surface drainage waters into evaporation or storage basins, preventing them from reaching rivers,[7] and improved irrigation practices reduce the recharge of saline groundwater. Maintaining discharges of freshwater from tributaries is also important for providing dilution of saline groundwater, so there is a salinity management imperative for the maintenance of environmental flows in the Murray–Darling Basin. Salinity management has also employed a cap and trade system, as proposed for carbon, as a means to allow new uses of water while preventing any increase in salt pollution, such as to control salt loads from mining in the Hunter River catchment NSW.[8]

A paradox of salinity is that, although it is a symptom of a dry continent, it expresses itself more in wet years. Much has been achieved in recent years in revegetation, drainage, and salt interception to alleviate salinity, but the millennium drought provided a reprieve through lower recharge. It was during the relatively wet early 1970s when the salinity problem began to manifest over large areas, and the exceptional rainfall and flooding in eastern Australia in 2010–11 is being carefully monitored to assess whether salinity returns as a result of rises in water tables and the drainage of salt from floodplains that have been dry for over a decade.

Blue-green algae in Chaffey Reservoir near Tamworth, New South Wales. Photo: Brad Sherman, CSIRO.

Algal blooms

Algae are a natural and essential component of water ecosystems. They photosynthesise, providing food for animals and include phytoplankton, cyanobacteria, diatoms and seaweed. However, many rivers, lakes, and coastal waters have become enriched in nitrogen and phosphorus – a process known as eutrophication – as a result of agriculture and urban discharges. Eutrophication leads to the overly rapid growth of algae (algal blooms) and the predominance of blue-green algae, which can excrete toxins that are hazardous to animals and people if they are consumed, inhaled, or contact the skin. Equally rapid decomposition of the blooms consumes dissolved oxygen in the water, leading to fish kills.

An increased frequency and consequences of algal blooms in the 1980s and 1990s stimulated a concerted effort to better understand their causes and to reduce their occurrence. It was revealed that, although rivers have chronically high levels of nitrogen and phosphorus, it is the local conditions of light, turbidity, and water stratification that are important triggers of algal blooms.[9] Many of Australia's river pools and reservoirs become stratified under warm conditions with low inflows. The bottom layer of water and sediments becomes oxygen deficient, changing the chemistry of the sediment, causing phosphorus and nitrogen to dissolve into the water, and stimulating algal blooms.[10] Turbid waters are more prone to toxic algal blooms because the toxic algae float and out-compete algae deeper in the water that receive even less light.

It became clear that managing the local conditions was more effective in the short term than reducing the runoff of sediment, nitrogen, and phosphorus, even though that helps in the longer term. Environmental flows can be used to flush and dilute nutrients and algae and reduce periods of low or no flow. In reservoirs prone to algal blooms, water is now mechanically stirred to increase oxygen and reduce stratification,[10] and in urban areas the treatment of sewage and reductions in stormwater runoff reduce nutrient loads. Alternatively, phosphorus can be removed from waterbodies, using products such as Phoslock™, which is a clay that has been modified to bind phosphorus tightly so that it is not released, even under anoxic conditions.[11]

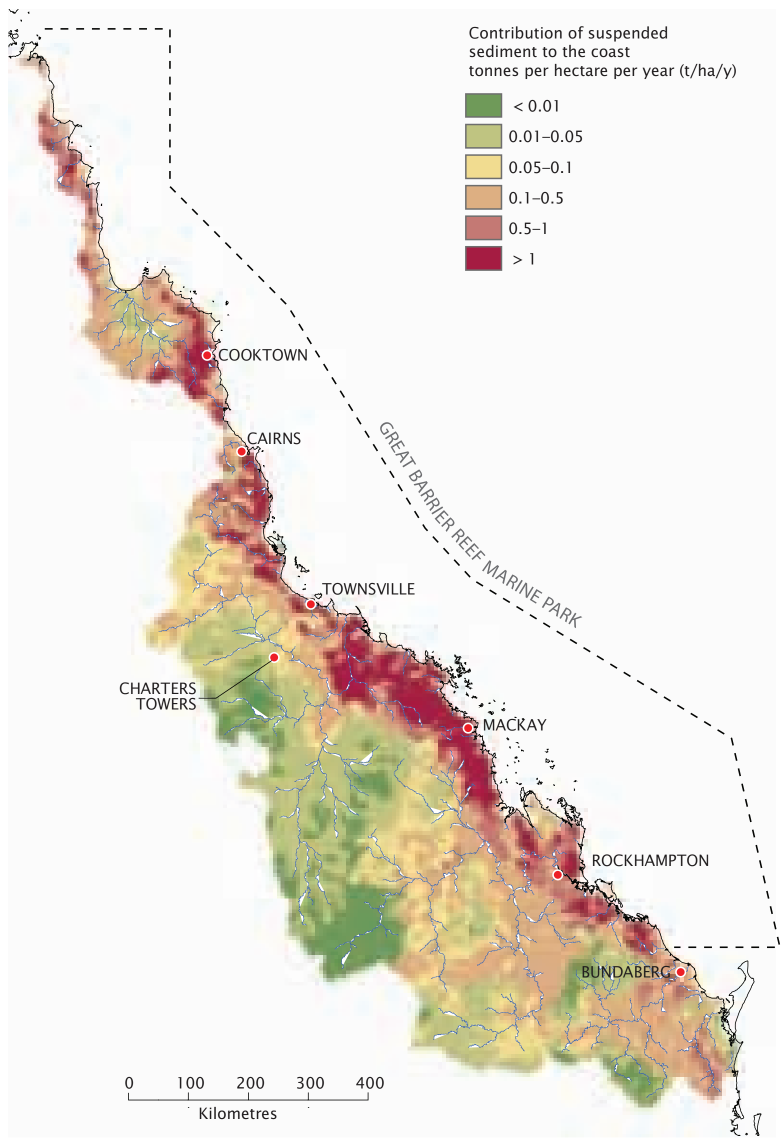
Sediments

A peculiarity of Australia is the very low natural loads of sediment and nutrients in rivers, as a result of its extreme geological stability. The clearing of native vegetation and the development of agricultural land uses changed that, increasing the loads of sediment by 10 to 50 times – particularly in the years immediately following clearing.[4,12] Sediment is relatively easy to remove in town water supplies, but it can have significant ecological impacts. Sediment is transported during storms and is deposited as flows wane. The deposits can smother the bed, covering more suitable habitats, and killing plants and other organisms. The deposited sediments may re-suspend, causing high turbidity, or metals and nutrients contained in the sediment can be released into the water under some conditions. Metals contained in sediment can concentrate in the food chain when sediment is consumed by organisms such as worms, shellfish, and small crustaceans.

Sediment is an ideal example of a pollutant with diverse sources. Sediment erodes from all landscapes, but not uniformly. Typically about 70–80% of the sediment reaching estuaries is derived from just 20% of the upstream catchment area.[13] Thus, catchment management to control sediment pollution can be targeted at these hotspots once they are identified by catchment sediment modelling (Figure 5.3). Further targeting can occur by identifying the erosion processes that are responsible. Agricultural land is the obvious source of erosion, but tracing of sediment sources using the chemical composition of sediment has revealed that accelerated erosion of riverbanks and gullies is responsible for up to 90% of the total sediment yield from a catchment.[12,14] By identifying the source of sediment, management can be much more effectively targeted to the precise sources. The most effective means of reducing erosion is to restore adequate vegetation cover by rehabilitating degraded riparian zones or improving farming practices.

Recycled water complex at Bolivar, South Australia. Photo: Greg Rinder, CSIRO.

Remediation of polluted sediments may be required if biological communities are severely impacted. Remediation of contaminated sites can simply involve dredging and licensed disposal of contaminated sediments, excavation and incineration on-site, capping of affected areas with barrier materials that prevent water infiltration and transport of contaminants, or the application of sophisticated clean-up technologies that use chemical procedures (e.g. oxidation or reduction) to destroy or extract the contaminants. Bioremediation, using microbes to degrade the pollutants, can be used for some contaminants. Two of the biggest sediment remediation activities in Australia are currently underway at Homebush Bay in Sydney Harbour (the source of historical dioxin contamination), and Newcastle Harbour, where oil and metal contamination levels are high.



▸ ***Figure 5.3**: Results of catchment sediment modelling for the catchments draining to the Great Barrier Reef. The model shows which of the more than 5000 sub-catchments contribute the most sediment to the coast. Catchments close to the coast and with intensive land use are predicted to be the highest contributors because sediment from inland catchments is trapped before reaching the coast or those catchments have a lower erosion rate as a result of less rainfall and less intense land use.*[13]

Estuaries and coastal waters

It is the combined impacts of sediment, eutrophication, and other pollutants that have had major impacts on estuaries and coastal waters including the inshore areas of the Great Barrier Reef.[15] Increased nutrient inputs, particularly nitrogen combined with increased turbidity, have led to growth of algae on seagrass beds or on corals, resulting in decline of seagrass and corals and the predominance of algae. High turbidity from re-suspension of sediments reduces light levels, thus favouring algae over seagrass and coral. Examples of seagrass bed decline include Port Phillip Bay, Moreton Bay, and the coastal waters around Adelaide and Perth. Seagrasses are an important food source and a nursery for fish and prawns. When seagrass is lost, the underlying sediments are exposed and move under currents, making for slow recovery. It has taken up to 20 years in other parts of the world for seagrass meadows to regrow once suitable conditions were re-established.

Recovery of seagrass beds requires a combination of reducing sediment and nutrient inputs and restoring seagrass. Sources of nitrogen in coastal waters near Adelaide include a wastewater treatment plant, discharge from major industries, and stormwater runoff. Large-scale recovery of seagrass meadows along Adelaide's coast will require intervention, by providing appropriate settlement substrates for seedlings, transplanting of mature stock, or the harvesting and planting of germinated seedlings. Similar management controls would be needed to restore seagrasses in Perth and Moreton Bay.

Organic chemicals and pesticides

More than 20 000 human-made industrial and household chemicals are used routinely in Australia. These can enter waterways as runoff, through deposition from the air, or by direct discharge of treated wastewaters from sewerage plants and industry. Industrial discharges are usually licensed to protect the environment, and can include organic as well as chemical contaminants. Because of the sheer number of substances, it is not practical to set water quality guidelines for all of them. Guidelines are in place for organic chemicals that are discharged in high volumes or are particularly toxic.

Chemicals found in waterways include pesticides, herbicides, antifouling paints, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons. Commercial fishing in Sydney Harbour is currently banned due to the build-up of toxic organochlorine chemicals in fish and prawns. These contaminants originate from former industrial sites, are leached from contaminated soils, or are deposited in the Harbour through eroded sediments. From the sediments, they accumulate in the tissues of the aquatic organisms.

Pesticides can be broadly grouped into chemicals used to control weeds, insects and fungi (i.e. herbicides, insecticides, and fungicides). In common with most developed countries, Australia continues to be a large user. Pesticides find their way into waterways either as spray drift or in

Aerial spraying, Virginia, South Australia. Photo: Greg Rinder, CSIRO.

runoff. In some cases, they are even used to control water weeds. As well as targeting unwanted weeds and pests, these chemicals are also a hazard to aquatic organisms, even at very low concentrations. Residues from the use of now-banned compounds such as DDT, chlordane, and dieldrin are remarkably persistent and can still be found in both water and sediments.

Reducing the pollution from pesticides and other chemicals can be achieved in three ways: replacing them with less persistent chemicals; recycling or storing water onsite to prevent discharge into waterways; and reducing use through new agricultural and industrial practices. The original persistent pesticides have now been replaced by ones that degrade more rapidly after performing their desired function. Glyphosate (or 'Roundup™') is now the most common herbicide in Australia and degrades within a few days.

Historically, the cotton industry was one of the biggest users of pesticides, and was associated with numerous fish kills from the use of endosulfan (a pesticide that is toxic at parts per trillion concentrations) but all three treatment mechanisms have greatly reduced the risks. Endosulfan is gradually being replaced by the less persistent chlorpyrifos and cypermethrin, and water used in cotton growing is now retained on the farm, although there is still risk from aerial spray drift. The use of genetically modified strains of cotton, commercially available in Australia since 1996,[16] have reduced insecticide use by as much as 80% compared with conventional cotton.[17] These new varieties contain proteins from a soil bacterium that confer insecticidal properties to the whole plant.

Pathogens

Pathogens are disease-causing organisms that end up in waters due to the discharge of sewage effluents or as diffuse inputs from animal wastes. They comprise a wide range of living microorganisms including bacteria, viruses, and protozoa. Very stringent regulations apply to ensure that drinking water supplies are adequately treated and are free from microbial contamination.[18] These include managing pathogen sources and pathways of transport within the catchment, and multiple treatments (see future urban water supplies chapter). For instance, animal wastes from grazing livestock can represent a significant source of pathogens to water reservoirs, which is why many of Australia's urban water supply catchments have strict land use restrictions and largely retain natural vegetation cover, thereby maintaining very high water quality.

Because there is a very wide range of potential pathogens, routine analysis of each pathogen is not feasible, so indicators such as fecal matter are used to monitor microbial water quality. Currently, microbial tests are slow to perform and at best take 15–24 hours because they rely on culturing the bacteria. This leaves a delay before contamination can be managed. A major goal, therefore, is to develop rapid analytical techniques for pathogens and indicator organisms to enable a more rapid response. This could be most useful for applications in potable recycling.

Metal contaminants

Metal contamination from point sources include mining and mineral processing activities, as well as from specific industries with metal-containing wastes, such as fly ash from coal combustion. Many Australian examples are largely associated with historical contaminations, when regulatory controls were poor or non-existent. Examples include the lead/zinc smelter at Lake Macquarie (New South Wales), lead smelting at Port Pirie (South Australia), zinc refining in Hobart (Tasmania), and copper mining and processing near the King River and Macquarie Harbour in western Tasmania.[19] These extreme cases had serious impacts on aquatic ecosystems. In addition, metals accumulated to alarmingly high concentrations in some organisms. For example, in the 1970s, oysters from the Derwent River in Tasmania were grossly contaminated with zinc discharged from a local smelter and were unfit for human consumption.[20] Metals, unlike most organic contaminants, are persistent and do not break down with time, so prevention at source is preferable to remediation, which can be both very expensive and slow.

Active mining sites in many areas of Australia contribute low concentrations of metals such as copper, lead, zinc, nickel, and uranium to local waters, but such releases now have to meet strict regulatory control and only in extreme cases do concentrations exceed water quality guidelines. Typically mining wastes are retained in sealed tailings dams and are not discharged to the environment.

Urban and residential areas are diffuse sources of trace concentrations of metals (parts per billion levels) to waters, which can lead to a complex mixture of contaminants. For instance, stormwater runoff from roads carries zinc from tyres and copper from brake linings. Dissolved zinc is borne by rainwater washing galvanised metal roofs and quantities of dissolved copper


Rising groundwater tables affecting salinity, Griffith, New South Wales. Photo: Bill van Aken, CSIRO.

originate from the slow leaching of water pipes. Many metals are essential nutrients for humans and aquatic organisms, particularly copper (Cu), cobalt, zinc, and iron. Although organisms are reasonably tolerant of higher than normal iron concentrations, excesses of the other metals can be quite toxic even at part per billion concentrations. Metal toxicity is largely associated with certain chemical forms of the elements: in particular, the free metal cations (e.g. Cu^{2+}).[21] Analyses that determine only the bioavailable and potentially toxic fractions of metal contaminants are now being used to better specify the risks to ecosystem health and ensures that industry is not subjected to unnecessarily strict discharge controls.

Acid sulfate soils

The polluting effects of acid sulfate soils were realised when fish kills and fish disease (e.g. red spot ulceration) were observed. Acid sulfate materials are found naturally and typically form under waterlogging of organic sediment (such as mangrove mud), which causes iron sulfides to form. Left undisturbed, these soils are harmless, but when excavated or drained, the sulfides within the soil react with the oxygen in the air to form sulfuric acid. The acid can dissolve metals such as aluminium and, if discharged to rivers and estuaries, the combination of metals and acidity can kill plants and animals, contaminate drinking water and food such as oysters, and corrode concrete and steel.

Acid-forming soils can be found at many coastal locations and are particularly prevalent in northern New South Wales and Queensland, associated with organic mangrove sediments. The millennium drought exacerbated the problem of acid sulfate soils in the Lower Lakes and wetlands along the Murray River, where the drop in water levels exposed sulfidic materials. Acid formation was mitigated by careful management of water levels and the addition of lime to some rivers and creeks that drain into the Lower Lakes. Recent re-flooding of the acid materials seems to have occurred without harmful acid discharge.

Groundwater contamination

Groundwater contamination occurs through accidental spills and other unintended releases of chemicals, which move downwards through soils into underlying groundwater. It can pollute drinking water supplies, irrigation water, and ecosystems, where groundwater discharges to surface waterbodies. The slow movement and lack of mixing and dilution in groundwater can preserve high concentrations of pollutants for decades and at distances well away from the initial source so, again, prevention is the most effective management option.

Groundwater pollutants include organic liquids such as petroleum fuels and industrial solvents (e.g. perchloroethene, which was used for many years by the dry-cleaning industry and in plastics manufacturing). Petroleum fuels are less-dense than water so they float on the groundwater table. Some solvents are denser than water and sink below the water table towards the base of aquifer systems. Both types of organic liquids slowly dissolve into groundwater over decades to centuries.

Remediation of groundwater pollution can be achieved by biodegradation; for example, by using bacteria that can consume organic contaminants such as benzene, but they require the correct chemical conditions – such as an abundance of oxygen, nitrate or sulfate. Establishing an artificial barrier across the leading edge of a pollution plume can reduce contaminant transport. Such barriers are expensive to install, but low ongoing costs make them financially attractive. Permeable reactive barriers allow some throughflow of water but contain active ingredients that can degrade or immobilise contaminants.[22]

Removal of service station fuel tanks which can leak into groundwater, Perth, Western Australia. Photo: Bill van Aken, CSIRO.

Monitoring water quality in Lake Wivenhoe, Brisbane, Queensland. Photo: CSIRO.

Emerging contaminants

New chemicals are introduced continually, but only a small proportion of them are routinely monitored in water. The release of emerging chemical or microbial contaminants may have gone unrecognised for long periods until new, more-sensitive analytical detection methods were developed. Studies in the United States of America and Europe show that a broad range of chemicals found in residential, industrial, and agricultural wastewaters commonly occur as mixtures at low concentrations in rivers and streams. The chemicals detected include human and veterinary drugs, natural and synthetic hormones, detergent metabolites, plasticisers, insecticides, and fire retardants. Similar results are now being found in Australia. The presence and significance of such contaminants is particularly pertinent to water recycling.

Low levels of certain pharmaceuticals in the environment could affect aquatic life through patient use of prescription and non-prescription medicines, especially if there is little degradation or removal during sewage treatment. Veterinary chemicals may enter waterbodies through animal excreta and farm runoff. Dilution can reduce the concentration of these contaminants to below levels of concern, but the problem is exacerbated by Australia's low discharge rivers and streams.

Much recent effort has focussed on organic contaminants, which can disrupt animal reproduction or growth by modulating, mimicking, or interfering with hormones. These compounds are called endocrine disrupting chemicals. They include hormones created in the body, synthetic hormones (such as those manufactured for birth control), and industrial/commercial compounds that can have some hormonal function (such as alkylphenols, pesticides, pharmaceuticals, and phthalates). Natural estrogen is excreted from the female body in a deactivated form, but, during the process of sewage treatment, chemical changes occur that restore estrogen to its original chemical form and biological activity. A major challenge in this area is to understand how very dilute mixtures of bioactive contaminants interact with living organisms, and how interactions between contaminants may magnify biological effects.

Nanomaterials represent a new class of contaminants. They have an extremely varied composition and, because of their small size, may possess chemical and physical properties that are unlike their equivalent macro-sized forms. There is a good deal of research activity in Australia and overseas dedicated to evaluating the potential impact of these new materials on aquatic environments and to determine if they require their own water and sediment quality guidelines.

Further reading

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Urban water sustainability

Alan Gregory and Murray Hall

Key messages

- An extra 10 to 20 million people could be living in Australian cities by 2050, requiring more water supplies, more wastewater disposal, and greater energy use to provide these services.
- The increasing demands for water, energy, and other resources in cities are leading to new approaches to urban water as part of broader urban sustainability and liveability.
- There is considerable potential to improve urban sustainability by recovering water, energy, carbon, and nutrients from wastewater and reusing them in the city and as fertiliser for food production.

Growing cities and the need for sustainability

The world's population in the 21st century will become predominantly urban. Half of the world's population is already living in cities and this proportion will increase to about 70% by 2050 (Figure 6.1). Nearly all of the expected growth in the world's population will occur in urban areas by 2050.[1]

Demand for urban water supplies will grow across the world and Australia is no different. Australia is already highly urbanised, with almost 90% of the population living in cities, but in the next 50 years 10 to 20 million extra people will live in Australian cities.[2] The capital cities alone will need to accommodate an additional 10.5 million people by 2056[2] – the equivalent of the current population of Sydney, Melbourne, Perth, and Adelaide. Not only will more water be needed to supply this population, but more sewage will be produced and treated, and more urban stormwater will be generated from the additional roofs, roads, and paved areas. The impacts of these discharges on the valued rivers, estuaries, coasts, and groundwater systems surrounding our cities is already significant, and this level of urban growth will place waterways under increasing pressure.

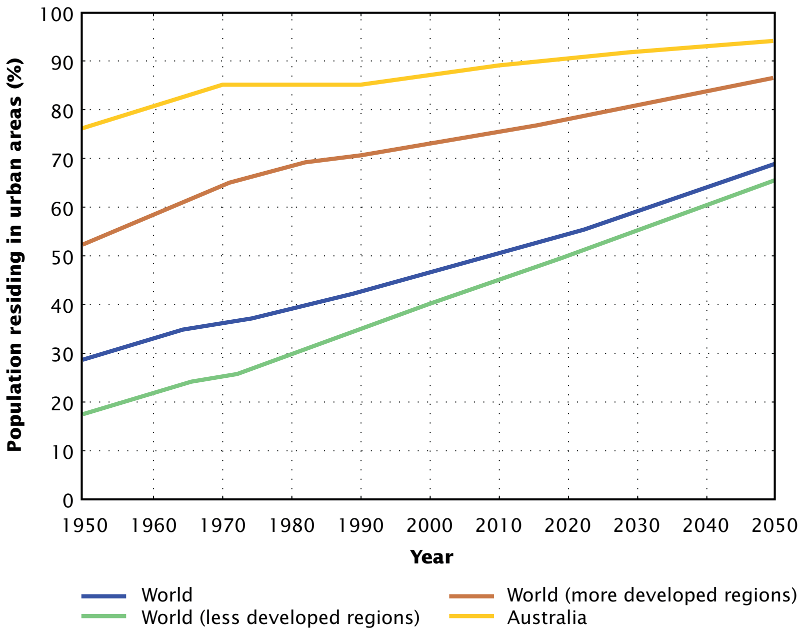
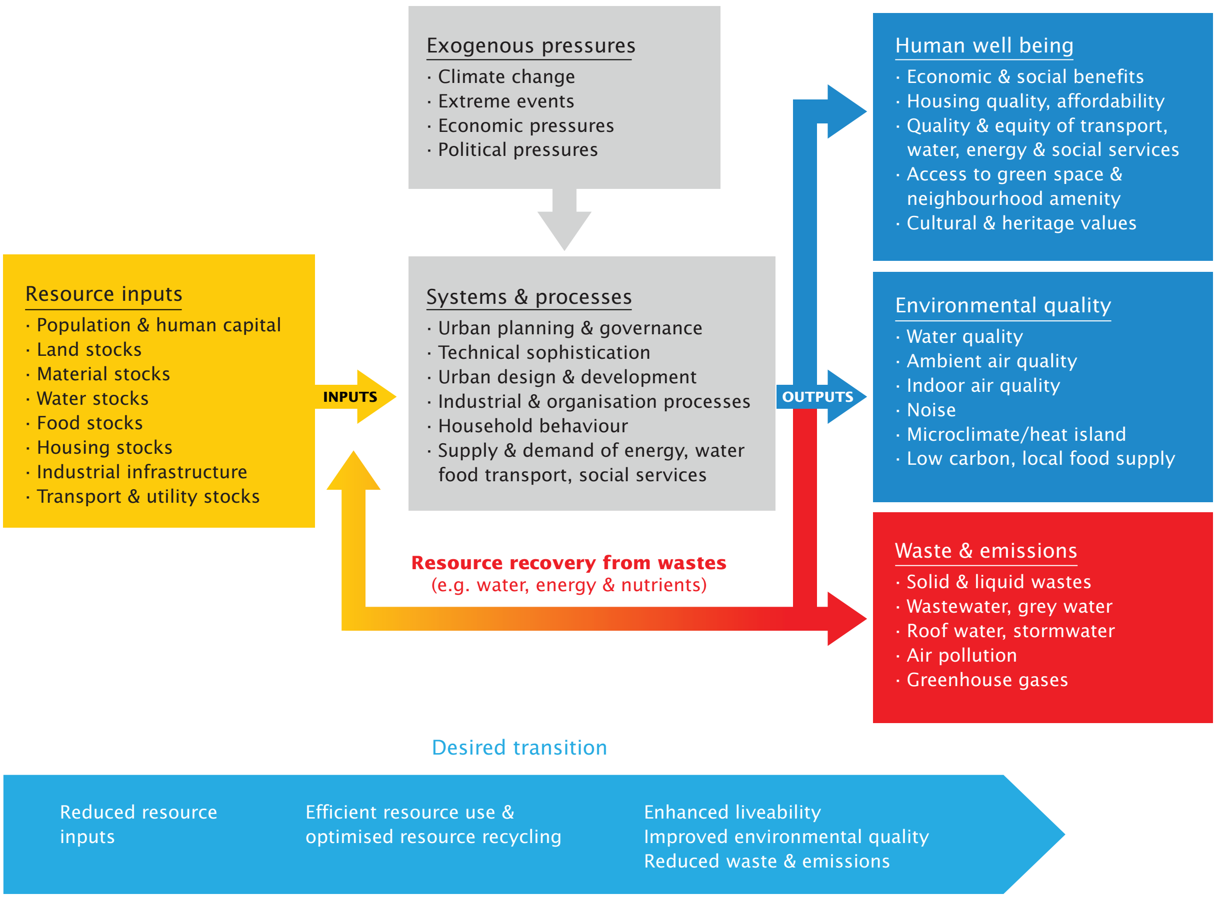


Figure 6.1: The percentage of global population living in urban areas is increasing especially in less developed regions. Australia already has a highly urbanised population but it too will become more urbanised.[1]

The strong growth of cities and the emergence of mega cities raises questions about their future sustainability, and the way water is managed is central to these concerns. Urban water systems have evolved into large, highly engineered systems in which water is imported from surrounding catchments and aquifers, distributed through extensive pipeline networks, and used just once. Most of the used water is then collected in large sewerage systems, treated to remove contaminants and nutrients, and discharged back to rivers and the sea. These systems provide reliable clean water for residents and industry, and they protect public health, but there are concerns that water systems could be much more efficient, rather than just importing more water, disposing of more wastewater and removing more stormwater. They will need to more efficiently use local sources of water as populations grow, water resources become fully allocated, and climate change reduces the supply of water from catchments and aquifers.

The International Water Association argues that the objectives of urban water management should expand to contribute to the development of more liveable and sustainable cities.[3] Urban water systems do not exist and operate in isolation: they have many linkages to other systems within a city and its surrounding regions. For example, population growth and urban density influences water demand, and water use influences wastewater generation and energy use for treatment and transport. Urban design influences stormwater generation and flows, which in turn influences flood risk and water quality. Green space and open water in cities can reduce extreme temperatures, perhaps using more water, but requiring less energy for cooling. There are other direct and indirect connections, some of which will be discussed further in this chapter.

'Urban metabolism' is a useful metaphor to visualise the city as a system, rather like a living organism (Figure 6.2).[4] Resource inputs, such as water, are translated through a series of connected urban systems and processes into a range of human wellbeing and liveability outcomes, and, in this process, waste streams are generated, which can impact on the local and surrounding natural environment. The system can be made more efficient by improving the benefits from the resources, such as by reusing them or recycling resources, and reducing impacts on the environment. Resources can potentially be recovered from these wastes to reduce the need for new inputs. By changing the urban system and processes within a city, including the way we design and manage water systems, the 'metabolic efficiency' of a city can be enhanced.



▲ ***Figure 6.2***: *Cities from an urban metabolism perspective: consuming resources, processing them to produce wellbeing, and producing waste products.*[5]

An example of the potential for greater efficiency in urban water use is shown in Figure 6.3. Depending on each city's outdoor water use, up to 75% of water supplied becomes sewage effluent, which could be recycled to offset input of additional water. Urban stormwater is an additional resource that often exceeds the volumes of mains water, but except for Perth, less than 3% of urban stormwater is harvested. Perth recycles an estimated 80% of stormwater for irrigation reuse following recharge to aquifers. Until recently, all household water use was of potable quality even though up to half was used for garden watering and less than a third is used in the kitchen or bathroom.

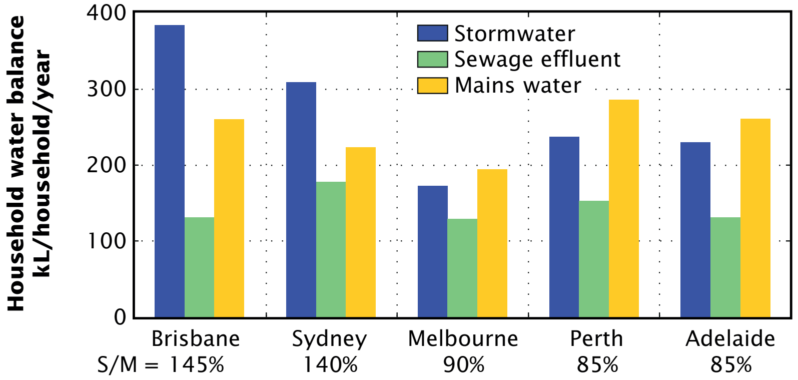


Figure 6.3: Water balances per household in Australia's five largest cities. Much mains water ends up as sewage effluent, and stormwater is an even larger waste stream that can exceed the volumes of mains water. S/M refers to stormwater volumes as a percentage of mains water supply.[6]

This chapter examines how urban water management can respond to the challenges of sustainability. Chapter 7 explores in more detail the options for augmenting supplies in Australian cities to meet the growing demand for water.

Managing demand

Households use 70–80% of total urban consumption, so, historically, water use tended to rise in line with population. However, since the early 1990s, per capita water use has declined in most cities as a result of greater water use efficiency in households and industry, higher prices for water, and changing urban design such as increasing multi-unit housing and smaller sizes of household blocks. Figure 6.4 demonstrates the effect of this trend in Sydney, where total water use today is the equivalent of demand in the early 1970s, despite an additional 1.2 million residents.

Consumers do not require a specific volume of water: they want the services that water provides such as clean clothes, pleasant landscapes, or waste removal, in addition to safe water for drinking, cooking, and bathing. These services can be provided while using less water through better system design, technology efficiency, or changed behaviour.

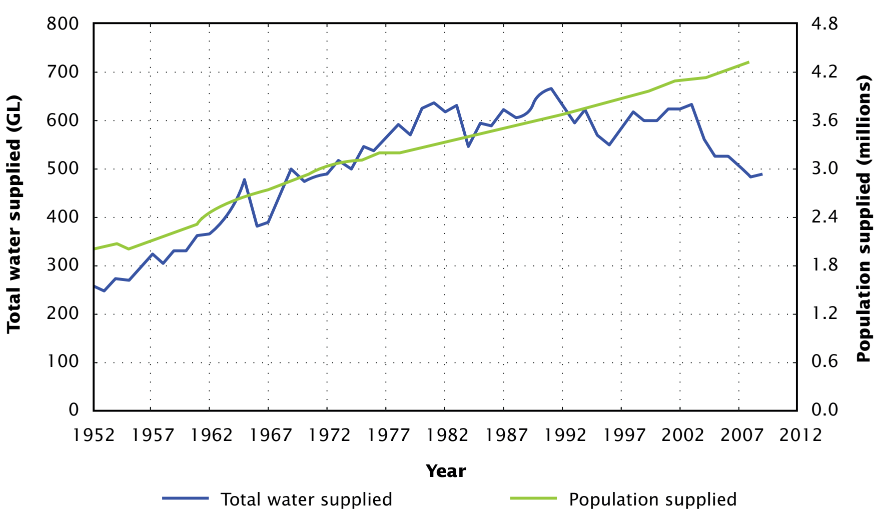


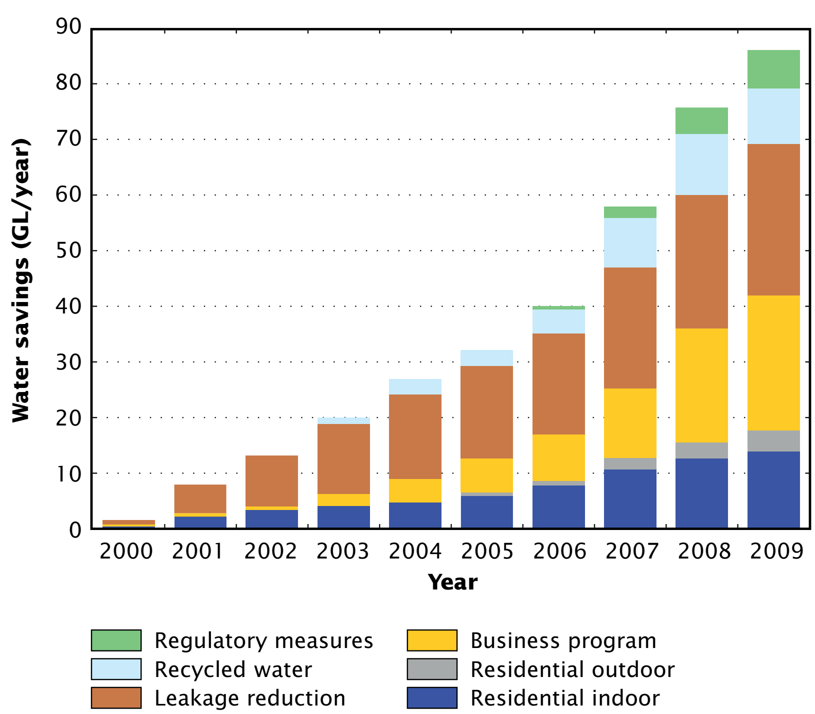
Figure 6.4: Long-term trend in Sydney water supply. Water supply used to grow in line with population, but reduced per capita consumption since 1992 enabled more people to be supported from the same total supply.[7]

Efficient water use delays the need for expensive augmentation of supplies, such as from new dams or desalination plants. Reducing per capita use is invariably less expensive than sourcing, processing, and supplying more water. Demand management can also reduce per capita wastewater flows, providing additional capacity in existing sewers to cater for population growth.

Strategies to reduce demand include adoption of appliances that are more water-efficient such as shower nozzles, dishwashers, and washing machines. Garden water use efficiency has improved through the use of drought tolerant species, more efficient irrigation systems, and education on garden watering. For many purposes, drinking water could be substituted by water sourced from rainwater, stormwater, or recycling. The water supply system can also be made more efficient by reducing distribution losses through leakage control and pressure management, using less water to provide the same service.

A prominent Australian example is the potable water savings of 85 GL/year achieved in Sydney over the last decade from sustained demand management and water recycling strategies (Figure 6.5). These water use reductions equate to the volumes that can be provided by the recently constructed Sydney desalination plant, or 15% of annual supply to Sydney.

During the millennium drought in the southern capitals, restrictions were imposed to reduce household water use as supplies dwindled. The most extreme reductions occurred in South East Queensland where the average per person residential consumption dropped from 300 to 130 L/person/day in response to dam storages dropping below 20%. Historically, water restrictions have been an effective temporary response to drought. The longer term use of restrictions required



▸ ***Figure 6.5**: Water saving measures in Sydney, which have made savings equivalent to 15% of supply.[8] (Adapted from Sydney Water Corporation 2010.)*

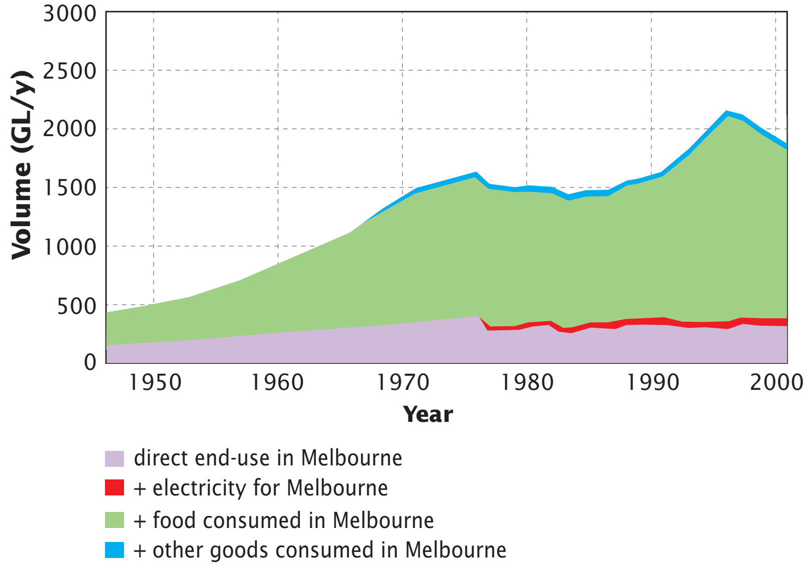
during the millennium drought highlighted the impact on some services such as the quality of parks and gardens, and the detrimental effects on landscape and garden industries. The drought and associated restrictions did galvanise community action on water conservation through lower water use appliances, use of rainwater tanks, and improved garden design. Since restrictions were lifted, water use has increased slightly,[9] indicating that there has probably been a permanent change in behaviour that will not see a return to pre-restriction levels of water use.

The density and design of housing will influence residential water use, particularly outdoor water consumption, in the future. In some Australian cities, backyard irrigation is almost half of total household water use. A recent study in Melbourne found that adopting a more compact city design could reduce residential water consumption by 100 GL/year by 2045, compared with more traditional low density urban expansion.[10] Higher housing density brings other benefits of reduced transport and energy costs and is thus a part of urban planning in most cities.

There has been considerable debate over the potential for water pricing to be used as a mechanism to moderate demand.[11,12] Many utilities charge higher prices for water above a basic supply charge, but the prices do not change over time with the scarcity of water. The price for high rates of domestic consumption could be increased during drought as an alternative to water restrictions.[13] This would work if demand was sensitive to price, but there is conflicting evidence for that at present. It also requires effective price signals, which are lacking when only a small part of the cost is variable, when the costs are paid 3 months in arrears, and when costs are shared equally across multi-unit apartments.

The water effectively consumed by a city includes not just the water directly supplied but the water used in rural areas to produce food and fibre for city residents and to generate the city's electricity. The fact that the produce from irrigated agriculture is predominantly consumed in cities is often forgotten in polarised conflicts between urban and rural communities. For example, the amount of water used to produce food, fibre, and electricity consumed in Melbourne is

Low water use shower head. Photo: CSIRO.



▸ ***Figure 6.6**: Total effective consumption of water in Melbourne includes not just the direct supply of water to the city but also the water consumed to produce electricity, food, and other goods consumed in the city.*[10]

approximately four times the water directly used by city residents and businesses, and has grown faster than direct water use (Figure 6.6). A further significant share of water use is to produce exports, which provide earnings to offset imports that are a large part of consumption of all Australians.

Water and energy

To provide water and wastewater services requires energy for treatment and pumping, and the dominant forms of current energy generation require large volumes of water. The choices made about urban design, water, and energy use, and the sources of both water and energy will influence the future sustainability of cities.

The recent growth in desalination and water recycling has put a focus on energy use in water supply. Direct energy use for the provision of water services in 2007 represented only about 0.2% of total city energy use (about 7 Petajoules (PJ)/ year).[14] By comparison, residential hot water heating uses 46 PJ/year, nearly seven times the amount used to supply water.[14] Even more energy is used in association with commercial and industrial uses of water, mainly for heating and transport processes.[15]

A breakdown of energy consumption by water utilities for 2006–07 (a year that precedes desalination and large-scale reuse), shows that each of the major cities differ substantially in their energy use because of differences in topography or system configuration (Figure 6.7). Figure 6.7 clearly shows the energy penalty associated with pumping, where both Sydney and Adelaide were transferring bulk water over long distances to maintain supplies during drought. Water is very heavy at 1 tonne for every kilolitre. Sourcing water close to its end use has definite energy benefits.

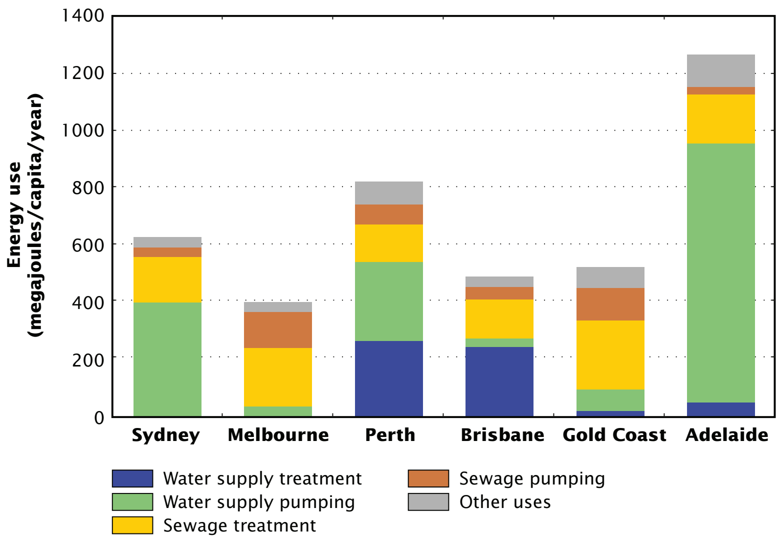


Figure 6.7: *Energy use for water and wastewater services differs markedly among cities (2006–07) depending upon the type and location of their supplies and the location of sewage disposal.*[14]

Unfortunately, future water supplies are likely to use more energy. Until recent times, most of Australia's coastal cities were supplied by water fed by gravity from inland dams. Future supplies will have to rely upon piping water over catchment divides or will interconnect systems across regional water grids or entail desalination plants and recycled water schemes, all of which use more energy. A 25% population growth by 2030 is anticipated to increase energy use by water utilities to twice that of 2006–07 levels.[14] Even decentralised supplies, such as rainwater tanks, stormwater harvesting, and local wastewater recycling, can be more energy intensive than existing supplies if poorly designed or maintained.

The largest energy use associated with water though is in heating of water in homes, commercial, and industrial applications, and there are opportunities to reduce this use. Water heating accounts for about 25% of all residential energy use[16] but it could be halved through water-efficient appliances and more efficient water heaters.[14] Even greater energy benefits may be gained in industry, where reductions in steam and hot water losses, reduced pumping in manufacturing, and cooling result in significant energy savings.

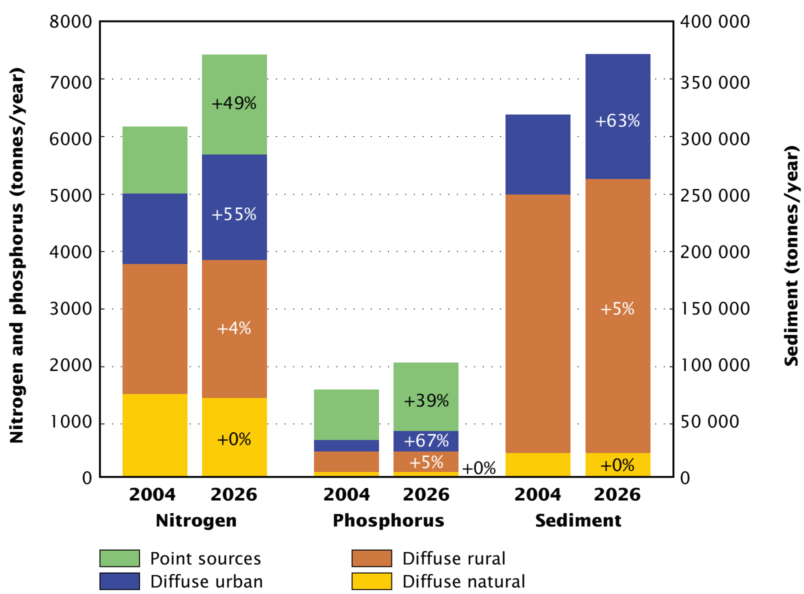
There are growing international efforts to reduce greenhouse gas emissions from water use for environmental and economic reasons. Large and increasing energy use combined with rising energy costs provide strong business incentives for water utilities to reduce their energy use. Measures being pursued by Australian utilities include optimising system operations to minimise energy use, generating renewable energy through installing mini-hydro systems in pipeline networks, recovering biogas during wastewater treatment, sequestering carbon through tree farms and woodlots, or offsetting by purchasing renewable energy.[17]

Reducing wastewater and stormwater impacts

The growth of cities will produce an equivalent increase in the amount of human waste that needs to be managed and increased stormwater runoff. Most rivers, estuaries, coastlines, and groundwater systems close to cities and towns have suffered environmental impacts from various forms of pollution. The waterways and coasts are among the most heavily used and valued, placing pressures on water managers to reduce the impacts of stormwater and sewage.

From a wastewater management perspective, the removal of nutrients such as phosphorus and nitrogen contained in human waste is the primary focus for current and future sewage treatment. Strengthening regulation of industrial and commercial pollution at its source over the last 20 years in Australian cities means that the discharge of other contaminants to sewer systems is strictly controlled to avoid waterway pollution. Since the early 1990s, the gradual adoption of load-based environmental regulation across Australia has resulted in upgrade to sewage treatment plants, which use advanced biological treatment processes to improve effluent discharge quality into receiving waters.

Despite these gains, total sewage volumes and nutrient loads will increase over the coming decades because of population growth. Additional measures will be required to constrain nutrient loads to environmentally sustainable levels. The cost of additional treatment to further reduce nutrient concentrations is relatively expensive and energy intensive – a significant problem for fast-growing regions such as South East Queensland which have sensitive aquatic ecosystems. Figure 6.8 shows that the expected increase in phosphorus, nitrogen, and sediment loads to Moreton Bay over the coming decades will be predominantly from point sources such as sewage effluent and diffuse urban sources such as stormwater runoff.



▸ ***Figure 6.8**: Predicted increases in nitrogen, phosphorus and sediment loads to Moreton Bay over the next 20 years showing that urban sources will soon dominate nitrogen loads.*[18]

Diffuse pollution from stormwater runoff remains a significant problem for cities. Stormwater typically contains litter, sediment, vegetation, nutrients, chemicals, pesticides, metals, and bacteria. Stormwater can also be contaminated with bacteria and nutrients from sewage overflows and animal faeces after rain. Urbanisation increases the volume of and speed of runoff, helping entrain more pollutants and impacting on receiving waterbodies and riparian vegetation.

Water sensitive urban design is an increasingly adopted approach to urban development to minimise the impacts of urbanisation and improve the liveability of cities. It recognises that the way we design buildings, landscapes, and public infrastructure can incorporate water design features that enhance public amenity, cool surfaces and the surrounding air, capture and store stormwater for recycling, improve water quality outcomes in waterways, and protect local biodiversity.

Examples of these approaches include the use of stormwater retention and storage ponds, managed aquifer recharge, constructed wetlands, bio-filtration beds, grassed swales, permeable paving and roadways, and the increased use of water features in public spaces.

Resource recovery

It may be possible to reduce the export of wastewater from a city in a way that recovers resources and substitutes them for inputs into the city. Treated wastewater can be used as a recycled water source for a city, but it can also be a valuable source for nitrogen and phosphorus fertiliser to grow food and fibre, and be a source of energy while reducing greenhouse gas emissions from the treatment process. In essence, some of the inputs and outputs to a city could be internalised into its metabolism, making it more efficient and sustainable.

Growing global populations require increased food and fibre production and increased demand for fertilisers. In Australia, fertiliser use has increased seven fold over the last 40 years.[19] All phosphorus-based fertilisers are sourced from phosphate rock, and it is predicted that high- grade phosphate rock will become depleted over the coming century and lower grade resources will be used instead. Production and energy costs will be greater for these resources and they present other problems such as potential contamination with heavy metals.[20] An alternative source for phosphorus could be to recover it from treated wastewater.

Similarly for nitrogen, fertilisers are produced using a very energy-intensive process and then nitrogen is removed during wastewater treatment at a high energy cost. Tertiary wastewater treatment processes can also generate and emit nitrous oxide to the atmosphere: a very potent greenhouse gas. Again there could be many benefits of recovering nitrogen from wastewater as an alternative source of nitrogen fertiliser.

Human waste contributes about 80% of the nitrogen and phosphorus in domestic sewage. The world's population excrete about 25 million tonnes of nitrogen per annum and about 4.4 million tonnes of phosphorus. This is the equivalent of about 17% of the total worldwide production of nitrogen fertiliser and about 22% of that for phosphorus. The amount of nitrogen and phosphorus in agricultural wastes is at least as large, so nutrient recovery from these sources has the potential to supply a significant fraction of the total worldwide fertiliser demand and contribute to more sustainable food production.

Because urban populations provide a concentrated source of nutrient flows in wastewater, sewage treatment plants are an ideal focus for resource recovery in a city. Recent innovations in nutrient recovery from wastewater streams highlight the potential to produce struvite (a slow-release fertiliser of magnesium, ammonium, and phosphate).[21] Commercial application of this technology is progressing in sewage treatment plants in Canada and the United States of America. Vacuum stripping of ammonia is a new technique and simulation studies on the impact of the ammonia recovery process indicate a reduction in greenhouse gas emissions of between 25% and 48%, compared with current advanced biological treatment.[22]

Table 6.1 illustrates the approximate potential value of methane, ammonia, and phosphorus in Melbourne's sewage, based on 2008 prices for these resources. Methane can be used as an energy source to make the treatment plant a net source of energy. The value of water contained in the sewage would be many times the value of the resources. The challenge is to develop and adopt technologies to realise this value in a cost-effective way while protecting environments from pollution.

Table 6.1: Estimate of annual quantities and values of methane, ammonia, and phosphorus available from Melbourne's sewage.[23]

	Yearly (tonnes)	Value ($/year)
Methane	93 200	$30 million
Ammonia	22 500	$22.5 million
Phosphorus	3660	$12 million

Melbourne CBD, Yarra River and urban parkland.
Photo: Robert Kerton, CSIRO.

Domestic rainwater tank. Photo: CSIRO.

One way to realise the potential of resource recovery is to separate black water (toilet wastewater) at its source. Current sewers collect black water and grey water flows. However, black water contributes about 20% of residential sewage discharges but contains some 90% of the nitrogen and 60% of the phosphorus discharged.[24] Black water separation would concentrate the flows of nutrients and carbon in sewage to enable purpose-built energy and nutrient recovery treatment processes. The remaining grey water sewage flows would be significantly lower in nutrients, greatly reducing the need for tertiary treatment based on nitrogen removal, thereby reducing energy use and facilitating simpler and safer grey water recycling (Figure 6.9).

Black water separation is easier to implement in new developments, but a transition to such a system may also be possible in existing areas of a city as wastewater infrastructure and housing stock is renewed over time. The economics of such a transition are complex but should consider the value of all the components and resource flows beyond simply the cost of sewage treatment. Black water separation requires additional collection pipelines (possibly within the existing sewer), as well as a resource recovery treatment processes – both significant investments. These could be offset by new income from the fertilisers and energy produced, a new water source from recycled grey water, lower capacity required for sewage treatment plants, and lower pollutant discharges to the environment.

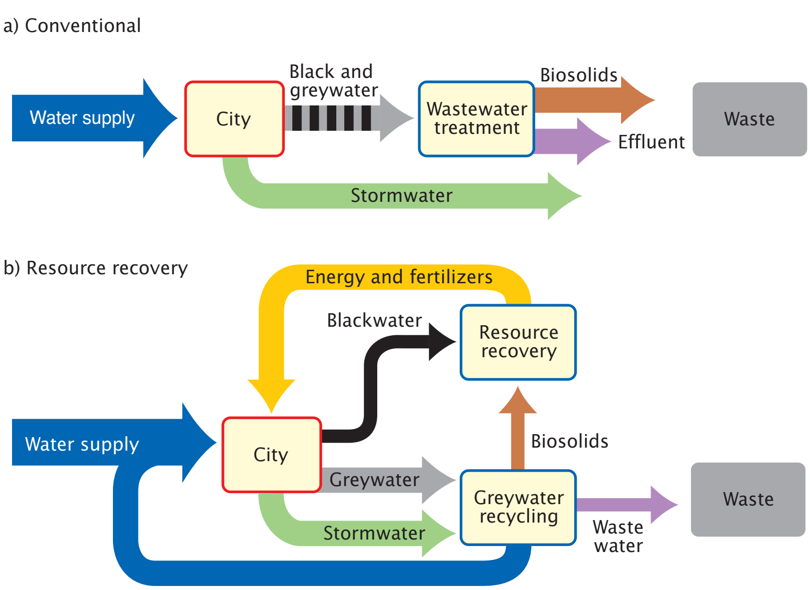


Figure 6.9: A conventional urban water system compared with one designed to recover resources from black water and recycle grey water.

Transitioning to a sustainable urban water system

Today, society has the advanced technologies and the economic capacity that allow us to manufacture clean drinking water or water fit for other purposes from virtually any source of water, wastewater, or stormwater. Technologies are emerging that will enable more effective recovery of resources from wastewater, that will provide real-time management of water quality and water use, and optimise integrated water system operation for a range of environmental, public health, and service quality outcomes.

Across the globe, water managers are grappling with the challenge of how to use these technologies to evolve to more sustainable water systems. The first step is to define a new vision for urban water management in light of 21st century challenges. With significant input from the Australian water sector, the International Water Association recently endorsed a set of principles that describe the water related characteristics to which cities can aspire. These principles include:[3]

- Liveable and sustainable cities that have a compact footprint and use green urban design and green space to cool cities and provide low-impact transport corridors.
- Cities that generate water, energy, and nutrient by-products in a way that is carbon neutral and recognises resource connections with surrounding regions.
- In addition to public health and water security, recognise the role that water provides for urban ecosystems, waterways, and a green city.
- A greater choice of water services and ones that bear the full environmental and social cost of these choices. Choices that are informed by improved access to useful and accurate information about costs and benefits and their own resource usage.
- City planning that integrates water, energy, and urban design at all scales to enhance sustainability benefits.

The expanded contribution to more liveable, sustainable cities is appropriate where broader social, public health, and environmental benefits and costs are defined or where there is a willingness by water consumers or other urban beneficiaries to pay for the outcomes.[12] This highlights the challenge of effectively valuing the wider social and environmental benefits and costs of alternative water servicing approaches. All major cities in Australia have progressed towards pricing based on the recovery of direct capital and operating costs, although governments have directly subsidised some recent large water projects.[12] The inclusion of indirect costs and benefits or externalities into water prices has generally been limited to cases where these costs are internalised through regulation.

A shift from conventional to more integrated water, wastewater, and stormwater systems often requires an increased level of involvement from the community due to the increasingly decentralised nature of these systems. Recent research highlights the benefits from engaging and educating the community in order to identify acceptable management and ownership of water sensitive systems and overcome the sometimes poor understanding of water sensitive urban design and inappropriate uses of non-potable water sources. Some plans for potable recycling of water, such as in Toowoomba, have been defeated as a result of the lack of community acceptance.

Conclusions

Over the past 100 years the water sector has expanded its range of functions, evolving from water delivery to wastewater, drainage, and pollution control functions. It has also begun to recover energy and capture nutrients in bio-solids and to implement water-sensitive urban design. Climate change, limited and decreasing catchment water supplies, and the relatively high cost of manufactured water will continue to place pressure on water services, just as waterway health and rising treatment costs will continue to place pressure on wastewater services. Large price increases have already been foreshadowed, but it is perhaps only by considering the full range of values gained from water that the sector will evolve towards sustainability.

Further reading

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