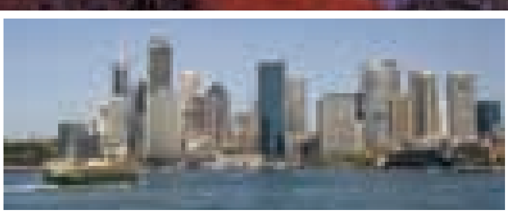
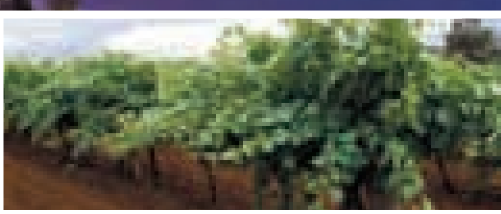
SCIENCE AND SOLUTIONS FOR AUSTRALIA

WATER





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Editor: Ian P Prosser

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Foreword

By Megan Clark, CSIRO Chief Executive and Andrew Johnson, Group Executive – Environment, CSIRO

CSIRO is committed to providing scientific advice on the major challenges and opportunities that face Australia. We commend to you this summary of the latest scientific knowledge on the challenges and prospects for managing water resources in Australia.

Australians have always had a strong sense of living in a dry continent, and have a long history of adapting to the extremes of floods and droughts. This has only been heightened in the last decade or so, revealing the vulnerabilities of our water resources and the ecosystems that depend upon them. It is no surprise that our society is increasingly seeking information about the challenges of securing water resources for all users, especially with prospects of growing use of water and changing climate. This book seeks to provide a bridge from the peer-reviewed scientific literature to a broader audience of society while providing the depth of science that this complex issue demands and deserves. The chapters cover the status of Australia's water resources and its future prospects, the many values we hold for water, and how water can be used most effectively to meet the needs of cities, farmers, industries, and the environment. It is important to find a balance between these sometimes conflicting uses and improve their efficiency.

Through the Water for a Healthy Country National Research Flagship, CSIRO is conducting research to help Australia and the world respond to the challenges of providing and sustaining water resources under strongly increasing demand. For more than 50 years, our scientists have been contributing to the growing body of scientific knowledge about water and are now seeking and finding new ways in which Australian communities, industries, and ecosystems, can improve how they use and dispose of water.

We cannot do this important work without the numerous national and international partnerships, collaborations, and networks. We collaborate with Australian and international universities, industry groups, research organisations, government agencies, and governments at every level to undertake excellent science and find and implement practical, scientifically based solutions.

As your national science agency, we will continue to provide scientific input and solutions to the community, industry, and government on understanding and improving the management of our nation's water resources.

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Introduction

Bill Young and Ian Prosser

Around the world, access to water has always been a key determinant of how and where human populations have flourished. Australia is no different. Both Indigenous people and European settlers were mainly drawn to those parts of the country with more abundant and reliable water supplies. Thus, in spite of being the driest inhabited continent, 80% of Australia's population inhabits a comparatively well-watered green fringe.

Water is essential to our economy and our way of life and its use has continued to increase due to population growth and expansion of agriculture and other industries. This increase in water use – significantly underpinned by investment in major water infrastructure – has helped fuel Australia's economic growth, but at an environmental cost.

Australia's water use is dominated by irrigated agriculture, industry, and households. The water is extracted from rivers, lakes, and groundwater. Nationally, Australia uses approximately 6% of the available renewable water (surface runoff and groundwater recharge), but use is focussed in a few areas, such as the Murray–Darling Basin and the catchments surrounding capital cities where the resources are fully allocated.

Australia faces challenges of a growing and urbanising population, of growing demand for water for food and fibre production, and of environmental sustainability, particularly in the face of climate change. These are not unique to this country, but, unlike other developed nations, Australia faces the added complications of high rainfall variability and general aridity. The scarcity of water in Australia depends as much on the variation between years as it does on the long-term average. The highly variable climate means proportionally more water has to be stored to provide the same reliability of supply compared with less variable climates. For example, Melbourne's water supply system has 10 times the per capita storage volume of London's water supply system.

In contrast to human populations, Australia's unique flora and fauna are well adapted to high variability in available water. Recognising this dependency on variable water supply is central to ensuring the protection of ecosystems and the services they provide. Australians highly value their rivers and estuaries for tourism, amenity, and commercial and recreational boating and fishing. These values can be considered as services provided by aquatic ecosystems. Other less obvious aquatic ecosystem services include waste treatment, flood mitigation, biodiversity, and weed and pest control. Increasing levels of water use and expansion of water infrastructure have, however, led to worrying levels of environmental degradation in some areas, affecting the provision of these natural services. In addition, many intrinsically valuable environmental assets,

Discussing water, Hillston, New South Wales. Photo: Bill van Aken, CSIRO.

including extensive floodplain wetlands and forests, and iconic species such as the Murray Cod, are in marked decline from water use and other threats such as pests and water quality.

The challenge for Australia is to not only to deal with the present problems, but to prepare for the future. Demand for water will continue to grow, to support a population that is anticipated to increase by at least 50% by 2050. Global demand for food is expected to double, and growth in the mining and industrial sectors will place even greater pressures on water resources. Competing demands will mean that returning over-allocated systems to sustainable levels of use will be even more difficult than at present. Securing reliable urban water supplies – especially for Australia's four major urban areas (Perth, Melbourne, Sydney, and South East Queensland), requires far-sighted planning and billions of dollars of infrastructure investment. To continue to increase agricultural productivity with limited water will require many innovations in policies, technology, and knowledge that enable smarter and more efficient delivery and application of irrigation water.

As well as increasing demands, there are clear signs of decreasing water availability in parts of the country. In South West of Western Australia, climate change observed since the mid 1970s has seen stream flow into Perth's reservoirs more than halved, compared with the earlier long-term average. Research has shown that the unprecedented 1997–2009 drought in south-eastern Australia included a climate-change signal: a signal consistent with climate change predictions for a future of global warming producing lower rainfall in southern Australia. Further research continues to better quantify these signals.

Traditionally, water resource planning and engineering design of major infrastructure, including dams, were guided by measurements of past rainfall, temperature, and river flows. Scientists, engineers, and policy makers now agree that water resource planning and investment should consider multiple plausible climate and hydrology futures, not just historical records. The road ahead is uncertain, but relying only on the rear-view mirror would be negligent.

In the face of increasing demand and dwindling supply in some regions, Australia has the difficult task of balancing the use of water for direct economic benefits against indirect benefits such as environmental water use of water for conservation and the provision of ecosystems services.

There is a water quality dimension, as well as quantity, that needs to be considered for the future. Water quality should be at a level fit for its intended use; pollution of water can prevent or diminish future use and make it harder to meet increased demands on the resource. This is particularly a challenge for groundwater, where over-use of fresh groundwater can lead to salinisation reducing or preventing future use and degrading freshwater ecosystems reliant on the groundwater resource.

Responding to the challenge

Australian Governments have been actively reforming water management in response to the evolving water challenge. Under Australia's constitution, water resources are the responsibility of state and territory governments, but the Australian Government is involved through national competition policy, national and international environment policy, and the management of water resources that cross state borders (mainly the Murray–Darling Basin, Great Artesian Basin, and Lake Eyre Basin), and associated funding programs.

Monoman Creek, Chowilla Floodplain, South Australia during the millennium drought showing dying red gums and a blue green algae bloom. Photo: Ian Overton, CSIRO.

Googong Reservoir, Murrumbidgee catchment, New South Wales. Photo: Greg Heath, CSIRO.

The reforms increasingly treat water as an economic good or service, including formal legal entitlements to access water, which enable entitlements and seasonal allocations of water to be traded among users. Water supply services have been privatised, including in cases where infrastructure is government-owned, and the roles of water supply and regulation of use have been separated. Water prices are changing to reflect the full costs of supply and disposal, including separate charges for separate services.

A second key objective of the reforms is to make water management more environmentally sustainable. Water resources are thought to be over allocated in many parts of Australia, in the sense that the amount of water used, or the way that it is used, has caused socially unacceptable levels of environmental decline. An important milestone in the reform process was the passing of the *Water Act 2007 (Commonwealth)*, which has a focus on achieving sustainable management of the water resources of the Murray–Darling Basin through implementation of a Basin Plan. The Act paves the way for more formal environmental water management by establishing the Commonwealth Environmental Water Holder, which will hold in excess of 1000 GL of water entitlements and associated seasonal allocations to be actively managed for environmental benefit, just as other entitlements are managed for economic uses.

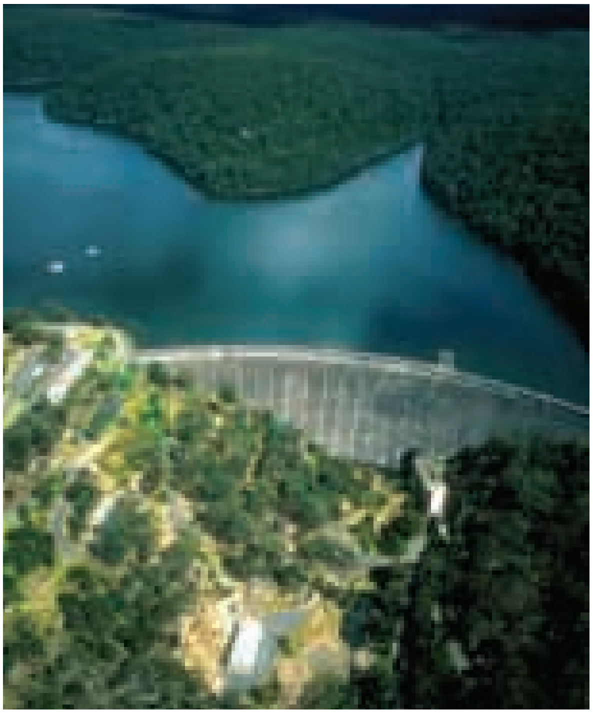
The reforms show that water is becoming an increasingly valuable commodity, and they provide an incentive for greater investment in the technologies and knowledge base required for smarter and more efficient management. In a carbon-constrained world, the large amounts of energy required to pump and desalinate water will increasingly mean the water and energy footprints of economic development will be considered jointly. Opportunities will be sought to reuse and recycle water rather than just using it once and disposing of the wastewater.

Wivenhoe Dam, Brisbane, during a controlled release, October 2010. Photo: Mat Gilfedder, CSIRO.

The role of science and technology

In order to secure water for future generations, Australian governments, industries, and communities will want to understand current and future water availability and explore ways of meeting the demands on these water supplies. They will want to better understand how river systems and groundwater systems respond to a changing climate and to increasing water use, and they will want to be confident that water use will not unduly harm future water supplies through pollution, over-use or environmental degradation. Improvements in ecological understanding, and in understanding the human health and other implications of contaminants in water, can provide vital help in developing water plans and provide safe and reliable water for all uses, including environmental water.

With increasing demands on a limited resource, there are strong incentives for more efficient ways of using water in irrigation, in cities, and for the environment. This will stimulate innovation in ways of providing the same or greater production and service provision using less water. Solutions are likely to include greater efficiency of water use in food production, in mineral processing, and for domestic use, to reduce demand while maintaining outcomes. Other opportunities may emerge from how water is managed for multiple benefits such as through recycling and reuse. New supplies will be sought through more efficient desalination and recycling technologies or through better use of groundwater. In the future, it is likely that the management of dams and rivers will shift from a primary focus on supply for cities or for irrigation, to balancing urban, agricultural, and environmental uses of water. New technologies are emerging with the potential to better understand and manage water resources. For example, ground-based


Woronora Dam, Sydney. Photo: Greg Heath, CSIRO.

radar and satellite-based remote sensing technologies are providing improved measurements of rainfall that will improve forecasting skill across the continent.

The scientist's techniques for employing accurate measurements, experimentation, hypothesis testing, and critical analysis, will assist in making major strategic decisions with confidence, and adapting to unforeseen consequences in the future. For example, new sensors and information technology are allowing early detection and remediation of urban water pollution. Careful monitoring and evaluation can improve the uncertain outcomes of providing water to restore degraded ecosystems. Accurate projections of the impacts of future climate on water resources and future demands on resources will help ensure enduring value from major investments in infrastructure.

Water science and technology has evolved in tandem with the water resource management challenges over the years. Research on aquatic ecosystems directly contributed to policies to tackle over allocation of water resources and return water to the environment. Now research is focussing on predictive ecology, to maximise the ecological benefit from the increasing volumes of water being managed for the environment, just as water supplies for irrigation are being improved to increase food production.

Billions of dollars of expenditure on water infrastructure is occurring now and this level of expenditure is expected to continue into the future, and similar amounts are spent on operating and maintaining water treatment, supply, and wastewater systems. Research that reduces operating costs or delays capital costs can have significant economic value. The well-being of the nation may depend, in future, on the ability to deliver high-quality water supplies to the many competing users. Scientific research continues to find solutions that greatly improve the effectiveness of water supplies and the benefits gained from them for all users.

Current water availability and use

Ian Prosser

Key messages
✻ Overall, Australia has sufficient water resources to support its current uses, consuming 6% of renewable water resources each year.
✻ Current use of rainfall and water resources in effect meet the needs of more than 60 million people, through Australia's exports of agricultural produce.
✻ A very uneven distribution of water resources across Australia and high year-to-year variability means that water resources in some regions are fully or over allocated, while others remain largely undeveloped.
✻ Australia's arid landscape and high potential evaporation pose challenges from the high demand for water by crops and cities, and large water losses from reservoirs and inland rivers.
✻ Some water resources are at risk from bushfires and unlicensed uses, which can reduce water availability to licensed users.

A summary of Australia's water resources and their use

A pervasive question is whether Australia has sufficient water resources to meet current and future uses. To answer that question fully, requires considerations of sustainability and likely changes to the resource as a consequence of climate change, but the key starting point is to compare Australia's water resources with the uses placed on them.

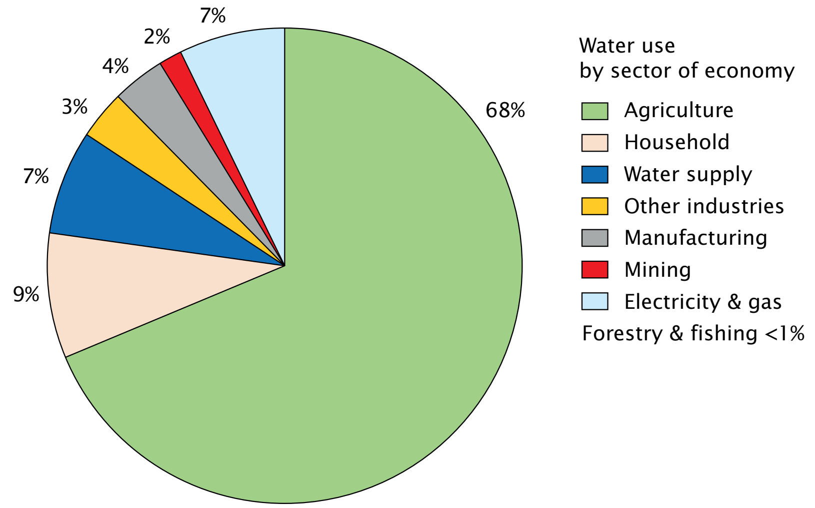
Australia receives an average of 417 mm of rainfall per year (Table 1.1),[1] which adds up to 3 700 000 GL of water per year (a gigalitre is 1×10^9 litres). Rainfall supports Australia's dryland (non-irrigated) agriculture and some domestic water supplies (via rainwater tanks), but is not itself considered a water resource for statutory water management. It is only when rainfall runs off into creeks, rivers, and lakes or recharges groundwater aquifers that it becomes a managed resource.

The sum of runoff and recharge is the total renewable water resource. It can be extracted, stored, managed, regulated, distributed, and used for a range of purposes. On average, only 9% of rainfall in Australia becomes runoff, and approximately 2% percolates through the soil to recharge groundwater (Table 1.1).[2] The rest evaporates back into the atmosphere, mainly through vegetation.

Table 1.1: Water use compared with average total renewable resource.[1, 2, 3]

	Average annual fluxes
Rainfall	3 700 000 GL (417 mm of rainfall)
Runoff	350 000 GL (9% of rainfall)
Groundwater recharge	64 000 GL (2% of rainfall)
Total renewable water resources	414 000 GL (11% of rainfall)
Evapotranspiration	3 286 000 GL (89% of rainfall)
	Average annual fluxes
Total extraction	72 431 GL (17% of renewable resource)
Total consumption	24 449 GL (6% of renewable resource)

Only a small proportion of Australia's renewable water resources is consumed each year. The Australian Bureau of Statistics produces reports on water use every 4 years. Levels of water use in 2008–09 and 2004–05 were reduced by drought across southern Australia so the statistics for 2000–01 are used here to better reflect unrestricted demand for water. In 2000–01, of the total 72 431 GL that was extracted for use, 47 982 GL was returned to rivers, mainly being used for hydroelectric power generation, and 24 449 GL was consumed by industry, households, and agriculture (Table 1.1). Of the water consumed, 68% was used in irrigated agriculture to produce food and fibre, 23% was consumed in various industries, and 9% was taken for household water use (Figure 1.1). It will be interesting to see the next set of statistics on water use because restrictions on use have eased and the population has increased, but people are now more conscious of water conservation.



▸ ***Figure 1.1****: Water consumption by different sectors of the economy for 2000–01. Consumption in the water supply industry is mainly the losses of water that occur in supplying water and providing sewerage services.[3]*

Australia is a generally arid continent but it uses only a low proportion of its water resources compared with other regions of the world (Table 1.2). It is the driest populated continent, and has the lowest proportion of rainfall converted to runoff,[4] giving it slightly less water per unit area than any other region of the world (Table 1.2). However, Australia has by far the lowest population density of any major region, so it has moderately plentiful water resources per person and consumes a smaller percentage of its water resources than other dry regions and the most densely populated regions of the world (Table 1.2).

Table 1.2: Global comparison of water resources and use.[5]

Region	Available water per area	Population density	Available water per capita	Water consumed	Consumption per resource
	ML/ha	People/km²	ML/person/year	10^3GL/year	%
Australia[(a)]	0.5	2.5	21.3	25	6.0
North America	2.8	20.7	13.4	603	9.9
Central America	11.2	115.7	9.6	23	2.9
Southern America	6.9	21.5	32.2	165	1.3
Western and Central Europe	4.3	107.1	4.0	265	12.6
Eastern Europe	2.5	11.5	21.4	110	2.5
Africa	1.3	32.7	4.0	215	5.5
Middle East	0.8	47.1	1.6	271	56.0
Central Asia	0.6	18.5	3.0	163	62.0
Southern and Eastern Asia	5.5	174.4	3.2	1991	17.1
Oceania and Pacific[(b)]	1.1	3.3	33.0	26	2.9
World	3.2	50.4	6.4	3832	8.9

[(a)] Data from Table 1.1
[(b)] Includes Australia

Inspecting rice near Yenda, New South Wales. Photo: Greg Heath, CSIRO.

Australia's water resources are in effect used to support more than our domestic population of 22 million people. Water is used in the production of almost all goods and services, and particularly in the production of food and fibre (e.g. cotton). For instance, it takes about 8000 L of water to produce a pair of leather shoes and about 5000 L of water to produce a kilogram of cheese.[6] This principle of water required for production can be applied on a global scale to show that some countries, such as Australia, use more water to produce their exports than is embodied in their imports. Countries with very high population densities and only small areas of arable land tend to be net importers of embodied water because they import much of their food and export manufactured goods that require less water.

Australia exports a majority of its agricultural produce and imports many manufactured goods, using far more water to support domestic consumption and exports than is used to produce the imports. Using the data of the Water Footprint Network,[7] Australia is effectively supporting a population of about 67 million people at our own high levels of consumption.

Much of the water used in agricultural produce is rainfall used in dryland agriculture, not water extracted from rivers and groundwater for irrigation. The two types of water should not be compared directly with each other when examining the water use efficiency of different crops. Irrigation consumes water resources from rivers and groundwater, the use of which competes with other uses, including for the environmental values that rivers, lakes, and estuaries support. By contrast, the rainfall that evaporates through dryland crops would also have evaporated through the natural vegetation cover on the land, or other vegetation covers. Only where dryland agriculture reduces the amount of water flowing into rivers and groundwater (perhaps by storing water in farm dams) does it impact on water resources and other water users.

Putting Australia in a global perspective shows that although it has enough water to meet its needs and to support trade, there have still been recent water shortages. The problems emerge in the very uneven distribution of the water and where it is used.

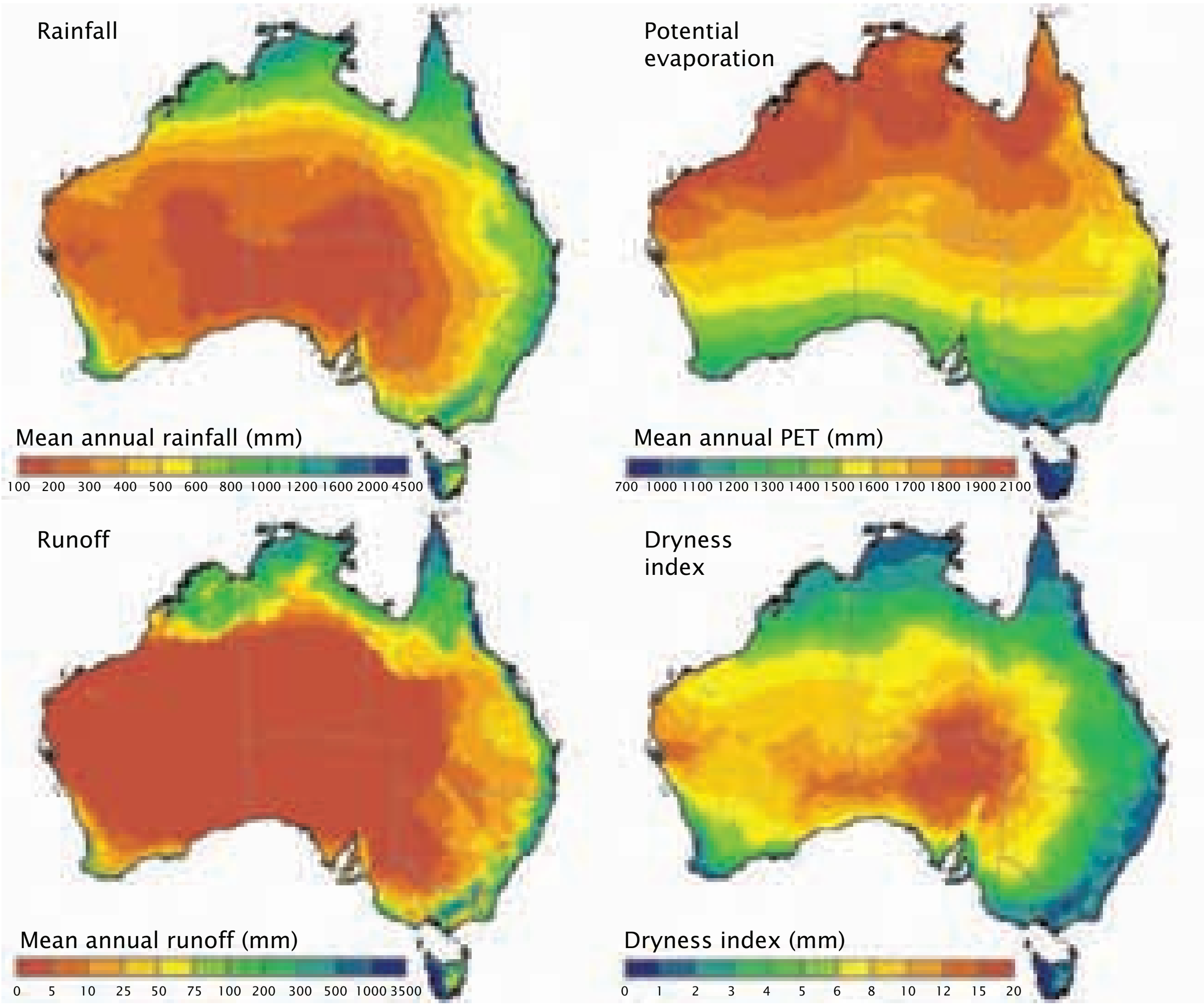
Water resource patterns across Australia

Australia has a thin wet margin and a dry interior. The north, east and south-west coasts and ranges receive moderate to high rainfall while the rest of the continent is dry. A better indicator of the aridity of the continent, though, is the dryness index, which is the ratio of potential evaporation to rainfall (Figure 1.2). Potential evaporation is the amount of evaporation that would occur if an endless supply of water were available, whereas actual evaporation is much lower, because a landscape may be dry for much of the time. If rainfall is insufficient to meet the demand of potential evaporation, the landscape is at least seasonally dry. Where rainfall is greater than potential evaporation, the dryness index is less than 1.0, there is excess water to keep soils moist, excess rainfall becomes runoff and plant growth is not limited by water availability. On a mean annual basis, only western Tasmania, the Australian Alps and the Wet Tropics have a dryness index less than 1.0.

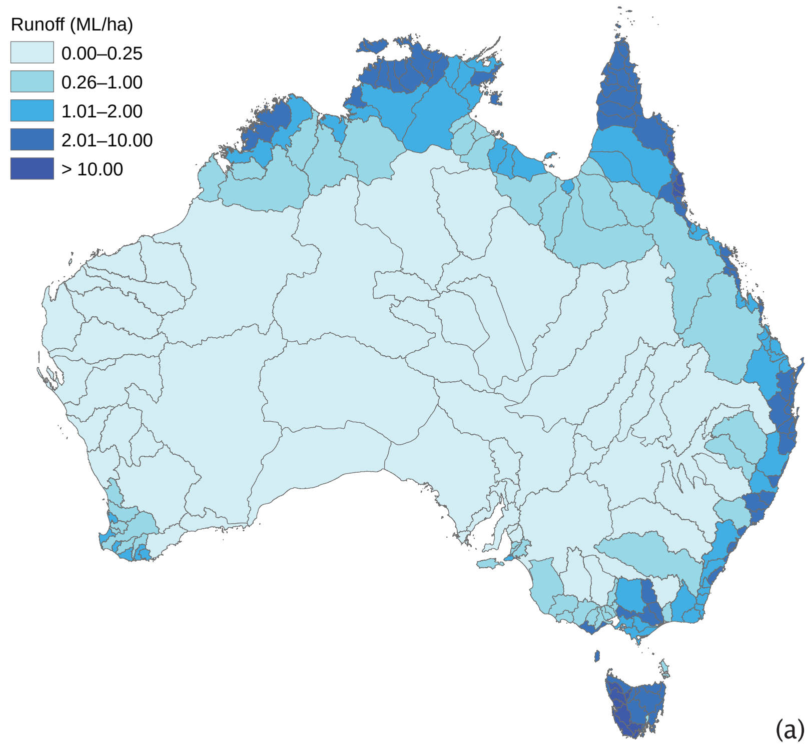
Where the dryness index is greater than 1.0, the landscape is water-limited for at least part of the year and plant growth is limited by water availability. The larger the dryness index, the greater the moisture deficit and the lower the amount of runoff. Most of Australia is water-limited, producing little runoff either seasonally or over the whole year. These annual averages mask strong variations between years, controlled by climate variability. Almost every year, some part of Australia experiences drought, where low rainfall and high potential evaporation cause more intense aridity than normal, and this can persist for several years.

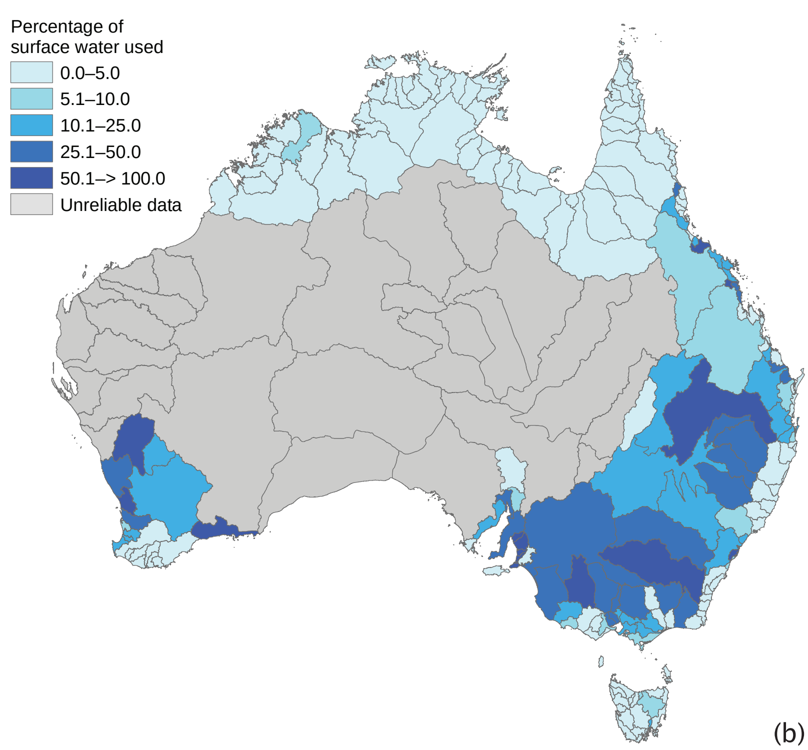
Not only are Australia's water resources concentrated around the coastal rim, so too is its population and water use. Figure 1.3(a) shows how the pattern of runoff is distributed as surface water resources among the 224 river basins in Australia. Figure 1.3(b) shows what proportion of surface water resource is used. Water use is greater than 40% of the surface water available in and around capital cities and across the Murray–Darling Basin. Small coastal rivers tend to have higher rates of use than the larger rivers, showing that intense use is local, close to the coast and does not fully utilise the resources of the larger basins.

The Murray–Darling Basin is Australia's most developed rural water resource, where 48% of surface water is consumed on average each year, mainly in the southern part of the Basin.[8] This water resource is considered to be over allocated[9,10] in the sense that the high levels of water use have degraded the rivers and wetlands that rely on them (see Chapter 9). Coastal cities largely rely upon small river basins that are fully developed, so water is transferred from neighbouring river basins (e.g. piping water from the Thompson River in Victoria to supply Melbourne or from the Shoalhaven River to supply Sydney). Water use in other coastal areas of Victoria, New South Wales, Queensland, northern Australia, and much of Tasmania is below 10% of runoff. These are areas with potential for further development, although factors other than water availability need to be considered.



▲ ***Figure 1.2**: Rainfall, potential evaporation (PET), runoff, and dryness index across Australia. The dryness index is the ratio of potential evaporation to rainfall. Where the dryness index is less than 1.0, there is on average more rainfall than can be evaporated giving large volumes of runoff. Where dryness index values are greater than 1.0, there is a deficit between rainfall and evaporation potential leaving a dry landscape, with little runoff and the need for irrigation to support vibrant plant growth. Rainfall and potential evaporation data were obtained from Bureau of Meteorology databases and runoff is a CSIRO compilation of modelling and measurements.*





▸ ***Figure 1.3**: (a) Availability of surface water shown as average annual volume of surface water (ML) per hectare of land for each Australian river basin; (b) Percentage of surface water used for each Australian river basin.[8,11,12] Arid areas rely mainly upon groundwater and have unreliable data for surface water use.*

Constraints on water use

Even in the fully developed river basins, only about half of the available surface water is consumed over time. This reflects some physical constraints on water resource development and use as well as limits imposed to protect rivers and wetland environments from degradation. Some of these constraints are more extreme in Australia than elsewhere.

As well as very uneven spatial distribution of water resources, the regions with temperate climate (outside of tropical and desert climates) have the highest year-to-year variability of runoff in the world.[13] For example, in the Murray River a dry year produces approximately one-tenth the river flow of a wet year. Typically, the difference in runoff between wet and dry years in Australian temperate climates is twice that of the northern hemisphere temperate regions. This is partly due to a higher rainfall variability in Australia that is amplified in the amount of runoff, and is linked to the strong influence of El Niño and La Niña seasonal weather patterns and the high potential evaporation of Australia.

The high variability of runoff from year to year puts a constraint on the amount of water that can be reliably supplied even with large storages. In the Murray–Darling Basin in the drier years, which have low flow, more than 60% of all water available is used and in nearly one-third of years more than 70% is used (Figure 1.4). After accounting for the need to leave sufficient water in the river to keep supplying users downstream, no further water could be used. In wetter years, large flows coincide with low demand for water because of the good rainfall, so only a small proportion of water is used. When yearly supply is balanced against demand, only about half of the water is used.

Australia's high potential evaporation and variable runoff mean that very large dams are needed to provide a reliable supply of water to cities. More than 23 000 GL/year is lost to evaporation from Australia's major dams, similar to the volume that is used.[14,15] Wivenhoe Dam stores 10 years of supply for Brisbane when it is full, yet the high evaporation and drought up to 2009 meant it

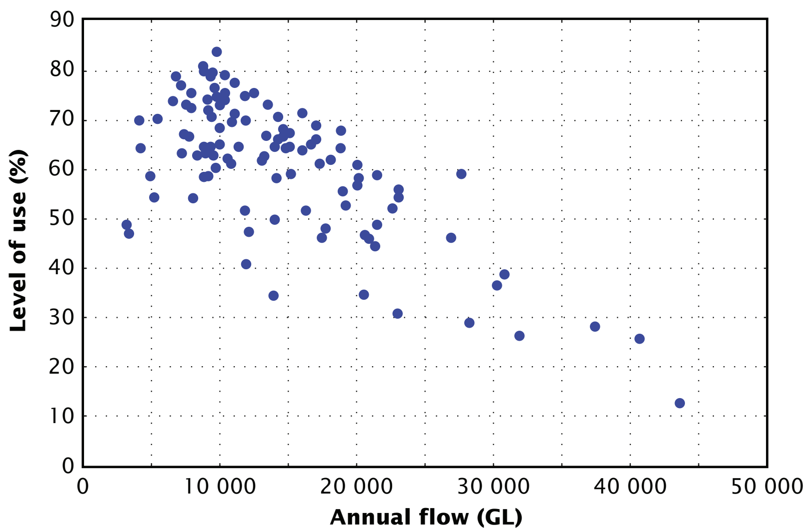


Figure 1.4: Water used in the Murray–Darling Basin as a percentage of the annual flow at Wentworth. Wentworth is the point of maximum flow in the Basin.[8] In dry years, almost all water is used, while wet years have low levels of use because of both higher supply and lower demand.

came close to emptying, before rapidly refilling when above average rainfall returned. In large river systems there are also significant losses of river flow as water moves downstream. Across the Murray–Darling Basin there is 28 900 GL/year of runoff on average, but by the junction of the Murray and the Darling Rivers half of this has evaporated or seeped into groundwater.[8] When the sources of water are very distant from the points of use, only a fraction of runoff is usable.

A dry climate means that water use per capita is high. Use in Australian houses is comparable with other cities of the world with similar standards of living, but more water is used outdoors because of the high irrigation demands of gardens and parklands. Domestic water use has decreased in recent years as a result of conservation measures. For example, in cities with hot or dry summers such as Brisbane, Adelaide, and Perth, over 100 kL was consumed per person per year prior to water restrictions and a new focus on water conservation.[16] In European cities with high housing density and low garden watering, use is of the order of 50 kL per person per year. During water restrictions, Brisbane achieved a use of 53 kL per person per year.[16]

A similar situation of high water demand occurs in irrigated agriculture in Australia. The larger the gap between rainfall and potential evapotranspiration, the greater the amount of irrigation water needed to support highly productive agriculture. Some Australian irrigation areas have evaporative demands that are three to eight times greater than the rainfall (Table 1.3).

Table 1.3: Rainfall (P), potential evaporation (Epot), rainfall deficit (Epot-P), and aridity index Epot/P for selected city and irrigation locations.

Location	P[(a)] (mm/year)	Epot[(a)] (mm/year)	Epot-P	Epot/P
Brisbane	1046	1821	775	1.7
Sydney	1156	1624	468	1.4
Melbourne	598	1525	927	3.1
Adelaide	500	1751	1251	3.4
Perth	766	1884	1118	2.4
Ord irrigation	870	2535	1665	2.9
Burdekin	569	2229	1660	3.8
Griffith	401	1808	1407	4.5
Narrabri	635	2023	1388	3.2
Renmark	239	1878	1639	7.7

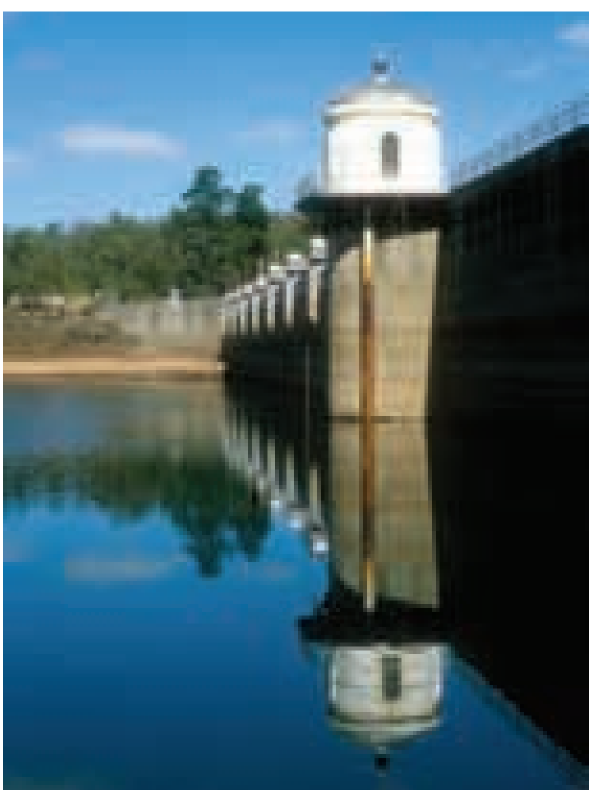
[(a)] *Obtained from Bureau of Meteorology databases*

Australia is similar to other subtropical and arid continental regions such as India, central and east Asia, and western United States of America in requiring irrigation to support the most productive agriculture. In temperate Europe and America and the Wet Tropics, most agricultural production is supported directly by rainfall.[17]

Opportunities for development of water resources

The contrast of high levels of water use in some basins with low levels of use elsewhere raises the prospect of increasing use by transferring water between river basins. The Snowy Mountains scheme transfers 1000 GL/year from the Snowy River into the Murray–Darling Basin.[18] Several smaller transfers take water from the Murray–Darling Basin to augment supplies for Adelaide and Melbourne. More ambitious schemes such as piping water from northern Australia to the Murray–Darling Basin, the Bradfield Scheme[4] or the proposal to augment Perth's dwindling surface water supplies with a canal from the Fitzroy River in the Kimberley region have all been suggested.

The more ambitious schemes have high financial and environmental costs. For example, the cost of building a canal from the Kimberley in northern Australia to augment Perth's supply was at least $20/kL.[19] Shipping using super-tankers would reduce the cost to $7/kL,[19] and the Perth desalination plant supplies water at $1.16/kL.[20] For irrigation water, the lower price and the larger quantities of water required make these schemes even less financially attractive. For example, a typical supply price for irrigation water is around $33/ML (3 cents/kL), more than 30 times lower than the price for urban water. A proposal to transfer water from the Clarence River into the Murray–Darling Basin, would supply 755 GL/year (7% of water use in the Basin) at a capital cost of



Mundaring Weir, east of Perth, Western Australia.
Photo: Bill van Aken, CSIRO.

$656 million and an operating cost of $130/ML (13 cents/kL).[4] More cost-effective solutions have been used to augment urban water supplies, and irrigated agriculture is being developed where there is more water available, such as in northern Tasmania.

There is renewed interest in developing water resources for irrigation in northern Australia to alleviate the pressure on the Murray–Darling Basin. Runoff from the two drainage divisions in the north is nearly eight times that of the Murray–Darling Basin. Although opportunities for water resource development exist in the north, they are not as straightforward as is suggested by the high runoff because some of the limiting factors of Australia's water resources described above are magnified in the north.

Northern Australia has a hot climate, with most rain falling from November to April. Water is in deficit with rainfall less than potential evaporation for 10 months of the year. The annual rainfall deficit is over 1500 mm/year for much of the region, and crop water demands are very high, as is evaporation from storages (Table 1.3). The ratio of dam storage to supply of water would need to be higher than for southern Australia. Much of the runoff occurs as major floods, which can be a hazard rather than a resource, causing extensive inundation of the lowland regions for weeks to months at a time. Northern Australia has fewer locations for large dams because of its open valleys and, aside from the most easterly ranges, the headwater regions are the driest and hottest parts of the catchments.[21]

Groundwater presents the most attractive opportunities for irrigation, with approximately 600 GL/year of groundwater available (Figure 1.5). The Daly, Wiso, and Georgina groundwater provinces in the Northern Territory and north-western Queensland have the greatest potential, although the Daly province is almost fully allocated. The Canning (east of Broome), Ord-Victoria

▲ ***Figure 1.5**: Groundwater resources and prospective use in northern Australia.[21]*


Maroondah Reservoir, near Healesville, Victoria. Photo: Nick Pitsas, CSIRO Publishing.

(east of Kununurra), Pine Creek (south-east of Darwin), McArthur and Great Artesian provinces could each be expected to deliver 10 to 100 GL of groundwater a year.

Water availability is just one factor contributing to irrigation development and is probably not the limiting factor in northern Australia at present. Other factors that need to be considered include suitable land and crops, and access to infrastructure, workforce, and markets.

Risks to water availability and use

The amount of water that is available to licensed users in the future is at risk from external impacts on the resource such as climate change and bushfires, and internal risks created by the way water use is licensed and managed. The main risks that have been identified are:

- climate change (see Chapter 3)
- bushfires
- plantations and other revegetation
- farm dams
- floodplain harvesting
- unlicensed groundwater bores (see Chapter 4)
- double accounting of surface and groundwater (see Chapter 4)
- mining water use (see Chapter 10)
- reduced return flows from irrigation (see Chapter 8).

Bushfires pose a risk to water availability when regenerating forests use more water than the mature forest they are replacing. This effect is most pronounced in the ash forests of south-eastern NSW and Victoria where the trees usually do not survive fire. The density of regrowth can reduce runoff for several decades. The major bushfires in Victoria in 2003 and 2006–07 burnt over a million hectares of forest. Their combined impact on the Murray River (at the confluence with the Ovens River) is expected to be 255 GL/year reduction or approximately 3% of the average annual flow.[22]

Forest plantations and farm dams use significantly larger volumes of water than the agricultural practices that they replace, so their expansion can reduce the amount of runoff in rivers. It is where plantations replace pastures, rather than existing forests, that water use increases significantly.

Floodplain harvesting, unregulated groundwater bores, and mining are direct uses of water that may not have water access entitlements and can impact on users with entitlements to the resource. These activities, together with plantations and farm dams, are termed 'intercepting activities' because they intercept (or use) water that would otherwise have contributed to the formal water resource. Their use is hard to measure, but a national assessment (Table 1.4) indicates that significant volumes of water are involved. Intercepting uses that have been in place for decades are not of concern because their use of water would have been included in assessing how much water was available and distributing that across entitlements. It is the future expansion of intercepting land activities that poses the larger risk because it reduces the amount of water available to those with entitlements. Although the projected future volumes in Table 1.4 are small on a national scale, development is usually focussed in particular valleys, where impacts can be locally significant.[23] Where there are significant impacts from intercepting land uses, a possible solution is to bring the uses into the system of entitlements.

Table 1.4: National assessment of intercepting activities.[23]

Activity	Current water use (GL/year)	Potential additional water use to 2030 (GL/year)
Plantations	2000	62
Farm dams	1600	300
Floodplain harvesting	890 [a]	0 [b]
Stock and domestic groundwater bores	1100	286

[a] 880 GL of this use occurs in the northern Murray–Darling Basin.
[b] Moratoriums on construction of storages are in place.

Better water information for Australia

With increasing demands on Australia's finite water resources, and concerns about risks to the resources, it is imperative that there is accurate information on availability and use of water. Water is a significant business, community, and ecological asset that deserves the same level of accountability as any other asset. There were few reliable and current sources for water information covering the whole of Australia available for compilation in this book. Statistics were highly variable depending on the period reported or the methods used, adding to uncertainty over the scarcity of water across Australia.

To overcome these problems at a national scale, the Bureau of Meteorology has been mandated to compile, analyse, forecast, and report on water across the country.[10] It estimates that water information is collected by some 200 agencies across Australia, and some of it is hard to access and compile to build a national picture. CSIRO is working with the Bureau of Meteorology to develop technologies for automatic accession, processing, analysis, and reporting of this information. Traditional field measurements of rainfall, river flow, and groundwater level, are being complemented with new satellite remote sensing of hard-to-measure water attributes such as the amount of water evaporating through vegetation or seeping from unlined irrigation canals.

The best opportunities come from combining on-ground measurements and remote sensing in computer models to map and forecast the state of water resources across the country. For example, remote sensing from satellites is being used to estimate rainfall between gauges that are widely spread across the landscape, to measure flows on floodplains, or to measure use of water by crops (Figure 1.6). An example of new seasonal forecasts of river flow is given in Chapter 3.

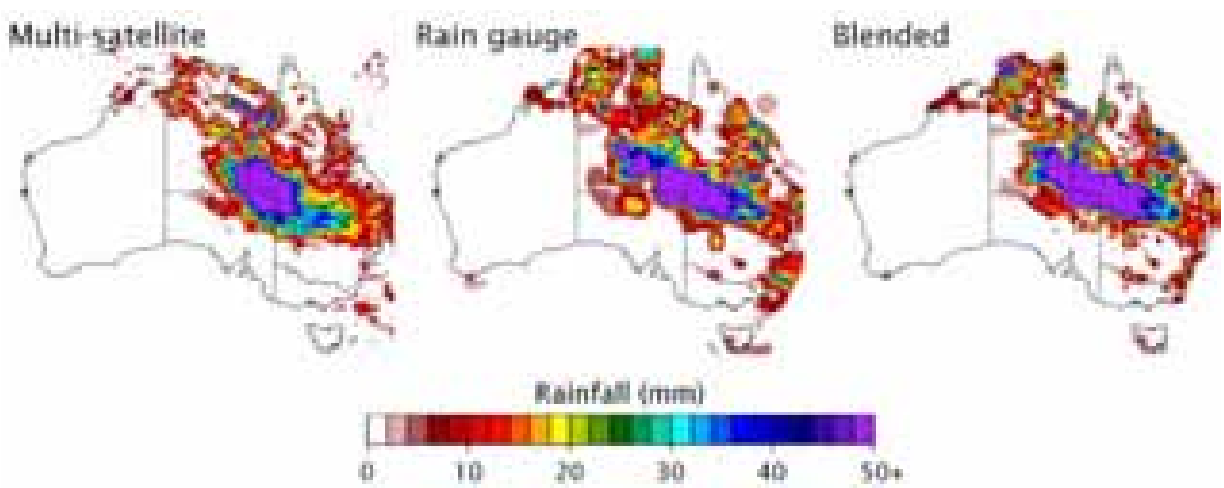
Farm dam near Wallacia, New South Wales. Photo: Greg Heath, CSIRO.

Conclusions

Australia is only partly a dry continent. It is a continent with a thin wet margin, where most of the population lives, but it is also sparsely populated and uses only a small proportion of its water resources. Australia exports much of its agricultural produce and its use of rainfall and water resources is enough to support, in effect, more than 60 million people. There is more than enough water overall to meet the country's needs yet the perception of aridity is real.

Australia's rainfall is notoriously unreliable, and in temperate regions its river flows are the most variable in the world. On top of that, high rates of potential evaporation place large demands on water for the irrigation of crops and household gardens, and results in much water being lost from rivers and dams. Australia has to store very large quantities of water to ensure reliable supplies, and even then some large dams used to supply cities have come close to running dry. The use of water resources is highly concentrated around the large capital cities and in the southern Murray–Darling Basin, which is considered to be over allocated. Future water supplies are at risk from climate change, bushfires, and the way water is licensed for use.

There are opportunities to develop new water resources but these are often, not coincidentally, in places with highly valued aquatic ecosystems, or where there are other factors that limit water use, such as lack of economic opportunity. Questions about the values or benefits obtained from water should be examined before considering whether and how water could be used more effectively.



▲ ***Figure 1.6****: Rainfall estimates for 1 March 2010. From left to right: from a NASA multi-satellite rainfall product; from analysis of rain gauges; and from combining the gauge and satellite rainfall estimates. The rain front shown led to widespread flooding in southern Queensland and northern New South Wales.*

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Water values

Rosalind Bark, Darla Hatton MacDonald, Jeff Connor, Neville Crossman, and Sue Jackson

Key messages

- As a society, Australians value water highly for a range of economic, environmental, social, and cultural benefits, which at times are in conflict with each other.
- Water resources are an input into the production of most goods, and water environments support economic uses such as fisheries, tourism, and recreation.
- Healthy water environments provide valuable ecosystem services such as maintenance of water quality and habitat, and many people intrinsically value and feel highly attached to water-related environments.
- For Indigenous Australians, water is central to culture and identity, as well as livelihood, but these values are poorly understood.
- Increasingly market mechanisms, such as water trading, are used to resolve competing uses, but regulation, community aspirations, and valuation of ecosystem services are also important future drivers.

People value water and water environments for a diverse range of reasons. Water is essential for human life and wellbeing, is critical to food production, and is a part of many manufacturing and industrial processes. Australians have a deep connection with the water environments of rivers, lakes, estuaries, and coasts, which are central to much recreation and tourism, and for Indigenous Australians water environments have a deep spiritual meaning. Perceptions of dryness of the continent have also shaped the Australian 'psyche'.[1]

Many of the values for water are shared, but it is the contested values that are at the heart of conflicts over water, such as determining sustainable levels of use. Large-scale water use inevitably has some impact on water ecosystems, so setting sustainable levels of use inevitably involves weighing up competing values. This chapter outlines the many benefits obtained from water and how they shape the way water is managed in Australia. Although it is convenient to describe separate social, cultural, environmental, and economic values for water, they are in fact closely intertwined.

Mandurah estuary, Western Australia. Photo: Bill van Aken, CSIRO.

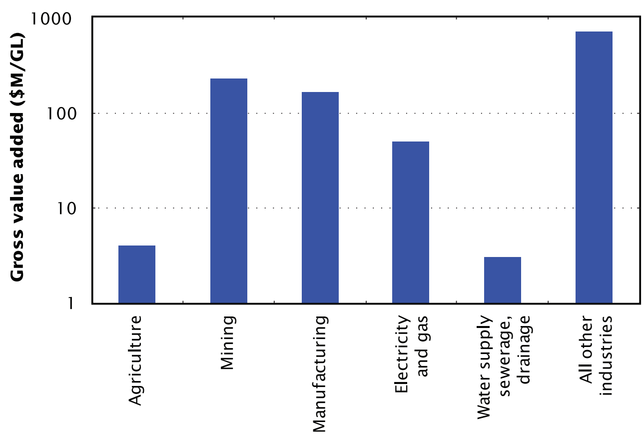
Water has been critical in Australia's history, both in shaping and responding to broader values that have changed over time. Some refer to the period from early European settlement through the first half of the 20th century as the expansionary phase of Australian water resources and the time since then as the maturing phase.[2] In the expansionary phase, the focus was on nation building, and populating rural areas, supported through irrigation. An icon of this phase was the Snowy Mountains Hydroelectric Scheme, the development of which reflected an emphasis at the time on the economic values associated with water.

The maturing phase has been marked by a shift to encompass a broader set of values, which at times compete with each other. These include increasing concerns over the condition of water ecosystems because water use led to degradation of natural environments, sometimes to the detriment of ongoing water use, such as high salinity levels having an impact on irrigated agriculture and town water supplies. At the same time, the economy has grown and become more diverse and settlement has concentrated in the large coastal cities. Decisions like the one to not proceed with dams on the Franklin River in Tasmania and the more recent moves to restore environmental flows in the Murray–Darling Basin reflect this shift in values.

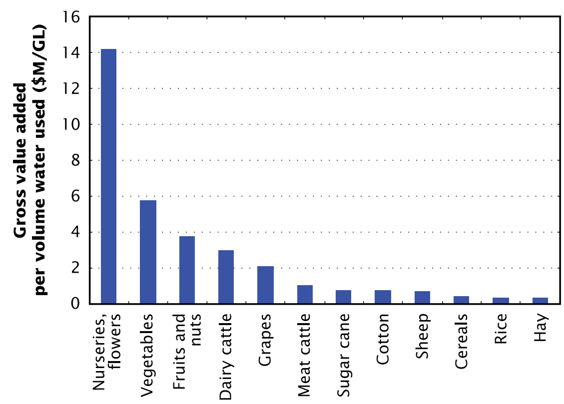
Economic values

Water is used in the production of almost all goods. Water resources are critical for irrigated agriculture, mining, households, and many industries, all of which are substantial users. The largest amount of water use is for irrigated agriculture, producing food and fibres (such as cotton).

The market value of water use can be described using marketplace concepts, such as the gross value added per gigalitre ($/GL) of water used in production (Figure 2.1). The gross value added is the wholesale value of the goods produced minus the operating costs of production (input goods and labour). By this measure, water used in mining and manufacturing produces much higher economic values than water for irrigated agriculture.[3] Within irrigated agriculture, nurseries, vegetables, and fruit have much higher gross value added than dairy and grapes, which in turn are higher than rice and cereals (Figure 2.2). The value added for each agricultural product can vary substantially from year to year as a result of changes in global commodity prices: for instance, the data shown in Figure 2.2 reflect the high price for dairy products in 2008–09.



▲ ***Figure 2.1***: *Gross value added per GL of water used by various industries, 2008–2009.*[3] *Mining, manufacturing, and other industries are high-value economic users of water while irrigated agriculture produces less value per GL of water used.*



▲ ***Figure 2.2***: *Gross value added of irrigated agricultural production across Australia for 2008–09. Nurseries, vegetables, fruits, and nuts produce the highest added value from irrigation.*[3]

While the $/GL metric is straightforward, it is not a reliable measure of the true value of water, because water is often a relatively small input cost and it is often not the input that limits production. The metric does not account for capital costs or any change in price that would come from changed production volume. Thus doubling the amount of water made available for manufacturing, for instance, would not produce double the value. Similarly, farm productivity, farm profits and, regional economies would not necessarily benefit from having all irrigation water go to the highest gross value crops. The costs of access to processing plants and the markets for those products needs to be considered, together with the impact on prices of increased production, and the suitability of the land and climate for the crop.

A better indicator of the economic value of a change in water use is the marginal profit added by an additional unit of water used. Those users who can generate the most value from using more water will be the ones that will purchase additional water. Alternatively, they would be the users who would benefit most from future development to make more water available for use.

Running tap, Perth. Photo: Bill van Aken, CSIRO.

Water ecosystems (rivers, lakes, estuaries, and wetlands) support a range of economic activities without water being consumed, including commercial fishing, tourism, and recreation. The economic value of freshwater extends to the coast and inshore marine environment. Some commercial species, such as prawns, rely on freshwater discharges from rivers, and the nutrients they bring, to sustain viable populations. The direct economic value of water environments can be estimated from the commercial value of the markets for tourism and other recreational activities. For example, Moreton Bay in south east Queensland is an estuary and marine area dependent on clean freshwater inflows from the adjacent rivers. Use of Moreton Bay earns $10.5 million per year for the South East Queensland tourism industry, $260 million for the recreational industry and $60.1 million for the commercial fishing industry.[4]

Values of household water use

Good quality water for drinking, washing, and cooking is essential to sustain human life. The values embedded in domestic water go well beyond its cost and quality, as revealed by community reactions to the option of using recycled water for human consumption. Recycling wastewater or storm water is a technically viable and cost-effective solution for urban water supply (see Chapters 6 and 7), but there is significant community resistance to some uses. The closer the use gets to direct human contact, the less acceptable recycled water becomes. It is more acceptable for uses such as toilet flushing and open space irrigation, less acceptable for growing fruit and vegetables, which get eaten directly, and least socially acceptable as water for drinking and personal hygiene.[5] At the heart of the concerns are emotions and perceptions of risk, and the perceived lack of trust in public institutions to be able to provide the highest level of drinking water service all day, everyday, for decades to come, especially in the face of emerging pollutants (see Chapter 5).

In Australia, up to half of domestic water use is for garden watering, providing the aesthetic and other values of a verdant garden. In recent years, under household water restrictions, surveys showed that people were willing to pay up to twice the price of water at the time to secure reliable supplies of water for their gardens.[6,7] Of course, garden watering does not require potable standards of water quality and alternative sources can be found for the price people are willing to pay.

Environmental water values

As well as the direct economic uses, water-dependent ecosystems provide a myriad of ecosystem services of indirect economic value and they have intrinsic value beyond any economic consideration. Water ecosystems provide services such as processing waste and keeping water clean, or providing biodiversity as genetic capital for future applications (Figure 2.3). Costs for human provision of the services (such as for treatment of water quality) might be much higher if the ecosystem services were not maintained. In this way, a monetary value to people can be placed on the ecosystem services provided. A highly influential analysis of global ecosystem services showed that ecosystems provided at least as much value to the economy as the human production of goods and services,[8] but ecosystems also have benefits beyond their human utility.

Ecosystems can be valued purely for their own sake, or merely from the knowledge of their existence. Individuals express bequest values for ecosystems, wanting to preserve them not just for their own benefit but for the equal benefit of generations to come: a core concept of environmentally sustainable development as first defined.[9] Others have deeply held sense of place and belonging towards water environments such as the Murray River, which has an emotional significance for people throughout Australia. Residents of Perth have developed a sense of attachment towards the many groundwater-fed lakes and wetlands of the city and support the use of water to sustain the wetlands.[10] Further, there is a strong sense of responsibility for the environment and a sense of entitlement to fair and equitable access to the continuing benefits deriving from these environments that extends beyond mere economic value.

Ecosystems may be appreciated purely for the diversity of organisms that they support, placing intrinsic worth on all organisms, including, but not limited to, humans. From this perspective, all ecosystems and species are of value whether they contribute to human wellbeing or not.

Paddle-steamer 'Emmylou' at Echuca, Victoria. Photo: Bill van Aken, CSIRO.

Provisioning Services
Food: Ecosystems provide the conditions for growing food such as fish in wild habitats.
Raw materials: Ecosystems provide materials for construction such as fine timbers.
Fresh water: Ecosystems provide surface and groundwater.
Medicinal resources: Many plants are used as traditional medicines and as input for the pharmaceutical industry.
Regulating Services
Local climate and air quality regulation: Water and vegetation reduce temperature extremes.
Carbon sequestration and storage: As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues.
Moderation of extreme events: Ecosystems can create buffers against natural hazards such as floods.
Waste–water treatment: Micro-organisms in soil and in wetlands decompose human and animal waste, as well as pollutants.
Erosion prevention: Vegetation prevents river and foreshore erosion.
Pollination: Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee.
Biological control: Ecosystems are important for regulating pests and vector borne diseases.
Habitat or Supporting Services
Habitats for species: Habitats provide everything that an individual plant or animal needs to survive. Migratory species need habitats along their migration routes.
Maintenance of genetic diversity: Genetic diversity distinguishes different breeds or races, providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial species.
Cultural Services
Recreation and mental and physical health: The roles of natural landscapes and green space for maintaining mental and physical health is increasingly being recognised.
Tourism: Nature tourism provides considerable economic benefits and is a vital source of income for some regions.
Aesthetic appreciation and inspiration for culture, art and design: Language, knowledge and appreciation of the natural environment have been intimately related throughout human history.
Spiritual experience and sense of place: Nature is a common element of all major religions; natural landscapes also form local identity and sense of belonging.

▲ *Figure 2.3: The range of services that water ecosystems may provide for people.*[11]

Legislation that protects species and ecosystems such as the *Australian Environment Protection and Biodiversity Conservation Act 1999*[12] protects species and habitat for their own sake, not because they have economic value per se. The Ramsar Convention is a similar international agreement to protect migratory birds and internationally significant wetlands.[13] Metrics used to value biological diversity in a marine or freshwater aquatic habitat include the number of endangered species, species richness and diversity, and the presence of indicator species.

Australia is fortunate in having many water ecosystems of high intrinsic worth or that are treasured by society, as evidenced by the results of surveys of their use for recreation and tourism, and the increased property values observed in the vicinity of water ecosystems. These include the Kakadu wetlands, Lake Eyre, the Murray and Darling Rivers, Moreton Bay, Port Phillip Bay, and the Swan River; and coastal rivers such as the Daly River, Clarence River, and Thompson River, to name a few. The degradation of rivers and estuaries in recent decades has led to public awareness of the importance of sustaining these environments (see Chapter 9).

There are over 1000 estuaries in Australia, of which 50% are in near pristine condition[14] and there are over 900 wetlands listed as being of national importance, of which 64 are also of international significance.[15] There are 346 species of native fish in Australia, and before their decline, wetlands supported over one million water birds, including plovers, sandpipers, and stints, which migrate seasonally from the Arctic Circle to Asia and then on to Australia and New Zealand.

It is often convenient to express environmental values of water in monetary terms so that their value can be compared directly with economic uses of water. The three main ways to monetise ecosystem values are: through conventional markets, such as the value the water would have if put to economic use; implicit markets, such as the value of an estuary estimated from the increase in nearby residential housing prices; and constructed markets, by eliciting the willingness to pay for improvements to an ecosystem.

More than 60 studies have estimated use and non-use values of the natural capital assets and the ecosystem services these assets supply across the Murray–Darling Basin.[16] For example, the willingness to pay to restore the Coorong and Lower Lakes of the Murray River, is estimated to be $5.8 billion.[17] Interestingly, while such attempts to put an economic price on the intrinsic values of water ecosystems are fraught with uncertainty, the revealed values for the Murray–Darling Basin are of the same magnitude as the $10 billion that is being spent by the Australian Government, with community support, to restore environmental health of the Basin. Support for such levels of government expenditure is another indicator of the importance society places on these ecosystems. Whether that ecological restoration should come at significant cost to irrigation water use, however, is being contested through reactions to the Murray–Darling Basin Plan at the time of writing.


Collecting bush tucker, Kakadu wetlands Northern Territory. © Skyscans.

Indigenous values

Indigenous Australians attach deep spiritual significance to water ecosystems. They believe water to be a sacred and elemental source and symbol of life, which has sustained watershed communities for thousands of years, and governed Indigenous peoples' relationships to each other and country.[18,19]

Indigenous perspectives and values relating to water are not widely understood and have been neglected in water use decisions and water management. There is now more attention being given to Indigenous beliefs, interests, and common-law rights under Native Title. National water policy now recognises the need to include Indigenous people in all activities relating to water planning and management.[20] Indigenous groups have identified water management as one of the most pressing environmental problems they face, alongside climate change. The diversity across Indigenous communities throughout Australia is likely reflected in a diversity of views and opinions about water use and management. Indigenous people express a strong desire to be involved in land and water management in order to fulfil customary obligations to care for their country.

Water is also of value to contemporary Indigenous livelihoods. Indigenous people have rights under the common law to access cultural water sites and to maintain customary use and access of places and the plants and animals that depend on water. Many Indigenous people and communities rely heavily on aquatic resources to supplement their household incomes. Some Indigenous landowners and corporate organisations also have water entitlements and wish to develop water-based enterprises. Indigenous organisations have argued that their people have a right to benefit from the economic use of water and the development of water resources. Greater access to economic opportunities from water could improve the socio-economic position of Indigenous people.

Water policy reform, ratified by the Commonwealth, states and territories in the National Water Initiative, has started to enable some dimensions of Indigenous water values to be recognised,[21] but progress towards including Indigenous values in water planning remains slow.[22]

Resolving conflicts in values

Competing values for water and increasing demands on a fixed resource often result in conflicts over access to water, and trade-offs or compromises between different groups are inevitable. The over-arching challenge of sustainable water use, for example, is to balance the consumption of water with the intrinsic and economic values of maintaining water environments in good condition. The resolution of conflicting values for water in Australia is being achieved through a combination of regulation, planning, and markets.

The increased recognition of the economic importance of water has led to a recent trend towards using market mechanisms to resolve competing uses, particularly in rural areas. Entitlements to access water have been formalised and separated from land titles and can now be bought and sold, as can the annual allocations of water for those entitlements (see Chapter 8). In 2007–08, over 1500 GL of water was traded in the Murray–Darling Basin, mitigating the economic losses as a result of low allocations in that drought year.[23] Water markets are imperfect, because regulations exclude some users (such as the limits on trade from some irrigation districts discussed in Chapter 8), but there are opportunities for further innovations. One example might be to enable irrigators to manage their own reliability of supply by purchasing ongoing storage in a reservoir rather than being given an annual allocation of water. Carry-over rights are a form of this access to storage and are implemented in some systems.

For markets to work well, the price of water should include all costs. Although the price of water has increased to reflect true costs, capital costs are sometimes subsidised by governments and costs to the environment are not always included. In some areas, the price of water has been disaggregated to reflect different aspects of cost, including storage in reservoirs, costs of supply infrastructure, and costs of managing the provision of water. Treating water as an economic commodity is not acceptable in many societies, because it is not always considered ethical to charge people the full cost for an essential and natural resource such as water. The price of water, though, is typically for the provision of services such as safe, reliable, piped water. Bottled water, which is of high quality, refrigerated, and is widely available in a convenient container is priced at a few dollars per litre. Potable and reliably supplied domestic water, piped to your home, is priced at a few dollars per thousand litres, whereas irrigation water, provided in larger quantities and of variable quality and reliability, costs much less than a dollar per thousand litres. In an open market, therefore, the price of water reflects the balance of supply and demand for the service, and its perceived value, not just its cost.

Water plans and regulations are used to ensure that licensed users have equitable and reliable access to water and to ensure protection of water environments. For example, an interim cap on diversions in the Murray–Darling Basin was introduced in 1995 to ensure the reliability of existing entitlements and to halt further ecological degradation of river, wetlands, and floodplains. The limits on use of water in the Murray–Darling Basin are being revised now, through the Murray–Darling Basin Plan, to restore and protect ecosystems.

There is now much more knowledge being generated to better inform water plans. The water requirements of ecosystems are increasingly well understood and can be applied to set limits to use that protect ecosystem values (see Chapter 9). There are also several techniques to include non-market values of water and users of water who do not have entitlements, such as cultural uses of water by Indigenous communities and others. An important first step is to catalogue these broader sets of values, such as poorly appreciated Indigenous water uses, and incorporate them into decision making, and this is a current area of research.

The trade-offs between different levels of water use can be shown in a cost–benefit analysis, where all costs and benefits can be expressed in monetary terms. This can reveal whether a community's overall welfare will be improved as a result of a particular water project or policy decision. Ecosystem services can be included in a cost–benefit analysis to broaden its scope, which is another active area of international research. Where there are non-monetary values, multi-criteria analysis can used to include different social, cultural, and environmental aspirations. Each aspiration is weighted in importance and prospective water plans are scored as to how well they meet these aspirations.

Despite the rapidly improving knowledge and techniques used to value water, they are yet to be fully incorporated in water plans. The National Water Commission observes that many plans still lack any transparent consideration of community values or the needs of the environment and trade-offs between values are rarely shown or used in community consultation.[21] Recent public criticism of the lack of transparency and consultation in the proposed Murray–Darling Basin Plan is a stark example.

A benefit of showing trade-offs between competing values is that it can drive innovation towards finding solutions where both human and environmental benefits are increased. This might be achieved by changing the timing of water use or the way water is supplied down a river. This raises the prospect of optimising the planning and operation of water resources to meet multiple values: an area of research that is growing as the potential cost of conflicts over water use increases. As demand for water grows, the best solution for communities might be to look for more efficient and equitable ways of meeting their needs.

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Water and climate

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Key messages

- Floods, droughts, and climate change are the three most important influences of climate on Australia's water resources.
- Water resources are vulnerable to both climate variability and change; for example, runoff into Perth's reservoirs has declined by 55% since the 1970s and the 1997 to 2009 drought resulted in unprecedented decline in runoff and water use in the southern Murray–Darling Basin.
- Climate change has played a part in recent reductions in rainfall and water resources, however its specific contribution is difficult to quantify.
- Climate change by 2030 is likely to reduce average river flows by 10% to 25% in some regions of southern Australia but further climate change could produce even more profound reductions of water resources in southern Australia.
- The relationships between climate and runoff are now being used to provide more accurate seasonal forecasts of water resources useful for irrigators, dam operators, and environmental managers.

Weather and climate are the primary influences on Australia's water resources. Extreme storms and cyclones produce floods that can rise and fall within hours or that can last for months, while yearly variability in rainfall can produce droughts that may last for a decade or longer. Longer-term climate change increases or decreases average rainfall and evaporation, fundamentally changing the amount of water resources available. This chapter describes the influences of climatic events, variability, and change on water resources through their influence on floods, droughts, and water resources.

'Weather' is the brief, rapidly changing daily and seasonal conditions in the atmosphere, while 'climate' is the average weather experienced over years to decades. 'Climate variability' is the year to year and decade to decade noise or variability around the average climate, while 'climate change' is the longer term change in average conditions over several decades to centuries. The noise of weather and climate variability can occur around a changing average climate, making it difficult to detect long-term trends, especially for rainfall, which, in Australia, is highly variable from year to year.

Yearly variations in rainfall, or changes between centuries are amplified as even greater changes to runoff and river flows, making impacts on water resources one of the greatest concerns about climate change. Annual variations in rainfall are typically amplified as two- to three-times larger variations to annual runoff. So a 10% reduction in rainfall typically leads to a 20 to 30% reduction in runoff.[1] This amplification applies to climate change as well, so small reductions in average rainfall as a result of climate change will lead to two- to three-times larger reductions in water resources.

Weather and climate drivers

Floods, drought, and climate change are all driven by a number of processes in the atmosphere and oceans (Figure 3.1), but the changes are driven at different timescales. The drivers shown in Figure 3.1 interact with each other and influence different parts of the continent to bring local weather and climate. The drivers include circulation patterns in the Pacific Ocean that bring El Niño conditions associated with drought in eastern Australia and La Niña conditions that are associated with floods. The Indian Ocean Dipole is a similar pattern in the Indian Ocean that can bring drought to south-west and south-east Australia, and the Southern Annular Mode is a

Figure 3.1: The major influences on rainfall (and thus runoff) in Australia.[2] (Reproduced with permission from Australian Bureau of Meteorology. © Commonwealth of Australia.)

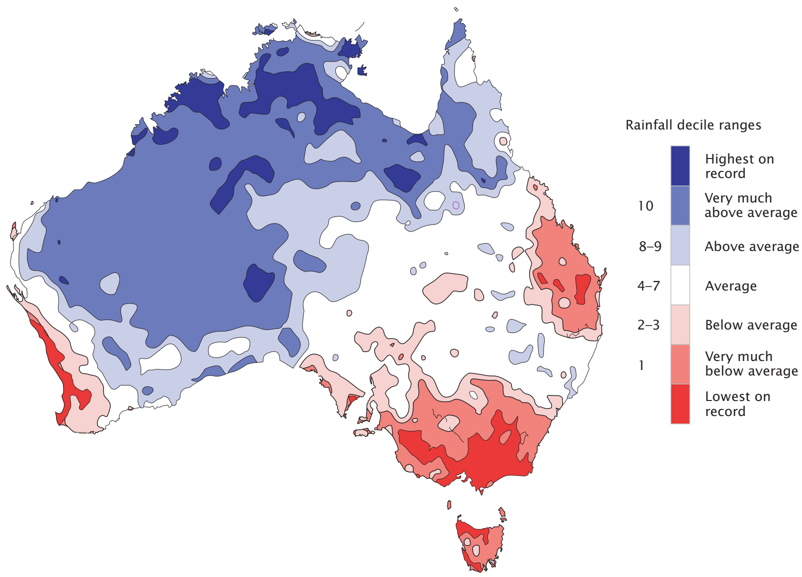


Figure 3.2: Rainfall conditions across Australia from 1 January 1997 to 31 December 2009 relative to the 1900–2009 climate, showing the extreme dry conditions across the south-east, the far south-west of Australia, and south-east Queensland.[3]

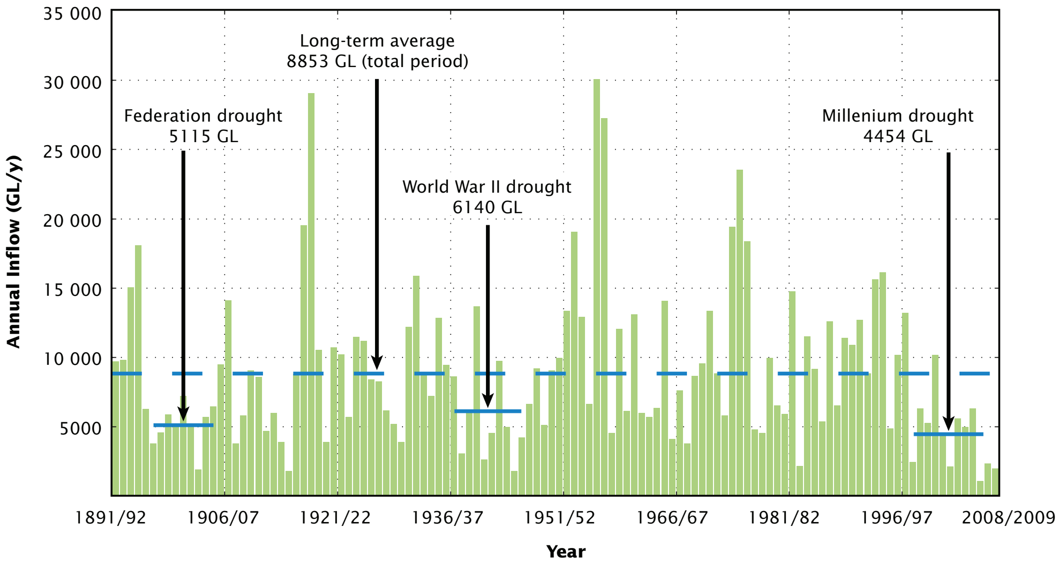
feature of the Southern Ocean that affects weather and climate in southern Australia. Atmospheric patterns such as the monsoon winds and southern ocean frontal systems bring rain, whereas southerly tracks of blocking highs and the subtropical ridge tend to bring dry weather.

Recent drought in southern Australia

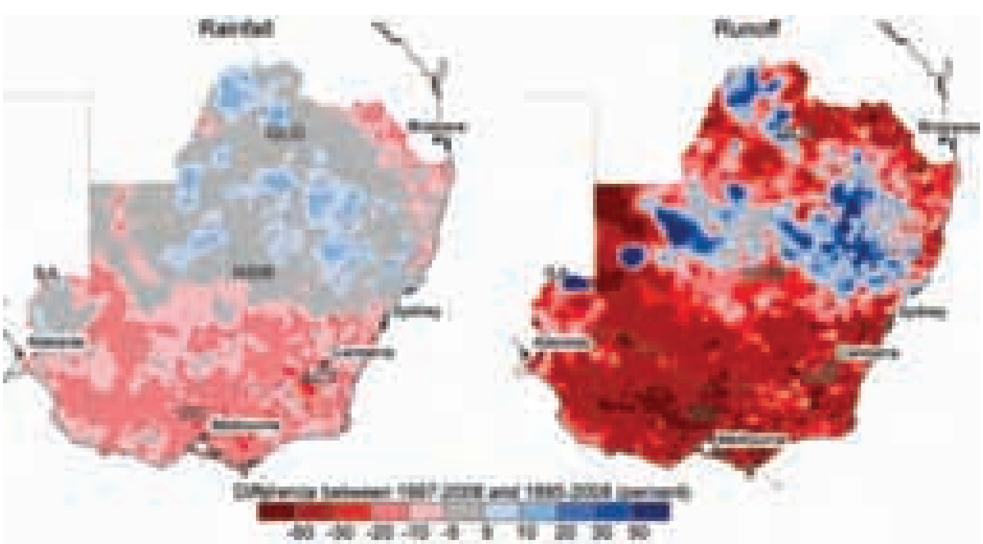
From 1997 to 2009, large areas of southern Australia, in particular the southern Murray–Darling Basin, Victoria, south-west Australia, and South East Queensland experienced prolonged drought, often referred to as the millennium drought (Figure 3.2, Figure 3.3).

The millennium drought in the southern Murray–Darling Basin was unprecedented in the 110 years of reliable rainfall records.[4] It resulted in declining storage levels in reservoirs, several years of severe water restrictions in cities, and years of low water allocations to irrigators in the southern Murray–Darling Basin and elsewhere in Victoria. Water sharing arrangements for the Murray, Murrumbidgee, and Lachlan Rivers were suspended because they were not designed for such extreme conditions.

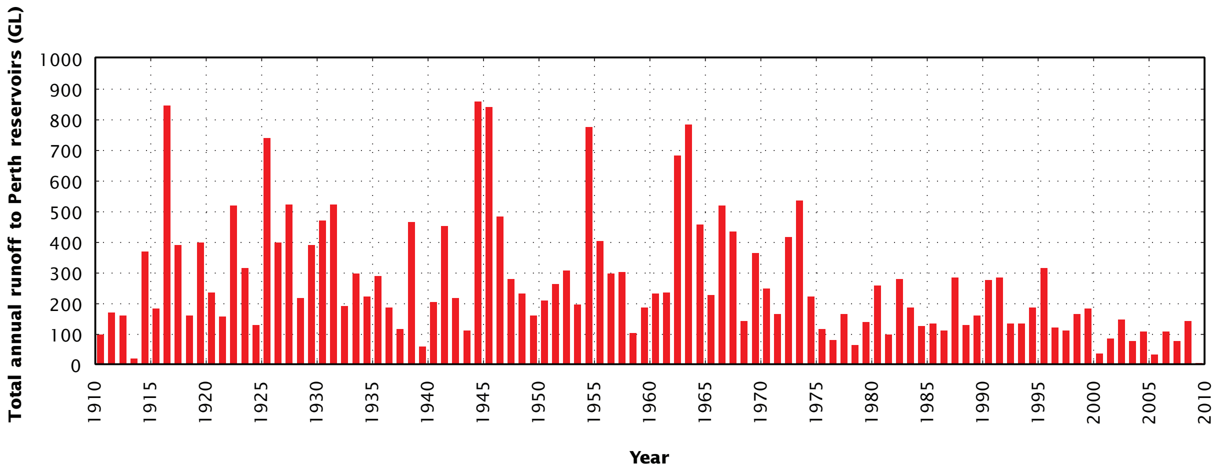
The drought had major environmental impacts.[5] For example, the Lower Lakes of the Murray River fell more than 1 m below previously record low levels, exposing potentially toxic acidic sediments and increasing salinity in the lakes. Across the Murray–Darling Basin, there was either extensive death or stress to river red gums on floodplains, and low river flows led to the isolation of fish communities and a decline in fish breeding. Water use for irrigation fell by 64%[6] and it was the first time that drought had caused a major fall in use for an extended period (see Chapter 8). Most of Australia's water use is in southern Australia, so the drought had a substantial economic, environmental, and social impact.



▲ ***Figure 3.3**: Annual total inflows into the Murray River showing the high year to year and decade to decade variability and the low inflows from 1997 to 2009 and during earlier droughts. (Data provided by the Murray–Darling Basin Authority.)*



▲ ***Figure 3.4**: Percentage difference between recent (1997–2008) rainfall and runoff in south-eastern Australia and the long-term (1895–2008) averages.[8] Although rainfall in Victoria and southern NSW was only 10–30% below average, runoff was 30–60% below average.*

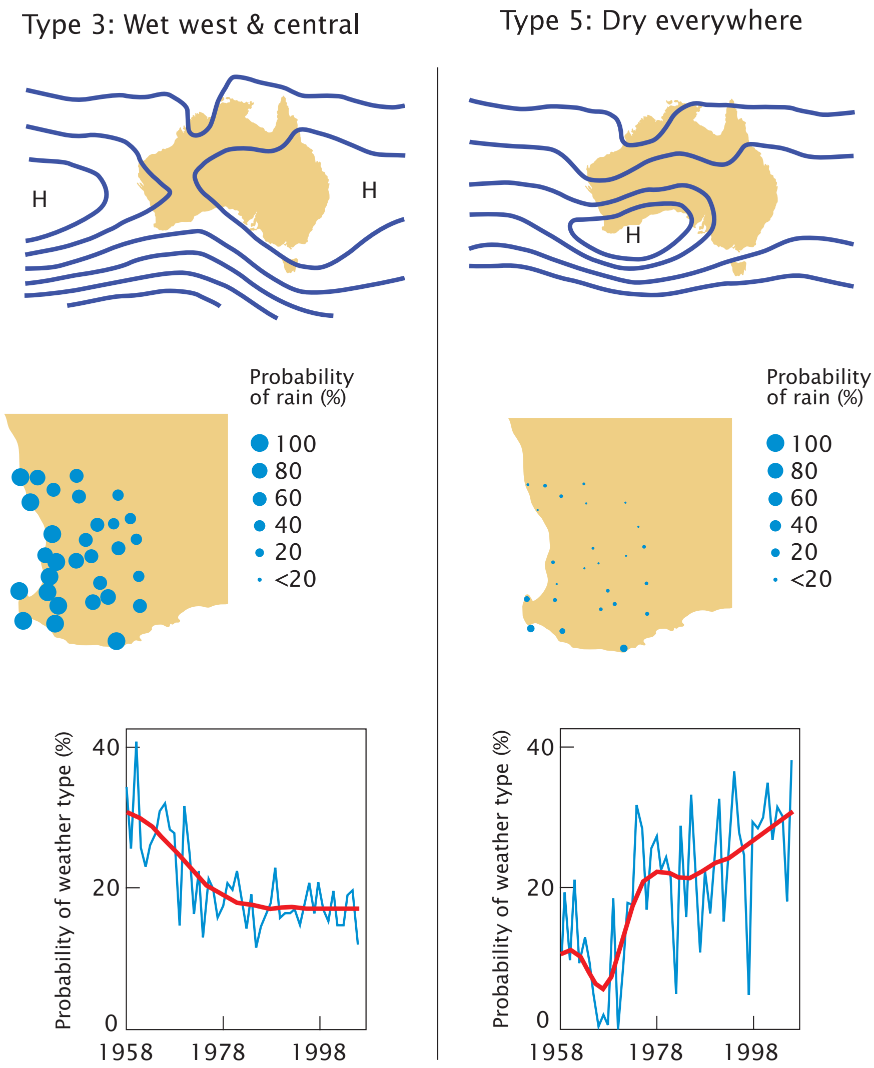


▲ ***Figure 3.5****: Annual series of runoff into Perth reservoirs showing a persistent decline in inflows since the mid-1970s.*[10]

There had been earlier multi-year droughts in the southern Murray–Darling Basin such as the Federation drought of 1895 to 1903 and the depression drought of the late 1930s and early 1940s (Figure 3.3), but none were as severe in terms of reduced runoff as the millennium drought. In places, runoff was less than half of the long-term average, even though average rainfall had decreased by less than 20% (Figure 3.4).[7] The amplification of change from rainfall to runoff was greater than expected from previous droughts. Possible reasons include: a disproportionate rainfall decline in autumn resulting in dry soil at the start of the runoff season; rainfall decline in winter when most of the runoff occurs; the lack of any high rainfall years, which produce disproportionately high runoff; and higher temperatures driving greater evaporation.[3]

In the South West region of Western Australia, the very low rainfall from 1997 to 2009 has been part of a longer 35-year trend of gradually declining rainfall.[9] The average runoff to Perth reservoirs was 338 GL/year before 1975 but from 1975 to 2009 it was only 181 GL/year, or 55% lower than before, as a result of a 16% fall in average annual rainfall (Figure 3.5). The higher runoff years are now nowhere near as high as previously (i.e. since 1975, no annual runoff to Perth reservoirs was above the pre-1975 average). This persistently low runoff led the Western Australian Government to secure additional water supplies for Perth, leading to a greater reliance on groundwater and the opening of Australia's first desalination plant for supply of water to major city (see Chapter 7). Whether the change since the 1970s is a result of global warming or whether it reflects long-term natural variation in climate is discussed below.

The decline in rainfall around Perth has been attributed to changes in weather patterns across south-west Australia (Figure 3.6). Since the 1970s, high pressure systems and associated cold fronts have moved south bringing less rainfall than their previous more northerly track across southern Australia.[11] These changes most strongly affect autumn and winter rainfall and are the same sort of changes predicted to intensify with increasing global temperatures in future.



▲ ***Figure 3.6***: *The relationship between two weather patterns and winter rainfall in the South West of Western Australia, showing the changed frequency of the weather patterns as an explanation for why rainfall has declined in the region since the 1970s. In Type 3 weather, high pressure systems and the subtropical ridge occur over the centre of Australia. This weather produces rain over south-west Australia as shown by the blue circles. During Type 5 weather, the high pressure systems occur further south and produce weather that brings very little rainfall to the region. The graphs at the bottom show that since the 1970s the frequency of Type 3 weather has declined and Type 5 weather has increased, explaining the decline in rainfall since that time.*

Floods

At the opposite end of the range of climate variability are floods such as those experienced in 2010 and 2011 across eastern Australia. These were associated with one of the strongest La Niña events on record, the opposite to the El Niño conditions that were associated with drought. During La Niña conditions, the eastern Pacific Ocean is unusually cool as a result of upwelling of deep ocean water, strengthening the easterly trade winds coming to Australia from the western Pacific Ocean. This brings warm moist air over eastern Australia, causing widespread above-average rainfall.

Floods are the most costly natural disaster in Australia. The average direct annual cost of flooding between 1967 and 1999 has been estimated at $314 million.[12] Costs vary widely between flood events (depending on flood volumes and infrastructure affected); for example, the Brisbane floods of 1974 caused $700 million damage at that time, while the damage from the 2011 floods is likely to be in the vicinity of $10 billion in current value. Moderate floods also have several benefits – they infill reservoirs, recharge groundwater, and replenish natural environments (see Chapter 9). These benefits can accrue for several years after the flood has subsided.

The Bureau of Meteorology issues flood warnings based on continuous monitoring and reporting of rainfall and river levels, rainfall forecasts, and hydrological modelling. Floods on small rivers generally have warning periods lasting from several hours to a couple of days. Large regional floods on lowland rivers occur with warning periods of days or weeks as they flow gradually downstream from runoff that is generated in tributaries. The most unpredictable form of flooding is local flash flooding in creeks and small rivers. This type of flooding is caused by locally intense storms that can cause a creek to rise to a major torrent in less than an hour. Flooding in Toowoomba and the Lockyer Valley in January 2011 were examples of flash flooding with tragic consequences.

Statistical analysis of historical floods shows that decades of higher than average rainfall, such as the 1950s to 1970s, can have higher magnitude floods than under average climatic conditions. A flood expected once every 100 years or so on average can be twice as large in these wetter decades than in drier decades.[13] The same could happen with global warming. The warmer ocean temperatures will produce stronger convection and the ability of the air to hold more moisture, which could increase the intensity of storms and cyclones.[14] Climate modelling also shows that extreme rainfall events such as cyclones are likely to be more intense in future, although less frequent,[15] resulting in bigger floods and greater costs from flooding.

Many large dams, such as the Wivenhoe Dam in Brisbane, are managed to store water supplies and to retain some empty storage capacity to absorb and mitigate floodwaters, protecting downstream communities. These two functions may appear in conflict but the level of water to be stored is determined well in advance. Better seasonal forecasts of inflows (see below) offer the prospect of increasing the flood storage volume in dams when the forecasts predict a high probability of flooding.

Brisbane floods, January 2011. Photo: Glenn Walker.

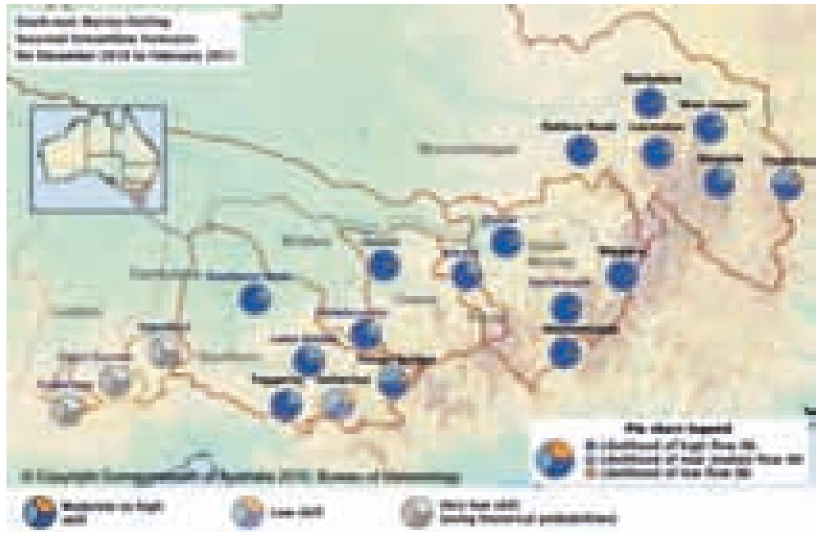
Short-term and seasonal forecasting of river flow

A paradox of Australia's highly variable rainfall and runoff is that it can be predicted several months in advance from the signals of global circulation such as El Niño and La Niña and other indicators. River flows can be forecast several months or seasons ahead using information on the soil moisture in the catchment, and the state of the ocean and atmosphere (e.g. droughts in eastern Australia are often linked to El Niño events in the equatorial Pacific Ocean).[16] Seasonal rainfall and runoff forecasts can help irrigators plan, support trade of water, and make water use more efficient, and help decide when to release water from reservoirs.

The Bureau of Meteorology has been issuing seasonal weather outlooks since the 1990s, and in 2010 it launched a new service on seasonal river flow forecasting.[17] This forecasting system is based on models developed by CSIRO[18] that give probabilistic forecasts of river flow several months ahead, in particular flows to major water storages (e.g. Hume and Dartmouth Dams in the upper Murray; Figure 3.7).

The Bureau of Meteorology is also responsible for issuing flood warnings and is planning to extend its current flood warning service to forecast river flows continuously up to 10 days ahead. The Bureau of Meteorology and CSIRO are jointly developing and testing a modelling system for this purpose combining hydrological and weather prediction models that use real-time data from climate stations, river flow gauging sites, and satellite data.

▸ ***Figure 3.7****: Seasonal forecast of runoff into the upper catchments of the Murrumbidgee and Murray Rivers issued in December 2010 for the 3-month period from December 2010 to February 2011.[19] Dark blue indicates the probability of markedly above average runoff; light blue indicates the probability of average runoff, and orange indicates the probability of markedly below average runoff. The prediction was for high flow across the region as a result of wet catchment conditions and the forecast for continuing La Niña conditions. High flows did persist through the summer.*



Impacts of climate change on river flows

Global temperatures of both the atmosphere and the oceans have been rising since the 1950s, and rising more rapidly than has been recorded in the geological past.[20] Many studies have linked most of the global warming to increasing greenhouse gas emissions.[20,21] There is less certainty whether human-induced increases in temperature are the cause of the decline in rainfall in south-west Australia since the 1970s and the historically unprecedented conditions of the recent millennium drought in south-east Australia. This is because the huge natural variability (or noise) in rainfall from year to year makes it difficult to detect an overall trend. Rainfall is also controlled by regional weather and climate patterns (Figure 3.1), which have a complex relationship with global temperatures.

Climate modelling indicates that the persistent dry conditions in the far south-west and the millennium drought in south-east of Australia are at least in part a result of climate change.[3,11,22] The dry conditions are associated with the shift of storm tracks towards the southern ocean. Climate models indicate that such changes are likely to intensify and become more persistent in future, so the dry conditions experienced are consistent with the trajectories of future climate for those regions.

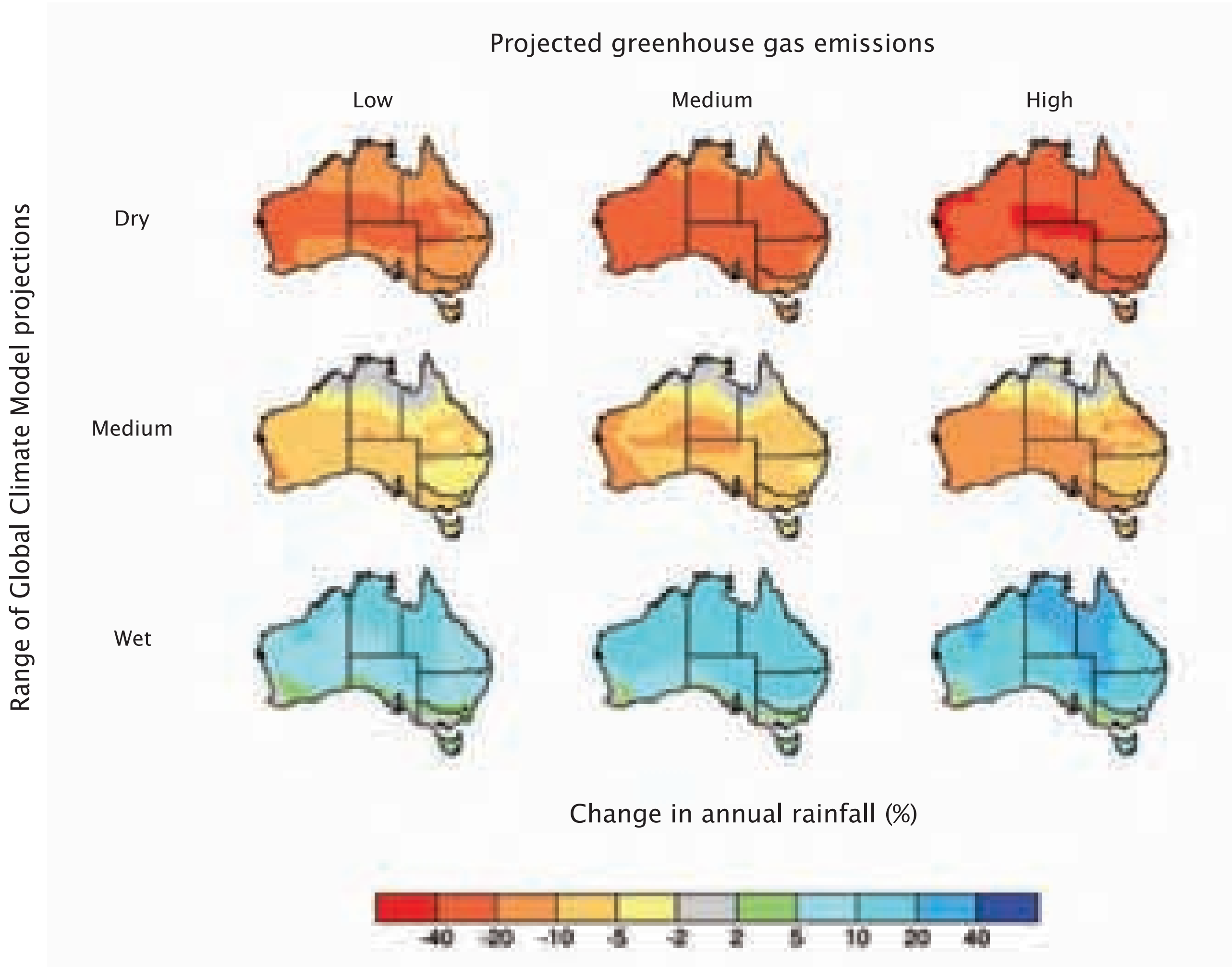
Extended droughts and decades of wetter conditions are also a natural feature of southern Australia's climate. With only a little over a century of measurements, it is hard to establish patterns that span several decades so proxy records from tree rings, corals, and caves are used to describe longer term climate patterns. These proxies are correlated for recent times with the historical measurements of the oceans and atmosphere and then used to extend those records further back in time. At shorter time scales, we know that El Niño and La Niña influence rainfall and runoff [23] and now additional longer decade cycles are being found of increased frequency of El Niño events followed by decades of increased frequency of La Niña events. Decades of high frequency of El Niño events are associated with extended periods of drier-than-average conditions in eastern Australia, such as in the last few decades, and vice versa for wetter than average conditions, such as in the 1950s and 1970s.[24]

It is possible that the millennium drought was a combination of natural variability and climate change and it is only through continued observations in coming years that any long-term trend in rainfall can be confirmed or not, and then, if the connection is evident, be attributed unequivocally to human-induced climate change. Regardless of the cause, though, a decade or more of drier conditions is enough to put water users, including ecosystems, under considerable stress and has tested whether water management is well adapted to such harsh conditions.

Predicting climate change impact on river flows involves three main components. Firstly, global climate models are used to project future climate change. Secondly, the results from these global climate models are 'downscaled' to the region of interest and its weather patterns, and finally, these regional weather patterns are used to run hydrological models to predict future river flows. Global climate models simulate complex global and regional climate systems. The Bureau of Meteorology and CSIRO have combined climate process understanding with global climate model simulations from the Intergovernmental Panel on Climate Change (IPCC)[20] to provide climate projections for Australia.[25] Figure 3.8 is an example of the range of projected changes in average annual rainfall by 2070 relative to 20th century rainfall.

There is a considerable difference in the projected rainfall in each of the maps in Figure 3.8. This is because of two key uncertainties about future climate. The first is the future level of greenhouse gas emissions, which will be determined by future industrial development and mitigation of emissions. The world is currently tracking toward the high end of emissions shown on the right hand column of Figure 3.8. The second uncertainty is how future rainfall in Australia will respond to changes in global temperature. Future rainfall is predicted from global climate models, through changes to conditions in the atmosphere and ocean, such as those shown in Figure 3.1. Figure 3.8 shows the range in projections from the various global climate models used by the IPCC.

Most climate models indicate that southern Australia, where most water is consumed, is on average likely to be drier in the future. The model projections are consistent with the patterns observed during the last decade or so, with a shift of autumn and winter storm tracks towards the South Pole. In northern Australia, the direction of change in average rainfall is uncertain, with as many models predicting a wetter future as a drier future.



▲ ***Figure 3.8***: *Projections for percentage change in average annual rainfall in Australia by 2070 relative to 20th century rainfall. Nine projections are shown. The columns of maps show projections for low, medium, and high future greenhouse gas emissions, showing the effects of different amounts of global warming. The rows of maps show the range of projections from different global climate models. The top row shows the drier model results, the middle row is the mid-range of results and the bottom row shows the wetter projections of average annual rainfall from the models.*[26]

Global climate models produce results at a very coarse spatial resolution. Victoria is typically represented by less than five grid cells in a global climate model and Tasmania is equivalent in area to a single grid cell. Although driven by global circulation patterns, rainfall and river flows are regional phenomena influenced by local topography, proximity to the coast, and local weather patterns. For regional and catchment hydrological modelling, the global climate model simulations need to be scaled down to catchment-scale rainfall and other climate variables.[27]

Dynamic downscaling models are fine-scale climate models nested inside the coarse-scale global climate models. They are able to represent fine-scale topography, vegetation, and weather patterns to produce more detailed patterns of rainfall and other climate variables. Figure 3.9 shows a dynamic downscaling example used for hydrological modelling in the CSIRO Tasmania Sustainable Yields project.

Statistical downscaling models statistically relate regional patterns of rainfall and other climate variables to its large-scale drivers in the atmosphere or oceans. Statistical relationships are built between regional rainfall observations and the larger scale properties of the atmosphere. These are then used to predict future regional rainfall under the changed atmospheric conditions of human-induced climate change. Figure 3.6 is an example of statistical downscaling, showing how rainfall across south-west Australia is related to larger scale patterns of atmospheric circulation.

The results from climate downscaling are used to run hydrological models to predict future catchment runoff and river flows.[29,30] Changes to the average annual runoff (and hence river flow) for a 1ºC global warming (median warming by 2030 relative to 1990) across Australia have been modelled (Figure 3.10, Table 3.1). The considerable range in runoff projections is mainly because of uncertainty of future rainfall under a changed climate. In the far south-west and south-east, a large majority of the climate models project a drier future and this translates to runoff declines of 25% in the south-west and 10% in southern Murray–Darling Basin and Victoria for a 1ºC global warming in the median projection. The hydrological models also simulate changes to other flow characteristics, such as the variability of reservoir inflows and floods and low flows. The low flows and loss of connectivity in the more frequent long dry periods in the future will affect aquatic ecosystems[5] and may exacerbate water quality problems. Larger changes than those shown are predicted to occur beyond 2030 as climate change continues (Figure 3.11); for example, if there is 2ºC or more of global warming, which now seems highly likely.[20,21]

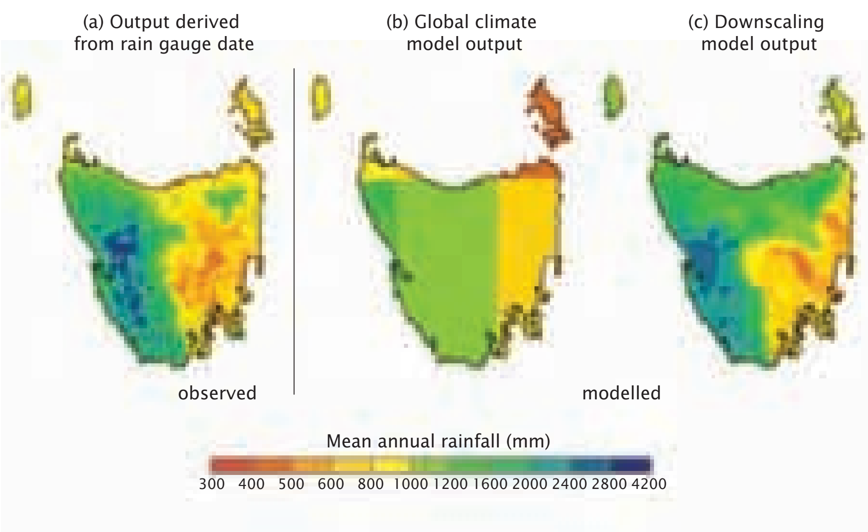
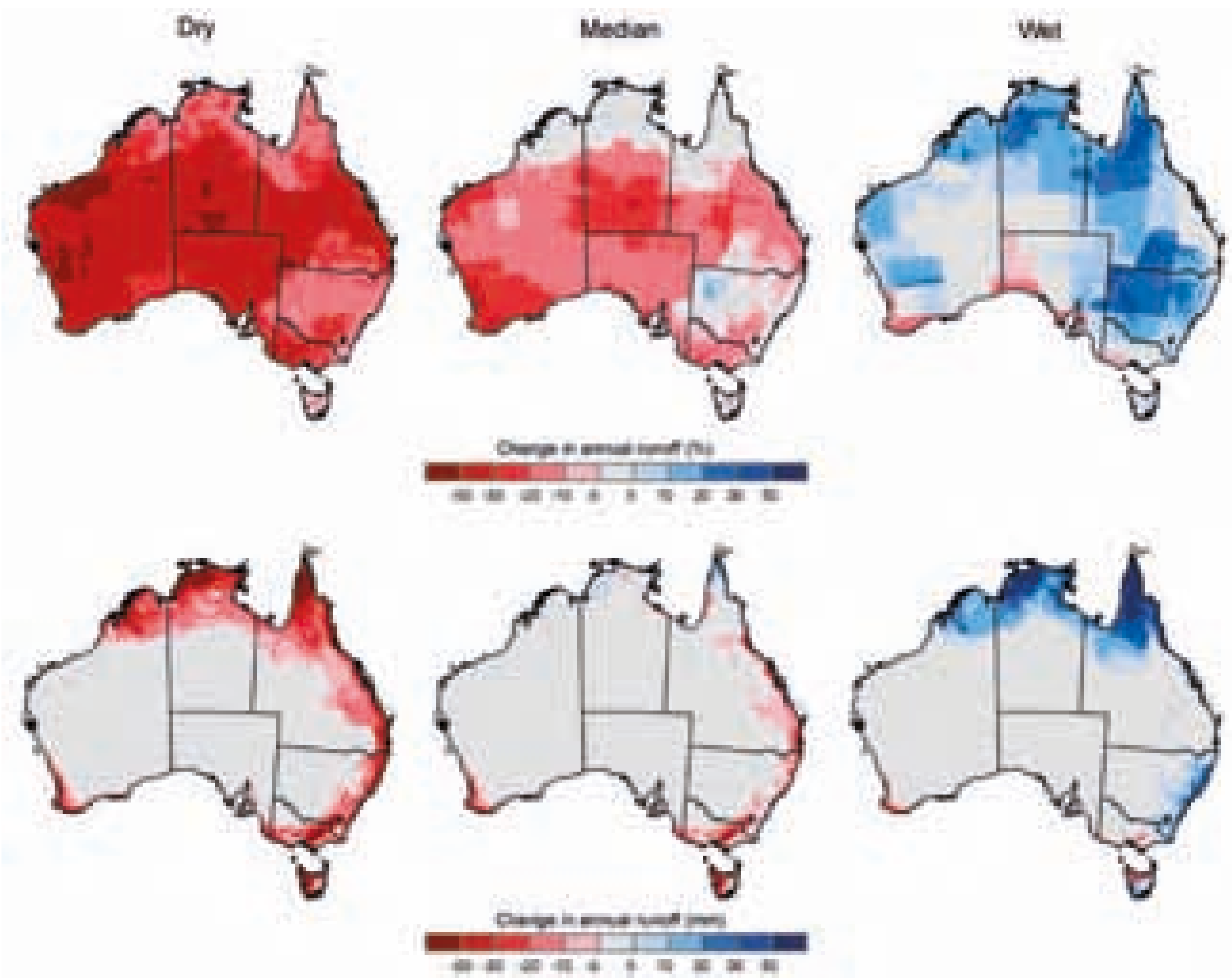


***Figure 3.9**: An example of the need to downscale rainfall from global climate models. (a) The observed patterns of rainfall across Tasmania. (b) A global climate model prediction of rainfall that portrays only the coarsest patterns. (c) Rainfall downscaled from the global climate model using a regional climate model that represents the topography and other influences on regional rainfall, producing patterns similar to those observed across Tasmania.[28]*



▲ ***Figure 3.10***: *Change in average annual runoff for 1ºC of global warming (~2030 relative to ~1990) across Australia. The top row shows percentage change in runoff and the bottom row shows change in runoff depth (mm). The median, dry and wet extremes of the range of climate projections are shown.*[28,29,31,32]

Table 3.1: Projected changes to average annual runoff for a 1ºC global warming from Figure 3.10.

Region	Modelled changes in average annual runoff (%)		
	Dry extreme	Median projection	Wet extreme
North-east Australia	–15	–1	+20
North-west Australia	–18	0	+16
South West of Western Australia	–37	–25	–12
Tasmania	–6	–3	0
Northern Murray–Darling Basin	–15	–5	+12
Southern Murray–Darling Basin and Victoria	–20	–10	+1

Although climate change is likely to reduce average rainfall and runoff in southern Australia, the climate will still be experienced largely as floods and droughts. The interactions between climate change, floods, and droughts are illustrated in Figure 3.11 for the southern Murray–Darling Basin and Victoria. A useful indicator for the use of water resources is the 10-year average of runoff. Large dams are able to buffer water supplies against the year to year variations in runoff and provide reliable supplies. However, they are unable to maintain supplies if there is a long drought with low runoff, as was seen in the millennium drought. Similarly, ecosystems have evolved to cope with floods and droughts, but a decade of drought in addition to other pressures can place them under stress.

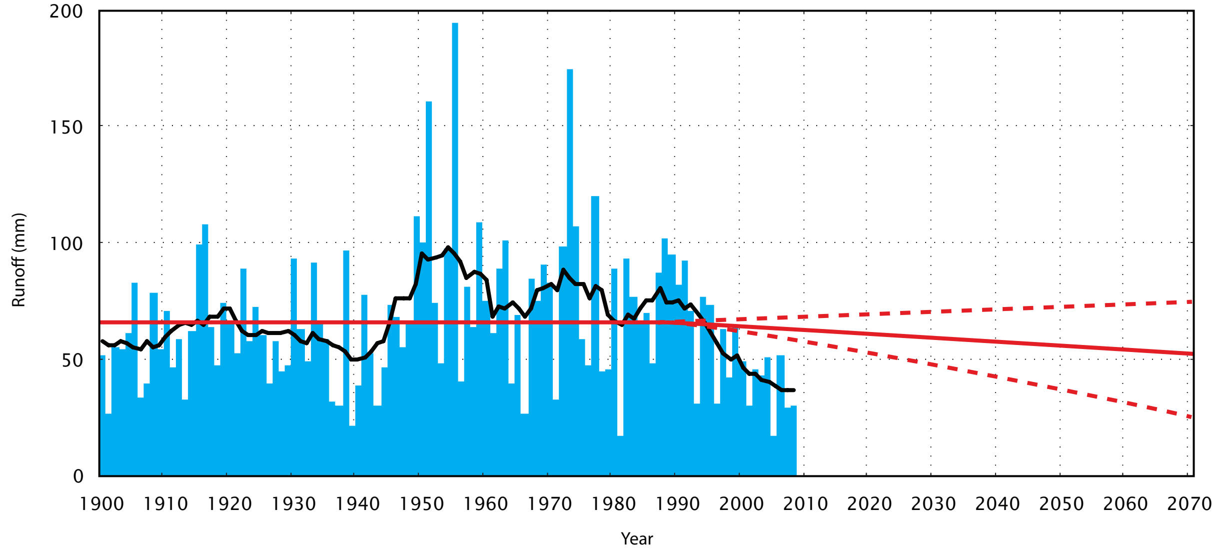
Figure 3.11 shows that the impact of climate change on runoff by 2030 is small relative to the year to year and decadal variability in runoff, where flood years can have 10 times the runoff of drought years. The climate in 2030 will still be one that produces floods and droughts, but with a lower average annual runoff: the droughts may be more intense and the floods less frequent. Projecting out to 2050 and 2070, more profound changes to average runoff are possible, with the prospect that the average runoff could be similar to that experienced in the decade of the millennium drought. Floods and droughts would still be superimposed on that, giving periods of very severe droughts in future. The experience of the millennium drought suggest that such a large reduction in average runoff and more severe droughts on top of that would have severe impacts on water use and on river ecosystems.

Water management and planning in a changing climate

As well as reducing runoff, a warmer climate could increase potential evaporation and hence increase the demand for water in irrigated agriculture, cities, and for use by wetlands and other water-dependent ecosystems. Evaporation though, like runoff, has a complex relationship with global warming and is influenced by other factors such as wind speeds and cloud cover. Thus climate change could not only reduce water availability in these regions but could further increase the gap between water supply and demand. Essentially, climate change intensifies the water scarcity challenge facing cities and rural catchments and intensifies the challenge of achieving environmentally sustainable levels of usage.

Water managers and policy makers in Australia are developing and updating plans to cope with a variable and changing water future. Most capital cities are investing in additional water supply infrastructure to meet the needs of growing populations. Some cities are moving away from their traditional reliance on catchment runoff and groundwater, because these sources are most sensitive to climate change and drought. Instead they are diversifying by investing in desalination plants and water reuse. Water demand per capita is reducing as a result of water use efficiencies, water-sensitive urban design, and water conservation by communities (see Chapter 6). In rural areas, the increased use of water markets, improvements in irrigation efficiency (see Chapter 8), and return of water to degraded ecosystems (see Chapter 9) are all improvements in water management that will also make water management more adaptable to climate change and variability.

It should not be assumed that under conditions of climate change all users of water, including the environment, will bear the reductions in runoff equally. In the highly managed rivers of the Murray–Darling Basin, and city water supplies, flows in the river are largely determined by the operation of dams in accordance with water plans. These river operations and plans are designed to provide reliable supplies, buffering users against a drop in runoff during dry years and storing more water during wet years to compensate. The plans also tend to pass on impacts of reduced flows to regions downstream. They were not designed to deal with long-term reductions in runoff due to climate change. Under the plans, long-term reductions in runoff would be largely borne by the environment and downstream regions.[33] In the Murrumbidgee River system, the median climate projection for 2030 predicts a 9% reduction in runoff, which under the existing water sharing plan would reduce water supply to irrigation districts by only 2%, whereas outflows to the Murray River would reduce by 17% and water for the major wetlands would reduce by over 30%. New arrangements would be needed to share the impacts of climate change more evenly while still providing reliable supplies to water users.



▲ ***Figure 3.11***: *Annual runoff across the southern Murray–Darling Basin and Victoria (blue bars) and the moving average of the previous 10 years runoff (black line) showing large year to year and decade to decade variability in runoff. The long-term average runoff from 1895 to 2008 (red line), is projected forward using the median climate change projection for mean annual runoff (1990 to 2070). The two dashed lines are the dry and wet extremes of projected average runoff under climate change.*[33] *By 2030 the change in average annual runoff is small compared to the variability in runoff, but by 2070 the average runoff could be as low as that experienced in some of the worst historical droughts.*

Dried-out lagoon on old station property at Big Bend, South Australia. Photo: Greg Rinder, CSIRO.

Advances in climate and hydrological sciences and modelling tools can be used to guide water management and planning in a changing climate. The predictions of future water availability are improving as more data become available and the science progresses, but the range of possible future runoff is likely to remain large. Water plans at present are almost exclusively based upon historical rainfall, runoff, and groundwater recharge measurements[34] because these data provide some confidence for assessing water resources and they encompass a range of historical conditions. However, the prospect of climate change and the experience of the millennium drought suggest that relying on history alone is insufficient. Formal risk management techniques can incorporate several future scenarios and the high uncertainties associated with them. These approaches can show how impacts from climate change would be shared among users and give certainty over how plans will be adapted to deal with new conditions if they emerge. Water planning can be made more effective by ongoing research to better understand climate, its relationship to water resources, and consequent impacts on water users and ecosystems.

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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