CLIMATE COUNCIL

DELUGE AND DROUGHT: AUSTRALIA'S WATER SECURITY IN A CHANGING CLIMATE

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Published by the Climate Council of Australia Limited

ISBN: 978-1-925573-81-7 (print)
978-1-925573-80-0 (digital)

Deluge and Drought: Australia's Water Security in a Changing Climate.

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Preface

Water is essential for life. It shapes where and how we live, determines the availability of food and other services that underpin human wellbeing and is crucial for healthy natural ecosystems. Yet in Australia and globally the water cycle has been significantly influenced by climate change, leading to more extreme droughts and floods.

The southeast of the continent and the southwest corner of Western Australia have experienced a pronounced cool-season drying trend over the past few decades, with serious consequences for agricultural heartlands such as Western Australia's wheatbelt and the Murray-Darling Basin. Droughts, such as the one currently gripping eastern Australia, are becoming more severe because they are occurring in hotter conditions, leading to declines in soil moisture. Prolonged droughts put serious pressure on urban water supplies, requiring water restrictions and changes to behaviour and consumption, and the need for new sources of water supply and water management frameworks.

The risks posed by the disruption of the water cycle will continue to worsen unless we phase out coal, oil and gas and deeply and rapidly reduce greenhouse gas pollution. Without action on climate change, short-term political solutions will be useless.

The focus of this report is how climate change is influencing the water cycle globally as well as here in Australia. We describe the economic importance of the Australian water sector, the changes that are already occurring because of climate change, the health implications of these changes, the water-energy nexus, and the impacts of changes in the water cycle on urban water supplies, agricultural productivity and natural ecosystems. We also examine global 'hot spots' where changes in the water cycle are already occurring, where slower, long-term changes could lead to high risks, and discuss the possible disruption of global food trade from droughts in critical regions.

We are grateful to the reviewers of the report for their frank and constructive comments: Dr Samantha Capon (Griffith University) and Associate Professor Jamie Pittock (Australian National University). Thanks also to Climate Council staff and volunteers for their assistance in the preparation of the report. Responsibility for the final content of the report remains with the authors.

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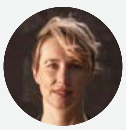

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Key Findings

1

Australia's water security has already been significantly influenced by climate change. Rainfall patterns are shifting and the severity of floods and droughts has increased.

- Droughts are becoming more severe due to drier, hotter conditions, leading to declines in soil moisture due to increased water loss from plants and soils.
- Southeast Australia has experienced a 15% decline in late autumn and early winter rainfall, and a 25% decline in average rainfall in April and May over the past two to three decades. This area includes major population centres of Brisbane, Sydney, Canberra, Melbourne and Adelaide.
- Hotter conditions and reduced rainfall have led to less runoff into streams, rivers, lakes and dams in the southwest and southeast of the continent. In southwest Western Australia, reductions in rainfall, due to climate change, have led to a more than 50 percent decline in streamflow. Across the Murray-Darling Basin, streamflows have declined by 41 percent since the mid-1990s.
- A warmer atmosphere can hold more water vapour, contributing to an increase in heavy rainfall events and an increased risk of flash flooding.

2

The severe drought being experienced across Queensland, NSW and northern Victoria is being influenced by climate change.

- The severity of the current drought is being increased by the long-term declines in rainfall and the hotter conditions associated with climate change.
- Since the mid-20th century, the severity of droughts, such as the Millennium Drought, has also been increased by climate change.

3

On-going failure to reduce greenhouse gas emissions from coal, oil and gas, globally and here in Australia, has already negatively affected Australia's water security and will increasingly affect it into the future. Profound changes to Australia's water cycle are projected, with increasing threats to our urban water supplies, the agriculture sector and natural ecosystems.

- Severe droughts are expected to become more frequent, especially across southern Australia, while extreme rainfall events are expected to become more intense everywhere except, perhaps, for the southwest corner of Western Australia.
- Across southern Australia, cool season rainfall is projected to continue decreasing and time spent in drought is projected to increase.
- Less water is likely to be available for agriculture, urban water supplies and ecosystems in coming decades across southern Australia including regions surrounding Melbourne, Adelaide and Perth.
- A 2°C rise in average global temperatures could lead to an 11–30 percent increase in extreme rain events (wettest day of the year and wettest day in 20 years) across Australia.

4

Significant impacts on and risks to our water security are already evident, and these risks will continue to escalate unless deep and rapid reductions in global greenhouse gas pollution can be achieved.

- **Health:** Severe droughts, heavy rainfall and floods all affect our health in many ways – contaminating water supplies, increasing mosquito-borne diseases such as Dengue and Ross River virus, and increasing psychological stress in rural communities.

- **Agriculture:** Drought has a significant impact on agricultural industries and communities. Severe droughts kill livestock, destroy crops and increase soil erosion, leading to higher food prices and loss of livelihoods.
- **Water supplies:** Less water is likely to flow into dams in southern Australia as a result of human-driven climate change.
- **Water infrastructure:** Water-related infrastructure, such as water supply reservoirs, dam spillways and river levees, have been designed for historic rainfall patterns. Upgrading this infrastructure to cope with increased flooding and drought, as well as building new infrastructure like desalination plants, is expensive. Over $10 billion has been spent recently on desalination plants to improve water security in our major cities.
- **Energy:** Coal, gas and hydro power stations require significant amounts of water and can be negatively affected by drought.
- **Bushfires:** Severe drought leads to higher bushfire risk as shown by the current bushfire season across the southeast of Australia. Changes in land cover due to fire can adversely affect catchment water supplies.
- **Flooding:** The economic consequences of floods and droughts are significant; the extensive Queensland floods of 2010-2011, for example, cost to the state more than $6 billion (directly).
- **Plants, animals and ecosystems:** Declining rainfall in southwest Western Australia has affected freshwater fish species. The Murray-Darling Basin has been under considerable pressure, further reductions in rainfall and runoff will make it even harder to rehabilitate degraded aquatic ecosystems, affecting bird and fish life. In 2016 warmer and drier conditions in Tasmania triggered bushfires that severely damaged over 70,000 hectares of western Tasmania's World Heritage-listed forests and alpine areas.

5

Increasing global water insecurity is becoming a 'threat multiplier', with significant implications for Australia and other regions.

- The worst drought in Syria's history, likely influenced by climate change, was a factor in triggering conflict and instability in that region, leading to a surge of refugees into Europe.
- Agricultural systems on the Indian sub-continent are vulnerable to the melting of Himalayan glaciers and instability in the Indian monsoon system, with implications for political and social stability in our region.
- The global food trade system is vulnerable to prolonged and severe droughts in major food-producing regions, such as the central United States and southeast Australia.

6

Australia's water security is dependent on action on climate change, particularly on the rapid phase-out of fossil fuels.

- Australia's water security is threatened by climate change. Coping with increased frequency and severity of drought and floods is costly and will become progressively more challenging into the future.
- Continuing on our current trajectory of high emissions has enormous and growing risks.
- Short-term drought solutions will ultimately be futile without concerted and rapid action to tackle climate change, both here in Australia and globally.

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1. Introduction

The Australian climate is characterised by a highly variable water cycle. Indigenous Australians were adept at navigating this variability, particularly during ice-age times (Williams et al. 2015).

Post-European colonisation history also demonstrates that we have proven to be an innovative and resilient society when it comes to coping with erratic rainfall (Gergis 2018), capable of providing a reliable supply of water and food to support an expanding population, at least up until now. But the rapid pace of climate change is now challenging that capacity.

With much of eastern Australia in the grip of a severe drought, the role of climate change in worsening the country's episodic droughts has again become front-page news. While politicians are acting as though drought is simply another political issue and are scrambling to respond with short-term solutions, the current drought highlights a far deeper and more serious issue - declining water security caused by climate change (Table 1). Any short-term drought solutions will be ineffective without concerted and rapid action to tackle climate change.

Table 1: Australian drought today and tomorrow.

	Long term trend	Future
Australia as a whole	Droughts are becoming more severe due to hotter conditions around the continent, and drier conditions in many regions.	Greater frequency of extreme droughts and a lower frequency of moderate to severe drought.
Southern Australia (Southeast Qld, NSW, Victoria, ACT)	First significant rains of the growing season have become less reliable and tend to happen later in the season.	Possible further reduction in streamflows into the Murray-Darling system.
Victoria	Melbourne's dams have experienced long-term declining inflows. Over the last two decades, many catchments in Victoria have recorded streamflow reductions of up to 50 percent based on the long-term average.	Average annual streamflow reductions of up to a further 50 percent, based on current levels, could occur in many catchments across Victoria by 2065.
Southwest WA	Fivefold reduction of inflows to Perth's dams.	Total reductions in autumn and winter precipitation potentially as high as 50 percent by the late 21st century.

Climate-driven changes in the global water cycle have already had serious implications for Australia. Water restrictions and desalination plants have been required to secure the water supplies of many of Australia's largest cities, at significant cost. Rapidly regrowing forests after the 2003 megafires in the southeast reduced urban water supplies in the region (Buckley et al. 2012; WRF 2013). The Millennium Drought (1997 – 2009) seriously affected Australia's agricultural sector, putting a dent in our GDP and eroding the health and wellbeing of humans and natural ecosystems alike. The combination of drying, extreme heat and increasingly intense bushfires has damaged or destroyed several of our most valued ecosystems, including Tasmania's World Heritage forests and alpine areas.

Water security is fundamental for human wellbeing and development (Box 1). Changes to the water cycle, particularly extremes such as floods and droughts, have serious impacts on human health. Access to clean water and sanitation is Goal Six of the United Nations' Sustainable Development Goals, and is central to achieving many of the other goals (such as good health and wellbeing) (UN 2018). Many factors influence the ability of societies to provide sufficient clean freshwater for their citizens. These include long-term planning, effective social institutions and governance, and appropriate technologies and engineering approaches. But climate change is playing an increasingly important role in water security by driving rapid and far-reaching changes to the global water cycle.

Australia is subject to risks created by decreasing water security in other parts of the world. In this way climate change is rapidly becoming a 'threat multiplier' with significant national and regional security implications, often through its contribution to forced migration of people within and between nations. When countries already suffer from high levels of poverty, poor governance, and pre-existing tensions with their neighbours, climate change-driven water insecurity can heighten these existing social and political tensions, sometimes spilling over into regional conflicts that send victims seeking safer destinations such as Australia (Climate Council 2015a).

About 70 percent of the Earth's surface is covered by water, and the planet's abundant life, both in the oceans and on the land, is dependent on patterns of water circulation in the oceans and atmosphere. Water is thus central to Earth's climate system. Yet only three percent of the water on Earth is freshwater with the majority locked up in polar icecaps and glaciers that are inaccessible for use, or found in underground aquifers. This leaves only about one percent of water on Earth easily accessible in surface freshwater bodies such as lakes, rivers, ponds, streams and swamps (see Figure 1).

BOX 1: WATER SECURITY

The most widely accepted definition of water security is "The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water 2013). This concept encompasses both water quantity (both too little and too much) and water quality. It includes ecosystems, humans and their health, and supporting social and economic systems.

SALTWATER AND FRESHWATER ON EARTH

About 70 percent of the Earth is covered by water, but the amount that is accessible to humans as surface freshwater in the form of streams, lakes, rivers and ponds or fresh groundwater is only around one percent of the water on Earth.

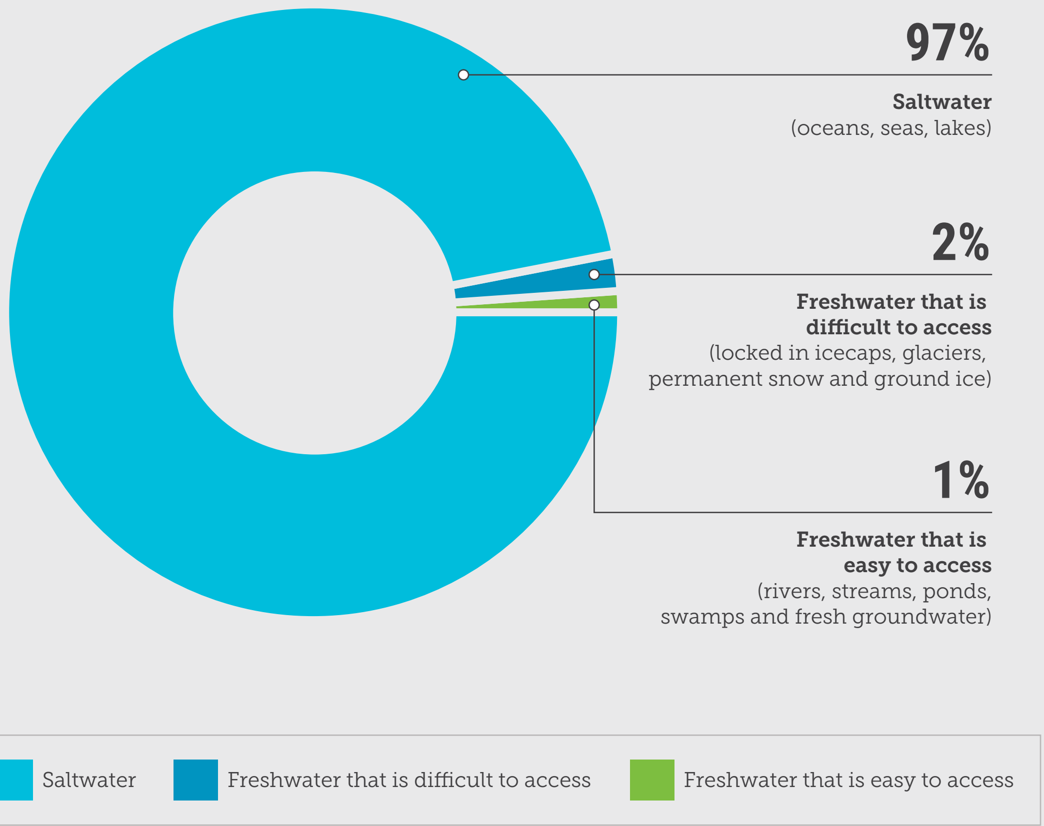


Figure 1: Earth's freshwater versus saltwater. **Source:** Data from Gleick (1996).

The change in the water cycle as the Earth moved out of the depths of the colder, drier ice age about 20,000 years ago to the recent 11,700-year Holocene period of warmer, wetter, more stable climatic conditions was crucial for the development of human civilisations. Only during the Holocene, with its more reliable water cycle, have humans developed agriculture, settlements, cities and the complex, increasingly globalised society of today.

The Holocene is typified by relatively stable patterns of large-scale atmospheric circulation that generate predictable distributions and timing of rainfall over many regions of the planet. Atmospheric circulation is maintained by seasonal differences in temperature and atmospheric pressure between the equator and the poles (see Figure 2). These atmospheric circulation cells, combined with the Earth's rotation, determine the prevailing winds and precipitation patterns at different latitudes.

Other important aspects of the global atmospheric circulation include the high latitude, circumpolar jet streams, particularly important for the northern hemisphere, that steer storm systems across the continents, as well as the longitudinal pattern of updrafts and downdrafts over the Pacific Ocean (the Walker Circulation), which has a role in the El Niño - Southern Oscillation phenomenon. Particularly important for Australia is the position and intensity of a belt of high pressure, known as the subtropical ridge, which causes arid conditions across much of Australia's interior. This zone of high pressure shifts seasonally, influencing the behaviour of the monsoon and the storm tracks that sweep across southern Australia.

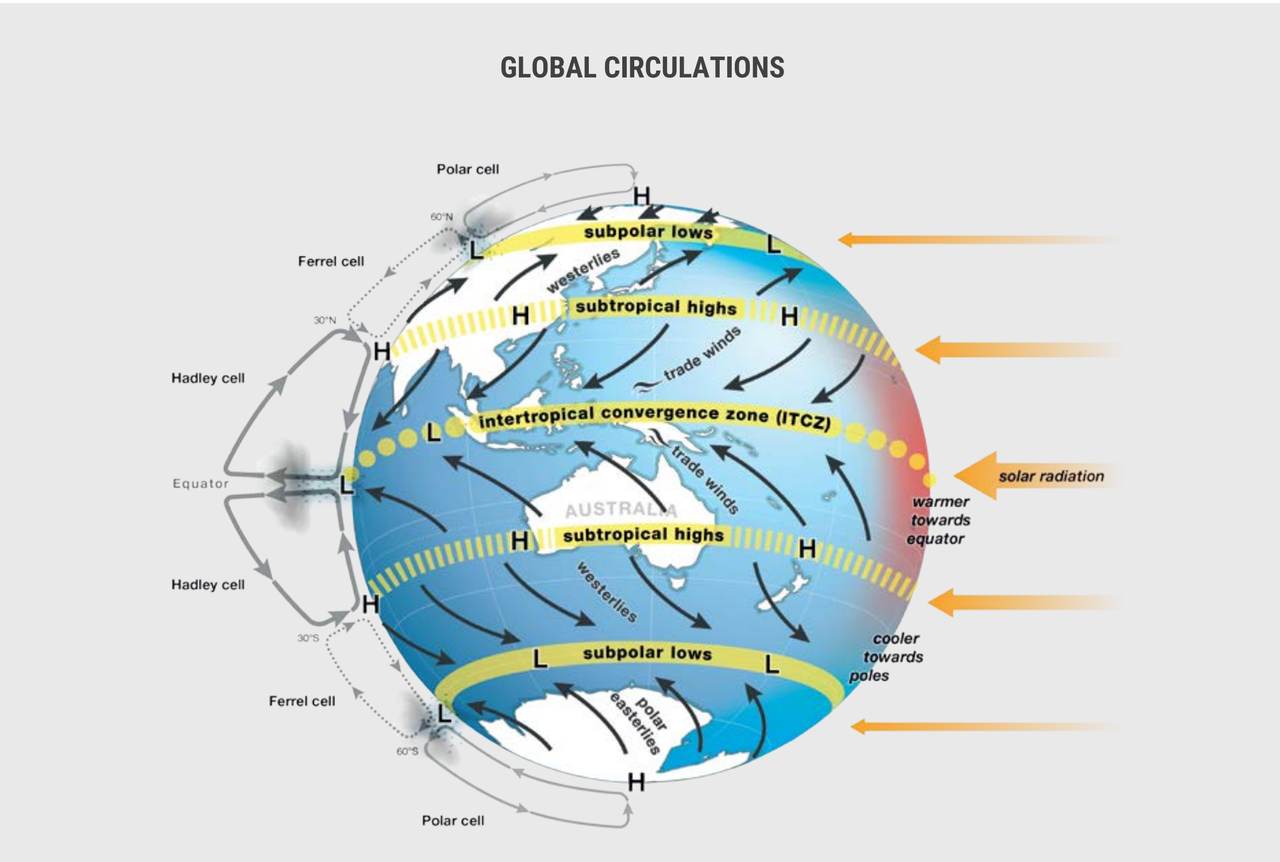


Figure 2: Major atmospheric circulation patterns at the global level. **Source:** Adapted from BoM (2018a).

Cities and major agricultural zones, supporting 7.6 billion humans on Earth, have developed in response to local and regional rainfall reliability and variability, and associated water availability. Terrestrial plants and animals also depend on freshwater for their survival and are adapted to historical rainfall patterns, which are influenced by aspects of global atmospheric circulation.

Human-driven climate change is now causing major changes in the global atmospheric circulation and the resulting patterns of temperature and rainfall. Changes in ocean and atmosphere circulation patterns, such as the Hadley and Walker circulations (Figure 2), are influencing where, when and how much precipitation falls across many parts of Earth. Overall the cycle is becoming more extreme, with both heavier rainfall and more severe droughts. Melting of land-based glaciers is also changing the timing and magnitude of water flowing into continental basins.

Life on Earth is adapted to the stable climatic conditions and relatively reliable rainfall patterns of the past 11,700 years.

In many locations, these climatic changes are decreasing water security. Already, with just a 1°C increase in global average surface temperature since pre-industrial times, changes in the water cycle are increasing stress on many natural ecosystems, destabilising urban water supplies, threatening the capacity of many important agricultural zones to continue to provide sufficient food for an increasing global population, and contributing to displacement of people.

In this report, we first describe how climate change is influencing the global water cycle. We then focus on Australia's water sector, highlighting the economic importance of the sector, the changes that are already occurring because of climate change (see, for example, Table 2), the health implications of these changes, the water-energy nexus, and the impacts of changes in the water cycle on urban water supplies, agricultural productivity and natural ecosystems. The impacts of changes in the water cycle on other parts of the world are also discussed, because ultimately, they affect Australia too. We examine global 'hot spots' where changes in the water cycle are already occurring, other regions where slower, long-term changes could lead to high risks, and the potential disruption of the global food trade system via droughts in critical regions.

Figure 3: Most of the Earth's freshwater is frozen in the form of glaciers and polar ice caps. Glacier melt is now increasing due to rising average temperatures, changing the timing and magnitude of freshwater input into rivers.

Table 2: Observed and future changes in Australia's water cycle.

	Long-term trend (1970s – present for southwest WA; 1990s -present for southeast Australia)	Future
Rainfall	Decline	Further decline
Runoff	Decline	5 – 30% decrease in the southeast. 20 – 50% decrease in the southwest.
Soil moisture	Decreased	Continue to decrease
Streamflow	Decline	Further decline
Dam inflows	Decline	Further decline
Time spent in drought	Increase	Increase

Despite the adaptability and resilience of Australian society, climate-driven changes in the water cycle over recent decades are challenging our capacity to cope.

2. Australia's Variable Water Cycle

2.1 Water Availability and Human Development

Where, when and how much water falls on Australia's land surface has influenced patterns of human habitation and settlement across the continent for at least 60,000 years (Williams 2013). The distribution of water is a critical factor in determining the location, extent and characteristics of major ecological zones, influences the population sizes and ranges of plants and animals, supports freshwater and riparian (land alongside rivers) ecosystems, and regulates the interchange of carbon between vegetation, soil, and the atmosphere.

The patterns of where Australians live, grow food, build settlements and participate in recreation activities are also strongly influenced by freshwater availability, and by the need to avoid areas at high risk of water-related extreme events, such as river flood plains. We require sufficient, clean water to ensure good health and well-being, and for food production and industrial processes.

Coping with a changing climate and water security will be challenging and costly.

The balance between supply and demand is a key feature of water security, as is the existence of adequate legal, governance and financing arrangements, institutions and well-designed infrastructure. The supply-demand relationship is complex, dynamic and difficult to maintain. By international standards, Australia enjoys a reasonably secure supply of high quality water and adequate environmental protections for some key water-dependent ecosystems. This fact is borne out by Australia's high standing in the Asian Water Development Outlook 2016, which rates the national water security of 48 countries in the Asia-Pacific region, using a five-dimension index (Asian Development Bank 2016). The five dimensions of the index are household water security, economic water security, urban water security, environmental water security and resilience of water-related natural disasters. Australia was ranked amongst the highest of all countries on all five measures and was rated second overall in aggregate, just behind New Zealand. As such, we start the climate challenge to water security from a relatively strong position, but this does not mean that the adjustments we will need to make will be easy, cheap or painless.

2.2 Characteristics of the Australian Water Sector

The water sector is an extremely valuable component of the Australian economy. The urban water sector directly accounts for 0.75 percent of Australia's annual Gross Domestic Product with assets worth $160 billion as at 1 July 2015 and annual capital expenditure between $3.5-4.5 billion per year (IPA 2015). Annual capital expenditure in the urban water sector was as high as $6.0 billion in 2008-09 and $5.5 billion in 2009-10 in response to the Millennium Drought (BoM 2018d). The initial (capital) cost of Australia's six desalination plants installed between 2006-12 to reduce water security risks was $10.2 billion alone (AWA 2018).

Total revenue from sales of water and the provision of water services in 2015-16 was $17.7 billion (ABS 2017). Of this amount, households spent $10.1 billion, industry spent $6.9 billion and primary industries (including agriculture) spent $689 million (ABS 2017). The median national annual household water and waste water bill in 2016-17 was $1,332 (BoM 2018c). The gross value of irrigated agricultural production in 2015-16 was $10.5 billion, generated from 2.1 million hectares of production area, accounting for 0.6 percent of the land dedicated to all agriculture.

In 2016-17, 35,942 Gigalitres (GL) (one gigalitre equals one thousand million litres) of water entitlements (rights to access a share of a water resource) were issued across Australia, 78 percent of which were in the Murray-Darling Basin (ABARES 2018). The value of allocation (temporary) water trades across Australia in 2016-17 was about $131 million and the value of entitlement (permanent) water trades across Australia in 2016-17 was about $1.06 billion.

Agriculture is the primary user of water in Australia, accounting for around 70 percent of water extractions in 2015-16, followed by urban use (20 percent) (ABARES 2018; Figure 4).

Climate change poses a serious risk to existing water infrastructure, increasing the probability of failures.

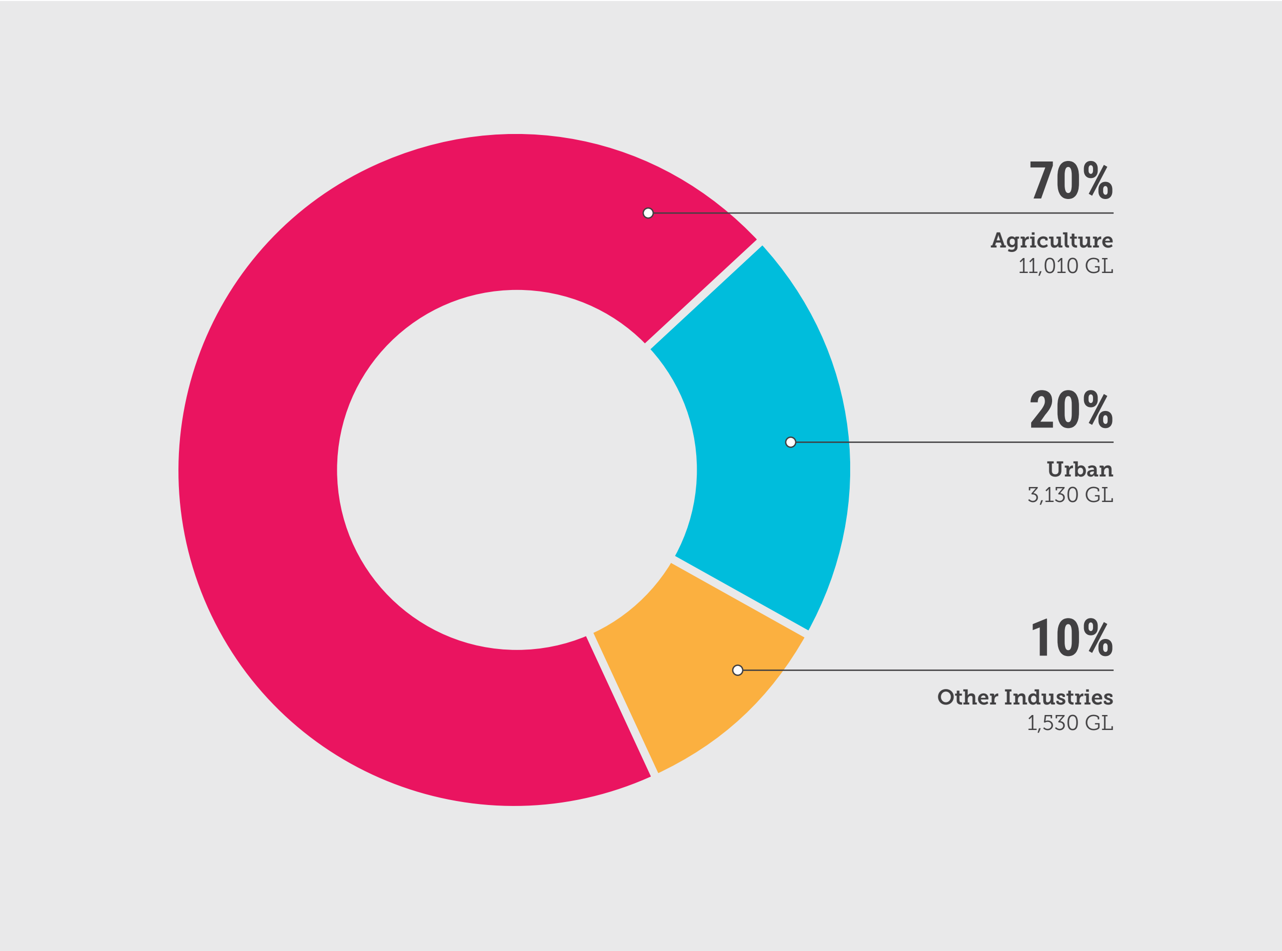


Figure 4: Bulk water abstractions in Australia, 2016-17. **Source:** BoM (2018c).

Not all water extracted from the environment each year is consumed. Some water is used in-stream only and then discharged back to the environment, for example, water used for hydropower generation (see Figure 5).

The Australian water sector is based on knowledge and understanding of the water cycle in the recent past. Instrumental records of Australian rainfall available from 1900 have been used to inform water infrastructure design, planning and policy. As the climate continues to change rapidly, these historic patterns are becoming increasingly unrepresentative and water-related infrastructure is at a growing risk of failure (Milly et al. 2008). Upgrading infrastructure to withstand new and changing conditions is often expensive, particularly in the case of those structures designed to withstand the highest rainfall extremes such as dam spillways and flood levees. At the same time, global water security is becoming increasingly challenged by increased demand associated with the explosive economic growth since the mid-20th century, and the rapidly increasing and wealthier global population, which is, on average, consuming more water per person. These opposing trends in water supply and demand may have serious implications for social and political stability in our region.

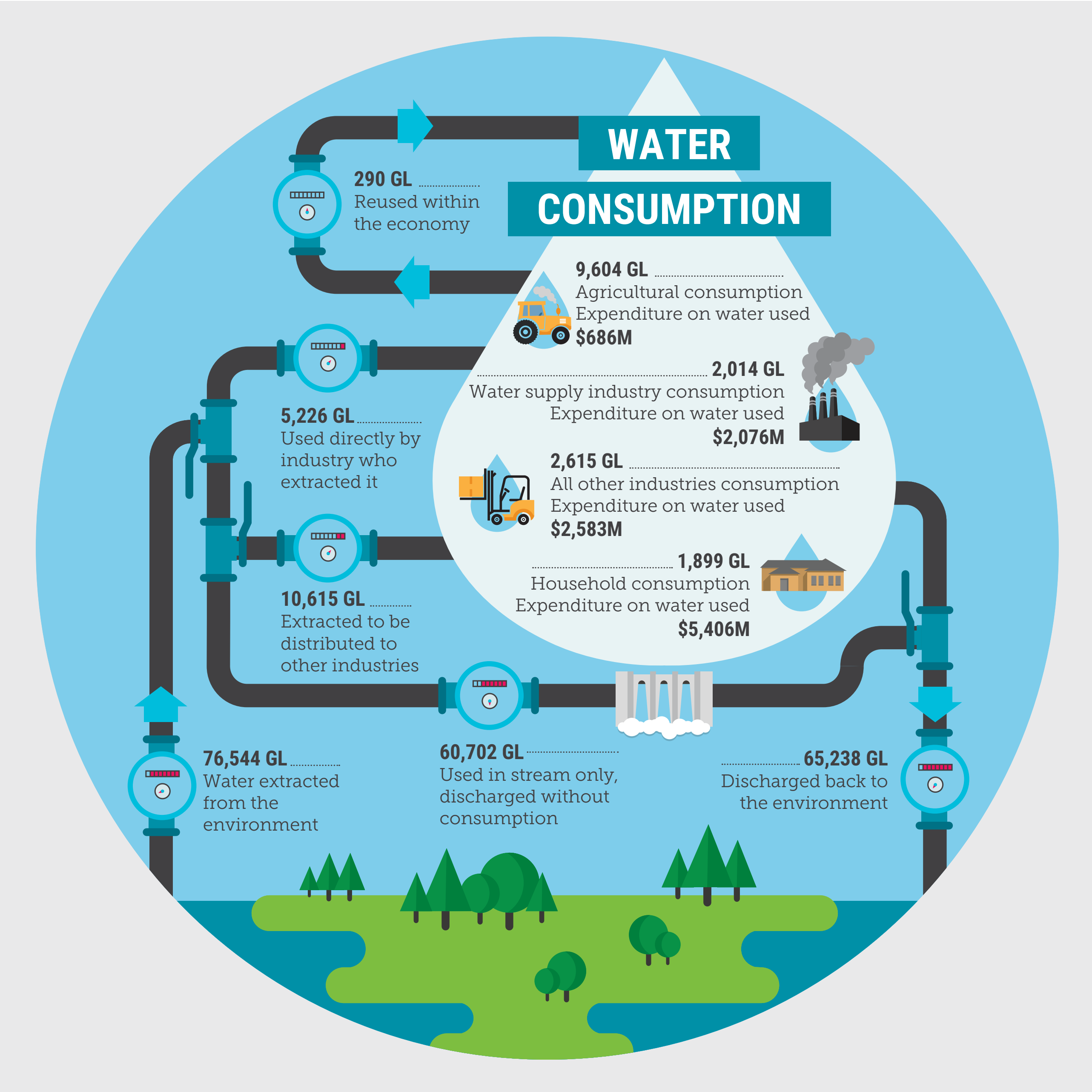


Figure 5: Water consumption and related flows in Australia, 2015-16. **Source**: ABS (2017).

2.3 Water Cycle Patterns and Influences

Australia is the driest inhabited continent on Earth, with approximately 70 percent of the landmass defined as arid (with average annual rainfall below 250 mm) or semi-arid (receiving annual average rainfall between 250-350 mm per year). The rain that does fall is highly variable in both space and time compared to other continents, presenting management challenges (Nicholls et al. 1997). These characteristics of Australia's water cycle are significant factors in where we live, how and where we grow our food, and how we organise our society and economy.

Rainfall is higher and more reliable in coastal regions, with the exception of the central coastal areas of Western Australia. Elevation is another factor that has an important influence on rainfall, with mountainous areas such as northeast Queensland, southeast Australia and western Tasmania receiving higher rainfall. Figure 6 below shows annual average rainfall across Australia (1961-1990).

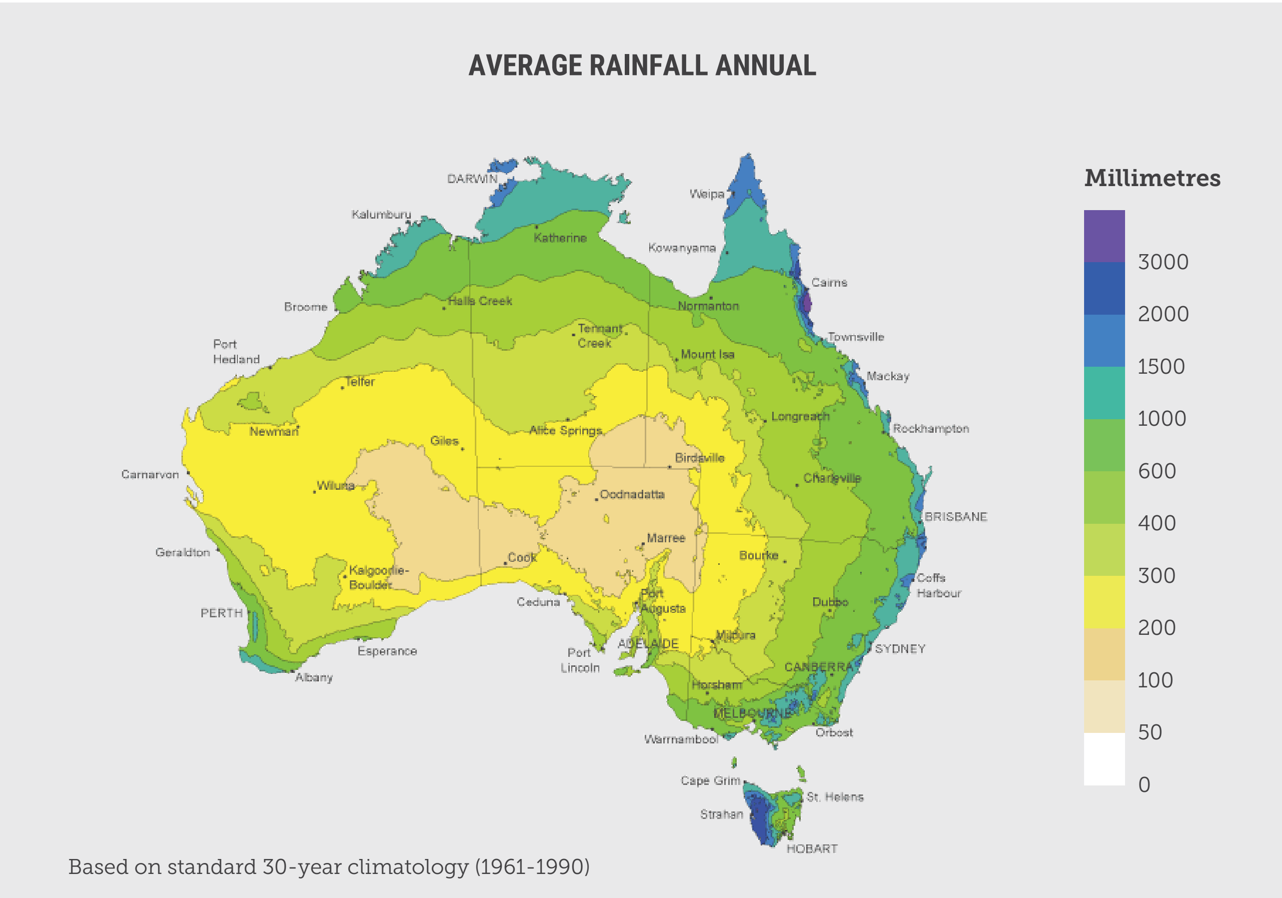


Figure 6: Average annual rainfall across Australia (BoM 2018b).

Australia is the driest inhabited continent on Earth with a water cycle that is highly variable both geographically and seasonally.

Seasonal patterns of rainfall vary in different parts of the continent. Northern Australia has a tropical and sub-tropical climate, with the majority of rain falling during the summer months. Tropical cyclones and monsoon depressions are the major rain-bearing climate systems that affect rainfall in this region. Across southern Australia, most rainfall occurs during the winter months, with mid-latitude frontal systems playing an important role. Figure 7 below shows average seasonal rainfall across Australia.

An important influence on Australian rainfall on seasonal timescales is the subtropical ridge; a belt of high-pressure (centred around 30 degrees south and 30 degrees north) associated with the descending air mass in the Hadley Cell (see Figure 2; BoM 2010). This zone of high pressure has a strong influence on the climate of Australia, particularly on rainfall in the southern regions. The subtropical ridge is associated with clear skies in these areas. From November to April, the ridge shifts south, blocking most of the Southern Ocean cold fronts from reaching southern Australia. As winter arrives, the ridge contracts northward, allowing these cold fronts to reach land and bring more rainfall (see Figures 7 and 8 below).

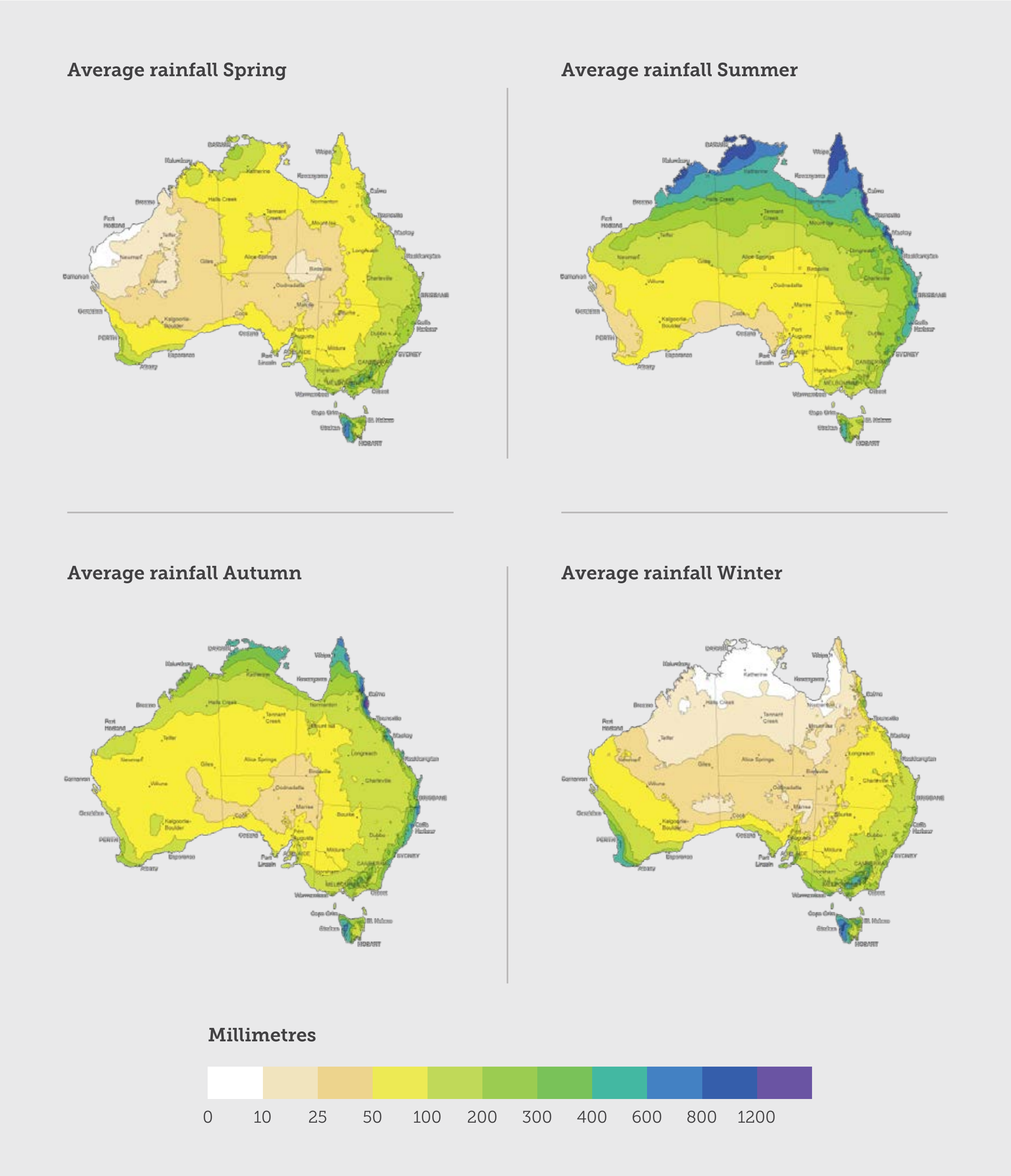


Figure 7: Seasonal variations in rainfall across Australia. **Source:** (BoM 2018b). Note the wet summer season in the north, but higher rainfall in autumn and winter across the south.

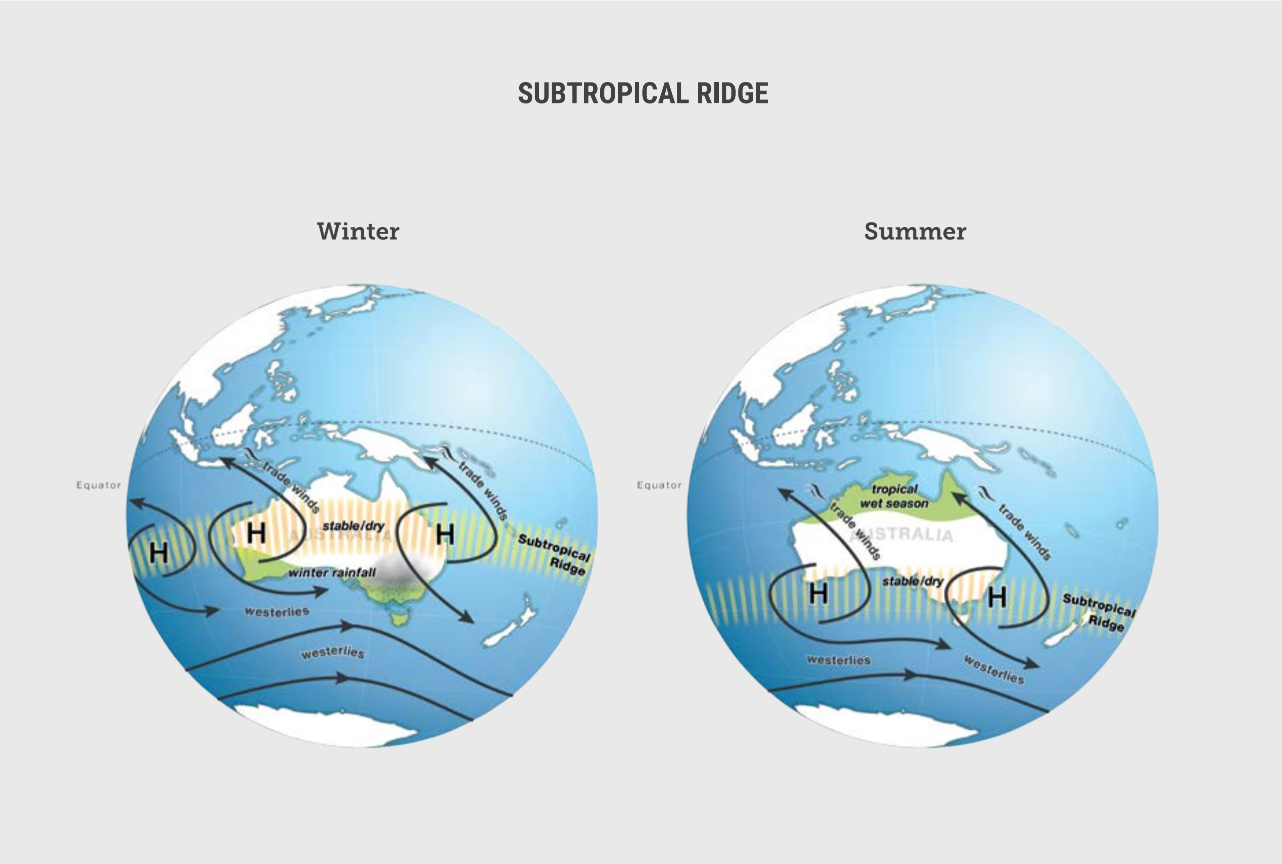


Figure 8: Movement of the sub-tropical ridge during winter (left) and summer (right). **Source:** BoM (2018a).

2.4 Modes of Natural Variability

Australia's rainfall is also influenced by various climate modes that generate strong interannual (year-to-year) variability; these include the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM) (Figure 9). East Coast Lows also bring significant rainfall to the east coast of Australia.

ENSO is the primary driver of interannual rainfall variability both globally and in Australia (aside from the seasons), and has a particularly strong influence on rainfall along Australia's east coast (BoM 2014). ENSO has three phases: La Niña, El Niño and neutral. During La Niña, the Pacific southeast trade winds push more moist air from the eastern Pacific Ocean towards Australia, resulting in higher rainfall during winter and spring. Conversely, during El Niño events, moist air is driven towards South America, resulting in less rainfall in Australia. The wettest year on record in Australia was 1974, which occurred during the strong and prolonged La Niña event of 1973–1976. The second and third wettest years on record were 2011 and 2010 respectively, which occurred during the successive La Niña events spanning 2010–12. These events were associated with record-breaking rainfall over some parts of Australia, and extensive flooding (BoM 2012).

During El Niño years, winters and springs are generally drier than average across eastern Australia. Nine out of ten of the driest winter-spring periods since 1900 have occurred during El Niño years, with the rainfall average across all events 28 percent below the long-term average (BoM 2014). ENSO also influences the monsoon season in northern Australia through its influence on the position of the South Pacific Convergence Zone (SPCZ) (Holland 1986). The location of the SPCZ in turn influences rainfall patterns in northeast Australia and the locations where cyclones are formed (Brown et al. 2011; Vincent et al. 2011).

The IOD is one of the key drivers of Australia's climate and can have a significant impact on agriculture because its influence generally coincides with the winter crop growing season. The IOD influences rainfall on interannual timescales in western and southern Australia during winter and spring by moving moist air from the Indian Ocean across the continent towards southeast Australia (Risbey et al. 2009). During a 'negative' phase of the IOD, the northeast Indian Ocean is warmer, increasing evaporation rates and bringing more rainfall to southeast Australia during winter and spring. During a 'positive' phase, cooler ocean temperatures provide less moisture to the atmosphere from the northeast Indian Ocean, resulting in drier conditions during winter and spring across southeast Australia.

The SAM affects winter rainfall across southern Australia by influencing the tracks of cold fronts from the Southern Ocean (Meneghini et al. 2007; Risbey et al. 2009). During a 'positive' phase of the SAM, circumpolar winds contract closer to the south pole, resulting in less rainfall across southern Australia. During a 'negative' phase, the belt of winds expands equatorward, driving more storms and low-pressure systems towards southern Australia during winter.

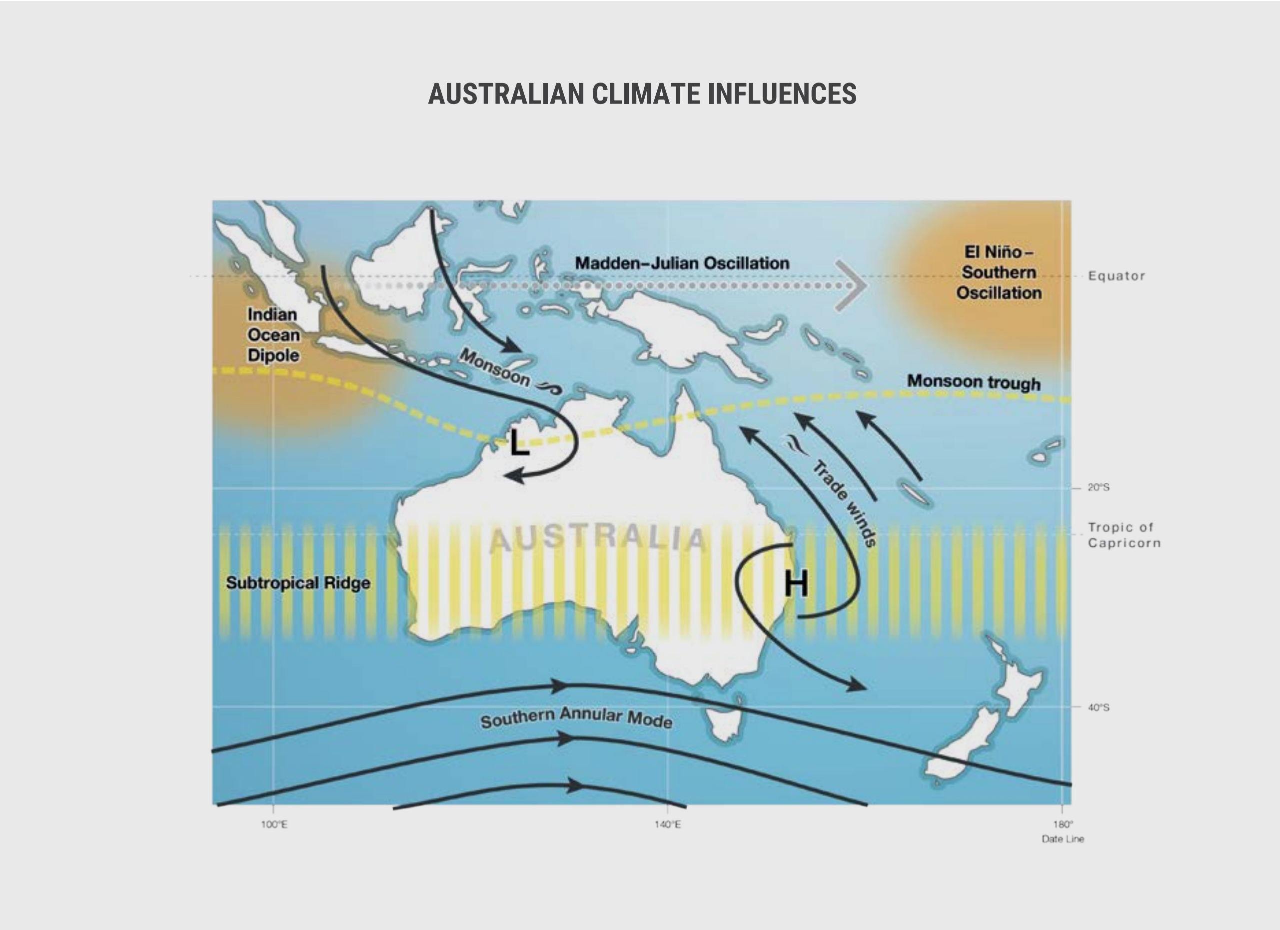


Figure 9: Climate drivers that influence Australian rainfall. **Source:** BoM (2018a).

3. Observed Changes in the Global Water Cycle

Climate change is now becoming an increasingly disruptive factor in the ongoing challenge to manage water supply-demand dynamics. The climate system and water cycle are highly intertwined and changes in one strongly influence the other. As the climate system is increasingly destabilised by greenhouse gas pollution from burning fossil fuels, the global water cycle is changing in complex ways.

With more energy in the climate system, the water cycle is intensifying (Figure 10). As sea surface temperatures rise, more water evaporates from the surface of the oceans. Furthermore, a warmer atmosphere can hold more water vapour. For every degree Celsius that the atmosphere warms, it can hold approximately six-seven percent more water vapour, a physical principle that is supported by observations (despite regional variability) (Hartmann et al. 2013).

A wetter, more energetic atmosphere stacks the odds towards more intense rainfall events. Analysis of long-term observations around the world suggest that it is likely that, since 1951, there has been an overall, net increase in the number of heavy precipitation events. The most consistent trends towards heavier precipitation events are found in central North America, while Europe has also likely experienced increases in more regions than decreases (Hartmann et al. 2013).

Climate change is making the atmosphere more energetic, increasing the likelihood of more intense rainfall events.

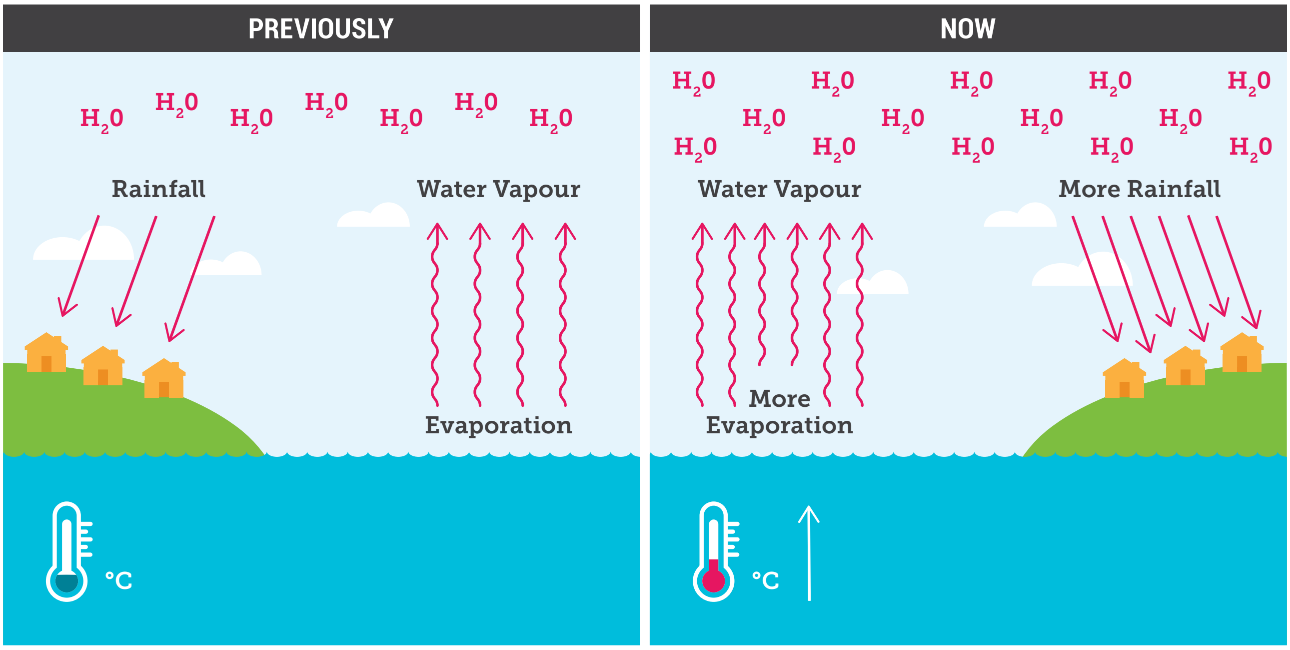


Figure 10: The influence of climate change on the water cycle. **Source:** Climate Commission 2013.

In addition to intensification of the water cycle, the geographical and seasonal patterns of precipitation are changing around the world as the climate continues to warm. There is a high level of natural variability in these patterns associated with climate drivers like ENSO, so the trends that are occurring over the last half-century are often difficult to differentiate from natural variability with a high degree of certainty, partly because the observational records are relatively short. Climate change itself can also be expected to influence some of the main drivers of natural variability.

Figure 11 shows how the patterns of precipitation around the globe have been changing for the period from 1901 through 2010 and from 1951 through 2010. The second period coincides with the pronounced rise in global mean surface temperature driven by increasing greenhouse gas emissions. Most trends over the full 110-year period are weak, but some important trends have emerged over the past 60 years as climate change exerts a stronger influence. In general, the mid-latitude land areas of the Northern Hemisphere have experienced more precipitation, consistent with the intensification of the water cycle with a warming climate (Figure 10). This trend towards wetter conditions has led to a reduction in the severity of droughts in central North America (IPCC 2013).

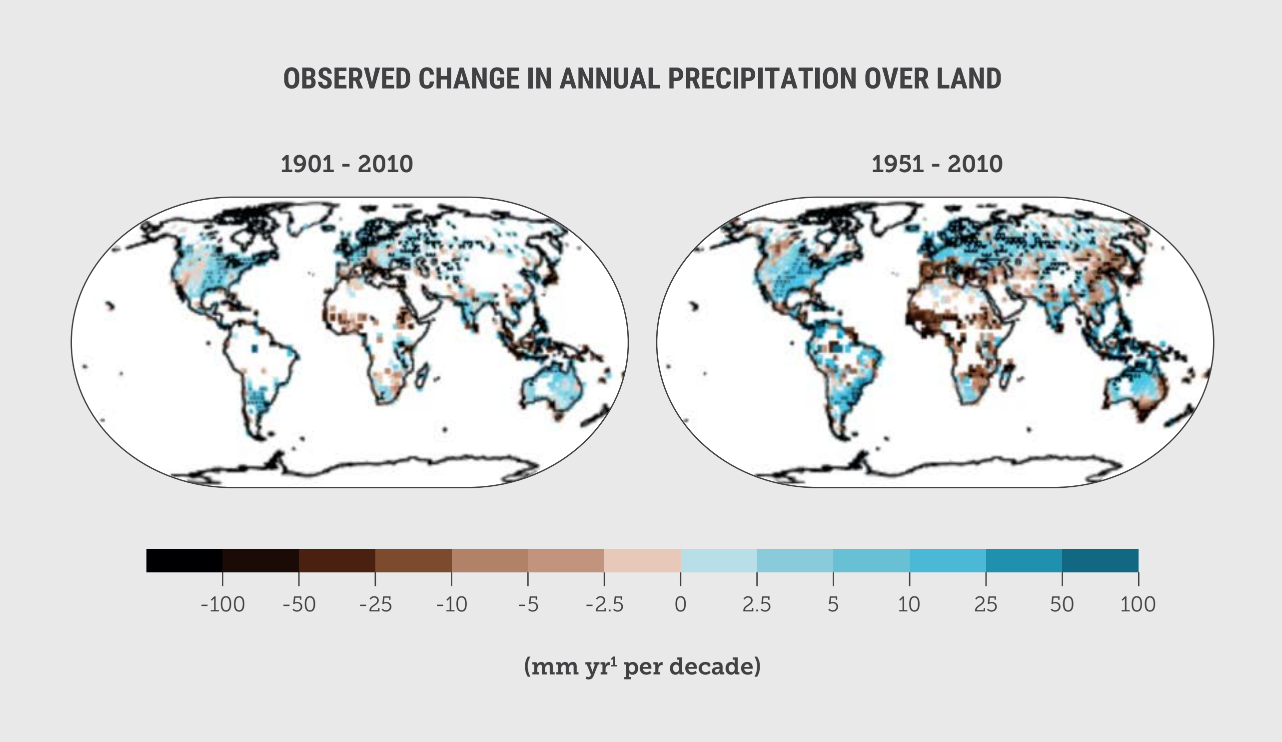


Figure 11: Observed change in precipitation over land from 1901 to 2010 (left) and 1951 to 2010 (right). **Source:** IPCC (2013).

In the Mediterranean and West Africa, it is likely that the frequency and intensity of drought has increased since 1950, as indicated by the strong drying trends in those regions shown in Figure 11. Some of these pronounced drying trends are occurring in regions with vulnerable populations and political instabilities, increasing the risk for conflict and migration (Section 7). A strong drying trend is also emerging in northeast China, the country's most important agricultural region.

In some other regions of the world, however, both wetting and drying trends are emerging. This is the case in Australia, where there has been an observed spatial pattern of wetting in northern Australia and drying in southern Australia.

Climate change has caused some regions to get wetter and some regions to get drier.

4. Observed Changes in the Australian Water Cycle

4.1 Rainfall Patterns

In Australia, it is clear that climate change has reduced rainfall in the southeast and southwest corners of the continent (CSIRO and BoM 2016, see Figure 12). Precipitation patterns have changed markedly over the past two decades, with a pronounced drying trend in these two important agricultural regions during the cool months of the year, the normal growing season. Since the mid-1990s, southeast Australia has experienced a 15 percent decline in late autumn and early winter rainfall, and a 25 percent decline in average rainfall in the autumn months of April and May compared to long-term averages (Climate Council 2015b; CSIRO and BoM 2016). Southwest Western Australia has also experienced a pronounced decline in cool season rainfall, with particularly strong drying from May through July. During that season rainfall since 1970 has declined by about 19 percent compared to the long-term average, a rate of decline that has increased to about 25 percent since 1996 (CSIRO and BoM 2016).

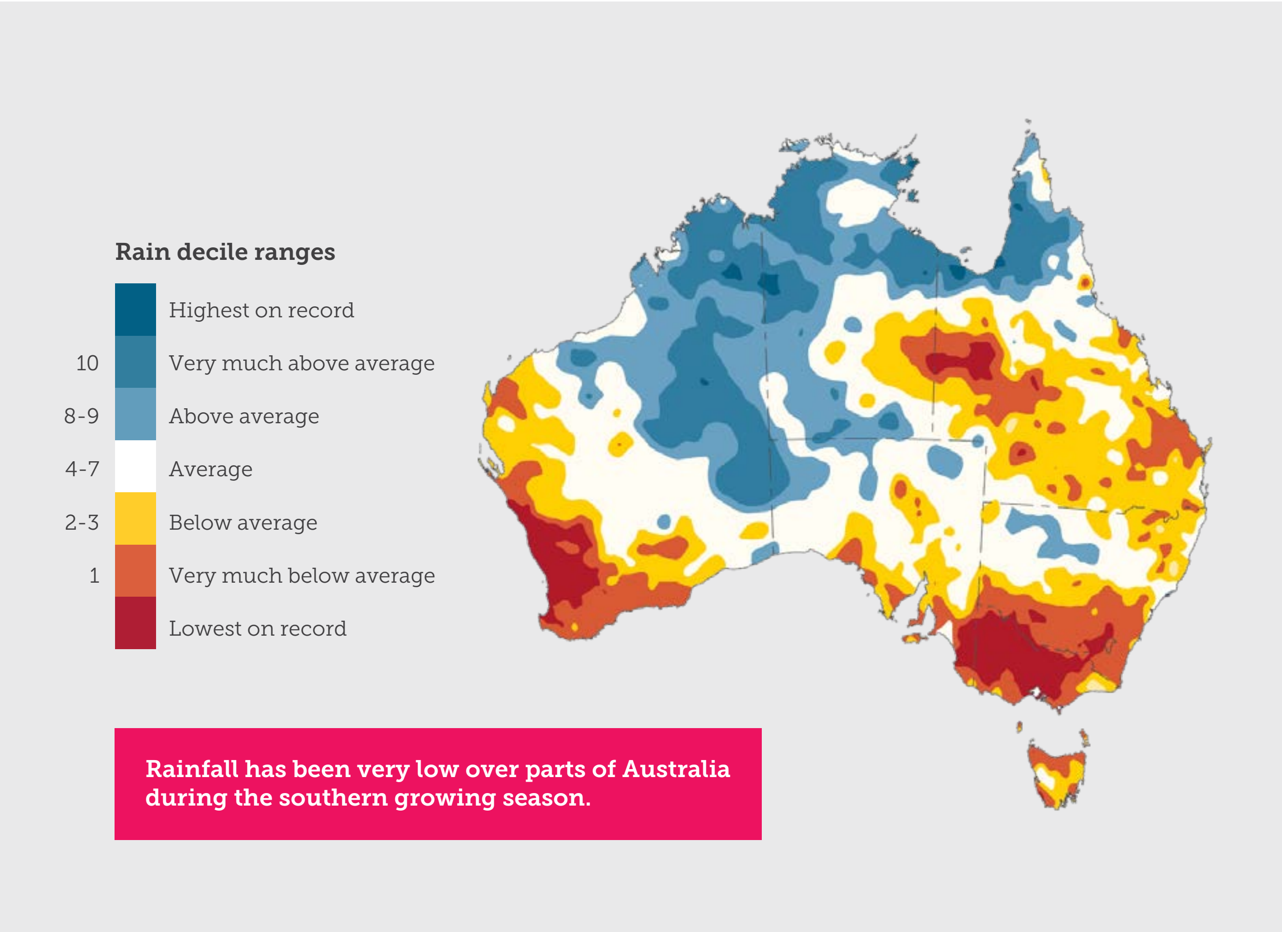


Figure 12: Southern Australia has experienced a drying trend in the April – October period from 1996-2015. **Source:** CSIRO and BoM (2016).

At the same time, northern Australia has become wetter, particularly in the northwest (Figure 13). Rainfall across most of northern Australia has been very much above average in the northern wet season. In northwest Western Australia, rainfall has also been above average in the dry season (CSIRO and BoM 2015; CSIRO and BoM 2016).

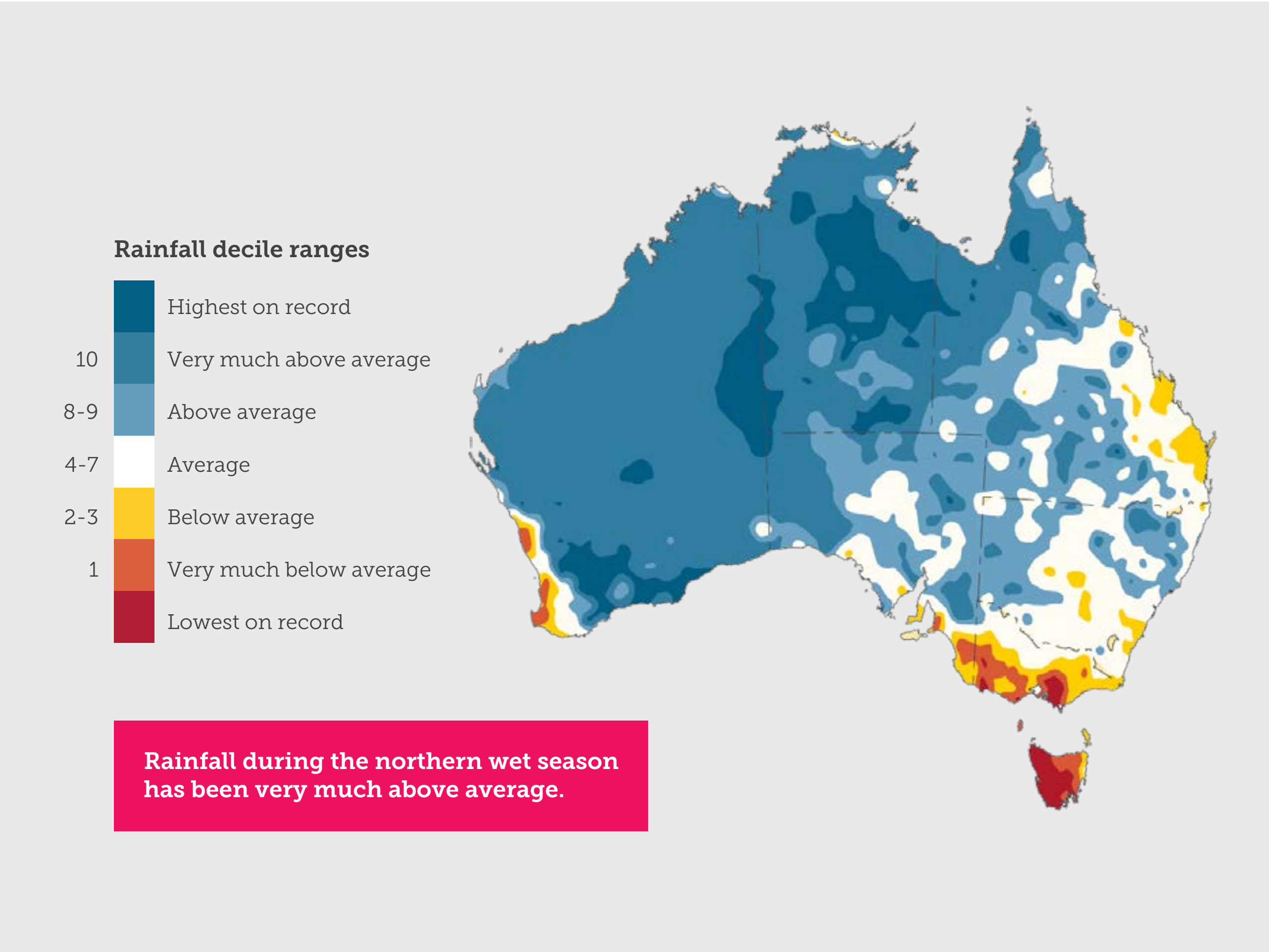


Figure 13: Northern Australia has experienced very much above average rainfall during October-April (1995-2016).
Source: CSIRO and BoM (2016).

Although changes to several influences on annual (seasonal) and interannual rainfall variability seemingly play a role in the observed rainfall declines, climate change has likely exacerbated these declines, including through the Millennium Drought, by its influence on the subtropical ridge of high pressure that extends across the southern part of the continent (see Section 2.3 above).

In recent decades, the subtropical ridge has intensified, blocking more cool season, rain-bearing systems from reaching southern Australia (see Figure 14 below).

The increased intensity of the subtropical ridge, related to rising global average temperature, is able to explain up to two-thirds of the decline in rainfall across southeast Australia between 1997 and 2009 (associated with the Millennium Drought) (Timbal and Drosdowsky 2013). The World War II drought is the first dry decade of the 20th century in southeast Australia that may have been influenced by climate change through the intensification of the subtropical ridge (Drosdowsky et al. 2005; Timbal and Drosdowsky 2013; Gergis 2018, p.102).

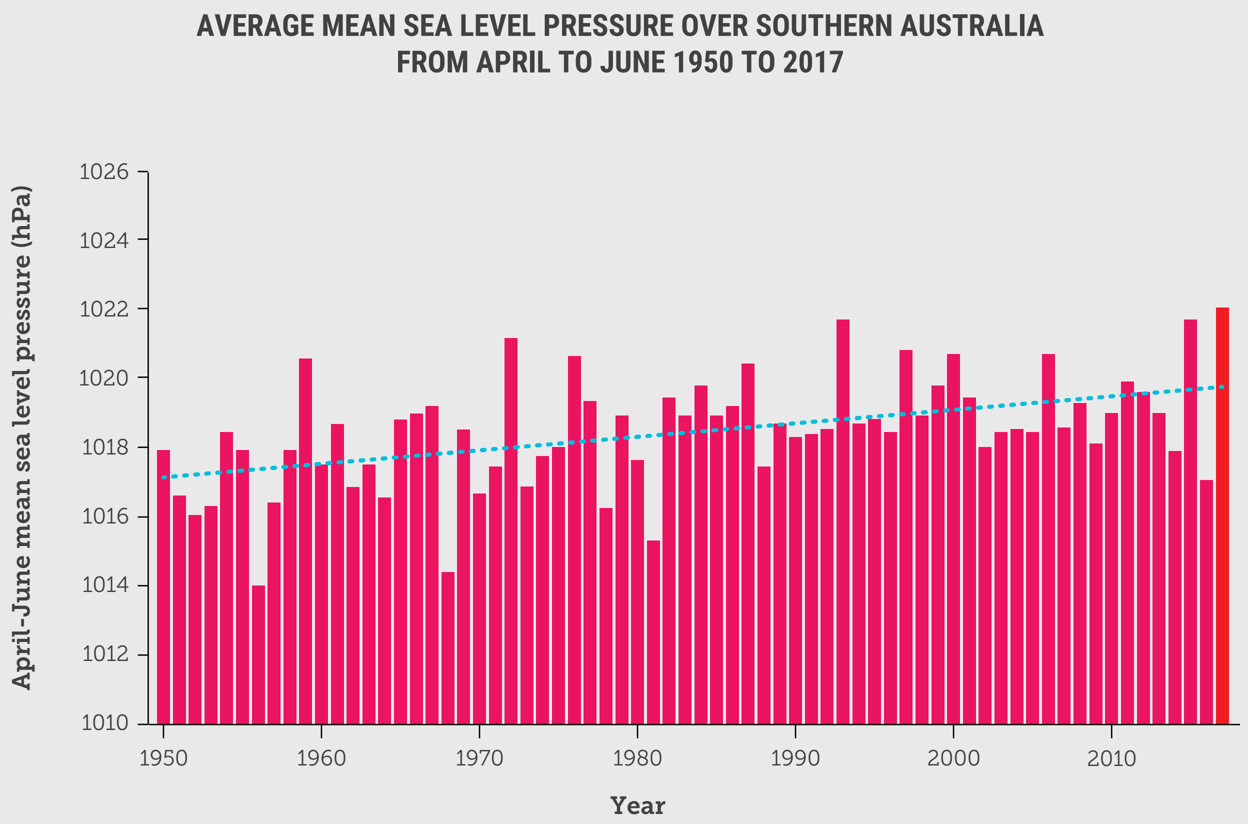


Figure 14: April – June mean sea level pressure over southern Australia, showing the effect of the strengthening of the sub-tropical ridge from 1950 to 2017. **Source:** BoM (2017).

Some studies have also suggested that climate change may be increasing the occurrence of positive phases of the IOD, which are associated with decreased rainfall in the southeast during the cool season (on interannual timescales) (Cai et al. 2009; Ummenhofer et al. 2009; Ummenhofer et al. 2011).

The behaviour of the Southern Annular Mode also appears to have changed in recent decades, but the extent to which climate change is responsible is equivocal. During the summer and autumn months (December through to May), the SAM shows an increasing tendency to remain in a positive phase, with westerly winds contracting towards the south pole. Palaeoclimatic evidence indicates that the SAM index is now at its highest level (indicating increased occurrence of positive phases) for at least the past 1,000 years (Abram et al. 2014; Dätwyler et al. 2018). The SAM may also be affected by the expansion of the Hadley Cell as the climate warms and the tropics expand.

4.2 Extremes: Floods and Droughts

Consistent with the global trends, an increase in the proportion of heavy rainfall events has been observed in Australia. The aggregated spatial area of the continent receiving a high proportion (in the wettest 10 percent of observations) of annual rainfall from extreme rain days has been increasing since the 1970s (see Figure 15), with considerable regional variability. There has also been an increase in the area receiving heavy summer rainfall (in the top 10 percent of observations) (BoM 2013).

Theory and model simulations indicate that extreme rainfall will continue to increase as a result of climate change. In Australia, observed increases in the magnitude of hourly rainfall extremes are close to or more than double this expected rate of precipitation (mm/hr), and in the tropical north of Australia, the magnitude of hourly rainfall extremes is triple this expected rate (see Figure 16) (Guerreiro et al. 2018).

Climate change has contributed to a reduction in cool season rainfall in southern Australia, and an increase in warm season rainfall in northern Australia.

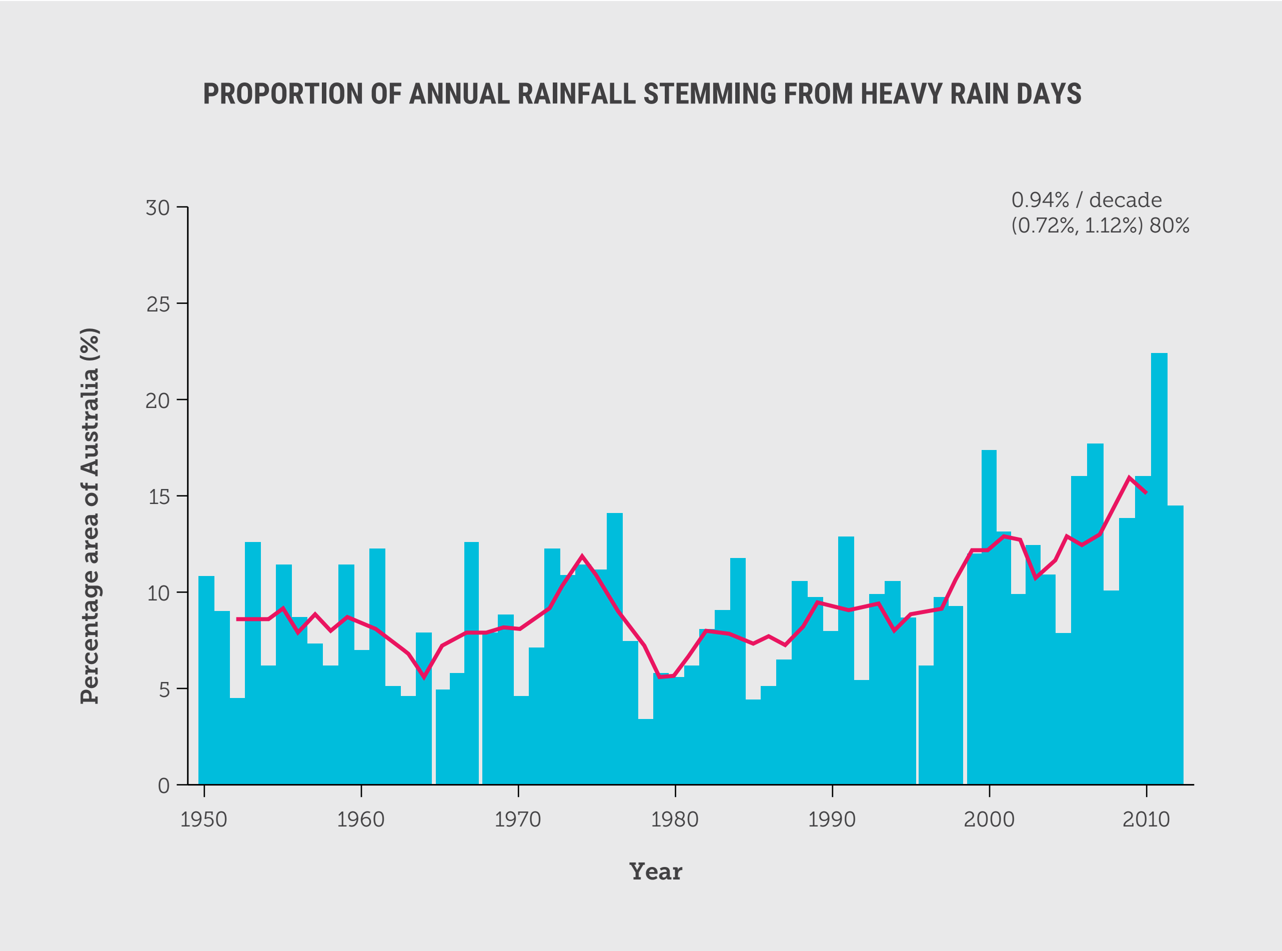


Figure 15: Increase in heavy rainfall in Australia. **Source:** Gallant et al. 2014, reprinted in CSIRO and BoM (2015).

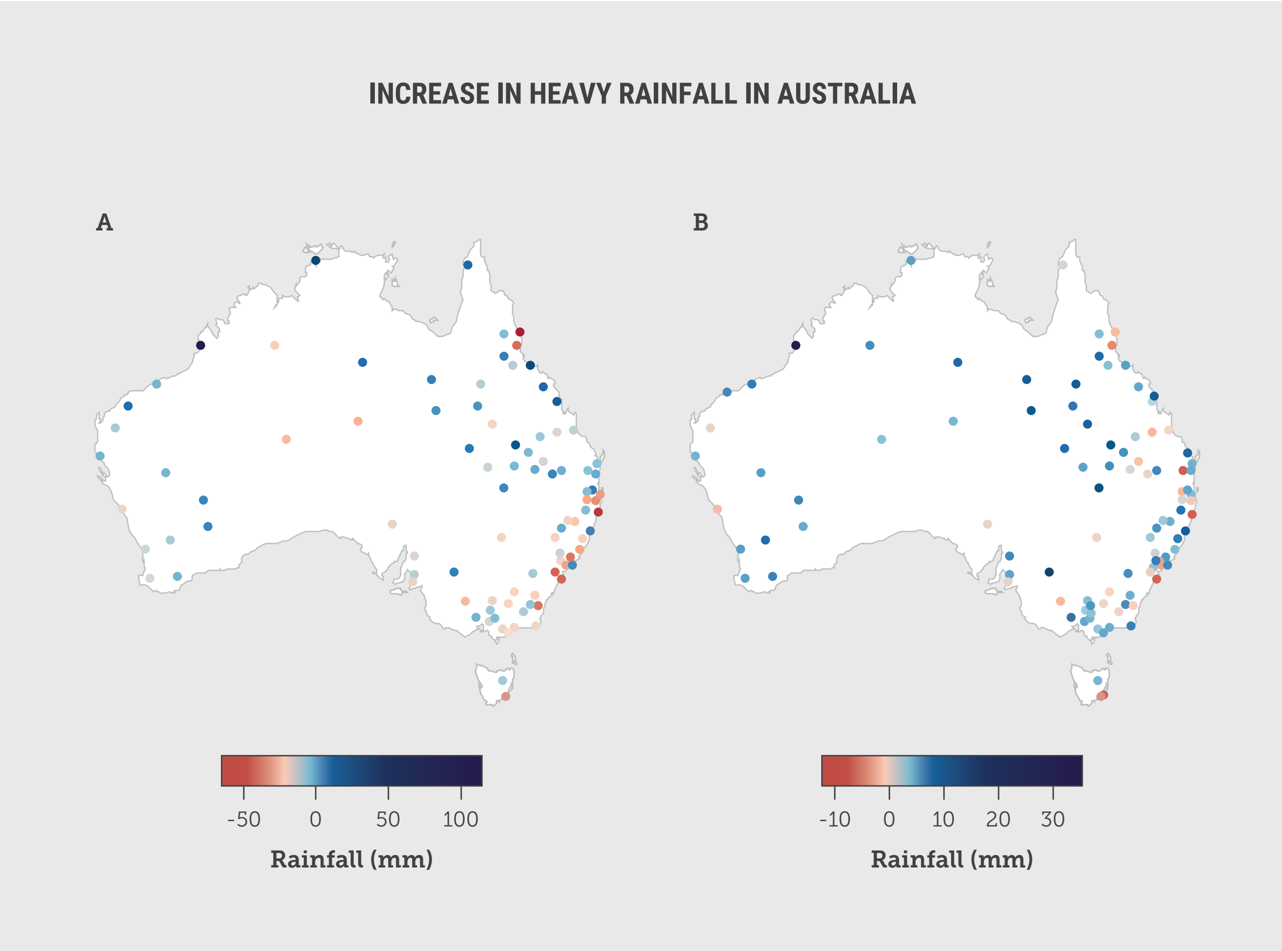


Figure 16: Changes in the magnitude of the 20 largest values of extreme daily rainfall (a) and hourly rainfall (b) during 1990 – 2013 compared to 1966-1989. **Source:** Guerreiro et al. (2018).

At the same time, climate change is likely making drought conditions in southwest and southeast Australia worse. In addition to decreasing rainfall, climate change is driving an increase in the average temperature and in the intensity and frequency of hot days and heatwaves, leading to increased water losses from plants and soils and thus exacerbating drought conditions (CSIRO and BoM 2015).

Australia has experienced several major droughts during the 20th and early 21st centuries. The most severe droughts were the Federation Drought (1895–1903), the World War II drought (1939–1945) and the Millennium Drought (1997–2009). A recent study has found that the Millennium Drought was unprecedented in terms of its concurrent spatial extent for at least the past 400 years (Freund et al. 2017), and its impact was exacerbated by the rising air temperatures driven by climate change.

BOX 2: AUSTRALIA'S CURRENT DROUGHT CONDITIONS

The recent dry conditions in eastern Australia have few precedents for their combination of extent and duration. While there have been individual years in the last century with rainfall similar to or less than that in 2018, only twice since 1900 have such dry conditions been sustained for a period of nearly two years across the Murray-Darling Basin (MDB). The intensity of the rainfall deficiencies in the MDB over the last two years is comparable with the worst two-year period experienced during the Millennium Drought (2006–2007). However, current dry conditions have not yet persisted for as long as they did during the Millennium Drought (BoM 2018f).

While many areas have been affected by drought conditions, regions which have been severely affected include, in New South Wales, parts of the central west, the New England Highway corridor from the Tamworth area south to the upper Hunter, and the Illawarra and Southern Highlands; and in Victoria, central and east Gippsland. At longer timescales, northern inland New South Wales near the Queensland border has also been badly affected (BoM 2018f).

The recent period has been notably dry at a range of timescales. Of the 388 long-term rainfall stations currently operating in New South Wales, 105 have had their driest period on record for at least one of the 9-month, 15-month or 21-month periods ending in September 2018. Nationally, 82 long-term stations had their driest 9-month period on record, 87 their driest 15-month period, and 50 their driest 21-month period (BoM 2018f; Figure 17).

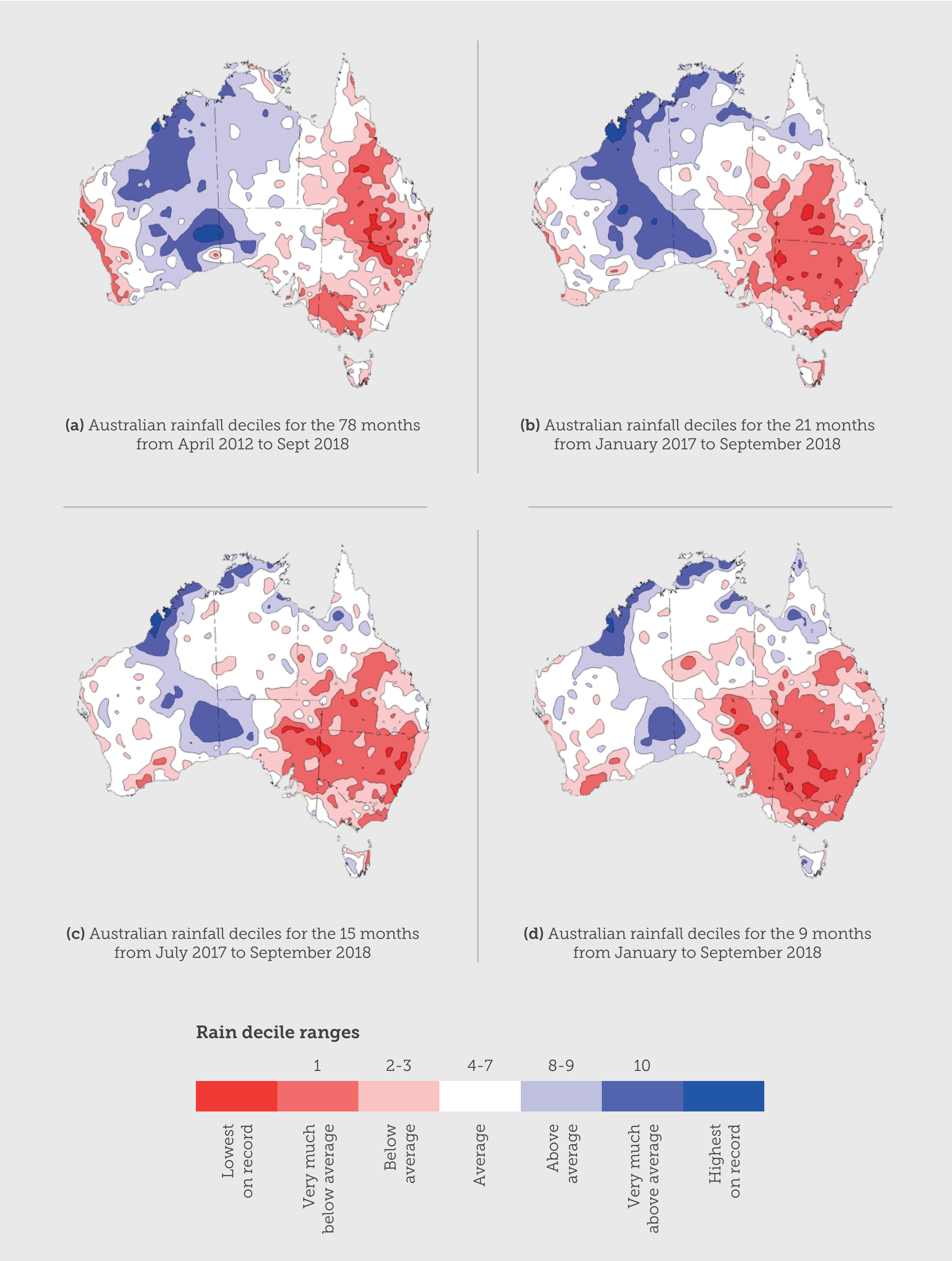


Figure 17: The long-term dry conditions in eastern Australia. **Source:** BoM (2018f).

BOX 2: CONTINUED

The current drought occurred against a background of long-term global and regional warming trends associated with the burning of fossil fuels and land use changes.

Warming was slower to develop in the Murray-Darling Basin than many other regions of Australia during the 20th century, but in recent decades it has seen the nation's most rapid warming. Since 1970 most of the MDB has been warming at a rate of between 0.2 and 0.4°C per decade, compared with a national average of around 0.15°C per decade. The last five years, which all had average temperatures at least 1°C above the 1961-1990 average, each ranked among the nine warmest on record for the MDB (with 2017 being the warmest). In fact, nine of the MDB's ten warmest years on record have occurred since 2005. This warming has exacerbated water stress in many systems within the MDB, compounding impacts associated with rainfall deficits experienced in the region (BoM 2018f).

Source: Selected findings from BoM (2018f).

The current severe drought is being influenced by climate change, with long-term rising temperatures driven by greenhouse gas pollution.

4.3 Streamflows

Streamflow is the flow of water in streams, rivers and other channels resulting from rainfall across a catchment area. Streamflow reductions are amplified by decreases in rainfall. A one percent reduction in rainfall can lead to an approximately 2-3.5 percent reduction in streamflow (Chiew 2006). In southwest Western Australia, climate change-induced reductions in rainfall have led to a more than 50 percent decline in streamflow (CSIRO and BoM 2016). In the southeast, streamflows have also declined significantly since the mid-1990s, compared to the long-term average. Across the Murray-Darling Basin streamflows have declined by 41 percent since the mid-1990s compared to the long-term average and in some catchment basins across central and western Victoria, streamflows have declined by more than 70 percent (see for instance Axe Creek at Longlea in the Campaspe Basin in Figure 18). By contrast, in northern Australia, there is a long-term trend towards higher streamflows (see Figure 19) (State of the Climate 2016).

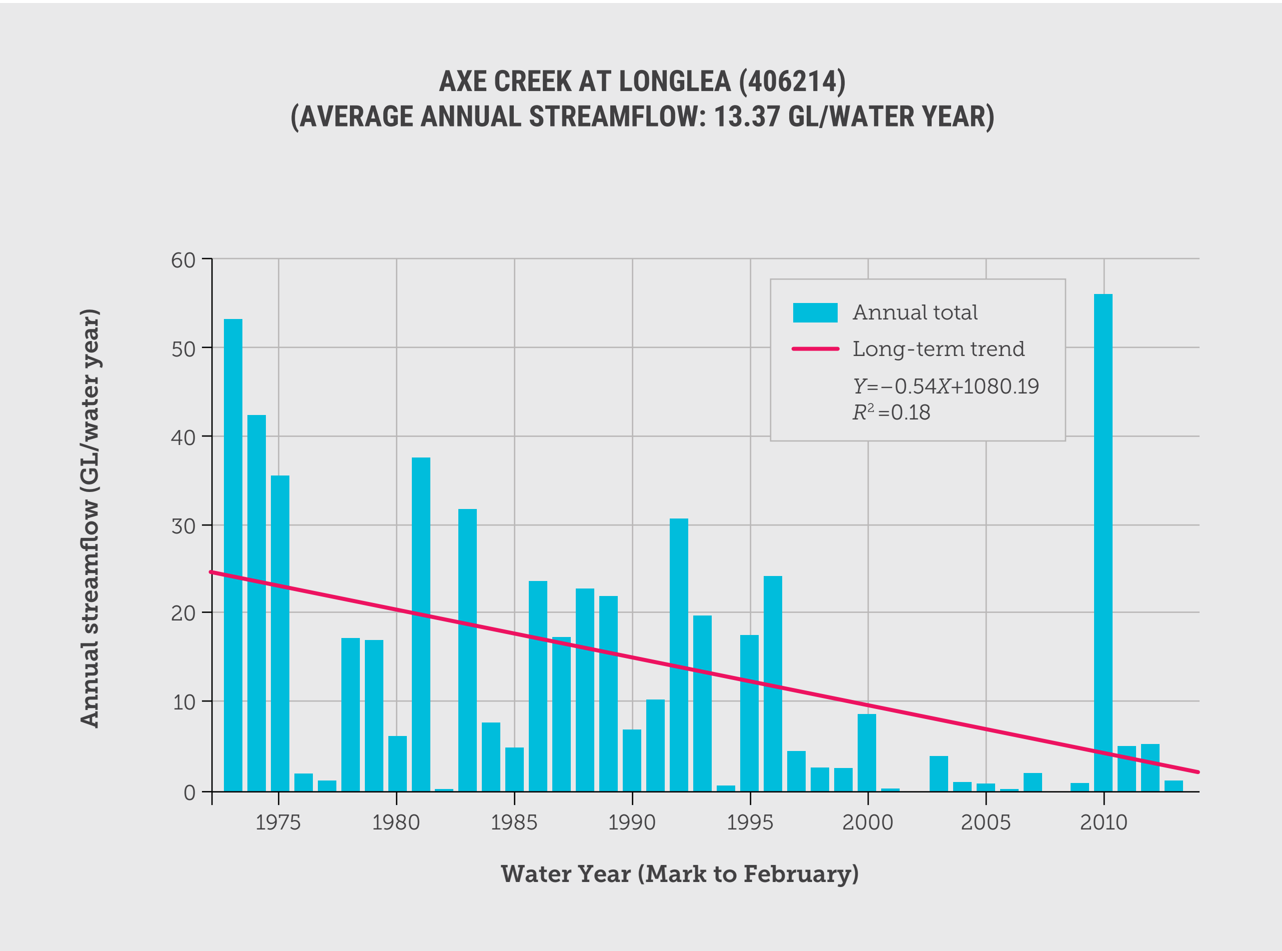


Figure 18: Annual total streamflow for Axe Creek at Longlea (Campaspe Basin), Victoria. **Source:** BoM (2015).

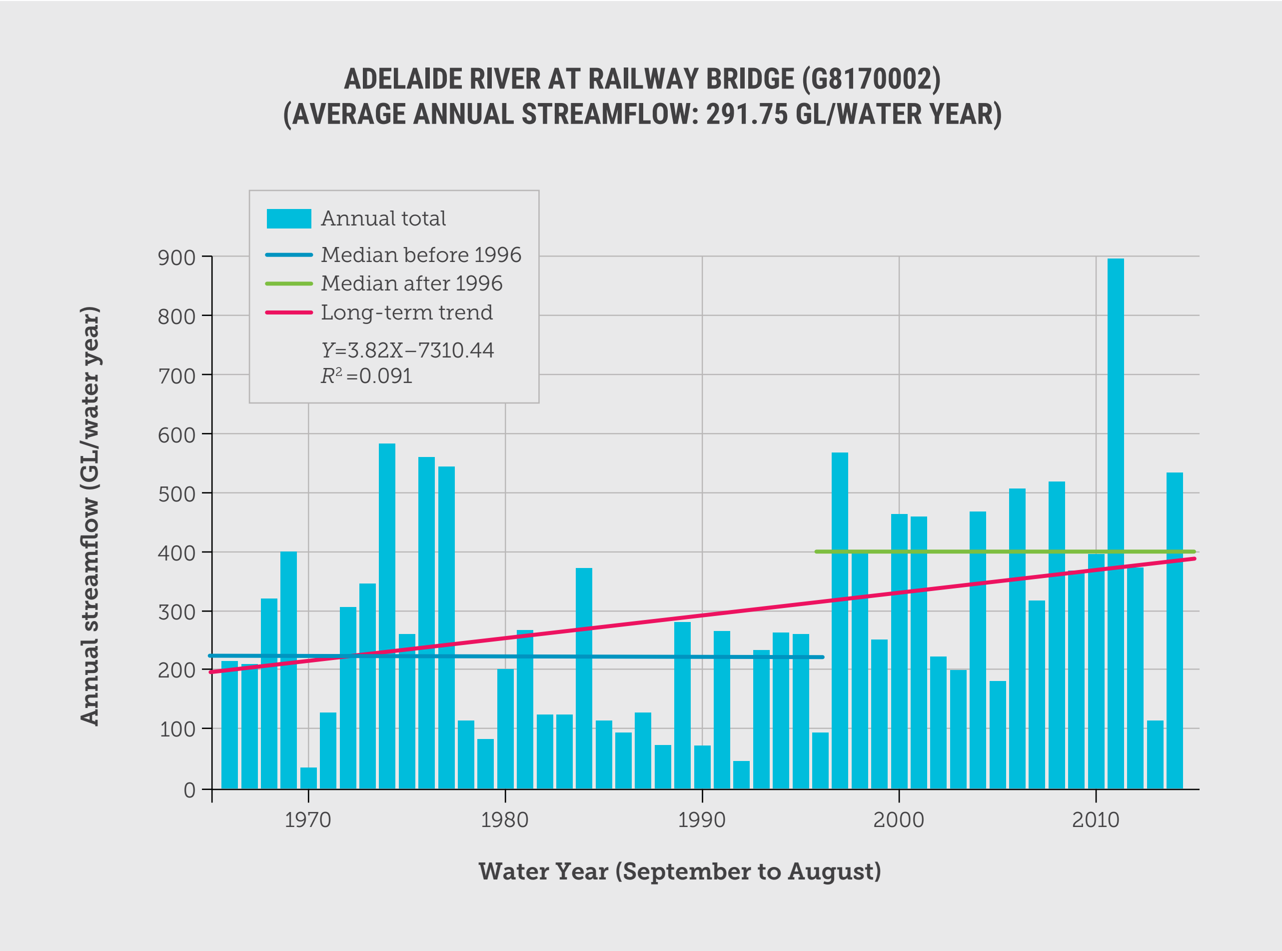


Figure 19: Annual total streamflow for Adelaide River at Railway Bridge (Adelaide Basin), Northern Territory. **Source:** BoM (2015).

Rainfall reductions are intensified by two to three times in catchment streamflow reductions.

5. Future Projections of Changes to the Global and Australian Water Cycle

The patterns and magnitudes of future changes in the water cycle are dependent on the level of future greenhouse gas emissions, with higher emissions driving more pronounced changes in the cycle. Even if the climate system can be stabilised at the Paris target of a 1.5-2°C temperature rise above pre-industrial levels, further significant changes to the water cycle are unavoidable (Collins et al. 2013). Temperature rises beyond these targets would be even more disruptive.

In general, the contrast of annual mean precipitation between wet and dry regions and between wet and dry seasons will increase over most of the Earth as the climate continues to warm. High latitude and some equatorial regions are likely to receive more precipitation, while many mid-latitude and subtropical arid and semi-arid regions will become drier. In addition, as temperatures increase, a shift to more intense individual storms and fewer weak storms is likely. Over most of the mid-latitude land masses and wet tropical regions, extreme precipitation events will very likely become more intense and more frequent (Collins et al. 2013).

Soil moisture and runoff (movement of water across the soil surface into drainage systems such as streams and rivers) are vital for agriculture and urban water supplies and they are both continuing to change. Increases in annual runoff are likely in the northern high latitudes, while decreases are likely in parts of southern Europe, the Middle East and southern Africa under a high emissions scenario. Soil moisture decreases under a high emissions scenario are projected in presently dry areas such as the Mediterranean, southwest USA and southern Africa, leading to an increased risk of drought in areas already short of water (Figure 20; Collins et al. 2013).

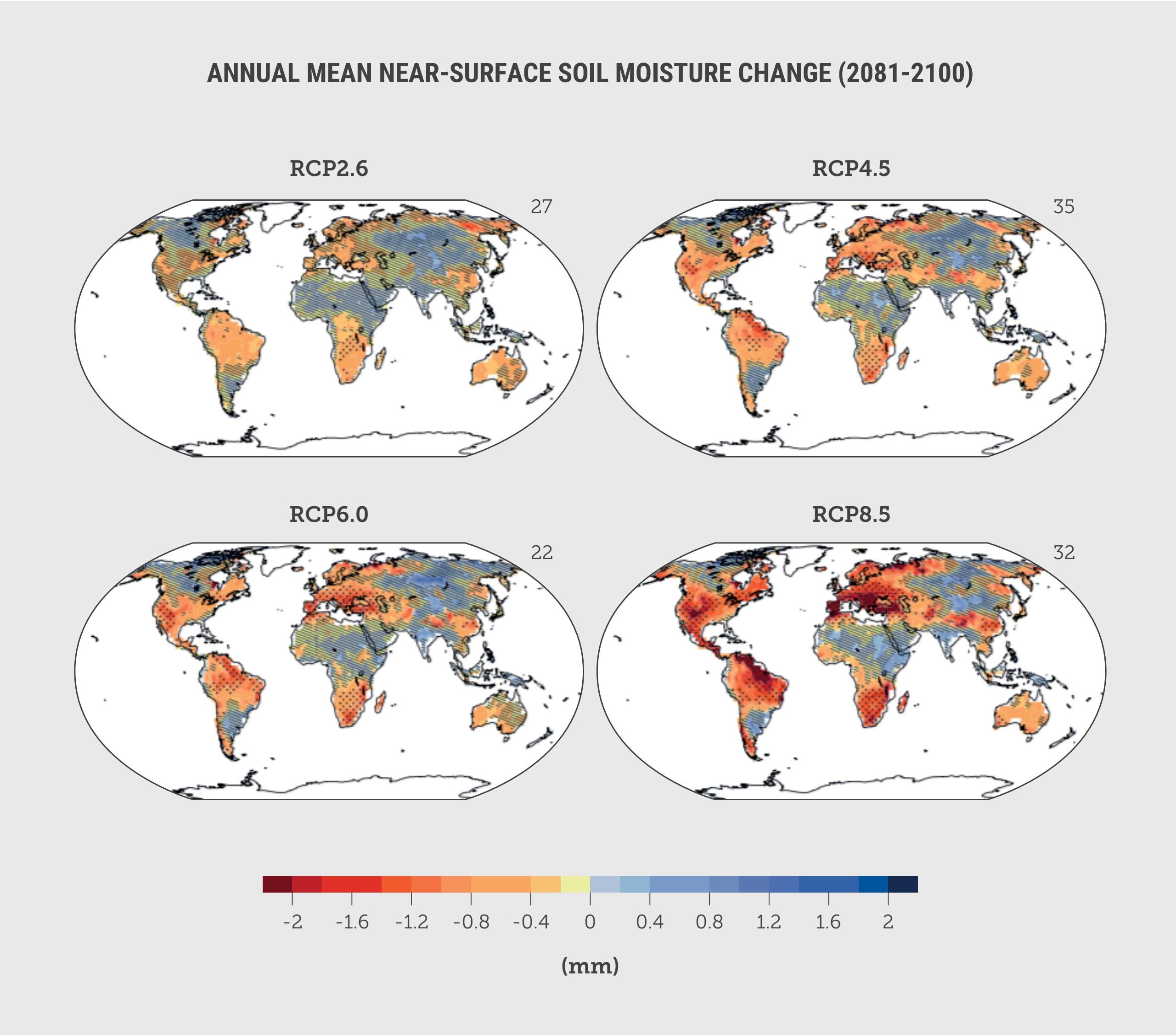


Figure 20: Change in annual mean soil moisture (Collins et al. 2013).

In general, wet areas of the world are becoming wetter and dry areas drier as the climate continues to change.

Australia is also vulnerable to significant changes to the water cycle, especially across southern Australia. Cool season (winter and spring) rainfall is projected to continue to decrease across southern regions, although little change, and perhaps an increase, is projected for Tasmania in winter.

Although the direction of rainfall change in summer and autumn cannot be reliably projected across all of southern Australia, there is medium confidence that southwest Victoria in autumn and western Tasmania in summer will experience declines in rainfall. In eastern and northern Australia and across the northern inland area, natural variability is expected to dominate over long-term trends until around 2030. However, in eastern Australia a decrease in winter rainfall is projected for late in the century with medium confidence (CSIRO and BoM 2016).

A 2°C rise in average global temperatures could lead to an 11–30 percent increase in extreme rain events (wettest day of the year and wettest day in 20 years) across Australia as a result of higher atmospheric water vapour content driven by increased temperatures (Bao et al. 2017; Gergis 2018; Figure 21). A possible exception is southwest Western Australia, where the reduction in mean annual rainfall may be so pronounced that the trend towards more extreme rainfall may be significantly weakened (CSIRO and BoM 2015).

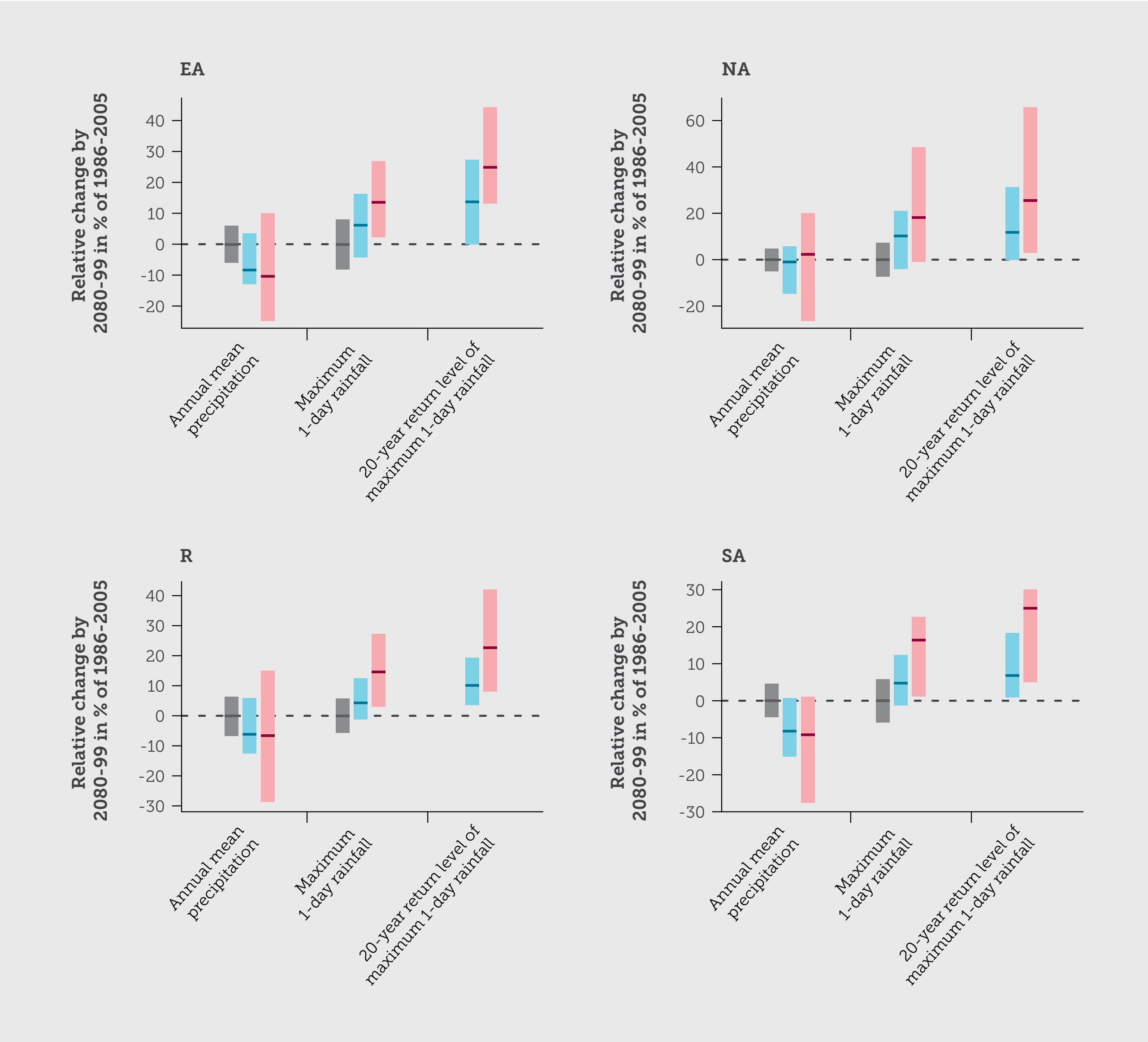


Figure 21: Changes to extreme rainfall for four regions (EA – Eastern Australia; NA – Northern Australia; R – Rangelands; AS – Southern Australia. **Source:** CSIRO and BoM (2015).

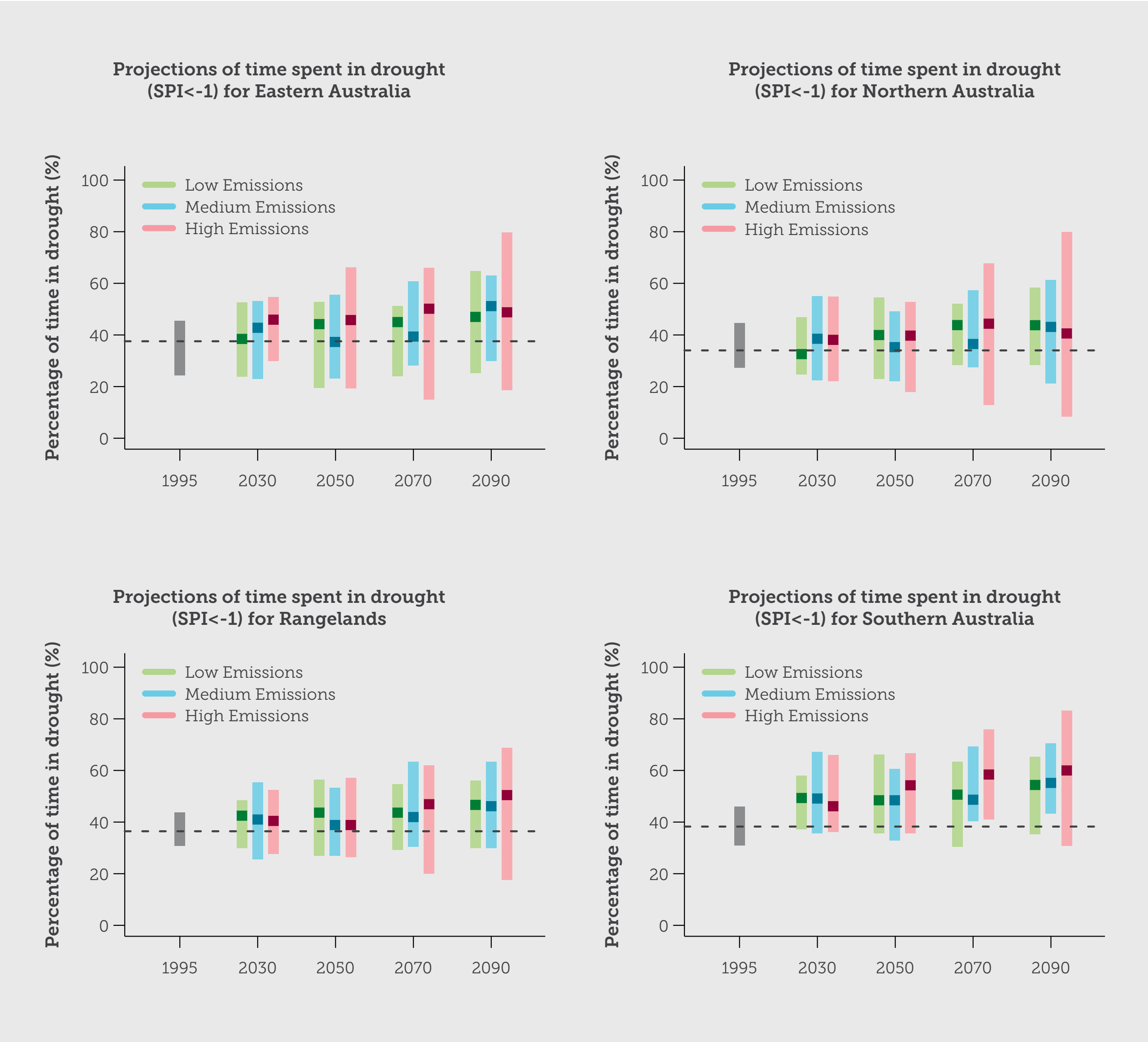


Figure 22: Changes in time spent in drought across Australia for five 20-year periods through the 21st century. **Source:** CSIRO and BoM (2015).

In southern Australia, time spent in drought is projected to increase, consistent with the projections of decreasing mean rainfall. Future drying trends will be most pronounced over southwest Western Australia, with total reductions in autumn and winter precipitation potentially as high as 50 percent by the late 21st century. A greater frequency of extreme droughts is also expected. In other regions of the country, time in drought is also projected to increase, but there is less confidence in this projection compared to that for southern Australia (Figure 22). In all regions, the nature of drought is projected to change, with a greater frequency of extreme droughts and a lower frequency of moderate to severe drought (CSIRO and BoM 2015; see Box 7.2.1 in this reference for definitions of "moderate", "severe" and "extreme" drought).

Climate change is likely to drive significant changes to other important features of the water cycle. For example, the combination of decreasing rainfall across southern Australia coupled with higher evapotranspiration rates as a result of higher temperatures is likely to lead to decreasing soil moisture across the region. Furthermore, it is very likely that southwest Western Australia and southern South Australia will experience decreased runoff through the rest of this century (Figure 23; Reisinger et al. 2014).

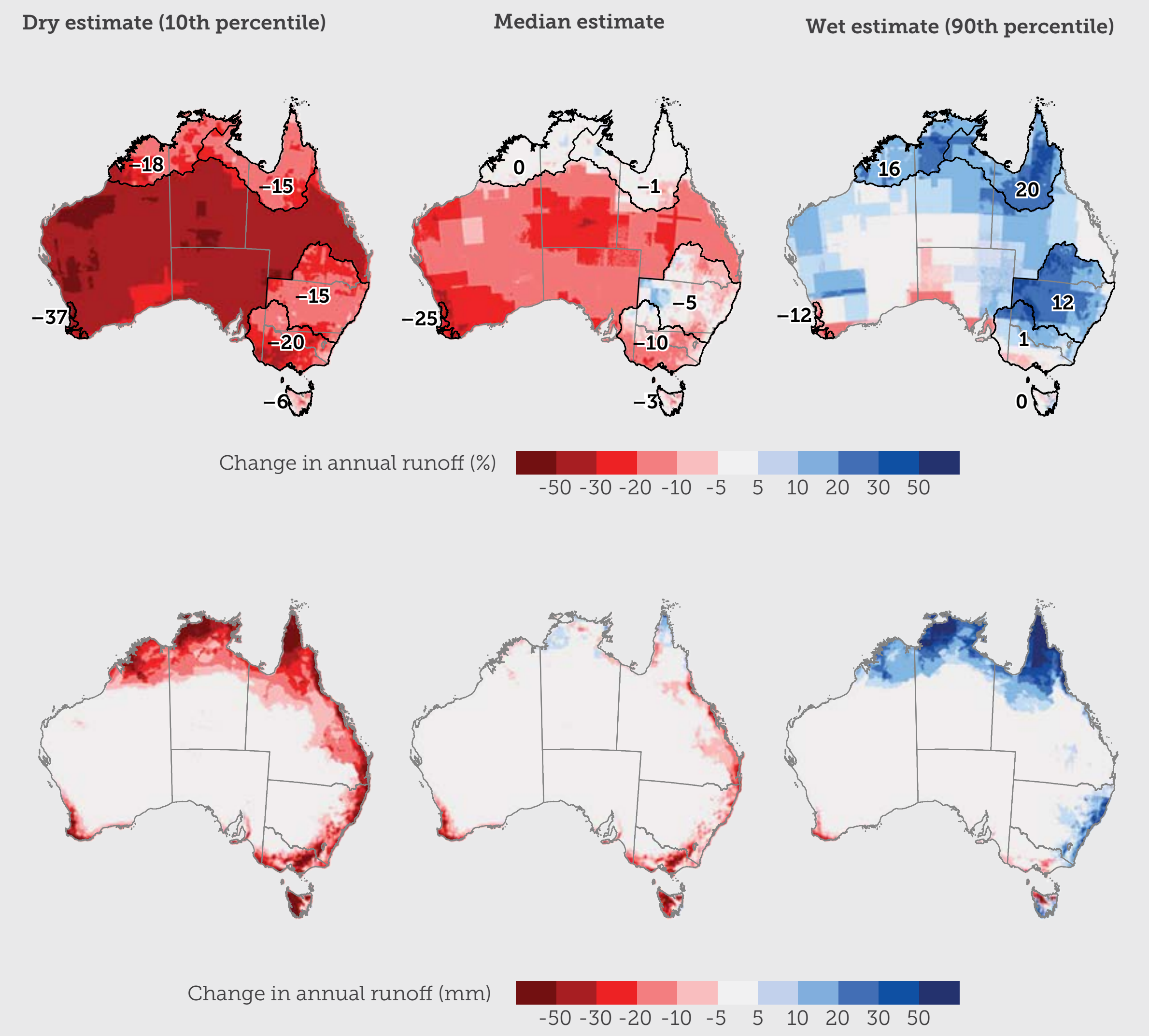


Figure 23: Estimated changes in mean annual runoff for a temperature rise of 1.5-2.0°C above pre-industrial (Reisinger et al. 2014 and references therein).

6. Impacts of a Changing Water Cycle in Australia

Changes to the water cycle, particularly hydrological extremes such as floods and droughts, have serious impacts on human health, urban water supplies, agriculture and ecosystems. The severity of these impacts in Australia and around the rest of the world are very likely to increase with rises in the global average temperature (Box 3).

BOX 3: CHANGES IN THE GLOBAL WATER CYCLE FOR 1.5°C AND 2°C TEMPERATURE RISES

Selected findings from the Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5°C (IPCC 2018), shown verbatim.

The impacts of climate change on the global water cycle are already evident at a rise of ~1°C in global average temperature. Impacts are projected to increase as temperature continues to rise, but there are large differences depending on the level of temperature rise. For example, the higher Paris target of 2°C above pre-industrial levels will drive more severe risks to the water cycle than would occur if the lower 1.5°C target could be achieved.

1. **Limiting global warming to 1.5°C is expected to substantially reduce the probability of drought and risks associated with water availability (i.e. water stress) in some regions *(medium confidence).*** In particular, risks associated with increases in drought frequency and magnitude are substantially larger at 2°C than at 1.5°C in the Mediterranean region (including Southern Europe, Northern Africa, and the Near-East) and Southern Africa *(medium confidence).*

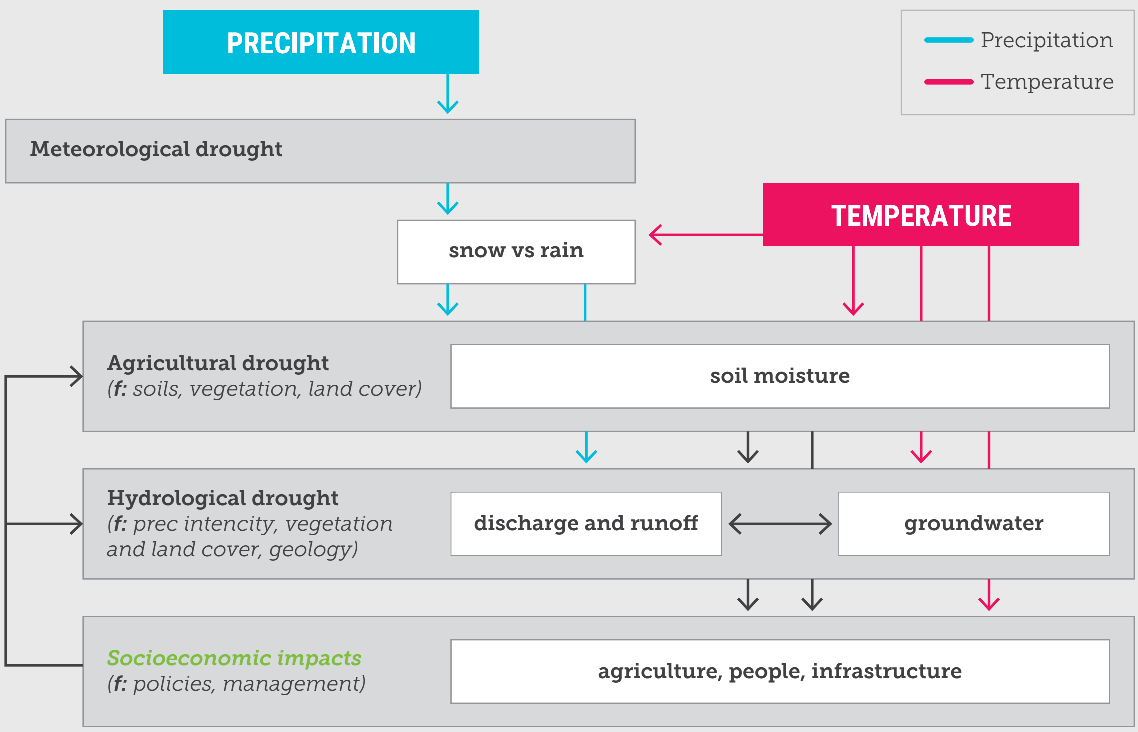
2. **The projected frequency and magnitude of floods and droughts in some regions are smaller under a 1.5°C versus 2°C of warming *(medium confidence).*** Human exposure to increased flooding is projected to be substantially lower at 1.5°C as compared to 2°C of global warming, although projected changes create regionally differentiated risks *(medium confidence).* The differences in the risks among regions are strongly influenced by local socio-economic conditions *(medium confidence).*

3. **Risks to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions *(medium confidence).*** Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions *(medium confidence).* Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate *(medium confidence).*

4. **Impacts associated with sea level rise and changes to the salinity of coastal groundwater, increased flooding and damage to infrastructure, are critically important in sensitive environments such as small islands, low lying coasts and deltas at global warming of 1.5°C and 2°C *(high confidence).*** Localised subsidence and changes to river discharge can potentially exacerbate these effects. Adaptation is happening today *(high confidence)* and remains important over multi-centennial timescales.

Source: IPCC (2018).

Droughts are difficult to measure and define as they affect multiple sectors of the economy at different timescales. As such, there is no universal definition of drought. Rather, drought is defined and measured in different ways by different users, according to where in the hydrological cycle they occur and how they affect different sectors. Droughts begin due to precipitation deficits (meteorological drought) and propagate through the hydrological cycle on a time cycle of days to years to affect soil moisture (agricultural drought) and streamflows, groundwater and surface reservoirs (hydrological drought). Rainfall deficits are the main driver of both hydrological droughts and agricultural droughts, but temperature is another important variable as it can increase evapotranspiration (Cook et al. 2018). Ultimately, droughts have multiple social, economic and ecological impacts (Figure 24).



Schematic illustrating the classical definitions of drought and the associated processes. Precipitation deficits are the ultimate driver of most drought events, with these deficits propogating over time through the hydrological cycle. Other climate variables, particularly temperature, can also affect both agricultural and hydrological drought. Credit: Cook et al. (2018)

Figure 24: Flow-chart of meteorological drought impacts on hydrological drought, and impacts on ecosystems, economy and society. **Source:** Cook et al. (2018).

6.1 Human Health

6.1.1 EXTREME WEATHER IMPACTS ON WATER

Water security is having sufficient amounts of clean, safe freshwater. Climate change threatens both the amount of water available and its quality, often through increasing the severity and frequency of extreme weather events that can change sediment loading, chemical composition, total organic carbon content and microbial quality of drinking water (WHO 2011). Heavy rainfall and floods, cyclones, drought, heatwaves and bushfires can all compromise water quality by their impact on catchments, storage dams, water treatment processes and water distribution systems. Climate change raises the risks of freshwater contamination by increasing the frequency and/or severity of these extreme weather events.

Drought and increased heat both reduce the quantity of water available. Reduced rainfall limits catchment flow into dams while higher temperatures increase loss of water through evaporation. Reduced rainfall and extreme temperatures also change how we use water, potentially increasing pressures on an increasingly limited supply through greater agricultural and domestic irrigation, or adding water to council and household swimming pools, for example. As domestic rainwater tanks dry up, more households switch to municipal water supplies, increasing demand pressures on water utilities.

Droughts can also have significant impacts on water quality, by increasing the concentration of pathogens and contaminants such as heavy metals and by depleting oxygen in what remains (Zwoslman and van Bokhoven 2007).

Then, when droughts are broken by heavy rainfall, sudden influxes of nutrients and sediments flow into rivers and streams (Wright et al. 2014). Reservoirs with low water levels are particularly prone to large changes in nutrient concentrations when rainfall occurs, and organic carbon concentrations can remain elevated for extended periods (Ritson et al. 2014; see Section 6.4.1 for hypoxic (oxygen deprivation) blackwater event).

Drought-breaking heavy rainfall can trigger health warnings. For example, in Sydney in 1998 high concentrations of the diarrhoea-causing organisms *Cryptosporidium* and *Giardia* in both raw and treated water led to a boil alert being issued (Khan et al. 2016), as did notable turbidity and concentrated pathogens in Gippsland, Victoria in 2007 (Khan et al. 2016). In Sydney in 2007, Lake Burragorang (Warragamba Dam) experienced potentially toxic cyanobacteria ('blue-green algae') levels that exceeded drinking water guidelines. The cyanobacteria bloom was first noticed near the dam wall in 2007 and continued to develop until December. During this time, toxigenic *Microcysitis* cell counts reach as high as 800,000 cells/mL (DECCW 2010). The National Health and Medical Research Guidelines label water that has a microcystin count of ≥50 000 cells/mL at 'red alert' risk levels, indicating that local authorities should issue warnings that the water body is unsuitable for primary contact (NHMRC 2010). As Sydney's water filtration plants were not designed to remove algal toxins from drinking water, the Sydney Catchment Authority resorted to drawing water only from 48 m or lower below the surface to avoid the surface algal bloom (DECC 2007).

Rising temperatures and extreme heat events can also affect water quality in a variety of ways. Temperature can alter the physical and chemical properties of water, such as toxicity and dissolved oxygen levels. Warmer water temperatures and higher rainfall are positively linked with diarrhoeal notifications regarding *Giardia* (Britton et al. 2010). Warmer water temperatures also create a more favourable environment for the growth of harmful algae, especially in waters that are rich in nutrients from sewerage overflow or nutrient runoff such as following heavy rains, as noted above. Algal blooms produce harmful toxins that affect liver function and increase the risks of hepatic cancer. Exposure can occur through direct consumption of contaminated drinking water, or via the consumption of ocean fish that have been exposed to toxins (Luber and Prudent 2009).

While drought and heat can both be detrimental to drinking water quality, heavy rainfall and flooding are the most common extreme weather events associated with threats to water quality (Stanford et al. 2014), often triggering outbreaks of gastrointestinal illness and other waterborne diseases because of contamination or disruption of potable water supplies (Cann et al. 2013; Ivers and Ryan 2006; Watkins 2012). During heavy rainfall events, various substances within water catchments can be mobilised into waterways from surface runoff, increasing levels of turbidity (water loses its transparency because of suspended particulates) and dissolved organic matter in source waters that supply dams (Hongve et al. 2004; Goransson et al. 2013; Murshed et al. 2014).

Heavy rainfall can also cause sewage overflow events in urban catchments, significantly increasing the levels of pathogenic bacteria, viruses and trace metals in water sources that flow into storage dams (Passerat et al. 2011; Schijven et al. 2013; Yard et al. 2014). The probability of identifying *Cryptosporidium* and *Giardia* in surface waters is two to three times more likely after extreme weather events, and average concentrations are also higher (Young et al. 2015). More extreme rainfall events, resulting in sewage overflow and surface runoff, have been identified as a key pathway through which climate change will increase waterborne pathogens and outbreaks of gastroenteritis (Beaudeau et al. 2011).

Storms, including cyclones and high wind events, can also have devastating effects on water supplies. The threats to water quality are the same as those encountered during heavy rainfall and flood events, but with the addition of physical damage to infrastructure and power cuts that can compromise the functioning of water treatment plants. For example, Tropical Cyclone Yasi, which made landfall as a Category 5 storm near Mission Beach between Cairns and Townsville on the 3rd February 2011, led to a power outage at the main water treatment plant in Townsville. Drinking water to Townsville residents was not available for some days after the event (Courier Mail, 2011). The powerful Tropical Cyclone Marcia, which made landfall near Rockhampton in February 2015 as a Category 5 storm, downed 1,800 power lines resulting in the loss of power to the Glenmore Water Treatment Plant. The back-up generator was being upgraded at the time and so could not be turned on. Approximately 12 days after the cyclone, elevated levels of manganese were found downstream of the water treatment plant. These levels lasted for approximately two weeks, including one day when the health guideline for manganese was exceeded (Khan 2017).

Bushfires can also affect water quality through altering catchment water balances and increasing the risks of contamination of water supplies. Bushfires generate large amounts of ash – particulate matter comprised of minerals and oxidised organic substances. Ash can be easily mobilised into streams, lakes or reservoirs within days or weeks after a bushfire, depending on wind and rainfall (Bodi et al. 2014).

The major impacts of bushfires on water quality generally occur when bushfires are followed by heavy rainfall events, which mobilise considerable quantities of sediment and soluble nutrients into catchment rivers and streams due to recently devegetated ground that is highly susceptible to erosion (Bodi et al. 2014). Bushfires can also affect hydrological processes, influencing the timing and magnitude of streamflows (Bladon et al. 2014). Destruction of forests and other plant ecosystems increases the amount of rainfall that directly reaches the ground and reduces the permeability of soil, in turn increasing runoff and increased peak flows and risk of flash flooding events (Burke et al. 2013; Bladon et al. 2014). However, in some wetter ecosystems, regenerating forests consume more water than prior to the fire, resulting in reduced streamflow into water supply systems (Vertessy et al. 2001).

In January 2003, major bushfires devastated large areas of the Australian Capital Territory (ACT), including virtually the entire Cotter catchment – the supply source for the ACT's major drinking water reservoirs (Worboys 2003). Following the bushfire, an intense 1-in-400-year thunderstorm hit the ACT, transporting large sediment loads into streams and rivers in the Cotter catchment and into the ACT's water supply reservoirs (White et al. 2015). This combination of events resulted in an unprecedented increase in turbidity, iron and manganese in the upper catchment storages, necessitating the construction of a water filtration plant and causing disruptions in water supply (White et al. 2015). More generally, the impacts of climate change on forests in water catchments through bushfires, spread of invasive species or mortality of trees due to drought can have long-term impacts on water catchments (Stanford et al. 2014).

Extreme weather events such as droughts, heatwaves, floods, tropical cyclones and bushfires can reduce water quality and availability, jeopardising water security and affecting human health.

Figure 25: Water contamination due to sewage overflows in New Zealand.

Table 3: Examples of water quality impacts of extreme weather events in Australia. **Source:** Khan et al. 2016.

Extreme weather event	Impacts to raw water quality	Impacts to finished water quality	Impacts to treatment and infrastructure	Impacts on the population
Drought-breaking heavy rainfall around Sydney, NSW 1998	*Cryptosporidium* and *Giardia* in water supply; increase in turbidity	*Cryptosporidium* and *Giardia* in treated water	Water filtration infrastructure damaged	Boil water alert issued
Wildfires around Sydney, NSW 2001/02	No direct impacts	Untreated water supplied to some customers	Infrastructure damage, power loss and inability to treat water from one source	Loss of water pressure; boil water alert issued
Drought breaking heavy rainfall in Gippsland, VIC, 2009	Increased turbidity and water colour	Increased turbidity and pathogen risk; high colour	Compromised disinfection processes; use of alternate water supply	Boil water alert issued; bottled water supplied
Drought-breaking heavy rainfall around Sydney, NSW, 2007	Increased turbidity; presence of toxic algal blooms and odorous chemicals	Presence of pathogens and toxic algal blooms; excessive nutrients	Reservoir off-take levels altered due to turbidity and algal blooms	Increased taste and odour complaints
Extreme wildfires around Melbourne, VIC, 2009	In one river supply: increased phosphorus and nitrogen; increased colour and turbidity	No impacts to quality of water that has passed through a water treatment plant	Large volumes of water transferred to more protected storages	No negative impacts
Drought-breaking rainfall in the Murray-Darling Basin, 2010	Low dissolved oxygen; increased colour and turbidity; increased dissolved organic carbon	High manganese; high turbidity; harmful by-products resulting from dissolved organic carbon and chlorine	Higher disinfectant dose rates required, coagulation required to remove dissolved organic carbon	Some people exposed to higher disinfectant concentrations and disinfection by-products
Flooding around Canberra, ACT, 2010 and 2012	Increased colour; manganese and iron; dissolved organic carbon. Decreased dissolved oxygen and alkalinity	No impacts to finished water quality	Reduced filtration rate due to sludge; increased water testing required	No negative impacts
Flooding around southeast Queensland, QLD, 2011	Increased turbidity and colour, increased conductivity; increased hardness	Inability to treat raw water to specified quality parameters	Threatened treatment filters caused plant shutdown or reduced production capacity	Water supply supplemented from other sources; no threat to public health
Flooding at Woorabinda, QLD, 2011	Increased turbidity, increased salinity from alternative source	Increased salinity	Supply pumps stop working	Water conservation measures in place during water carting period; concerns for hospital with no back-up treated water supply
Tropical cyclone at Rockhampton, QLD, 2015	Very low dissolved oxygen; high dissolved organic carbon; elevated manganese	Elevated taste, odour; total organic carbon and manganese; exceedance of harmful by-products	Controlled release of raw water; additional chlorine dosing; flushing of mains and scouring of reservoirs	Increase in taste, odour and discolouration complaints; provision of bottled drinking water

Turbidity = Measure of suspended particles in water. Dissolved Organic Carbon: Organic material from the decomposition of plants and animals dissolved in water.

Low Dissolved Oxygen can result from algal blooms and has negative impacts on aquatic life.

6.1.2 HEALTH IMPACTS OF FLOODS

Flash flooding can cause injuries and fatalities, as well as damage medical infrastructure and disrupt medical services. Between 1900 and 2015, flooding was responsible for 3,718 fatalities across Australia. Queensland has had the highest number of fatalities (37.8 percent) followed by NSW (36.7 percent) (Haynes et al. 2016).

The Queensland floods in 2010/2011 illustrate the enormous destructive potential of these extreme weather events. Major flooding occurred most severely in the Lockyer and Bremer catchments, and the Toowoomba area, with significant flooding also occurring in the Brisbane River catchment (Figure 26). The intense rainfall burst creek banks and caused flash flooding throughout Toowoomba's city centre. Around three quarters of Queensland (78 percent) was subsequently declared a disaster zone, with the floods tragically claiming 38 lives (van den Honert and McAneney 2011; Coates 2012; Deloitte Access Economics 2016). Damages from the floods cost Queensland more than $6 billion (Deloitte Access Economics 2016).

The floods reduced access to health services by cutting off roads and overloading the capacity of emergency services. The floods also created major ongoing health risks by contaminating food and drinking water. During the floods, almost one third of southeast Queensland's water treatment plants were not in operation due to flooded infrastructure or loss of power, causing poor raw water quality and necessitating the provision of bottled drinking water and public health alerts to boil water in some areas (Khan 2017).

Figure 26: Inundation of Brisbane during flood, 2011.

In addition to the direct health impacts of flooding described above, more frequent storms and flooding as a result of climate change may have important indirect effects on health. For example, flooding can increase the extent of mosquito breeding habitats, facilitating transmission of many vector-borne pathogens, and leading to an increase in vector-borne diseases (Tall et al. 2014). Excessive rainfall is the primary climatic factor influencing the transmission of Ross River virus disease in eastern Australia due to the mosquito vector's reliance on water to lay eggs and for larvae to develop (Tong and Hu 2002; Hu et al. 2004; AMCA 2018). Although Ross River virus disease can spread even without excessive rain, extreme rainfall increases the likelihood of large outbreaks (Epstein 2002). La Niña events, which are associated with high rainfall, have been correlated with increases in the occurrence of Ross River virus in southeast Australia close to the Murray and Darling rivers (Anderson and Davies 2015).

The combination of increased average global temperatures and more intense rainfall may lead to an increase in humidity, increasing the endemic potential of dengue in Australia. While control strategies are relatively effective for dengue under current conditions, areas such as inland Australia may become climatically favourable for *Aedes aegypti* (the mosquito vector) in the future (Khormi and Kumar 2014). Over recent years, however, Dengue outbreaks in the north Australian city of Townsville have been completely halted through the release of mosquitoes that are intentionally infected with *Wolbachia* bacteria, making them unable to transmit the virus. Though the trial is in its early days, it has been very successful to date and has the potential to eradicate Dengue in Australia (The Guardian 2018).

Households in southeast Australia are responding to climate change and reduced rainfall by installing water tanks. This response is inadvertently creating potential habitats for Dengue-carrying mosquitoes in urban and rural habitats. While tanks are supposed to have mesh to prevent mosquitoes laying eggs, they can be poorly maintained (e.g. mesh breaks). If the installation and maintenance of domestic water storage tanks is not rigorously assessed, there is a high potential Dengue transmission risk during warm summers (Beebe et al. 2009).

6.1.3 HEALTH IMPACTS OF DROUGHTS

Droughts also pose a serious health risk to human populations. Drought is associated with poor mental health in rural areas, arising both from personal distress and through the loss of community networks. Drought is particularly associated with increased distress among farmers, with self-reported distress highest among younger farmers living in remote areas experiencing financial hardship (Austin et al. 2018). A nearly four-decade study of suicide in rural areas in New South Wales found that suicide increased during drought (Hanigan et al. 2007). Strong social networks that exist in rural areas can ameliorate some of the personal distress experienced by farmers, but these networks can be eroded during prolonged periods of drought (Stain et al. 2011). With drought becoming increasingly frequent, severe and prolonged throughout much of southern Australia, maintaining social capital and connectedness in rural areas will need to be a key adaptation strategy to strengthen community networks and reduce the higher risks to mental distress and suicide.

Droughts and floods have direct and indirect impacts on human health.

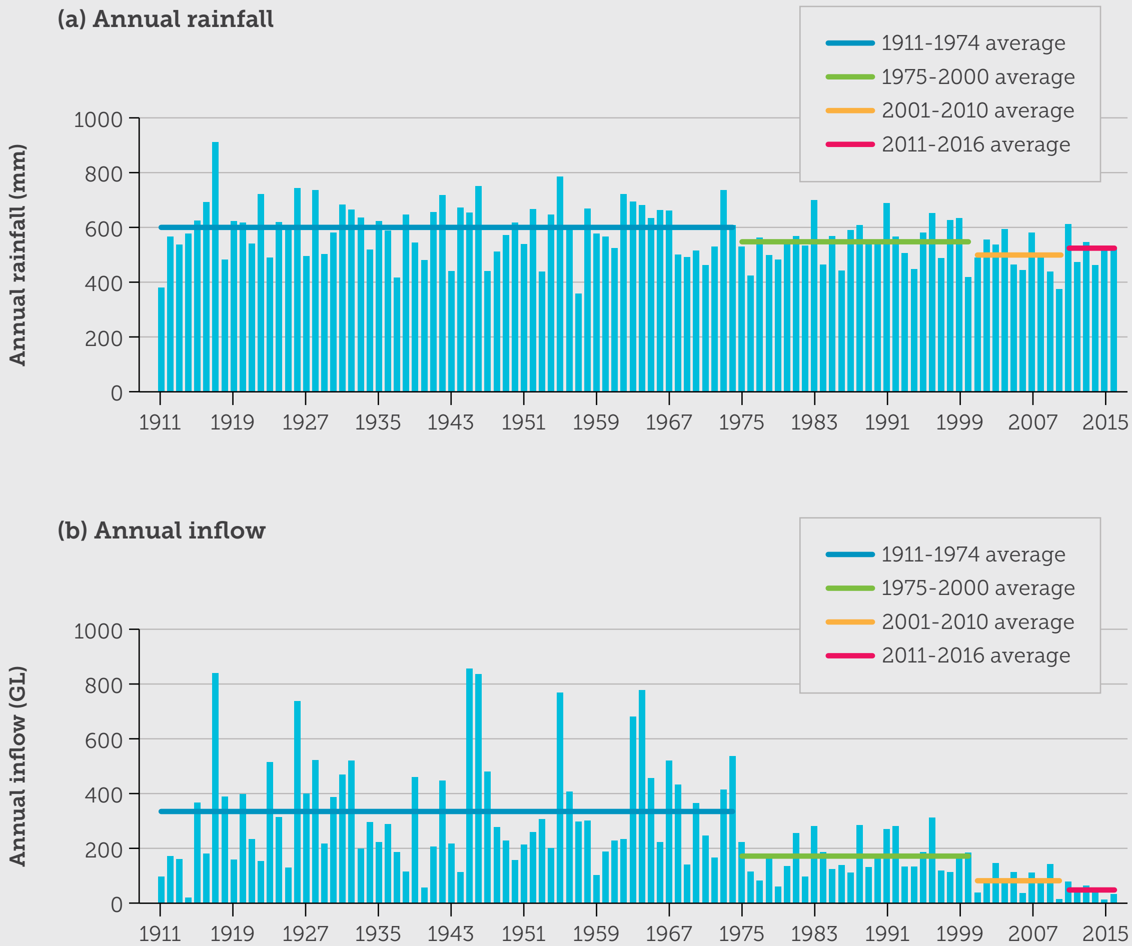
6.2 Urban Water Supplies

The first water regulation measure in Australia occurred in 1791 when the colonists chiselled water storage basins on the Tank Stream to deal with the 1790-1791 drought (Gergis 2018). Since this time, storing water in human-made dams has been important in securing urban water supplies. Nevertheless, prolonged droughts have placed serious pressure on urban water supplies, necessitating the introduction of water restrictions and changes to behaviour and consumption, and resulting in the need for new sources of water supply and water management frameworks.

6.2.1 LONG-TERM DECLINES IN DAM INFLOWS

Prolonged droughts such as the Millennium Drought have occurred against a background of long-term declines in cool season rainfall and in streamflows in southern Australia associated with climate change (see Figure 27 and section 4.3). This has had a particularly large impact on the inflows to Perth's dams. Whereas inflows to Perth's dams were on average 338 GL per year in the period from 1911 to 1974, they declined to an average of 177 GL per year in the period 1975–2000, with further reductions in the 2001-2010 and 2011-2016 periods, leading to an overall fivefold reduction from 1911 to 2016.

Melbourne's dams have also experienced long-term declining inflows. Over the last two decades, many catchments in Victoria have recorded streamflow reductions of up to 50 percent based on the long-term average. Average annual streamflow reductions of up to a further 50 percent, based on current levels, could occur in many catchments across Victoria by 2065 (DELWP 2016a).



Note: To provide an accurate historical comparison, streamflows from Stirling and Samson Brook dams are not included in these data because those dams only came online in 2001. Since the early 1980s, inflows have been estimated using the water balance technique.

Figure 27: (a) Annual rainfall in the Murray River (WA) and Swan Coast-Avon River regions and (b) annual inflow into water supply reservoirs in Perth (excluding Samson Brook dams). **Source:** BoM (2018c).

6.2.2 WATER SHORTAGES DURING THE MILLENNIUM DROUGHT

The Millennium Drought lasted from 1997 to 2009. The rainfall deficits experienced during this drought were very likely the worst since first European settlement of Australia (Gergis et al. 2012). Streamflow deficits in the River Murray were very large, with an estimated return period of 1 in 1,500 years (meaning that such an event could be expected to occur on average once every 1,500 years) (Gallant et al. 2011; Gergis et al. 2012).

During the Millennium Drought, inflows into vital urban catchments were significantly reduced, causing water levels in the major urban storage dams to shrink to their lowest levels in decades in Melbourne, Sydney, Brisbane, Adelaide and Perth.

By 2007, Victoria's major water storage dams held just 26 percent of their long-term average volume (DELWP 2016b), and just 16.5 percent in the largest storage reservoir (Melbourne Water 2018a). From 2007–2010 Melbourne was placed on Stage 3 restrictions and in 2009 Melbourne's water storage levels fell to a record minimum of 25.6 percent (Melbourne Water 2013; Melbourne Water 2014).

The Millennium Drought also created critical water shortages across southeast Queensland including Brisbane, with storage dams down to just 16.7 percent in 2007. This led to a range of institutional reforms, supply augmentations, and various demand management strategies including water use restrictions in cities and towns and severe reductions in water allocations in irrigation districts (Maloney and McDonald 2010).

In Sydney, water storage levels dropped as low as 35 percent in 2007, though algal blooms in Warragamba Dam further reduced the useable portion of this water (discussed in more detail in Section 6.1.1). Between 2003 and 2008, around 810 billion litres of water were pumped from the Shoalhaven River into Sydney's dams, and severe water restrictions were introduced. Without these strategies, Sydney would very likely have run out of water (SMH 2008).

Adelaide, which relies on the Murray River for a large portion of its drinking water, faced severe water shortages in 2006 when the river was reduced to a trickle.

In Perth, rainfall and streamflows into water storage dams have seen a long-term declining trend (Figure 27; Section 6.2.1). Water managers in Perth were well aware of this trend and had completed construction of the Kwinana desalination plant by 2006, helping Perth get through the worst impacts of the drought. Nearly half of Perth's water supply (47 percent) now relies on two desalination plants and the city has also tapped into groundwater to overcome supply shortages caused by rainfall declines (ABS 2008).

6.2.3 DESALINATION AND THE CHANGING MIX OF URBAN WATER SOURCES

The threat to household water supplies brought on by the Millennium Drought in cities across Australia prompted the construction of desalination plants in Adelaide, Perth, Sydney, Melbourne and Brisbane-Gold Coast (Table 4). Adelaide's desalination plant can supply nearly half the city's supply, but has seldom been used to date. Melbourne's plant is also rarely used, but if necessary, can supply one third of Melbourne's water. The desalination plant in Brisbane-Gold Coast is on permanent 'hot standby' mode. Perth derives half of its drinking water (nearly 150 billion litres in 2016-17) from two desalination plants and construction of a third plant is being considered. Sydney's plant was finished in 2010 and was operational for about two years, but was turned off in mid-2012 when dam levels reached 90 percent. These desalination plants, though not required much so far, have greatly improved the water security of our major urban areas, improving resilience to drought. However, they were extremely costly to construct and are more expensive to operate than traditional catchment water supplies, highlighting one of the significant economic costs of climate change-induced impacts on water security.

The contributions from different sources to urban water supplies between 2012 and 2017 are shown in Figure 28.

Table 4: Details of desalination plants in Australia.

Jurisdiction	Desalination plants	Initial investment $m	Capacity GL/ Year	Completion	Annual water supply
Western Australia	Perth Seawater Desalination Plant (Kwinana)	387	45	2006	18 percent
	Southern Seawater Desalination Plant (Binningup)	1400	100	2012	33 percent
Queensland	Gold Coast Desalination Plant	1200	49	2009	25 percent for Ipswich and Brisbane
South Australia	Adelaide Desalination Plant (Port Stanvac)	1830	100	2012	50 percent
Victoria	Victorian Desalination Plant (Wonthaggi)	3500	150	2012	33 percent
New South Wales	Sydney's Desalination Plant (Kurnell)	1890	90	2010	15 percent

Sources: AWA (2018).

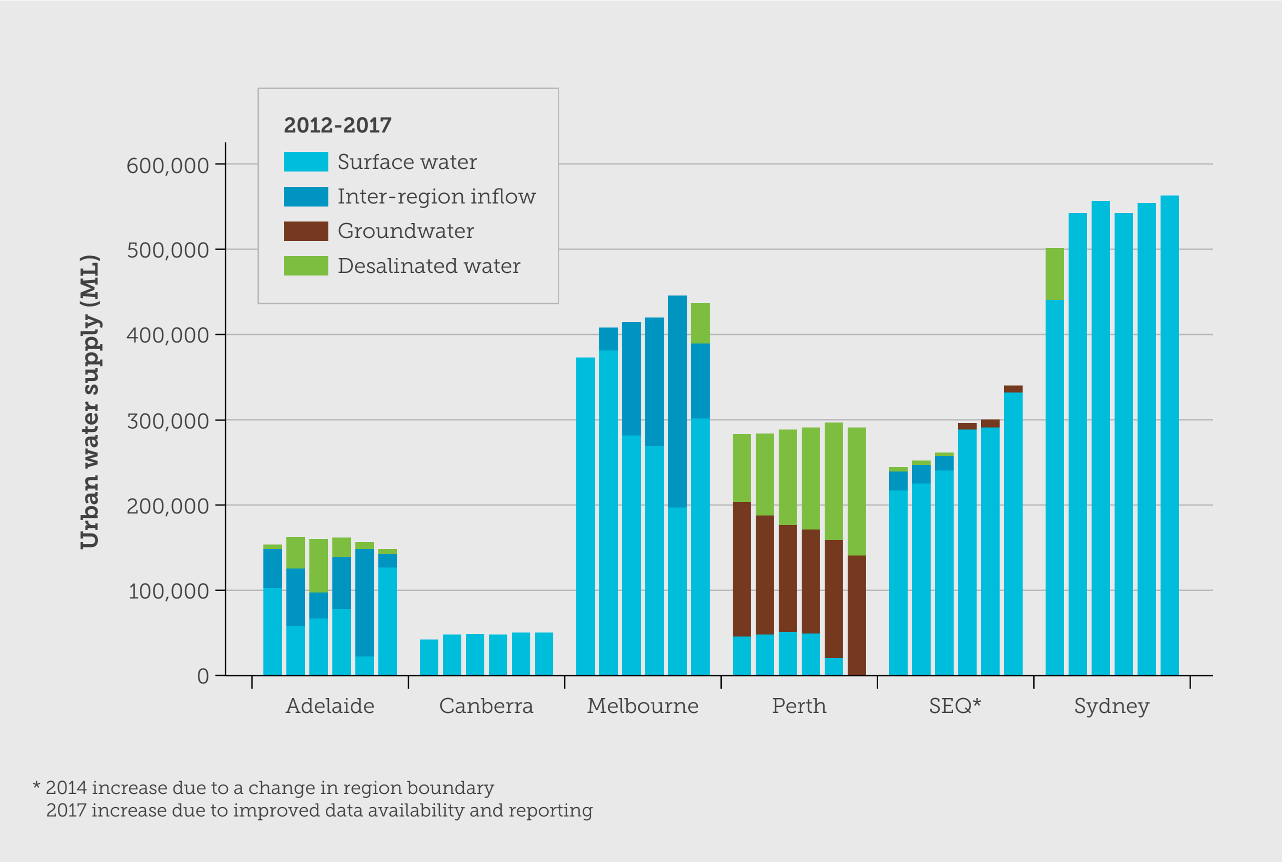


Figure 28: Sources of urban water supplies for major cities in Australia 2012 – 2017. **Source:** BoM (2018e).

The Millennium Drought caused critical shortages in urban water supplies with dam levels in many of Australia's major cities reduced to their lowest levels on record.

6.3 Agriculture

Droughts have direct and substantial impacts on agriculture, reducing livestock numbers, destroying crops, and resulting in soil erosion and loss. Local loss of production has flow-on effects to regional employment, local processing and other dependent industries, and to both domestic food prices and export earnings (Quiggin 2007).

6.3.1 IRRIGATED CROP YIELDS

The impact of the Millennium Drought on water and cotton production in the Murray-Darling Basin was substantial. Between 2002 and 2009, the operation of the water market directed the increasingly scarce water resources from lower-value broad-acre cropping to higher value permanent horticulture plantings. This reduced the socio-economic impact of the drought with the major impact focused on broad-acre cropping (AARES 2012). Irrigated production of rice fell by 99 percent and cotton by 84 percent (Figure 29) (ABS 2011). Dryland wheat yield per unit area also decreased by 12 percent during the drought compared to pre-drought years, but increased overall due to increased cropping area. Between 2002 and 2009, agricultural yields were 18-22 percent lower than average in the Murray-Darling Basin.

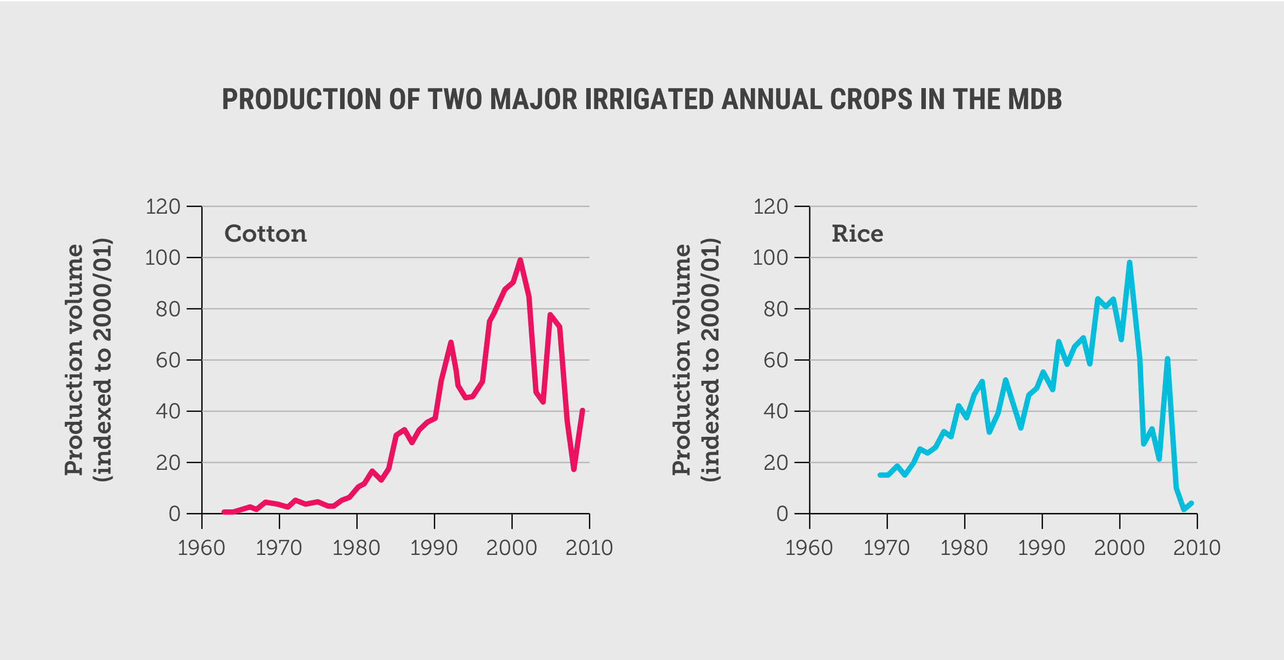


Figure 29: Reductions in production of major crops in the Murray-Darling Basin during the Millennium Drought. **Source:** van Dijk et al. (2013).

6.3.2 ECONOMIC CONTRIBUTION

Economically, the Murray-Darling Basin contributes 39 percent of Australia's total agricultural production, amounting to around $15 billion per year (Kiem 2013). However, from 2002 – 2009 the contribution of agricultural production to Gross Domestic Product (GDP) fell from 2.9 to 2.4 percent (van Dijk et al. 2013). In 2007, the Murray–Darling Basin experienced its hottest year and lowest water inflows on record causing regional GDP 2007 – 2008 to fall 5.7 percent below forecast, accompanied by the temporary loss of 6,000 jobs (Reisinger et al. 2014). Between 2006 and 2009 the drought reduced national GDP by an estimated 0.75 percent.

6.3.3 TIMING AND RELIABILITY OF THE 'AUTUMN BREAK'

The 'autumn break' refers to the first significant rainfall event of the winter growing season that breaks the prolonged dry conditions of summer. This is often a keenly anticipated event in the agricultural calendar across southern Australia as it marks the time when grain crops can be sown. If an autumn break does not occur, or occurs very late in the season, there are serious financial implications for farmers, especially if soil moisture levels are already low. Over the past few decades, the timing and reliability of the autumn break has changed, with serious implications for agriculture.

In northwest Victoria autumn breaks have declined since 1889, with 41 autumn breaks occurring in the period between 1889-1947 compared to 34 in the period from 1948 to 2006 (based on an average of records at eight weather stations in northwest Victoria). In the latter period, autumn breaks also occurred later in the growing season. Between 1996 and 2006, only three 'ideal' autumn breaks occurred (in 1999, 2000 and 2005) (Pook et al. 2009).

The Millennium Drought had serious impacts on agricultural yields in the Murray-Darling Basin with flow-on repercussions for farmers' livelihoods and the regional and national economy.

6.4 Ecosystems

6.4.1 FRESHWATER AND RIPARIAN SYSTEMS

Freshwater and riparian ecosystems worldwide have been severely degraded from over-extraction of water, pollution, over-harvesting, altered hydrological cycles, salinization, and introduced species. Climate change is exacerbating these stresses, negatively affecting aquatic and riparian species and communities, and the ecosystem services they provide. Many freshwater habitats in Australia have low overall diversity but harbour endemic species that have low ability to disperse. Species confined to aquatic habitats are particularly vulnerable to the combined impacts of warming and reduced streamflows, and have limited capacity to migrate to more suitable habitats as the climate continues to change rapidly.

Drought reduces runoff to lakes, streams and estuaries and leads to loss of freshwater and riparian habitat and to reduced or lost connectivity between waterways (Capon et al. 2013). Even relatively small marginal declines in precipitation that switch permanent waterholes to ephemeral systems have major consequences for ecological communities, especially in arid regions. Species such as water birds that use water level as a cue for breeding are particularly sensitive to changes in the hydrological cycle.

During drought, populations of many aquatic taxa decline (taxa is a group of similar organisms), with some undergoing local extinctions (Bond et al. 2008). As streams dry up, plants and animals can become stranded, and the temperature of the remaining water increases, accompanied by increased salinity, acidification, reduced oxygen, and nutrient build-up. These conditions in turn can result in algal blooms that are toxic to fish and can harm both livestock and native species (Bond et al. 2008). During the Millennium Drought, the lakes at the seaward end of the Murray River became toxic due to such algal blooms.

Freshwater fish species are particularly vulnerable to rainfall deficits and to more frequent and intense hot temperatures; climate change is expected to cause major reductions in the ranges of Australian inland fish species (Beatty et al. 2014). These projections are consistent with those predicted globally, with the diversity of freshwater fish expected to decline by up to 75 percent due to reduced streamflows from the combination of climate change and water extraction (Xenopoulos et al. 2005; Xenopoulos & Lodge 2006). Low streamflows are negatively associated with migration, reproduction and recruitment of fishes (Beatty et al. 2010, 2014; Walsh et al. 2012; Munz & Higgins 2013). A study focused on the Murray-Darling Basin found the traits that increase vulnerability to drought and climate change include low age at sexual maturity, small maximum body size, low spawning temperature, low fecundity, low upper thermal limit, and invertebrate diets (Chessman 2013).

Species modelling studies have projected that as the climate continues to change, losses of turtle species are projected in the northern Murray-Darling Basin, the Northeast Coast drainage divisions, and the Gulf of Carpentaria (James et al. 2017). Some gains in turtle species may occur in the southeast Murray-Darling Basin due to turtles moving to higher elevations, and in the Northern Territory due to species moving south and upstream in the Daly River. Loss of crayfish populations are projected along the southeast coast and loss of frog species along the eastern seaboard, with gains in frog species projected for northern Australia (James et al. 2017).

Some species of fish, amphibians and invertebrates that live in desert regions undergo a dormancy process called aestivation (similar to hibernation) in response to food or water shortages associated with hot temperatures and arid conditions. In southwest Australia, the long-term drying trend has caused large reductions in the ranges of the endemic aestivating fish species Salamanderfish *(Lepidogalaxias salamandroides)* and the Black-stripe Minnow *(Galaxiella nigrostriata)* (Ogston et al. 2016). Models suggest that future rainfall reductions may cause the water table to decline by as much as 4 m by 2030 in these regions, leading to further losses in fish populations. A review of studies found that globally, 75 percent of aestivating fish species are found in regions that are projected to experience rainfall reductions due to climate change (Ogston et al. 2016).

Many riparian and wetland species rely on seasonal inundation of floodplains which can decline or cease altogether during droughts. The Millennium Drought saw long-term rainfall deficiencies, which were amplified by evaporation and the damming and diversion of water for agricultural uses (van Dijk et al. 2013). This reduced flooding in the Murray-Darling Basin for an extended period, with significant impacts on water birds, fish, aquatic plant populations and riparian ecosystems (Bond et al. 2008; LeBlanc et al. 2012). Lack of flooding led to changes in the structure and composition of freshwater plant communities, with significant reductions in the cover of perennial aquatic plant species in wetlands along the Murray-Darling River (Wassens et al. 2017). The iconic river red gum *(Eucalyptus camaldulensis)* forests, which are adapted to periodic flooding, suffered declining condition and increased mortality during the drought (MDBC 2003; Gehrke et al. 2006; Victorian Environment Assessment Council 2006; Bond et al. 2008; Davies et al. 2008; van Dijk 2013). Some of these communities are now partially recovering in response to environmental watering.

Following extended droughts, rewetting of waterways and floodplains can result in blackwater events - the release of high levels of dissolved organic carbon (DOC) from decaying vegetation into the water column (Kerr et al. 2013). Blackwater events occur naturally in lowland rivers with forested floodplains and provide a variety of benefits for aquatic and floodplain biota. But after very severe droughts, especially if accompanied by high temperatures, respiration of the organic carbon by microorganisms can reduce the oxygen levels in the water to hypoxic levels, leading to extensive mortality in fish and other aquatic species (Hlaydz et al 2011; King et al. 2012). For example, a series of spring and summer floods in 2010-11 following the Millennium Drought caused unprecedented inundation of both forested and agricultural floodplains that had not been flooded for more than a decade. This mobilized large stores of reactive carbon on the floodplains and resulted in a large-scale hypoxic blackwater event in the southern Murray-Darling Basin that affected more than 2000 km of river channels and persisted for six months (Whitworth et al. 2012). Increasing severe droughts interspersed with more intense floods in the future are predicted to increase the risk of such hypoxic events.

Climate-driven changes to the water cycle are affecting species richness in freshwater ecosystems.

6.4.2 TERRESTRIAL ECOSYSTEMS

Drought-related mortality has been observed in many species, including amphibians in southeast Australia (MacNally et al. 2009), savanna trees in northeast Australia (Fensham et al. 2009; Allen et al. 2010), Mediterranean-type eucalypt forest in the southwest, and Western Box and eucalypts in sub-alpine regions in Tasmania (Calder and Kirkpatrick, 2008). The Millennium Drought is also estimated to have caused the loss of 57,000 ha of planted forest (van Dijk et al. 2013). Declining rainfall in southwest Western Australia is drying the ephemeral (wet only seasonally or during wet years) swamps that are home to our rarest reptile species, the endangered Western Swamp tortoise *(Pseudemydura umbrina)* (Figure 30). The tortoise is now restricted to only four locations near Perth, with fewer than 200 individuals remaining (Arnall et al. 2014).

Long-term reductions in rainfall also alter fire regimes and the interaction of drought and bushfires can have significant impacts on species and ecosystems. Drought-exacerbated bushfires are now occurring in vegetation types such as alpine areas and rainforests that are extremely sensitive to damage. For example, fires in January 2016 occurred in the alpine vegetation of Tasmania's World Heritage Area, destroying pencil pines that were over 1,000 years old. Recovery of these areas has been slow to non-existent to date.

Native fauna are also sensitive to the combination of drought and bushfires. For example, in southwest Western Australia, the combination of declining rainfall, drought and changing fire regimes has had significant negative impacts on mainland populations of the quokka *(Setonix brachyurus),* an endangered endemic macropod. (Gibson et al. 2010).

Figure 30: The western swamp tortoise is threatened by changes in the water cycle.

6.4.3 INVASIVE SPECIES

Riparian ecosystems are particularly sensitive to weed invasions, especially after extreme floods. Flooding may physically uproot or damage riparian vegetation and these gaps are then vulnerable to weed invasion from seeds carried in the water (Richardson et al. 2007). The tamarisk, *Tamarix aphylla* (also known as Athel pine), is considered one of the worst weeds in Australia because of its invasiveness, potential for spread, and economic and environmental impacts. A native of Asia and northern Africa, tamarisk seeds are spread by water and it can form dense stands along infested rivers. The species consumes water more rapidly than native plants, reducing the number and quality of watering holes. It makes the ground beneath saltier and excludes native pasture grasses and other salt-sensitive plants. The worst known infestation of tamarisk occurred along hundreds of km of the Finke River in central Australia near Alice Springs after severe floods in the 1970s and 80s that removed native eucalypt vegetation and washed seeds downstream (Griffin et al. 1989). The infestation has resulted in changes to the groundcover which is now dominated by introduced and salt-tolerant species. In turn, these areas have reduced diversity of native birds and reptiles.

Disturbances to the hydrological cycle, combined with warming, also have implications for invasive freshwater fauna. For example, the introduced Mosquito Fish *(Gambusia holbrooki),* and the Common Carp *(Cyprinus carpio)* are better able to cope with hot temperatures and low dissolved oxygen (hypoxic conditions) than many of the native fish with which they compete (King et al. 2012).

6.4.4 COASTAL FISHERIES

Sustained reductions in river outflows affect productivity of coastal waters, with important implications for fisheries. Historically low outflows from the Murray River during the Millennium Drought, for example, greatly reduced primary productivity in adjacent coastal waters, negatively affecting pipi *(Donax deltoids)* and mulloway *(Argyrosomus japonicus)* fisheries (Auricht et al. 2018).

6.4.5 INTERACTION WITH HUMAN ADAPTATION TO CLIMATE CHANGE

Species and ecosystems are not only affected directly by climate impacts on the hydrological cycle, but also by the indirect impacts of human adaptation to water insecurity (Maxwell et al. 2015). This may occur via increases in small scale farm dams and larger storage facilities, and by further extraction of "environmental water" for agricultural or urban uses. Further, mitigation measures such as increased infrastructure for hydropower and increased carbon sequestration in fast-growing plantations can also have negative impacts on local ecosystems and species via changes in local hydrological conditions.

BOX 4: WATER MARKETS AND WATER TRADING IN AUSTRALIA

To overcome the problem of finite, variable and scarce water resources, water markets have been developed in Australia for allocating water between competing uses, particularly in the Murray-Darling Basin. The development of water markets has been the product of concerted efforts on the part of governments, water service providers and other users. In the past, water licenses in Australia were tied to ownership of land and no mechanisms existed to transfer water between users. Water trading has largely enabled water to be used more productively, and provided greater flexibility for irrigators. For example, during the Millennium Drought, the net value of agricultural production was able to be maintained with only 30 percent of the regular water allocations in the Murray-Darling Basin (AARES 2012).

The first tentative steps towards water trading were made in the 1980s and 1990s. Initially, only temporary trading of water allocations was allowed (as opposed to permanent trading of water entitlements) and this was limited to certain areas. The expansion of water markets in Australia was facilitated by the nationally agreed framework for water reform in 1994 and the National Water Initiative in 2004. These agreements facilitated the expansion of water trading across state borders, particularly in the Murray-Darling Basin. *The Water Act 2007* further refined the rules for water trading in Australia and guides the implementation of the National Plan for Water Security in Australia.

The water market in the Murray-Darling Basin is based on a 'cap and trade' system. The total pool of water potentially available for irrigation is capped at the aggregate volume of all water use entitlements. If new users wish to access water, they need to acquire a water entitlement and this can only be obtained from an existing water entitlement holder because the consumptive pool is capped. Within an irrigation season, the amount permitted to be accessed is commonly less than the entitlement, because the actual availability of water is lower than normal. This permissible take of water is known as the 'allocation' and is based on the water held in storage at the start of the irrigation season, and then adjusted as the season progresses. As with entitlements, this 'allocated' amount can also be traded between users during the irrigation season. The price of both permanent entitlements and temporary allocations fluctuates according to supply and demand (MDBA 2018). Water trading has been a largely effective means of allocating water among different uses in Australia, helping farmers and communities through severe drought and providing a mechanism for allocating water towards the environment.

BOX 4: CONTINUED

During the Millennium Drought, temporary water prices reached over A$1000/ML in many regions. This facilitated the trade of water towards higher value uses. The Productivity Commission found that the use of water trading halved the impact of the Millennium Drought on the Australian economy (MDBA 2016). Water trading has delivered numerous benefits valued in the hundreds of millions and has been a major success story.

Challenges lie ahead in resolving issues around the future risks to supply from climate change, risks that have as yet not been adequately assigned to different users. As noted earlier, the mid-latitude location of the Murray-Darling Basin makes it particularly susceptible to long-term drying as a result of climate change (CSIRO and BoM 2015; Sections 4.1 and 5). Of major concern is a possible reduction in streamflows in the Basin associated with the projected cool season rainfall decline (CSIRO and BoM 2015), threatening riverine and riparian ecosystems (Cowan and Cai 2009). Future declines in streamflows, should they eventuate, will reduce the reliability of current water entitlements, increasing the risks to the ecological health of river systems and increasing the uncertainties surrounding water availability for communities in the Basin.

The Murray-Darling Basin Authority will introduce Sustainable Diversion Limits in 2019, which reduce how much water, on average, can be used by towns and communities, farmers, and industries, while keeping the MDB rivers and environment healthy (MDBA 2018). The Basin Plan makes provision for the periodic review of these limits, taking into account changes in climate and the resulting availability of water. Given the drying trends projected in the southern Murray-Darling Basin, it seems likely that the Sustainable Diversion Limits prescribed under the Basin Plan will need to be lowered at some point in the future. This has the potential to cause social distress and negative economic impacts if the runoff reductions are as great as projected (Pittock and Finlayson 2013; Pittock et al. 2015).

6.5 Energy Systems

Water and energy systems are closely linked. Changes to water systems affect electricity generation, particularly from hydro- and coal-fired power stations, which rely on the availability of large quantities of water (Smart and Aspinall 2009). Transitioning to renewable energy sources like wind and solar reduces water security risks for electricity generation. The water sector is also a large user of energy, particularly for processes like pumping and desalination. Some Australian water authorities are leading the way by reducing their energy use and emissions by switching to renewable energy. For example, North East Water, a Victorian water utility, is planning to install 43kW of solar panels and 40kW of battery storage to its water treatment plant in Yackandandah as part of the company's commitment to becoming carbon neutral (RenewEconomy 2017).

6.5.1 WATER, CLIMATE CHANGE AND ENERGY SECURITY

Extreme weather events (e.g., heatwaves and extreme rainfall) and other changes to water systems (e.g., dry spells and drought) can affect electricity generation from coal, gas and hydro. Coal and gas power stations require large amounts of water for cooling. Drought conditions may reduce power station access to cooling water, and heatwaves can increase water temperatures, reducing the effectiveness of cooling. Both circumstances can potentially reduce electricity generation (Marsh 2009; NSW Chief Scientist and Engineer 2017). Higher temperatures and lower rainfall lower dam levels and reduce water availability for hydro generation (NSW Chief Scientist and Engineer 2017). Flooding can affect the transportation of coal and can cause coal mines to close during the flooding event (NSW Chief Scientist and Engineer 2017). For example, in NSW in 2015, floods in the Hunter Valley damaged rail equipment and affected the transport of coal (ABC 2015). The Yallourn coal mine in Victoria flooded in 2008, 2012 and 2013. In 2012, the mine was flooded for six weeks, limiting the operation of the Yallourn coal-fired power station (The Age 2012; Australian Mining 2013).

Transitioning our electricity systems to renewable energy sources like wind and solar, which have minimal water requirements, can reduce overall water consumption (IRENA 2015), as well as reducing the risks to electricity generation associated with droughts, heatwaves and flooding. Modelling by the International Renewable Energy Agency found that by transitioning to 50 percent renewable energy in 2030 (excluding biofuels), Australia could reduce water consumption by the electricity sector by 24 percent, compared with business as usual (IRENA 2015).

6.5.2 RENEWABLE ENERGY AND STORAGE OPPORTUNITIES IN THE WATER SECTOR

There are numerous opportunities for the water sector to generate and facilitate renewable energy, ranging from renewable powered desalination, floating solar panels, mini-hydro and capturing biogas from wastewater treatment. Water infrastructure can also be used for pumped hydro energy storage to support increased uptake of renewable energy (Beca 2015; IRENA 2015).

Desalination projects in Australia have all contracted renewable energy sources to power their operations (or to 'offset' their emissions) (Acciona Australia 2018; Sydney Desalination Plant 2018; Water Corporation 2018; Water Technology 2018; Victoria State Government 2018; Table 4). Other organisations are demonstrating the use of solar power for on-site water desalination. For example, Sundrop Farms uses solar thermal energy to convert seawater into freshwater for use on its tomato greenhouses (ABC 2016). The Australian Renewable Energy Agency (2018) is funding a trial of a solar-powered water system to be rolled out across 150 sites. The system produces clean drinking water directly from the air using solar powered technology.

Floating solar panels (on water storages or wastewater treatment ponds) offer a range of unique benefits: cooling from the water improves the performance of the solar panels; the floating panels can be easily rotated to track the sun; and the shading from the panels reduces evaporation by up to 75 percent, saving water. Australia's largest floating solar farm is a 100kW system on ponds at the East Lismore Sewage Treatment Plant. This system generates 12 percent of the treatment plant's energy needs (One Step off the Grid 2018; Figure 31). In September 2018, the Lismore Community Solar initiative won a national award for community partnerships and collaboration (Lismore City Council 2018).

Figure 31: Lismore's solar plant, Australia's largest floating solar plant.

6.5.3 WATER AUTHORITIES LEADING THE WAY

Metropolitan water authorities in Melbourne have a target to reduce emissions to net-zero by 2030 and are taking steps to transition away from fossil fuels to renewable energy. For example, Melbourne Water generates more renewable energy than it uses and is shifting its fleet of vehicles away from combustion engine vehicles to zero emission electric vehicles (Melbourne Water 2018b; 2018c).

7. Implications for Australia of Changes in the Global Water Cycle

Changes to the global water cycle could lead to large-scale political and social instabilities and conflict, with potential knock-on effects for Australia's security. In some global hotspots, changes to the water cycle are already occurring, and could have flow-on implications for our region. Water scarcity in global hotspots could lead to conflict within the Asia-Pacific region, or to conflict in other regions that could lead to Australian involvement. Water scarcity could also lead to destabilisation of the global geopolitical and economic order more generally, resulting in an increased flow of refugees due to food and water shortages or conflict elsewhere. Australia would not be immune from the effects of such political and social destabilisation, which could extend out from their regions of origin to have potentially global consequences (Climate Council 2015a).

7.1 Global Hotspots

The most well-known global hotspot for water-related risks is the Middle East and North Africa (MENA) region[1]. Many of that region's water resources are transboundary (shared amongst two or more countries), including the Nile, the Jordan and the Tigris-Euphrates, the three most significant rivers. About 60 percent of surface waters are shared resources, and each country in the region shares at least one underground aquifer (World Bank 2017). Water use agreements made between countries have been effective in the past in managing scarce water resources, but such agreements are usually based on historical average streamflows. These agreements may come under pressure as climate-induced changes in the water cycle accelerate - declining rainfall, increased variability, and increasing average and extreme temperatures, resulting in more evapotranspiration and rising water requirements for agriculture (Verner 2012; IPCC 2014; Lelieveld et al. 2016). These climatic changes are very likely to cause streamflows to fall below historical average rates (World Bank 2017).

Indeed, water scarcity in the MENA region has already reached very high levels and is projected to increase due to climate change (see Figures 11 and 20 and Section 5). About 60 percent of the region's population live in areas with very high surface water stress (World Bank 2017). Although water scarcity in this region has been apparent for hundreds of years, recent pressures such as accelerating population and economic growth, poor governance and climate change have led to an unsustainable supply-demand imbalance with resultant depletion of groundwater and surface water supplies. The cascading social, economic and political impacts of this increasing water scarcity have become apparent in recent years.

Syria's worst drought in recorded history (2007 – 2010), was likely a contributory factor in the political unrest and instability that sparked the Syrian civil war, leading in turn to the flow of refugees out of the country (Hoerling et al. 2011; Slaughter et al. 2013; Homer-Dixon et al. 2015). The drought was caused by a combination of natural variability and a long-term declining rainfall trend (Kelley 2015; Cook et al. 2016). At the same time, temperatures in the eastern Mediterranean have risen, leading to increased evaporation and reduced soil moisture. Observations of decreased rainfall and increased temperature are consistent with current and future climate change projections for this region. Model simulations compared to observed trends indicate that human interference with the climate system has increased the probability of severe and prolonged droughts in the region by two to three times (Kelley 2015).

[1] This region includes Algeria, Bahrain, Dijbouti, the Arab Republic of Egypt, the Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, Tunisia, the United Arab Emirates, West Bank and Gaza, and the Republic of Yemen.

The Syrian drought contributed to the failure of agricultural crops and the migration of an estimated 1.5 million people from rural areas to the outskirts of urban areas. This in turn led to the establishment of overcrowded settlements with insufficient infrastructure. Rapid demographic change resulted in growing inequality, unemployment and increased crime, feeding unrest and dissatisfaction with the government. Although it is impossible to determine the precise extent to which the drought contributed towards the ensuing civil unrest, it is evident that it played a role by increasing pressure on water supplies, intensifying the pre-existing threats posed by poor policies, unsustainable agricultural practices, and rapid population growth (Kelley 2015). In that regard, drought and other climate-related factors that can contribute to conflict are often referred to as "threat-multipliers" in the security and defence communities (Climate Council 2015a).

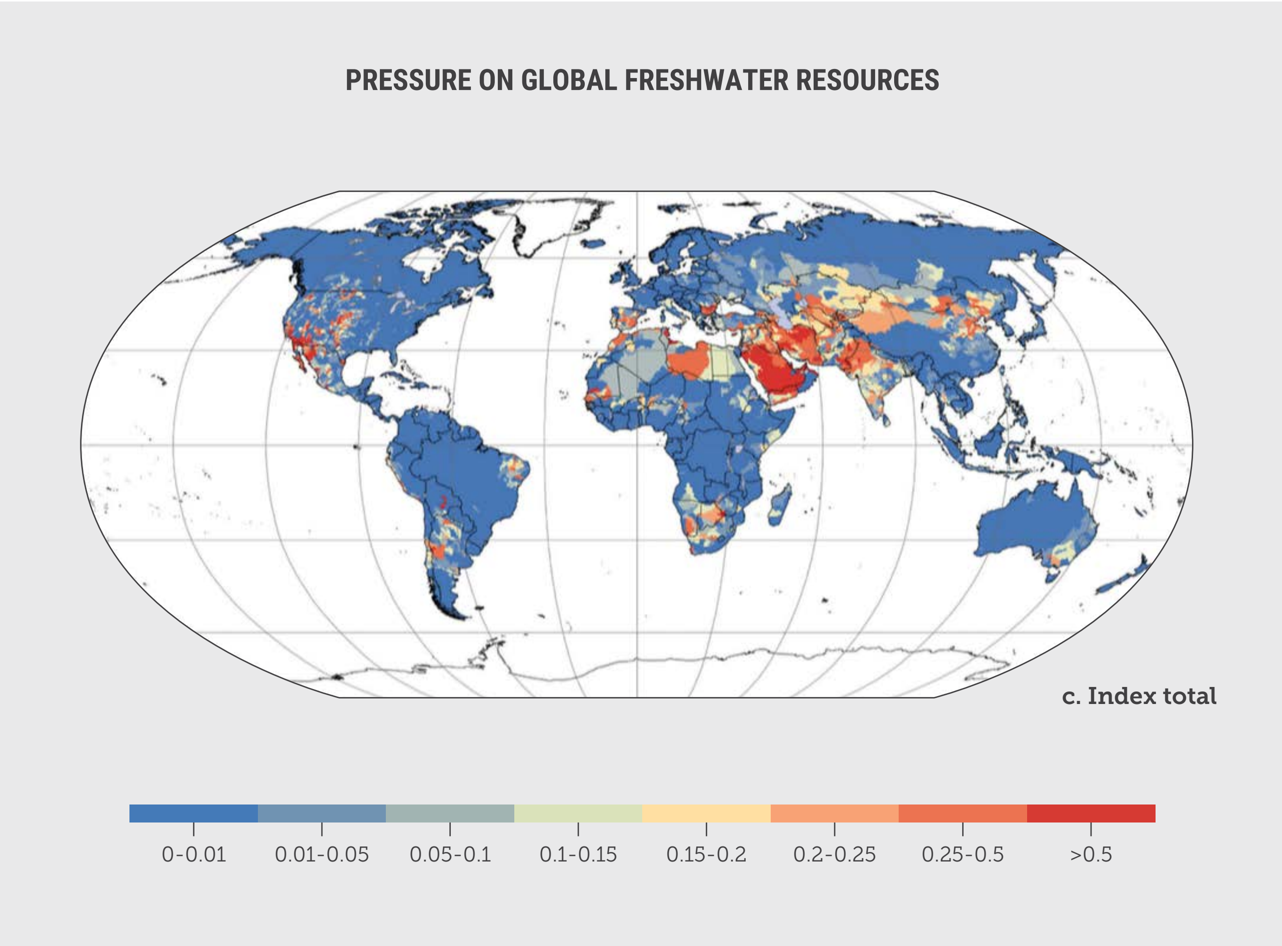


Figure 32: Map shows the portion of consumptive water use that is from unsustainable surface and groundwater water sources. Unsustainable surface water is the amount of environmental flow requirements not satisfied due to over extraction. Unsustainable groundwater use is the difference between groundwater abstraction and groundwater recharge (natural and human). Based on the Blue Water Sustainability Index from Wada and Bierkens (2014).

Water insecurity is likely to increase even further in the MENA region in coming decades. Projections indicate that Syria, Morocco, Jordan, Lebanon and Iraq will all face a significant increase in water stress as a result of climate change (Figures 32; 33), exacerbating the social and political fragility already faced by these states. Climate change-related impacts on water scarcity are projected to result in economic losses of between 6-14 percent of GDP by 2050 in the MENA region (World Bank 2016; World Bank 2017). Economic impacts are expected to be worse in areas where governments are already failing to deliver sufficient water services and mitigate water-related risks and hazards.

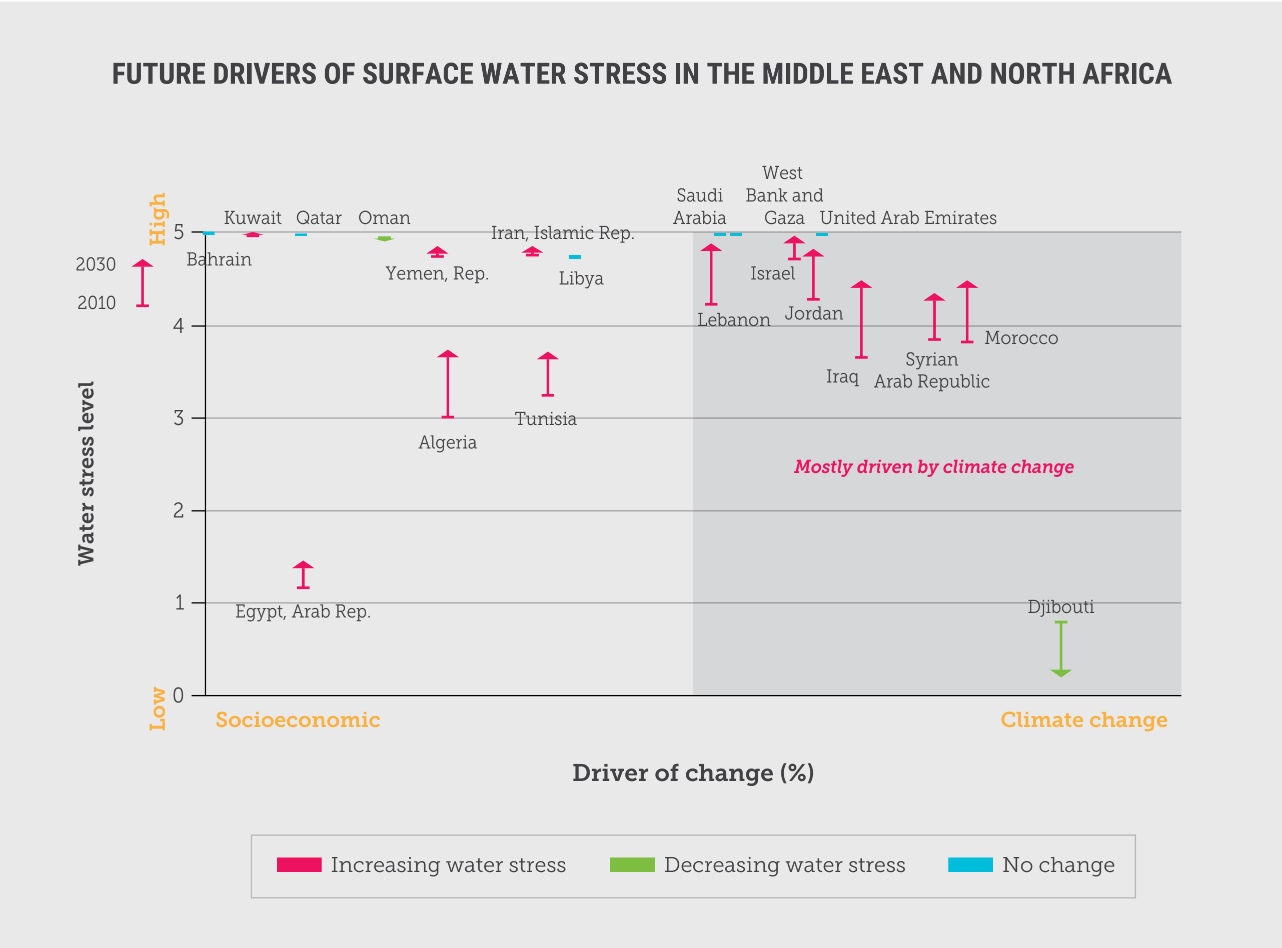


Figure 33: Future Drivers of Surface Water Stress in the Middle East and North Africa. Water stress is calculated based on annual water withdrawals compared to annual surface water availability under a business as usual (high emission) scenario and a business as usual scenario for socio-economic change. **Source:** World Bank (2017) based on World Resources Institute Aqueduct data.

Further south in Africa, climate change has also contributed to increasing water insecurity, playing a role in Cape Town's recent severe drought (Otto el al. 2018), together with poor water management (Muller 2018). Between 2015 and 2017, the Western Cape region experienced three consecutive years of below-average precipitation, leading to acute water shortages in the storage reservoirs that provide water to Cape Town's population of about 3.7 million people. Water levels were so low by early 2018 that a water ration of 50 litres per person per day was mandated, and washing cars, watering gardens and filling pools was banned (Figure 34). At the beginning of 2018 it was anticipated Cape Town would face 'Day Zero' by March 2018, which was when the city's six storage dams were expected to fall to just 13.5 percent of capacity, leaving just enough water to supply critical services (Welz 2018). At Day Zero, the taps would be switched off and citizens would have to line up at distribution points throughout the city to receive an allocation of 25 litres of water per person per day.

Fortunately, Day Zero was avoided through the return of rains and a concerted demand management campaign that achieved a major cultural change in water use, as had similar campaigns in Australia during our own drought. Through demand management, the city almost halved its water use during 2018 compared to the average over the previous five years, tracking very closely to the Department of Water and Sanitation restriction requirements (City of Cape Town 2018). Water security will become increasingly challenging in Cape Town in the future. Rainfall is projected to continue to decline due to climate change, placing pressure on the supply-demand balance. Indeed, scientists have calculated that climate change tripled the likelihood of the 2015-2017 Cape Town drought and that the probability of similar droughts occurring in the future will increase with further climate change (WWA 2018).

Despite the success story of Cape Town in avoiding Day Zero in the short term, the near-crisis highlighted the deep-seated inequalities between classes and races in South Africa, with wealthier people able to pay for expensive boreholes or bottled water whilst poorer people were forced to abide by the water rations and rely on the government. As shown in the Syrian example, deep inequalities and other social issues can intersect with climate change-driven changes in the water cycle to exacerbate existing tensions and generate conflict that leads to large-scale migration.

Figure 34: Queues for water in Cape Town during water shortages in 2018.

7.2 Long Fuse, Big Bang Impacts

In Asia, climate change will have 'long fuse, big bang' impacts on freshwater availability, meaning that the impacts of climate change will play out slowly but could have disastrous consequences (Homer Dixon et al. 2015). Besides the Arctic and Antarctica, the largest ice masses on Earth are located in the Tibetan Plateau and the mountain ranges of Asia - the Hindu Kush, the Himalayan Range and the Karakorum Range. These mountain ranges are covered in tens of thousands of glaciers whose meltwaters feed 267 river systems in Asia. The total freshwater resources in these glaciers are not known exactly, but estimates range from 2,100 Gt to 5,800 Gt of ice (equivalent to 2,100 to 5,800 km3 of water when it melts) (Bolch et al. 2012). The civilisations of Asia have evolved around the river systems that are fed by these glaciers, including the Ganges, Amu Darya, Indus, Brahmaputra, Irrawaddy, Mekong, Yellow and Yangtze Rivers. The Indian sub-continent, which includes Bangladesh, Bhutan, India, Nepal and Pakistan, is particularly reliant on melting glaciers for supplemental flows to river systems.

Over the last few thousand years (during the Holocene, the Earth's most recent geologic time interval), these glaciers have maintained their mass balance, accumulating ice at a rate equal to or greater than the melt rate. The glaciers of these mountains have thus functioned like an enormous storage reservoir for Asia, feeding freshwater into the river systems before the monsoon arrives. However, over the past 50 years the mass balance of these glaciers has been negative, with the rate of loss suspected to be greater since the mid-1990s. Climate change projections indicate that the Himalayan glaciers will lose on average 45 percent (with a range of 15-78 percent) of their mass by 2100 under a scenario where warming is limited to no more than 2°C above pre-industrial levels. Under a scenario where greenhouse gas pollution continues on a business as usual scenario, the Himalayan glaciers are projected to lose an average of 68 percent of their mass by 2100 (NASEM 2012; Cisneros et al. 2014). Over shorter time periods, the region faces the risk of sudden flooding in steep river catchments as water from ice melt, accumulating in high altitude glacial lakes, can suddenly be released if the natural dams forming the lakes burst (Emmer 2017).

South Asia faces compounding risks to its water resources due to climate change. The South Asian monsoon system, which brings regular rainfall to the sub-continent during the May-September period and is the ultimate source of water for the Himalayan glaciers, is also at risk from the combination of climate change and regional air pollution. The monsoon depends on the temperature difference between the land and the Indian Ocean. The emission of aerosol particles (certain types of air pollutants) can reduce incoming sunlight by 10-15 percent (Ramanathan et al. 2005), thereby cooling the land surface, at the same time that climate change is driving rapid warming of the Indian Ocean surface waters. The combination of these effects is decreasing the land-sea temperature difference and thus increasing the risk that the monsoon system will weaken or even flip to a much drier state (Zickfeld et al. 2005).

Growing water insecurity in South Asia could well exacerbate existing tensions and threats, acting as a 'threat multiplier'. With growing population and increasing risks to its water resources, India's water supply is projected to fall 50 percent below demand by 2030 (Ahmed 2017; Figure 35). Neighbouring Pakistan is already regarded as one of the most water-stressed countries in the world. Furthermore, its water demand is growing rapidly, and there appears to be few feasible options to mobilize much more water than it currently uses (Briscoe and Qamar, 2008). Increased pressures on freshwater resources will increase competition between neighbouring countries sharing transboundary water resources, and if not handled successfully through agreed sharing arrangements, the risks of conflict and unrest may increase. This is particularly so in contexts where prior geopolitical tensions exist, as is the case with nuclear-armed India and Pakistan.

Figure 35: Pastoralist community of Rajasthan, India move their flocks in search of water during shortages in 2014.

8. Conclusion

The spatial and temporal patterns of the water cycle shape the distribution of human populations and their livelihoods, and support many diverse ecosystems. This is particularly true for Australia, the driest inhabited continent on Earth with a highly variable water cycle – the land of drought and flooding rains. Australia's human populations have long had to cope with this variability, clustering along the coastal fringes where water is more reliably available. Our ecosystems are also finely tuned to these long-term patterns.

Climate change has already altered the long-term patterns of Australia's water cycle in profound ways, exacerbating the already high level of natural variability. The proportion of rainfall occurring as heavy events has increased and droughts are becoming more severe. Long-term patterns of rainfall are also changing. The densely populated, agriculturally important southeast corner of the continent has experienced a cool-season drying trend over the past few decades. Southwest Western Australia is experiencing a similar, but more pronounced, drying trend.

The impacts of these changes in our water cycle are already severe. Recent droughts have threatened water supplies in our large capital cities, resulting in the rushed and very costly construction of six major desalination plants. Droughts have afflicted the agricultural sector, resulting in the failure of crops, declines in livestock, and increased soil loss. Heavy rainfall, floods and droughts have damaged human health, with increases in vector-borne diseases during floods and an increase in rural suicides during droughts. Dry conditions and extreme heat in Tasmania triggered bushfires that destroyed large areas of World Heritage forests, and even larger areas of the Australian Alps were burned in the massive 2003 fires. During the Millennium Drought the contribution of the agricultural sector to Australia's GDP fell from 2.9 to 2.4 percent.

As high levels of greenhouse gas pollution drive more severe changes to the climate system, even more profound changes to Australia's water cycle are expected, with increasing threats to urban water supplies, the agriculture sector and natural ecosystems. A greater frequency of extreme droughts is expected in all regions. Across the country, except possibly southwest Western Australia, extreme rainfall events are projected to become even more intense. Cool season rainfall is projected to continue to decrease across southern Australia, with an increased frequency of extreme drought. The costs of adapting to these changes are large and increasing.

Changes in the water cycle in other parts of the world will also likely have an impact on Australian society. Increasing water insecurity in many regions is now recognised as a threat multiplier, rapidly becoming a regional and even global security issue. The worst drought in Syria's history, likely influenced by climate change, is a key factor in the conflict there, leading to a surge of refugees that is challenging the stability of political systems in many European countries. Food security for large populations in the Indian sub-continent is vulnerable to melting Himalayan glaciers and potential instability of the Indian monsoon, with implications for political and social stability in our part of the world.

We are now facing a 'fork in the road' in terms of the choices we face. We are already committed to increased variability of our water cycle by the momentum in the climate system built in by past emissions. But if we can achieve the rapid emissions reduction pathway required to meet the Paris targets of keeping temperature rise to less than 2°C above pre-industrial levels, disruption of the water cycle will slow in coming decades with stabilisation possible later this century. But continuing on our current trajectory of high emissions has enormous and growing risks. Dealing decisively and effectively with climate change cannot be put off any longer. Solutions are available. We need to accelerate the transition to clean, affordable and reliable renewables and storage technologies and ramp up other climate solutions in the water, transport, agriculture and other sectors.

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