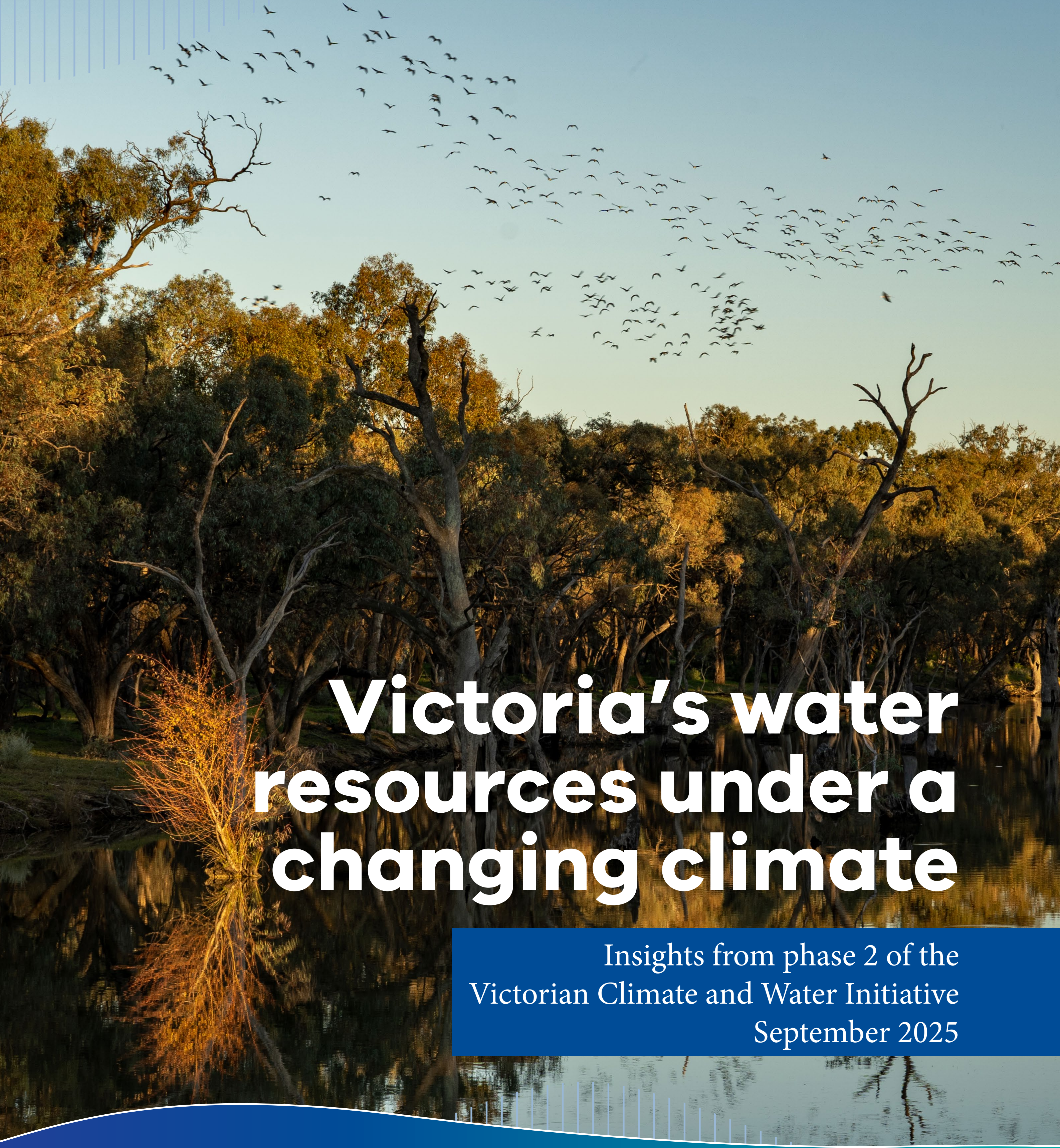


Victoria's water resources under a changing climate

Insights from phase 2 of the
Victorian Climate and Water Initiative
September 2025

Australian Government
Bureau of Meteorology
CSIRO
VICTORIA State Government
Energy, Environment and Climate Action

Acknowledgements

The Victorian Water and Climate Initiative was funded by the Victorian Government Department of Energy, Environment and Climate Action (DEECA), with financial contributions from the Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

This research was undertaken with the assistance of resources from the National Computational Infrastructure (NCI Australia), an NCRIS-enabled capability supported by the Australian Government.

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

DEECA is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.

ISBN 978-1-76176-032-7 **(pdf/online)**

Accessibility

To receive this document in an alternative format, phone the Customer Service Centre on 136 186, email customer.service@delwp.vic.gov.au, or contact National Relay Service on 133 677. Available at DEECA website (www.deeca.vic.gov.au).

Contributors

Project team

- **DEECA (Hydrology and Climate Science team):** Geoffrey Steendam, Sandra Dharmadi, Rachel Brown, Gil Aitken*, Jasmin Hartel* and Jacqui Lloyd.
- **Bureau of Meteorology:** Irina Rudeva and Pandora Hope (project leads), Ghyslaine Boschat, Surendra Rauniyar, Ulrike Bende-Michl, Eun-Pa Lim, Acacia Pepler, Roseanna McKay, Shamila Sur, Blair Trewin, Katayoon Bahramian*, Gen Tolhurst**, Chiara Holgate**, Steven Thomas** and Ali Azarnivand**.
- **CSIRO:** Francis Chiew (project lead), James Bennett, Steve Charles, Anjana Devanand, Guobin Fu, Zitian Gao, Zaved Khan, Julien Lerat, Seline Ng, David Post, Nick Potter, David Robertson, Jin Teng and Hongxing Zheng.

* Denotes a former member of the team.

** Denotes a former employee.

Other contributors

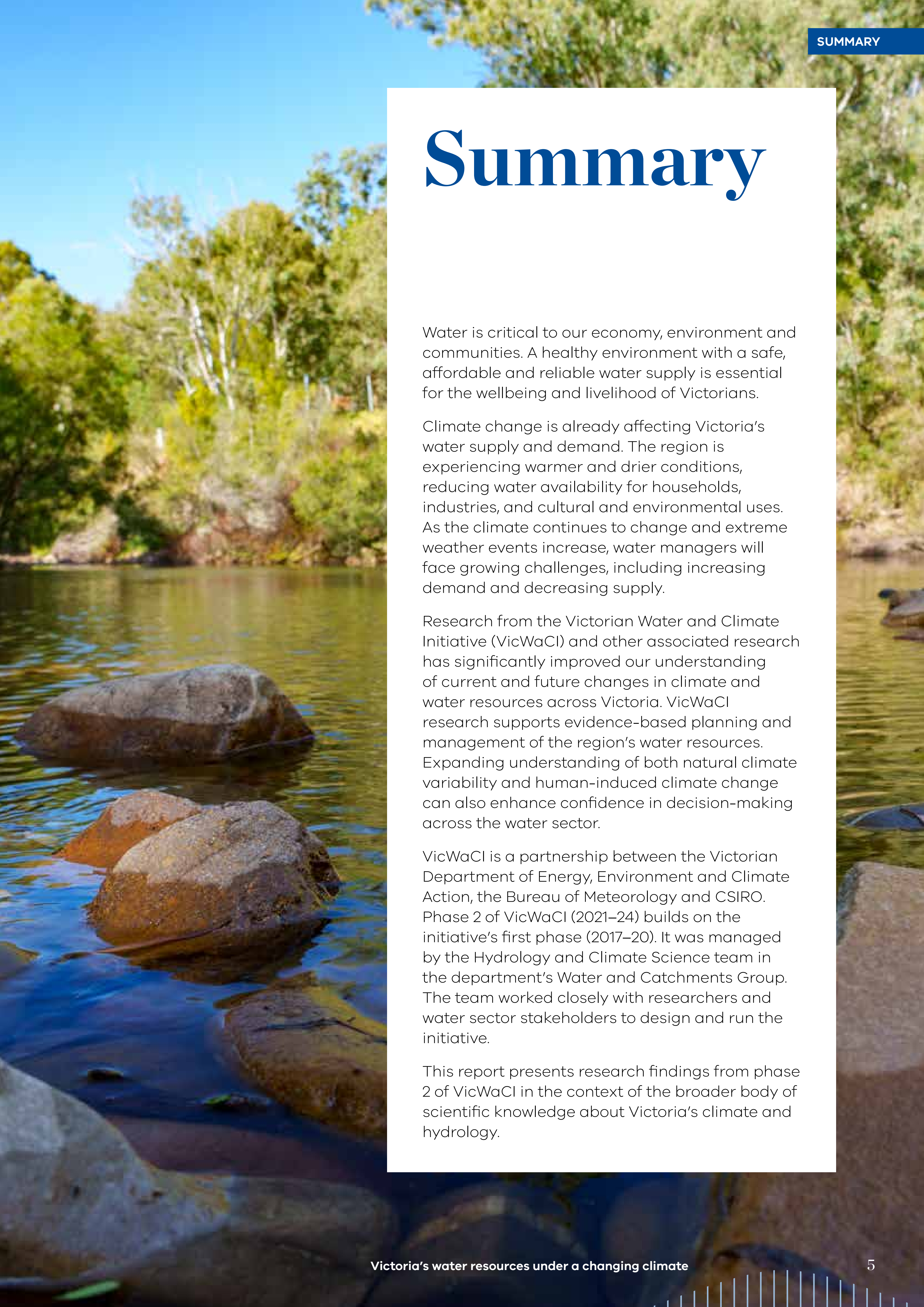
- **The University of Melbourne:** Murray Peel (project lead), Margarita Saft**, Keirnan Fowler and postgraduate students.
- **Monash University:** Tim Peterson and postgraduate students.
- **Case studies:** Charlie Showers (DEECA), Gary Sheridan (the University of Melbourne), Pat Lane (the University of Melbourne), Ben Henley (the University of Melbourne), KS Tan (Melbourne Water), Pat Russell, John Frdelja (Central Highlands Water), Ann Kollmorgen (DEECA) and Catherine McInerney (North East Catchment Management Authority).

Independent reviewers: Fiona Johnson and Neil Plummer.

Editorial and writing support: Scientell Pty Ltd

The project team acknowledges the input from water sector stakeholders and scientists and thanks the various internal and external reviewers for providing valuable feedback on the initiative's research program and this report.

Contents



Summary

Water is critical to our economy, environment and communities. A healthy environment with a safe, affordable and reliable water supply is essential for the wellbeing and livelihood of Victorians.

Climate change is already affecting Victoria's water supply and demand. The region is experiencing warmer and drier conditions, reducing water availability for households, industries, and cultural and environmental uses. As the climate continues to change and extreme weather events increase, water managers will face growing challenges, including increasing demand and decreasing supply.

Research from the Victorian Water and Climate Initiative (VicWaCI) and other associated research has significantly improved our understanding of current and future changes in climate and water resources across Victoria. VicWaCI research supports evidence-based planning and management of the region's water resources. Expanding understanding of both natural climate variability and human-induced climate change can also enhance confidence in decision-making across the water sector.

VicWaCI is a partnership between the Victorian Department of Energy, Environment and Climate Action, the Bureau of Meteorology and CSIRO. Phase 2 of VicWaCI (2021–24) builds on the initiative's first phase (2017–20). It was managed by the Hydrology and Climate Science team in the department's Water and Catchments Group. The team worked closely with researchers and water sector stakeholders to design and run the initiative.

This report presents research findings from phase 2 of VicWaCI in the context of the broader body of scientific knowledge about Victoria's climate and hydrology.

Victoria's changing climate

Victoria's weather and climate are highly variable. The high variability is caused by the region's location and the effects of large-scale seasonal influences and weather systems. Over recent decades, Victoria's temperatures have increased, cool season (April to October) rainfall has declined, snow has decreased, and evapotranspiration has been variable.

Victoria's rainfall is influenced by complex interactions between large-scale climate drivers (such as the El Niño Southern Oscillation and Indian Ocean Dipole) and weather systems, with variations depending on the season and location. The unusually dry conditions over Victoria since the start of the 21st century may signal a shift in rainfall patterns. While natural variability plays a significant role in this recent drying, the magnitude of the decline would not have been as large without the influence of increasing greenhouse gases in the atmosphere.

The weather systems that contribute to Victorian rainfall (and influence runoff) changed during and after the Millennium Drought. After the drought (2010-2015), rainfall intensity increased across most weather systems, while changes to the number of rainfall days were mixed.

Heavy and extreme rainfall events are also changing in Victoria. The occurrence of high-intensity rainfall events has increased since 1997. Interactions between a strong Antarctic stratospheric vortex and the positive phase of the Southern Annular Mode have contributed to heavy rainfalls in spring 2022 and summer 2023–2024.

In recent years, the frequency of compound drought and heatwave events has risen significantly, increasing fire risk in affected areas.

Victoria's changing hydrology

Victoria's rainfall and runoff vary significantly from year to year and at different locations. Most catchment runoff occurs in winter and spring when rainfall is higher and potential evapotranspiration is low.

Average runoff in Victoria has recently declined, mainly due to declines in rainfall. A significant reduction in rainfall and runoff occurred during the Millennium Drought. Compared with before the drought, there is now less annual runoff generated from a given amount of rainfall in about one-third of Victoria's catchments. Despite recent wet years, this drought-like, low runoff state has persisted in some catchments since the end of the Millennium Drought.

Persistent changes to streamflow characteristics, such as frequency, duration, and timing of peak and low flows, were observed in some catchments during and after the Millennium Drought. This mainly occurred in catchments at lower altitudes, in dry, sub-humid to semi-arid climates, and in flatter terrain with less forest cover. Low to extreme-low flows were especially affected, with streamflow reductions of up to 100% observed. Multi-year droughts can lead to persistent changes in streamflow characteristics, such as flow intermittency and increased days with no flow at all.

Depending on the region, there was also a persistent decline in groundwater levels during the Millennium Drought.

The unprecedented length of the Millennium Drought is likely the primary climatic driver of observed shifts in Victoria's catchment response during and after the drought. Emerging evidence suggests that changes in the interactions between groundwater and surface water, coupled with increased evaporative demand, may have also contributed.

Victoria's future climate

Victoria's temperatures are projected to continue increasing. Cool season rainfall will continue to decline, especially under moderate and high emissions scenarios. Changes to warm season (November to March) rainfall are less certain.

The likelihood of future step changes in rainfall was estimated using Coupled Model Intercomparison Project 5 (CMIP5) models, specifically assessing whether the next 20 years will be wetter or drier than the previous 20 years. Projections indicate a high likelihood of significant rainfall declines (including rainfall step-changes) under a high emissions scenario towards the end of the 21st century. The exact timing of the projected decrease in rainfall cannot be predicted, but there is high confidence that step-down changes in cool season rainfall will become more frequent in future.

Shorter-duration rainfall is projected to become more intense, and the intensity of the more extreme and rare rainfall events will likely increase. Changes will likely be smaller for long-duration rainfall events, particularly in regions such as Victoria, where total rainfall is projected to decline.

Under a warmer climate, droughts in south-east Australia are likely to become longer, more frequent and more intense. Changes in the climate will also impact other extreme events, including the risk of future floods and bushfires.

Victoria's future hydrology and water resources

The projected decline in cool season rainfall and higher potential evapotranspiration will likely lead to lower catchment runoff and water resources in Victoria in future. Mean annual runoff and water resources averaged across Victoria will likely decrease by about 25% by 2060, relative to 1976–2005.

Catchments in parts of Victoria that have experienced significant long-term reductions in streamflow may not return to the conditions experienced in the 20th century.

Long (multi-year) wet and dry periods observed in the past will continue to occur. This will occur against a background trend of declining streamflow. With lower mean annual runoff, hydrological droughts will become more severe and occur more often.

While higher interannual rainfall and runoff variability would reduce the security of Victoria's water, the influence of this variability is smaller than the significant reduction in mean annual rainfall and runoff projected for Victoria.

Projections of future catchment runoff are developed using hydrological models informed by climate change projections from global and regional climate models. Efforts, including under VicWaCI, to improve hydrology and climate projections include correcting bias in climate variables from dynamical regional models, improving rainfall-runoff models so they can better model prolonged dry periods, and adapting hydrological model conceptualisation and modelling techniques.

Implication of research and its use in supporting water sector decision-making

The research findings about Victoria's changing climate and hydrology have implications for the management of the state's water resources. For example, the future warmer and drier climate will likely result in a decline in water availability in Victoria's streams, lakes and storages, while the reduction in light to moderate rainfall and the increase in heavy and extreme rainfall will influence catchment wetness and streamflow generation. Victoria's variable climate conditions will also likely be exacerbated in the future, so assessments should consider the risk of more extreme dry and wet periods.

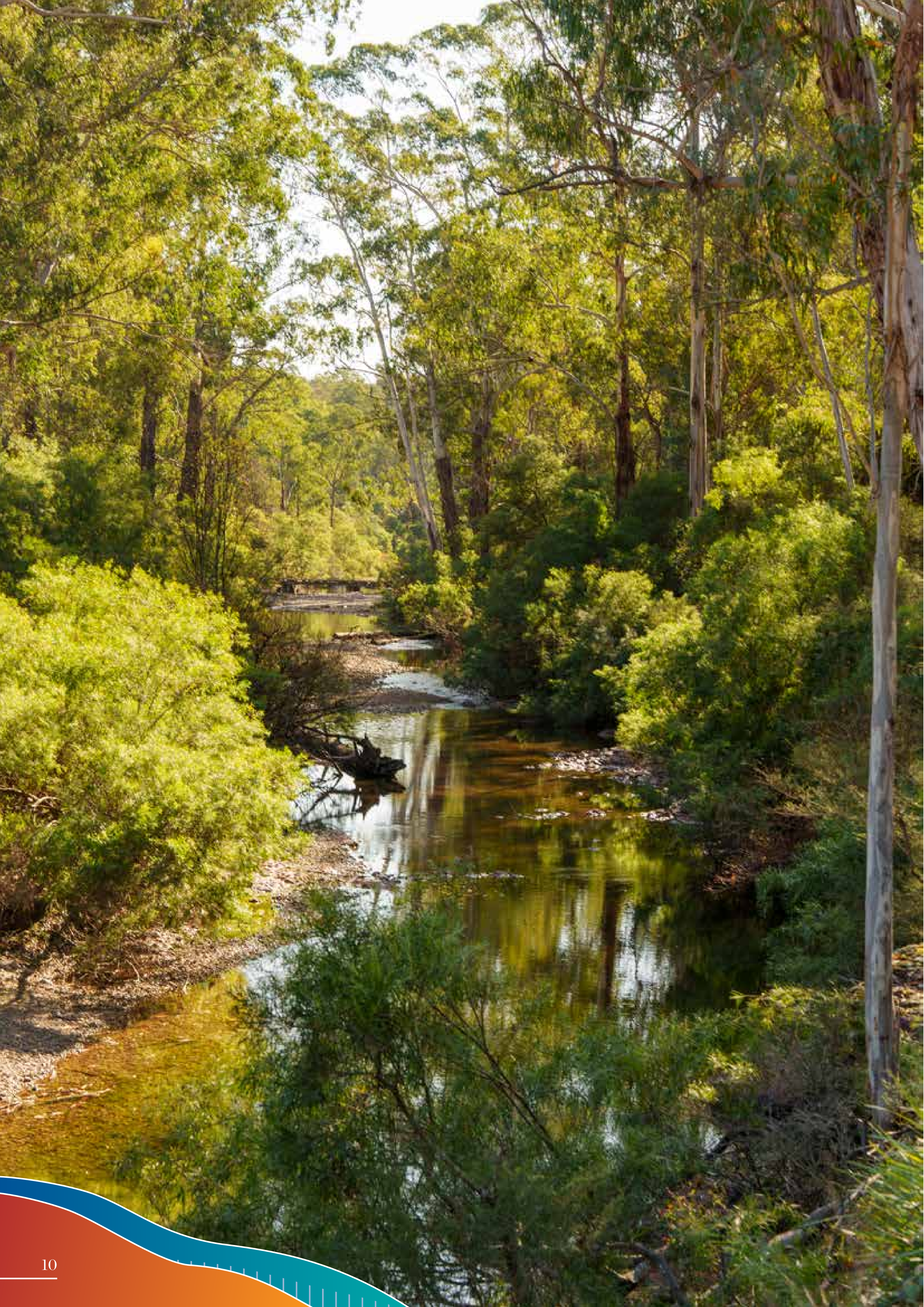
These research findings can inform current and future management and planning activities to ensure sustainable water availability and supply, especially as the climate continues to change.

Using research to support water sector decision-making

Victoria's investment in climate and hydrological research, such as through VicWaCI, has supported a range of water management and planning activities, including assessments of groundwater availability and recommendations for environmental flow.

Climate and hydrology research identifies and explains recent trends, as well as the drivers of those trends. Climate projections enable us to prepare and plan adaptation strategies. VicWaCI and related research investments inform the *Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria* (the Guidelines), which provide practical guidance on how to apply climate change scenarios to assessments of long-term water availability, supply and demand. The Guidelines also provide fit-for-purpose projected hydrological and climate (hydroclimate) variables that are important for managing water resources in Victoria.

Victoria's investment in climate and hydrological research is used by various water sector stakeholders to inform decision-making, strategies and management actions across the state. It remains vital for the sustainable management of the state's water resources.



New research outcomes

Investment in phase 2 of the Victorian Water and Climate Initiative has built on the previous phase and research across Victoria and Australia more broadly.

Some of the new research outcomes from phase 2 of the initiative include:

- Attributed the role of natural variability and greenhouse gas emissions in the observed declining cool season rainfall trend since the mid-1990s (see section 2.2.2).
- Identified changes in rainfall regimes affecting runoff across Victoria, including changes to multi-decadal averages and the occurrence of wet and dry events (see section 2.2.2).
- Improved understanding of influences on Victorian rainfall throughout the year, including from large-scale climate drivers, the Antarctic stratospheric vortex and weather systems (see section 2.3).
- Characterised changes in streamflow regime, particularly in catchments where flow intermittency developed or intensified during and after the Millennium Drought (see section 3.2.2).
- Improved understanding of hydrological processes that contributed to the greater than expected decrease in runoff during and after the Millennium Drought in many catchments (see section 3.3.1).
- Improved understanding of how well climate models simulate potential future changes in large-scale climate drivers and their relationships to Victorian rainfall (see section 4.1.2).
- Developed future projections of changes in rainfall, potential evapotranspiration, and runoff using hydrological models informed by the latest climate models (phase 6 of the Coupled Model Intercomparison Project, CMIP6) (see section 4.2.1).
- Quantified the impact of potential increases in year to year rainfall variability on the reliability of water supply (see section 4.2.2).
- Improved hydrological modelling methods to more robustly model future runoff under a drier climate (see section 4.2.4).
- Demonstrated the use of stochastic modelling in a case study to quantify water supply system reliability, accounting for internal hydroclimate variability and a changing climate (see the case study in section 4.2.2).

1. Introduction

At a glance

- The Victorian Water and Climate Initiative has increased the scientific understanding of the changes in climate and water resources across Victoria to support water management.
- This report presents the key findings of the second phase of the initiative (2021 to 2024), which built on previous phases of the initiative and other associated research.
- As the climate changes, increasing water demand and decreasing supply in Victoria's variable climate present an increasing challenge for water managers.
- Research into how the climate and hydrology, including extreme events and streamflow, have changed in the past and are expected to change in the future helps inform planning and adaptation to protect the economy, environment and communities.

1.1 Purpose and focus of this report

Research under the Victorian Water and Climate Initiative and associated research informs water managers and planners about changes in climate and water resources across Victoria. This report presents findings from phase 2 of the initiative (2021–2024), which built on previous research investments by the Victorian Government.

The Victorian Water and Climate Initiative (VicWaCI) has increased the scientific understanding of the changes in climate and water resources across Victoria. This information helps support water management and planning decisions across a range of applications, including the reliability of water supply for different uses and values across Victoria.

VicWaCI was managed by the Hydrology and Climate Science team of the Victorian Department of Energy, Environment and Climate Action's Water and Catchments Group. The team worked closely with researchers and water sector stakeholders to design and run the initiative, with the research delivered primarily by the Bureau of Meteorology and CSIRO.

The second phase of the VicWaCI began in 2021 and was completed in 2024. The research built on the initiative's first phase, which ran from 2017 to 2020. The initiative leveraged a range of other research activities underway, with a focus on extracting information relevant to the water sector in Victoria.

This report presents research findings from the second phase of VicWaCI in the context of the broader body of scientific knowledge about climate and hydrology. The report covers topics including changes in weather systems, rainfall, temperature, evaporation, and transpiration, as well as changes in hydrology and streamflow patterns across Victoria. The impact of these changes on Victoria's water resources is also explored in the report.

The findings presented here update the findings presented in the report from the first phase of VicWaCI, titled *Victoria's Water in a Changing Climate*, published in December 2020 (DELWP, 2020a).

1.2 Victoria's water sector: challenges and policies

Victoria's warming and drying climate has resulted in less water in rivers, streams, dams, and groundwater, as well as a greater risk of droughts, floods, fires and heatwaves. As the climate changes, increasing water demand and decreasing supply in Victoria's variable hydroclimate is challenging for water managers.

Victoria's water resources are threatened. Demand is increasing due to population increases occurring faster than any other state (DELWP, 2019), while supply decreases as average annual rainfall and streamflow across the state decline. Much of Victoria's older infrastructure was not built to withstand the increasing frequency and intensity of extreme events due to climate change, such as severe storms, bushfires and heatwaves.

Water managers have learned from experiences in our variable climate, such as the Millennium Drought (1997–2009), the 2019–20 Black Summer bushfires (the largest bushfires since 1939; Huf and McLean, 2020) and the floods during 2021. However, Victoria's highly variable rainfall and streamflow from year to year now occur against a backdrop of increasingly severe climate change.

Preparing for and responding to climate change is challenging. The severity of climate change will depend on future global emissions and flow-on effects on nature and society. Climate change is one of many pressures on water resources, including population growth and changing economic conditions. Decisions on how to adapt to changes in climate and other pressures are often informed by a range of scenarios – which are informed by science.

The *Victorian Climate Change Act 2017* sets a net zero emissions target for Victoria. It also requires the government to outline its approach to climate action every five years, including through seven state-wide system-based adaptation action plans.

The Water Cycle Climate Change Adaptation Action Plan (DELWP, 2021) is one of the seven system-based plans. It aims to ensure climate change adaptation is integrated into all relevant business decisions across the water sector. The plan covers the collection, storage, treatment, delivery and supply of water, as well as services for managing wastewater, drainage and flooding. The plan includes a range of actions, including the research discussed in this report and complementary activities, that aim to increase understanding of how climate change will affect the water cycle.

1.3 Science supporting water management

Science, such as VicWaCI research, is an important input into decisions on how to adapt to a changing climate and water cycle and other pressures. Understanding how extreme events and streamflow continue to change will inform planning to protect the economy, environment and communities.

Water is critical to our economy, environment and communities. A healthy environment with a safe, affordable and reliable water service is essential for people's well-being, jobs and a thriving economy. Advances in science help to better understand how Victoria's climate and water resources are changing and what we can expect in the future.

The impacts of climate change are already being felt across Victoria's water sector. As Victoria becomes warmer and drier, less water will enter rivers, streams, and dams, and there will be less recharge to groundwater. These decreases in rainfall and water availability have serious consequences for everyone – households, industry, agriculture, recreation, cultural values, liveability, and the health of our waterways and environment.

Victoria can expect more extreme events, including drought, floods, fire weather, heatwaves, and rising sea levels. These changes will increase threats to catchments, water quality and supply, and can reduce the resilience and lifespan of water infrastructure.

Investment in VicWaCI, in partnership with the Bureau of Meteorology and CSIRO, has contributed to the growing body of science that helps to explain changes in Victoria's climate and water cycle. VicWaCI forms part of the Victorian Government's plan for managing Victoria's water resources, as described in *Water for Victoria* (DELWP, 2016). In particular, VicWaCI is a response to *Water for Victoria*'s specific action on understanding and applying climate science to help water managers better meet the requirements of the water sector and the community.

The second phase of VicWaCI aimed to increase our understanding of the physical processes that drive Victoria's climate and hydrology, better understand past changes, and the types of changes we can expect in the future. This included identifying and explaining natural climate variability and human-caused climate change. The research supports assessments of current and future water availability and informs a range of climate change adaptation decisions.

2. Victoria's changing climate

At a glance

- Victoria's climate continues to warm and cool season rainfall continues to decline.
- There is large natural variability in rainfall patterns between seasons, years and locations across Victoria due to complex interactions between large-scale climate drivers and weather systems.
- The recent reduction in cool season rainfall can partly be attributed to natural variability. The influence of increasing greenhouse gas emissions has further enhanced the drying.
- Since the end of last century, there has been a decrease in light to moderate rainfall events but an increase in heavy to extreme rainfall events.
- The interaction between the Antarctic stratospheric vortex and tropical ocean influence in late spring and early summer contributed to drier conditions in 2019 and wetter conditions in 2020–22. The two drivers can also work against each other, reducing the expected influence of the tropical ocean on Victoria's rainfall (as occurred in 2023).
- The weather systems that contribute to Victorian rainfall (and influence runoff) have changed during and following the Millennium Drought. After the drought (2010–15), rainfall intensity increased across most weather systems, while changes to rainfall days were mixed.

2.1 Victoria's climate

Victoria's climate is variable, changing from year to year and decade to decade, and is influenced by large-scale climate drivers and weather systems.

Victoria's weather and climate are highly variable. This variability is caused by the region's location, including its latitude and topography, its proximity to the ocean in the south-east and the desert in the north-west, and the effects of large-scale seasonal influences and weather systems.

Victoria sits at the boundary between tropical and extratropical circulations. The southern section of the Great Dividing Range runs through Victoria, with drier conditions to the north of the mountains and a wetter coastline. The seasonal migration of the sub-tropical ridge further influences the distribution of Victoria's rainfall and snow.

During Victoria's cool season (April to October), the sub-tropical ridge migrates north towards the equator (Figure 2.1), bringing more rainfall from extratropical weather systems, such as cyclones and fronts, that often come from the Southern Ocean. The migration of the sub-tropical ridge south towards the pole in the warm season increases the atmospheric pressure, which reduces the frequency of extratropical weather systems reaching Victoria but leaves favourable conditions for thunderstorms. Thunderstorms provide the highest contribution of rain to Victoria's total summer rainfall (Pepler et al., 2020; Fiddes et al., 2021).

This report considers three distinct sub-regions of Victoria: northern Victoria, south-west Victoria, and south-east Victoria (shown in Figure 2.1). These three sub-regions are each characterised by different climate (Table 2.1), vegetation and hydrology. Northern Victoria and south-west Victoria have strong seasonal temperature and rainfall cycles. The northern Victoria sub-region receives less rainfall than the south-west region, with 10 mm per month less rainfall in the cool season and 18 mm per month less rainfall in the warm season (averaged over 1900–2023). Northern Victoria is only slightly warmer than the south-west region during the cool season, but in the warm season, northern Victoria's mean daily temperature is more than 2.5 °C higher than south-west Victoria (averaged over 1910–2023). The south-east Victoria sub-region is the coldest and wettest of the three sub-regions, with less variable rainfall throughout the year. South-east Victoria receives twice as much rain as northern Victoria in summer.

TABLE 2.1 Summary of mean temperature and rainfall amounts for the three Victorian sub-regions. Data sourced from the Australian Gridded Climate Data, Bureau of Meteorology, with temperature averaged over 1910–2023, and rainfall averaged over 1900–2023.

Sub-region	Mean daily temperature (ºC)	Mean monthly cool season rainfall (mm/month)	Mean monthly warm season rainfall (mm/month)
Northern Victoria	14.7	55	36
South-west Victoria	13.4	72	48
South-east Victoria	12.6	82	69

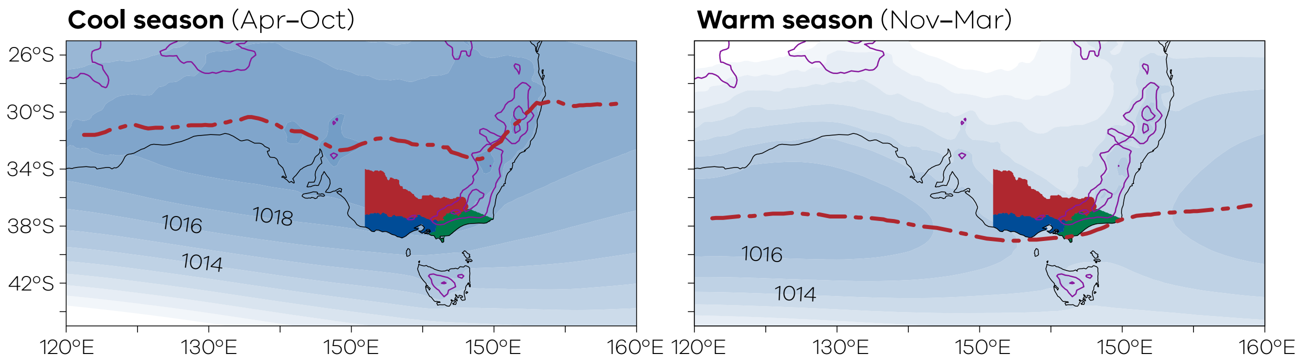


FIGURE 2.1 The location of the sub-tropical ridge (red dotted line) in the cool season (left) and warm season (right) relative to Victoria. The three sub-regions are shown in red (northern Victoria), blue (south-west Victoria), and green (south-east Victoria). Blue shading represents the mean sea level pressure (hPa), and the purple contour lines indicate elevated areas with 500 m intervals.

FIGURE 2.1 KEY TAKEAWAY

Seasonal shifts in atmospheric circulation result in different climates across Victoria's sub-regions during warm and cool seasons.

2.2 Past changes and trends

Over recent decades, Victoria's temperatures have increased, cool season rainfall has declined (especially since 1979), snow cover has decreased, and evapotranspiration has shown no discernible trend. These trends have been caused by a combination of natural variability and climate change.

2.2.1 Temperature trends

Victoria's climate has warmed since observational records began in 1910. Temperatures have increased more during the warmer months, particularly along the coast (Figure 2.2). Significant warming trends have been observed in both the cool and warm seasons over the three Victorian sub-regions. During more recent decades, the warming trend has amplified, especially inland. Warming in parts of northern Victoria has exceeded 0.3 °C per decade in the warm season since 1979. During the cool season, warming has been more significant in south-east and parts of south-west Victoria, increasing up to 0.2 °C per decade since 1979 toward the east of the state.

2.2.2 Changing rainfall

Trends in Victoria's rainfall vary greatly depending on the season and location. Victorian rainfall has declined during the cool season, especially after 1979 (Figure 2.3). The strongest, most significant decline has occurred on the northern slopes of the Great Dividing Range, with rainfall declining by over 30 mm per decade. In the warmer months, rainfall has increased, especially in the north-east of Victoria; however, the changes are not statistically significant.

The high variability of Victorian rainfall is demonstrated by numerous flooding and drought events. While this high variability may mask significant long-term rainfall trends (Hope et al., 2017), it is clear that the 1997–2018 period was drier than any other 22-year period since at least 1900 (Rauniyar & Power, 2023). Since 1997, all three Victorian sub-regions have experienced a notable decrease in cool season rainfall (Figure 2.4).

Compared with the long-term average, cool season rainfall declined during the 1997–2018 period by 15% in northern Victoria, 11% in south-east Victoria, and 8% in south-west Victoria. It is extremely unlikely that these declines could have occurred due to natural climate variability alone, suggesting that the declining trend is likely to be partially caused by climate change (Rauniyar & Power, 2023).

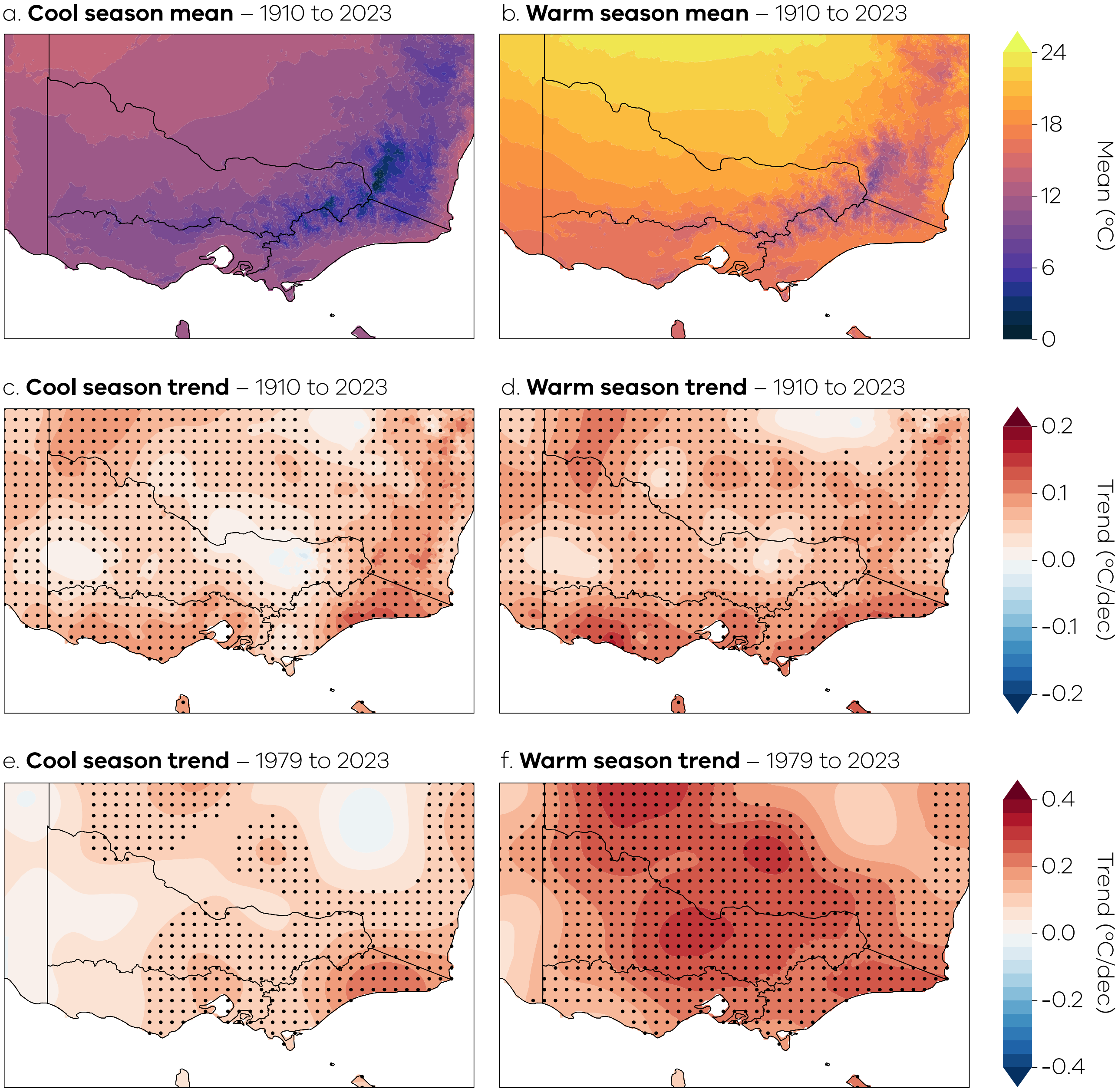


FIGURE 2.2 Mean temperature (a and b for 1910–2023) and trends (c and d for 1910–2023, and e and f for 1979–2023) during cool and warm seasons. Stippling indicates areas where the trends are statistically significant (at the 90% confidence interval). Data sourced from the Australian Gridded Climate Data, Bureau of Meteorology.

FIGURE 2.2 KEY TAKEAWAY

Mean temperatures over Victoria have increased, with the warming trend accelerating in recent decades.

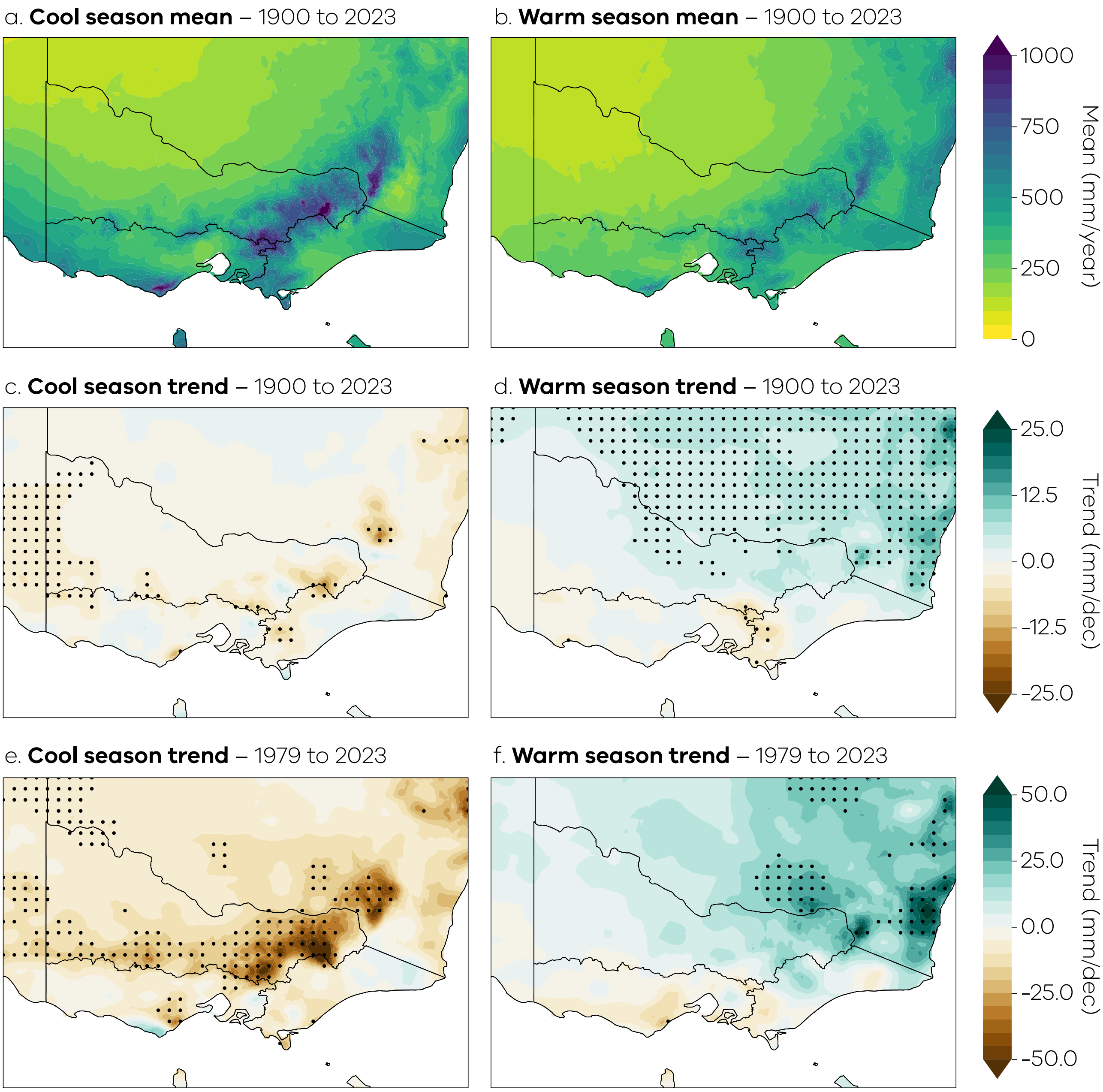


FIGURE 2.3 Mean rainfall (a and b for 1900–2023, mm/year) and trends (c and d for 1900–2023, and e and f for 1979–2023, mm/decade) during cool and warm seasons. Stippling indicates areas where the trends are statistically significant (at the 90% confidence interval). Data sourced from the Australian Gridded Climate Data, Bureau of Meteorology.

FIGURE 2.3 KEY TAKEAWAY

Victoria's rainfall is variable but has decreased in the cool season, with a more rapid decline in recent decades.

FIGURE 2.4 Observed area-averaged cool season rainfall for (a) northern Victoria, (b) south-east Victoria, and (c) south-west Victoria. Blue bars show rainfall above the average rainfall for 1900–1959, while orange bars show rainfall below the average rainfall for this period. The three horizontal shadings show the three different periods as identified by the step change analysis: grey shading represents the close to long-term average period (1900 to mid-1940); blue shading represents the very wet period (mid-1940s to mid-1990); and the pink shading represents the very dry period (mid-1990s to current). Corresponding period averages are also shown as dashed horizontal lines.

FIGURE 2.4 KEY TAKEAWAY

Average cool season rainfall over the mid-1990s to the early 2020s was below the 1900 to mid-1940s average in all three Victorian sub-regions.

The recent unusually dry conditions over Victoria may signal a shift in rainfall patterns. Figure 2.4 also shows that since 1900, there have been three distinct periods in cool-season rainfall: the period before the mid-1940s, which was close to the long-term average rainfall over 1900–2022; the period from the mid-1940s to the mid-1990s, which was wet; and the period after the mid-1990s, which was dry. Changes in annual rainfall for Victoria broadly align with changes in cool season rainfall. Annual rainfall during the earliest period (1900–45) averaged over Victoria was close to or slightly below average (-20 mm). Rainfall during the 1946–96 period was higher than normal (+49 mm). Rainfall since 1997 was below the 1900–2020 annual average of 643 mm (-65 mm).

Changes in the occurrence of light to moderate rainfall intensities (up to 15 mm per 6 hours, 50 mm per day, and 100 mm per 3 days) played a primary role in mean rainfall decline or increase (Tolhurst et al., 2023). In the recent 1997–2020 period, there were fewer light to moderate rainfall events annually across all sub-regions compared to the cool season in the second half of the 20th century. In contrast, the occurrence of high-intensity rainfall increased over some catchments in recent years. This played an important role in streamflow recovery after the Millennium Drought (Bende-Michl et al., *in review*).

In contrast to the changes in cool season rainfall, Victoria did not experience a statistically significant step change in warm season rainfall. However, the frequency of heavy rainfall has increased since 1997, particularly 6-hourly spring and summer rainfall in northern Victoria and winter rainfall in southern and eastern Victoria (Tolhurst et al., 2023). These results suggest that despite the weak long-term trends in rainfall (Figure 2.3), significant changes have occurred in recent decades.

Attribution of long-term rainfall declines

The rainfall changes across the three Victorian sub-regions since the late 1990s are unusual compared to historical variability (Rauniyar & Power, 2020 and 2023). According to global climate models, 30% of the observed drying in south-west Victoria, 18% in northern Victoria and 17% in south-east Victoria can be attributed to external forcing (human-caused forcing plus natural external forcings, such as changes in solar radiation), likely associated with increasing atmospheric greenhouse gases. This suggests that while natural variability plays a significant role in recent drying across all three sub-regions, the magnitude of these declines would not have been as large without the influence of increasing greenhouse gases.

The likelihood of rainfall changes as dry as or drier than the observed decline has increased by three times in the current climate (blue distribution line in Figure 2.5) compared to the pre-industrial climate in all three Victorian sub-regions (Rauniyar & Power, 2023). While this estimate is based on CMIP models and is contingent on their ability to accurately simulate regional climate (see Box D), other lines of evidence may support this result. For example, rainfall decline has also been observed across similar latitudes in south-east and south-west Australia (Timbal and Fawcett, 2013; Raut et al., 2017) as well as other continents in the Southern Hemisphere (Burls et al., 2019) in response to the tropical expansion attributed to climate change.

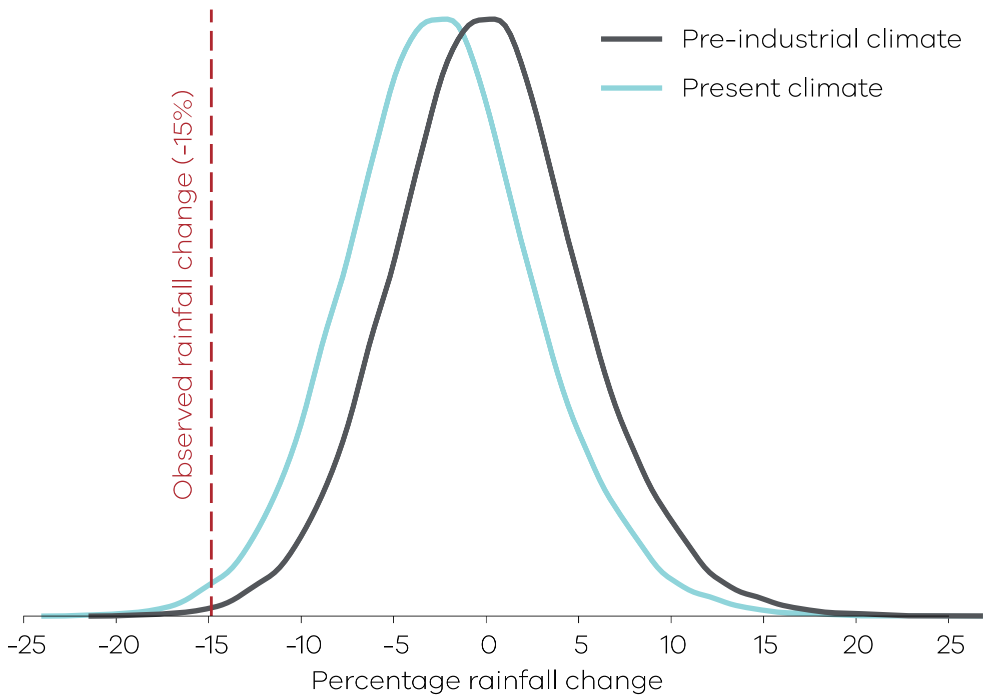


FIGURE 2.5 The observed decline in cool season rainfall over the 1997–2018 period relative to the 1900–59 period in northern Victoria (red dashed line) has a very low likelihood when compared with all possible cool season rainfall changes over equivalent periods from many climate model simulations under a pre-industrial climate (black distribution curve). The likelihood of the observed decline is greater under a present climate (blue distribution curve), reflecting the impact of increased greenhouse gases.

FIGURE 2.5 KEY TAKEAWAY

The observed dry period between 1997 and 2018 was extremely unusual compared to the average climate of early last century. Models suggest that the observed drying was significantly influenced by natural variability. Climate change has also contributed to and increased the likelihood of such an event.

2.2.3 Trends in snow cover

While trends in snow cover were not analysed as part of phase 2 of VicWaCI, previous work has highlighted observations that show Victoria experienced a decline in snow over the 1988–2013 period (Fiddes et al., 2015). There was a 15% decrease in total snow accumulation and a 9% decline in peak seasonal snow depth at Mount Hotham, Mount Buller and Falls Creek. However, due to the relatively short snow data sets in Victoria and the high interannual variability, these changes were not found to be significant at a 95% confidence level.

The observed decreases were caused mainly by a decline in light snow events, with the number of heavy snow events remaining relatively stable (Fiddes et al., 2015). Seasonal peak snow depths averaged over the 2014–23 decade were similar to means at the three locations during 1993–2013. Victorian alpine snowfall is closely correlated with snowfall in the NSW Snowy Mountains, where long-term declines in snow over the 1954–2013 period have been observed, with the largest decreases in the latter part of the season (Pepler et al., 2015).

The alpine regions of Australia are important for streamflow, providing 20 to 29% of the total water yield of the Murray–Darling Basin (Reinfelds et al., 2014). Runoff decreases by 15% per 1 °C temperature rise (Reinfelds et al., 2014), which can be partially attributed to runoff changes associated with snow cover decreases. However, these changes were primarily caused by decreases in total precipitation rather than changes in the proportion falling as snow (Bilish et al., 2020).

Snowmelt that occurs earlier may contribute to earlier seasonal runoff peaks in snowmelt-influenced catchments. For example, such peaks have moved forward by an average of six days per decade in the NSW Snowy Mountains since the 1950s (Reinfelds et al., 2014).

2.2.4 Trends in evapotranspiration

Potential evapotranspiration represents the estimated water loss (through soil evaporation and transpiration from plants to the atmosphere) if there is no limit to water availability. Actual evapotranspiration depends on water availability and, therefore, follows a more seasonal pattern, typically peaking in spring and early summer. It is not possible to measure actual evapotranspiration at the catchment scale, so modelled actual evapotranspiration estimates are used instead. The actual evapotranspiration estimates are based on the Bureau of Meteorology's operational Australian Water Resource Assessment Landscape (AWRA-L) model (Frost et al., 2018).

As Victoria is largely water-limited in summer and autumn, there is a large gap between potential and actual evapotranspiration during these seasons. During the winter and spring months, evapotranspiration can be energy-limited, meaning it is controlled by the temperature. However, both potential and actual evapotranspiration show large variations over time. For example, following the wet La Niña summer in 2010 and the wet 2022 spring and summer, the actual evapotranspiration increased in alignment with high mean minimum temperatures as well as water availability.

Potential evapotranspiration in the warm season is about double the amount of that in the cool season. Among the three Victorian sub-regions, northern Victoria has the highest potential evapotranspiration but the lowest actual evapotranspiration, consistent with higher mean temperature and lower precipitation compared to the two other sub-regions. In the cool season, south-east and south-west Victoria have similar potential and actual evapotranspiration. However, south-east Victoria has higher actual evapotranspiration in the warm season compared to south-west Victoria, reflecting higher rainfall in the south-east.

2.3 Influences on Victoria's rainfall variability

Victoria's rainfall is influenced by complex interactions between large-scale climate drivers and weather systems, with variations depending on the season and location. Some climate drivers can help to explain the cool season rainfall decline observed across the state and to predict changes in future rainfall.

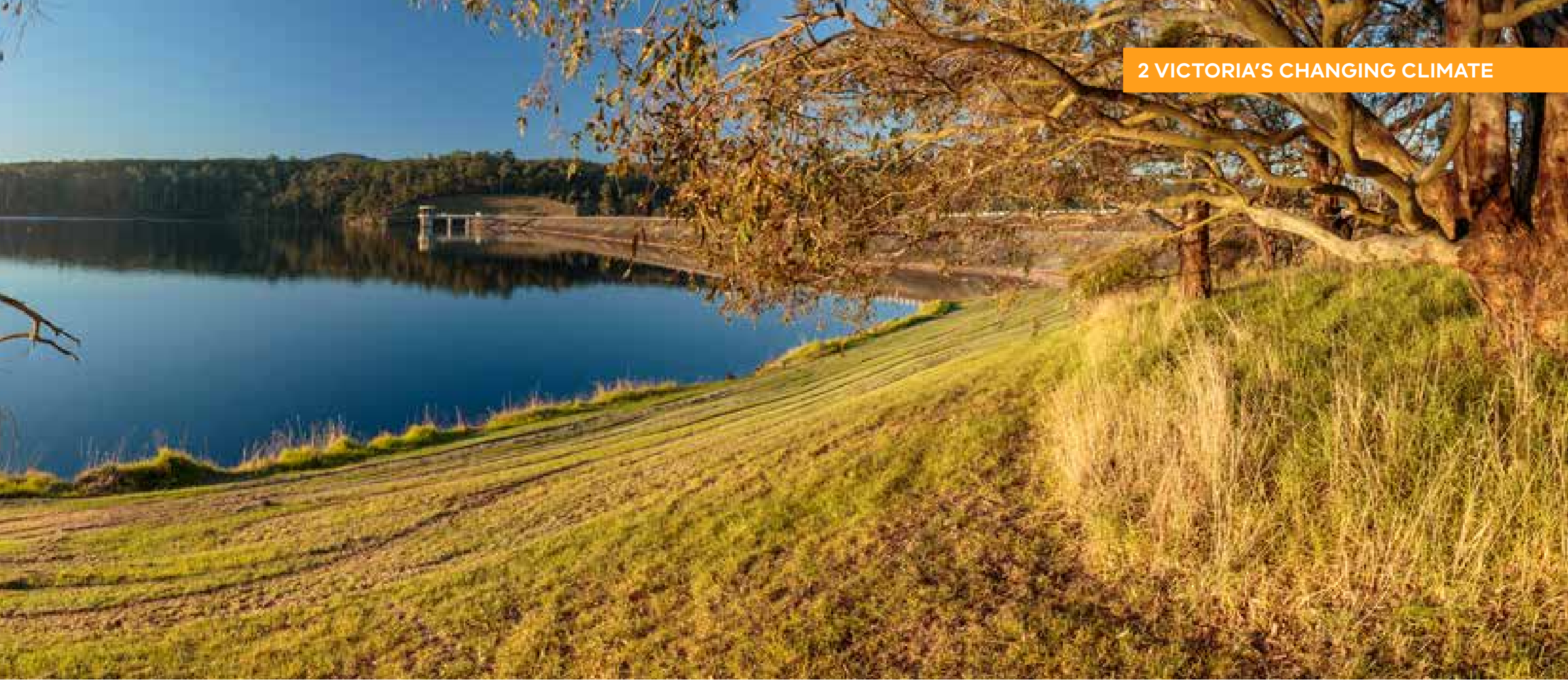
2.3.1 Large-scale climate drivers

Victoria's weather and climate are influenced by large-scale processes (climate drivers) in the atmosphere and ocean, such as the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Madden-Julian Oscillation (MJO) and the Southern Annular Mode (SAM) (Figure 2.6).

The tropical climate drivers, such as ENSO and IOD, regulate tropical convection, impacting the global atmospheric circulation. Therefore, the frequency and intensity of weather systems reaching Victoria may change in response to tropical climate variability.

Outside the tropics, SAM plays an important role in the variability of atmospheric circulation in the Southern Hemisphere. Anomalies in SAM can be either internally generated in the atmosphere or forced by slower-varying large-scale circulations, such as ENSO and the Antarctic stratospheric vortex in spring and summer. In particular, the relationship with the large-scale climate drivers provides SAM predictability on sub-seasonal to seasonal time scales.

ENSO and IOD influence regional climate and can be predicted at sub-seasonal to longer timescales with useful skill, particularly in spring. IOD and ENSO variability are highly correlated (Cai et al., 2012), increasing the predictability of the Australian climate during the later part of the year (Lim et al., 2021). Therefore, these climate drivers help explain and predict weather and climate anomalies. However, they can only explain about 30 to 40% of the observed variation in rainfall, depending on the time of year and the region of interest.



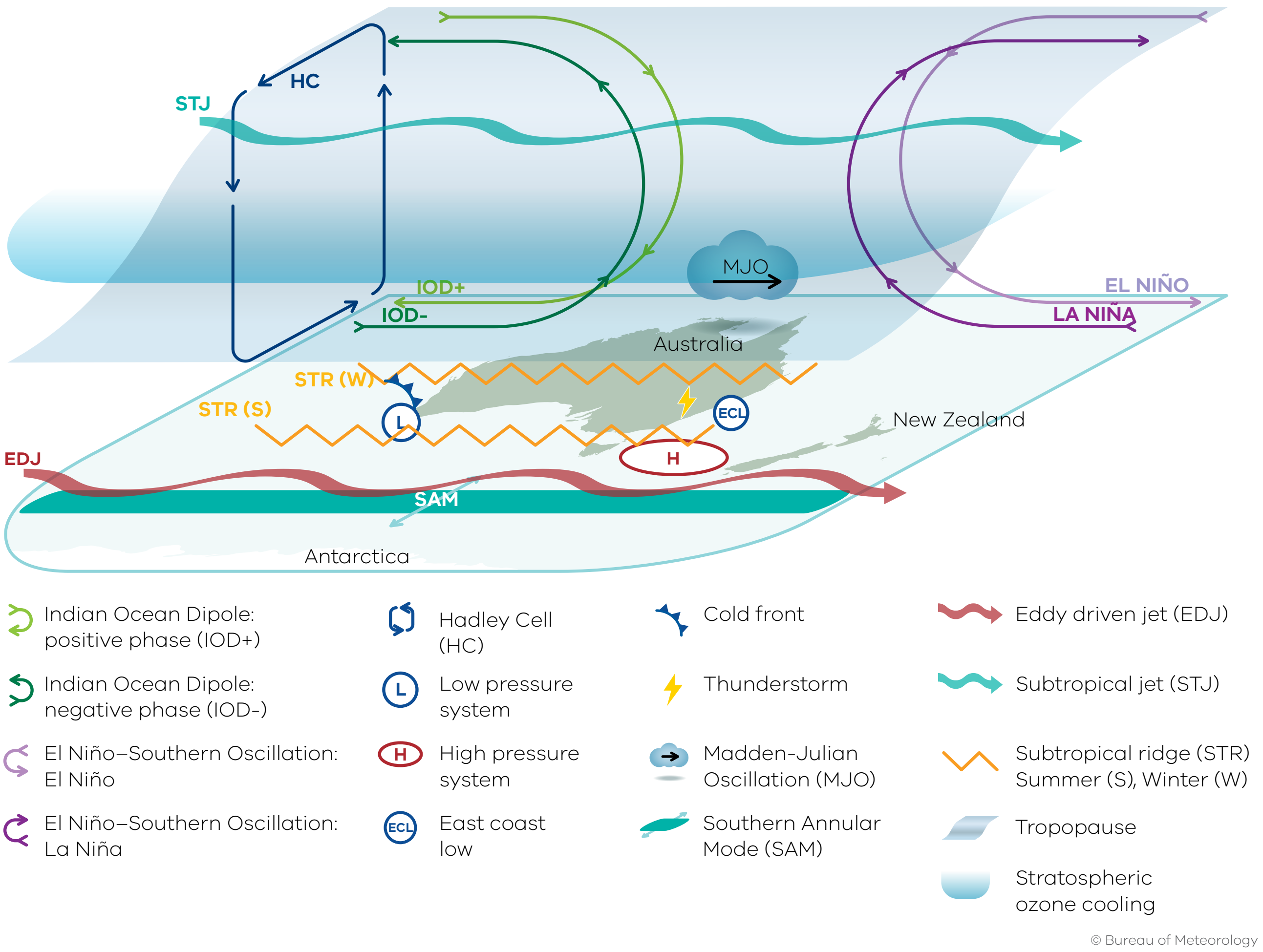


FIGURE 2.6 Climate drivers relevant to Victoria. Source: McKay et al., 2023.

FIGURE 2.6 KEY TAKEAWAY

Victoria's climate is influenced by several large-scale processes, such as ENSO, IOD, MJO, SAM and the sub-tropical ridge.

Seasonality of climate drivers

Year to year variations in Victoria's rainfall are most sensitive to climate drivers in spring. For example, positive phases of ENSO and IOD cause drier conditions over the eastern half of Australia, including Victoria, and a positive SAM promotes wetter conditions in large areas of south-eastern Australia (Figure 2.7).

The effect of large-scale climate drivers on Australian rainfall weakens significantly in other seasons. Apart from spring, the strongest relationship with Victorian rainfall is in winter, when the positive IOD leads to drier conditions. A positive SAM is associated with wetter conditions in summer (especially in Gippsland), whereas it is associated with drier conditions during winter (especially in western Victoria). The relationship between Victoria's rainfall and ENSO remains weak in summer and autumn, and the IOD is inactive. Victorian autumn rainfall does not have a relationship with SAM.

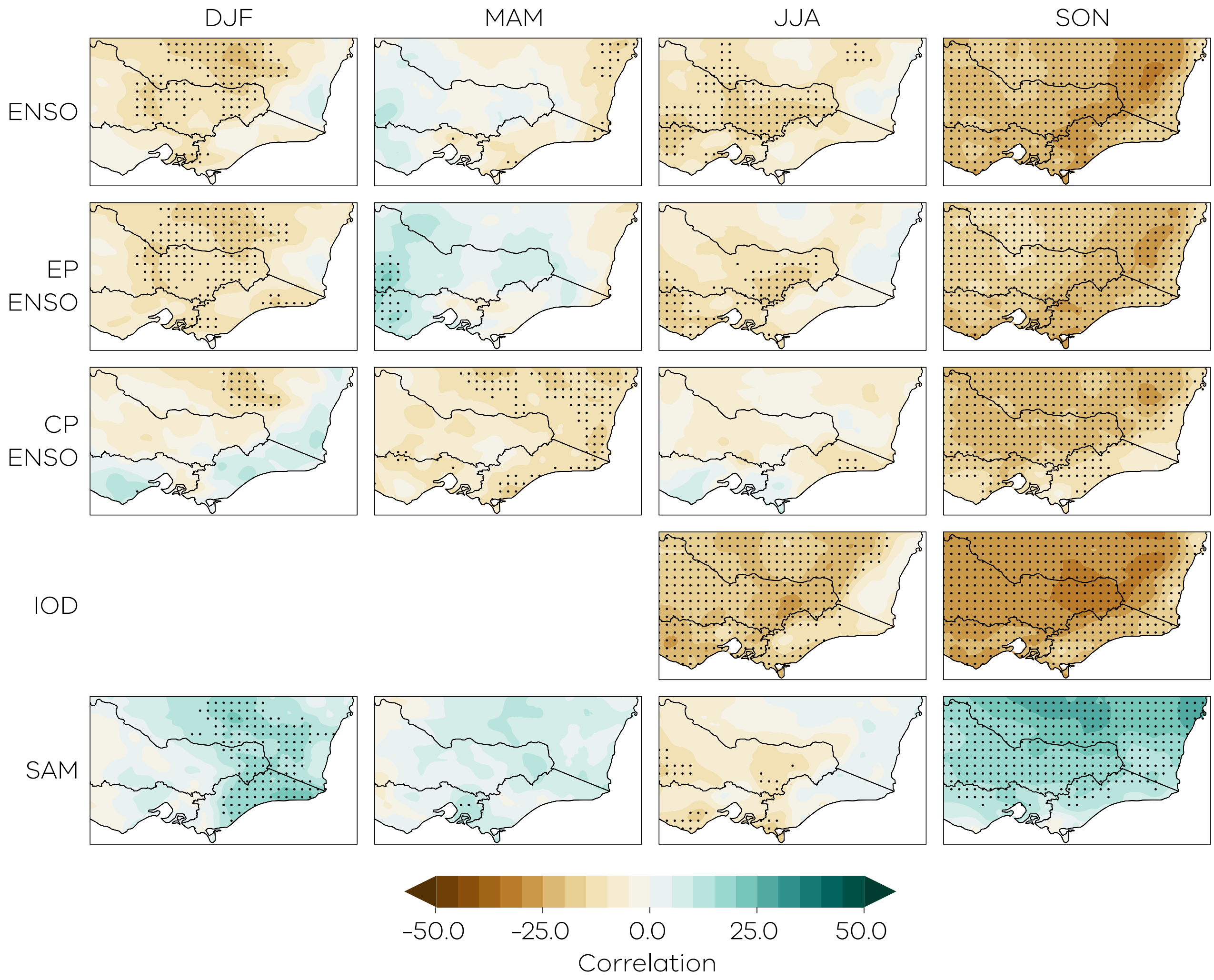


FIGURE 2.7 Correlation between key large-scale climate drivers (ENSO, East Pacific (EP) ENSO, Central Pacific (CP) ENSO, IOD and SAM) and Australian rainfall over summer (DJF), autumn (MAM), winter (JJA) and spring (SON) for the 1979–2022 period. The magnitude of the correlation shows the strength of the relationship between each driver and rainfall, with stippling indicating where this relationship is statistically significant (at the 90% confidence level). Green areas indicate the rainfall change is in the same direction as the climate driver phase (e.g. the positive climate mode is correlated with rainfall increases). Brown areas indicate the rainfall change is in the opposite direction to the climate phase (e.g. the positive climate mode is correlated with rainfall decreases).

FIGURE 2.7 KEY TAKEAWAY

The effect of large-scale climate drivers on Victoria's climate is most apparent in spring.

The remote links (or teleconnections) between large-scale drivers can be used to predict changes in regional climate. However, these teleconnections can change due to natural variability and climate change. For example, since the 1990s, there has been an increase in Central Pacific ENSO events (Freund et al., 2019), which have a stronger influence on Australian rainfall than Eastern Pacific ENSO events (Wang & Hendon, 2007; Santoso et al., 2019). However, despite a stronger influence of Central Pacific ENSO across Australia, in the southernmost sub-regions of Victoria, these events are not significantly correlated with rainfall, even in spring. This is likely due to a weaker relationship between the Central Pacific ENSO and the IOD (Lim and Hendon, 2015).

ENSO may also affect atmospheric circulation in higher latitudes by impacting SAM, particularly in summer. In spring and early summer, SAM is affected by strong winds circling the south pole at 10–60 km (called the Antarctic stratospheric vortex). During the past 20 years, the influence of the Antarctic stratospheric vortex on SAM has increased (Lim et al., 2023). For example, the effect of the stratospheric vortex on SAM was stronger than that of El Niño in the summer of 2023–24, resulting in a persistent positive SAM and associated wetter-than-normal conditions over Victoria from December 2023 to January 2024 (see Box A). The influence of SAM on the Australian climate can be further modified by atmospheric waves that regulate mean and extreme temperature and rainfall in low midlatitude and sub-tropical regions, including Victoria (Boschat et al., 2023).

2.3.2 Climatic drivers contributing to Victoria's cool season rainfall decline

The observed decline in Victoria's cool season rainfall is consistent with several changing climatic factors, including a strengthening of the sub-tropical ridge, poleward shifts in the Hadley Cell, decreasing rainfall from extratropical weather systems, and increasing frequency of positive IOD events. In addition, a recent preliminary VicWaCI investigation suggests that ozone anomalies in the Antarctic lower stratosphere could be related to autumn rainfall variability in Victoria. Therefore, the strong ozone-depleting trend caused by chemical substances such as chlorofluorocarbons was likely at least partly responsible for the decline in Victoria's autumn rainfall in the 1990s and 2000s. Ongoing research aims to better understand how Antarctic lower stratospheric ozone affects Victorian autumn rainfall.

As Victoria is located at sub-tropical latitudes, its climate is influenced by the mid-latitude westerly winds. This particularly occurs during the cool season when the sub-tropical ridge is located to the north of Victoria (see Figure 2.1), with stronger westerlies near Victoria linked to an increase in extratropical weather systems and cool season rainfall. These westerly winds are linked to the extratropical storm track, a belt of strong westerly winds that circle the globe at around 50-60°S.

In recent years, mean sea level pressure has increased, and the sub-tropical ridge near Victoria has strengthened, leading to a decrease in cool season rainfall from lows and cold fronts (Pepler et al., 2021). Recent research shows that changes in zonal winds near the Queensland border are weakening the northern edge of cold fronts, decreasing the proportion of cold fronts that generate rainfall over Victoria and contributing to the decrease in rainfall from cold fronts (Pepler & Rudeva, 2023). There has also been a decrease in the frequency of low-pressure systems and their rainfall over south-east Australia, as well as an increase in the frequency of high-pressure systems.

While similar decreases in extratropical weather systems are seen across many Southern Hemisphere land areas at latitudes similar to Victoria, they are not linked to a change in the latitude of the storm track peak, which is located far to the south of Australia. Therefore, Victoria's weather system change can be better described as a weakening of the northern edge of the storm track, rather than a southward shift of the storms.

In contrast to cool season rainfall changes, warm season rainfall increases in Victoria are better explained by changes in extreme rainfall linked to thunderstorms caused by a rapid increase in temperature over land and the higher moisture content of the warmer air (Pepler et al., 2021).

2.3.3 Understanding wet and dry seasons from a weather perspective

Is rainfall more frequent or intense during wet cool seasons?

Most of Victoria's rainfall (80%) is associated with either a low-pressure system or a cold front. Rainfall is enhanced when these weather systems co-occur with thunderstorm activity (Pepler et al., 2020). In contrast, dry weather is typically associated with the occurrence of a high-pressure system. However, further research has shown that slow-moving high-pressure systems in the Tasman Sea to the east of Victoria can play an important role in directing moisture into the state (Holgate et al., 2023). The presence of a high-pressure system in the Tasman Sea increases the intensity of rainfall over Victoria, particularly where it interacts with a low-pressure system over Victoria. This high-pressure/low-pressure system combination plays an important role in the development of heavy, drought-breaking rainfall. In addition, the amount of rainfall produced by this combination of weather systems is higher during wet seasons than in dry seasons, suggesting that moisture availability over the neighbouring tropical ocean and the transport of this moisture into Victoria are important causes of wet season rainfall.

Can heavy rainfall occur during dry and hot summers?

Victoria often experiences high-impact rainfall extremes, such as droughts, intense rainfall and flooding. The cumulative impacts from concurrent and consecutive extremes need to be considered in planning, as they may be more severe than impacts from individual extremes (Zscheischler et al., 2020; IPCC, 2021). Extremes can compound successively across different types of events. For example, instant rapid transition to extreme rainfall following hot and dry events.

In Victoria, compound droughts and heatwaves (dry and hot weather events occurring together) from November to March often lead to bushfires, crop damage and heat stress. These landscape changes can also trigger floods when followed by intense rain, as prolonged drought conditions can reduce water absorption rates (Sharmila et al., *in prep*, a and b). The frequency of compound drought and heatwave events has significantly increased in recent years, and the areas they affect have higher fire risk (Sharmila et al., *in prep*, b) (Figure 2.8). These compound events are associated with preceding drought conditions, a negative phase of SAM during spring, and positive phases of both IOD and ENSO.

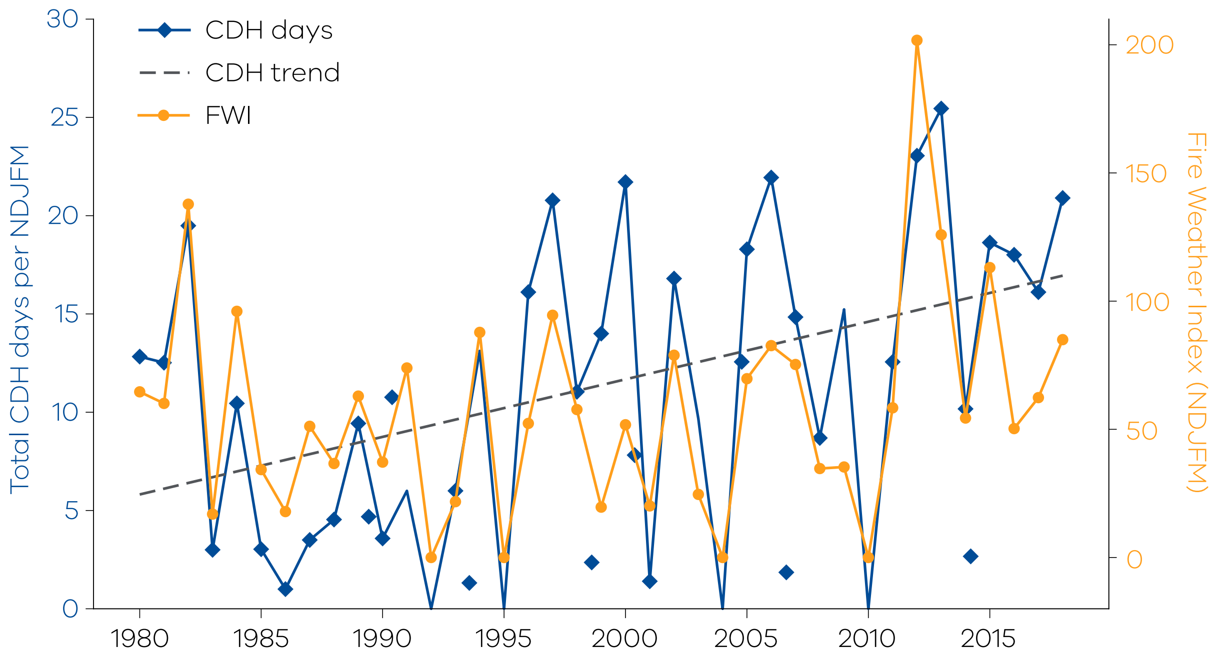


FIGURE 2.8 Interannual variation in total compound drought and heatwave (CDH) days (blue line, left y-axis) over November to March (NDJFM) based on high-resolution Australian Gridded Climate Data (AGCD), and fire weather indices (FWI) from ERA5 reanalysis (orange line, right y-axis) averaged over Victoria for the seasons 1980–81 to 2018–19. The dashed grey line denotes the linear increasing trend in CDH days.

FIGURE 2.8 KEY TAKEAWAY

The occurrence of compound drought and heatwave events has increased over recent decades, with affected areas experiencing higher fire risk.

Compound drought and heatwave events are sometimes followed in subsequent days by intense rainfall and flooding (Sharmila et al., *in prep*, b). As extratropical weather systems (usually fronts) approach south-east Australia, they can interact with enhanced convection from the north, bringing warm moist air inland to Victoria. The combination of enhanced instability, uplift and abundant moisture during active tropical convection creates conditions favourable for rapid transition from compound drought and heatwave events to extreme rainfall in Victoria.

Box A: Explaining the unusual summer rainfall in south-east Australia since 2019 - the surprising role of the Antarctic stratospheric vortex

The Antarctic stratospheric vortex has experienced extraordinarily large variability, particularly in the past five years, with a near-record vortex weakening in 2019 followed by four consecutive strong vortex events in 2020–23. The near-record vortex weakening event of 2019 led to higher-than-normal Antarctic polar cap ozone levels. The combination of the weakened vortex and enhanced ozone concentration resulted in an exceptionally intense negative SAM in late spring of 2019. This significantly contributed to the hot and dry conditions experienced across south-eastern Australia during late spring and early summer in 2019–20. These conditions were also influenced by a strong Central Pacific El Niño, a record-positive IOD, a multi-year drought, and the overarching impact of climate change (Abram et al., 2021; Lim et al., 2021).

South-east Australia received an unprecedented amount of spring rainfall in 2022. This was associated with the development of the third consecutive La Niña, a negative IOD, a strong Antarctic stratospheric vortex, and a positive SAM. While tropical drivers, such as La Niña and the negative IOD, contributed to the above-average spring rainfall, the positive SAM was the most important contributor to the significantly high rainfall (Reid et al., *in press*; Zhou et al., *submitted*). Climate change caused by increasing greenhouse gas emissions also contributed to this extreme rainfall. However, the extreme rainfall was beyond what could be accounted for by oceanic and atmospheric climate drivers and climate change, based on preliminary post-event attribution analysis. This poses a challenge for forecasting the unprecedented amount of spring rainfall and managing water resources.

In contrast, the large-scale oceanic conditions in 2023 were characterised by a typical Eastern Pacific El Niño and a strong positive IOD. These conditions increased the likelihood of drier conditions over Victoria from spring 2023 through to summer 2023–24. However, Victoria experienced heavy rainfall from December 2023 to 2024. This unexpected rainfall was partly influenced by a positive SAM, promoted by a stronger-than-normal Antarctic stratospheric vortex and therefore its delayed breakdown. It is very unusual for SAM to be consistently positive during El Niño. Positive SAM in late spring and summer is linked to an increased chance of heavy rainfall along the eastern seaboard (Hendon et al., 2007; Risbey et al., 2009). In addition, the sea surface temperatures around Australia were relatively warm (contrary to the typical El Niño pattern), further increasing moisture availability in the Australian region and creating favourable conditions for the likely enhanced rainfall that occurred in November 2023 to January 2024 in Victoria.

Improving seasonal forecasts

These recent extreme climate events underscore the need for accurate seasonal forecasts with long lead times. Such forecasts are essential for enabling timely preparedness and effective responses to climate-driven hazards, helping communities better manage and mitigate the impacts of these events.

Stratospheric ozone plays an important role in the successful prediction of the Antarctic stratospheric vortex and its impact on SAM and Victorian rainfall. However, the Bureau of Meteorology's sub-seasonal to seasonal forecast system does not currently incorporate observed stratospheric ozone. VicWaCI research has demonstrated the potential for significant improvements in forecast skill for Victorian rainfall during the warm seasons by substituting climatological ozone values with observed stratospheric ozone data (Hendon et al., 2020; Lim et al., 2024)

2.3.4 The influence of weather systems on Victoria's rainfall

Three types of weather systems (fronts, cyclones, and thunderstorms), and combinations of these, contribute 89% of the total annual rainfall in Victoria (Fu et al., 2024). The contributions vary through the year, with winter rainfall coming mainly from cyclones and fronts, and summer rainfall coming more from thunderstorms.

After the Millennium Drought, the influence of weather systems on Victoria's rainfall changed (Figure 2.9). For example, before and during the Millennium Drought, a combination of cyclones, fronts and thunderstorms was the largest contributor to rainfall. Since then, fronts and thunderstorms have been the largest contributor. There has also been a seasonal shift in the rainfall pattern after the drought, with higher rainfall in February and March and lower rainfall in September and October compared to before and during the drought (Fu et al., 2024). The higher rainfall in February mainly comes from thunderstorms and a combination of fronts and thunderstorms.

These weather systems influence rainfall characteristics important for streamflow generation, such as rainfall intensity, rainfall days, maximum daily rainfall and multi-day rainfall accumulation. For example, the number of rainfall days and rainfall intensity were higher before the Millennium Drought and lower during the drought. After the drought, there has been an increase in rainfall intensity but a decrease in rainfall days associated with the cyclone-only weather type (although the shorter period of observations post-drought means the post-drought changes may not be as reliable). There have also been increases in rainfall intensity and rainfall days for front-thunderstorm systems (Figure 2.9).

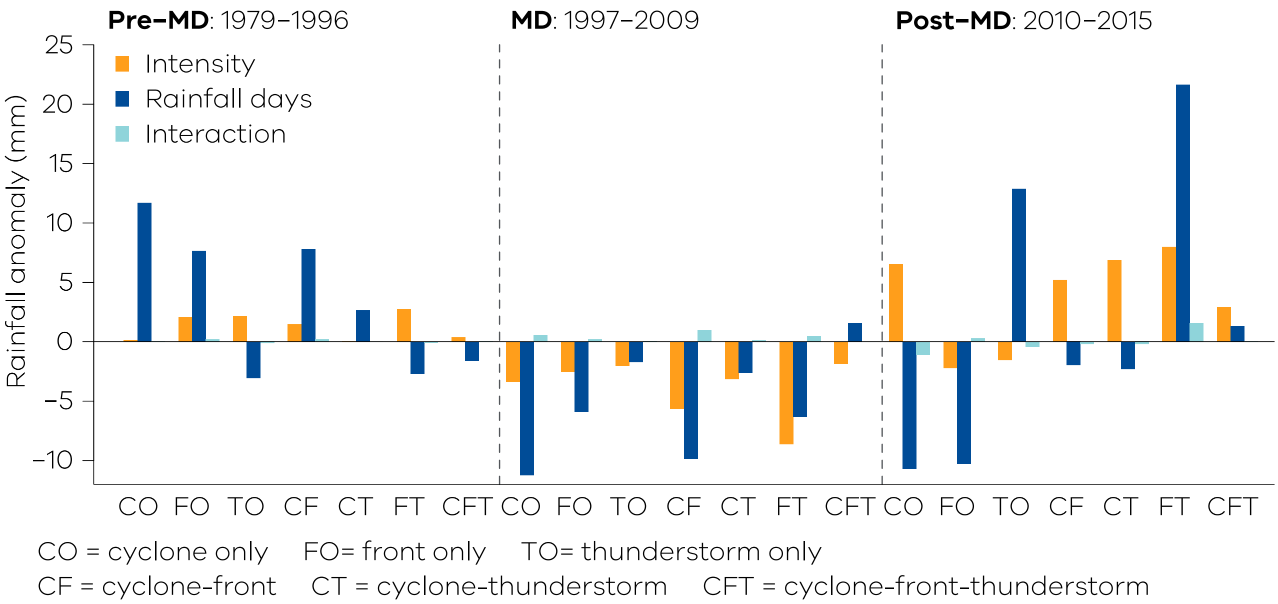


FIGURE 2.9 Rainfall intensity (orange bars), rainfall days (dark blue bars) and interaction from different weather systems (fronts, cyclones, thunderstorms, and their combinations, light blue bars) before (1979–1996), during (1997–2009) and after the Millennium Drought (MD) (2010–2015).

FIGURE 2.9 KEY TAKEAWAY

The weather systems that contribute to Victorian rainfall (and influence runoff) changed during and after the Millennium Drought. After the drought (2010-2015), rainfall intensity increased across most weather systems, while changes to rainfall days were mixed.

3. Victoria's changing hydrology

At a glance

- Average runoff in Victoria has declined since the 1990s, largely due to declines in rainfall.
- A significant change (shift) in the runoff response to rainfall was observed in many Victorian catchments during the Millennium Drought, where runoff decline was larger than expected from the reduced rainfall. Despite the recent wet years, this response persists after the drought in about one-third of the assessed catchments (primarily in central and western Victoria).
- Multi-year droughts can lead to persistent changes in streamflow characteristics, such as flow intermittency and increased no-flow days.
- Due to the unprecedented length of the Millennium Drought, different hydrological processes may have a greater influence on runoff generation than during shorter droughts. Emerging evidence suggests changes to groundwater–surface water interactions, coupled with increased evaporative demand, may explain the observed changes in runoff during and after the Millennium Drought.
- In the Wimmera region, connectivity between streams and catchment moisture storage appears to have greatly decreased during the Millennium Drought and is yet to recover.

3.1 Victoria's hydrology and water resources

Seasonal and regional runoff patterns closely follow rainfall patterns across Victoria. Peak runoff occurs in winter and spring, and regions with greater average rainfall produce greater average runoff.

Hydrology is the scientific study of the movement and distribution of water on and below the ground surface. Different climate and catchment characteristics across Victoria result in large variability in streamflow over time and in different regions.

Rainfall in Victoria tends to be higher in winter and early spring. While lower rainfall amounts occur in autumn, this rainfall is important to wet soils for runoff generation. Most of the catchment runoff in Victoria occurs in winter and spring when rainfall is higher (Figure 3.1) and potential evapotranspiration is low.

The mean annual rainfall averaged across Victoria is about 640 mm, and mean annual runoff is about 85 mm. However, this can vary significantly from year to year and across different regions.

Large amounts of runoff come from the Victorian slopes, as well as from coastal catchments. Both rainfall and the runoff coefficient are higher in these regions. Catchments here are perennial, with streamflow occurring throughout the year. There is less rainfall and runoff in north-central Victoria, and catchments there can be intermittent, with periods of very little or no flow (Figure 3.2).

The year to year variability of runoff in Victoria, and in Australia generally, is high. It tends to be higher than in similar hydroclimate regions in other parts of the world (Peel et al., 2004; Chiew et al., 2002).

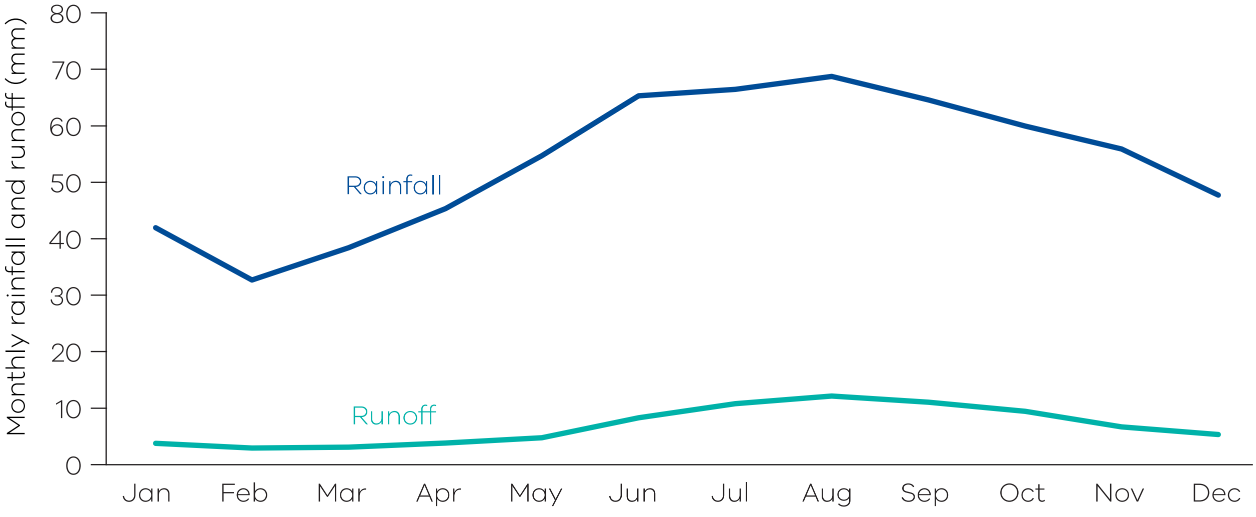


FIGURE 3.1 Monthly rainfall and runoff averaged across Victoria from 1976 to 2023. The green line shows monthly runoff (mm), while the blue line shows monthly rainfall (mm).

FIGURE 3.1 KEY TAKEAWAY

Most of the runoff in Victoria occurs in winter and spring.

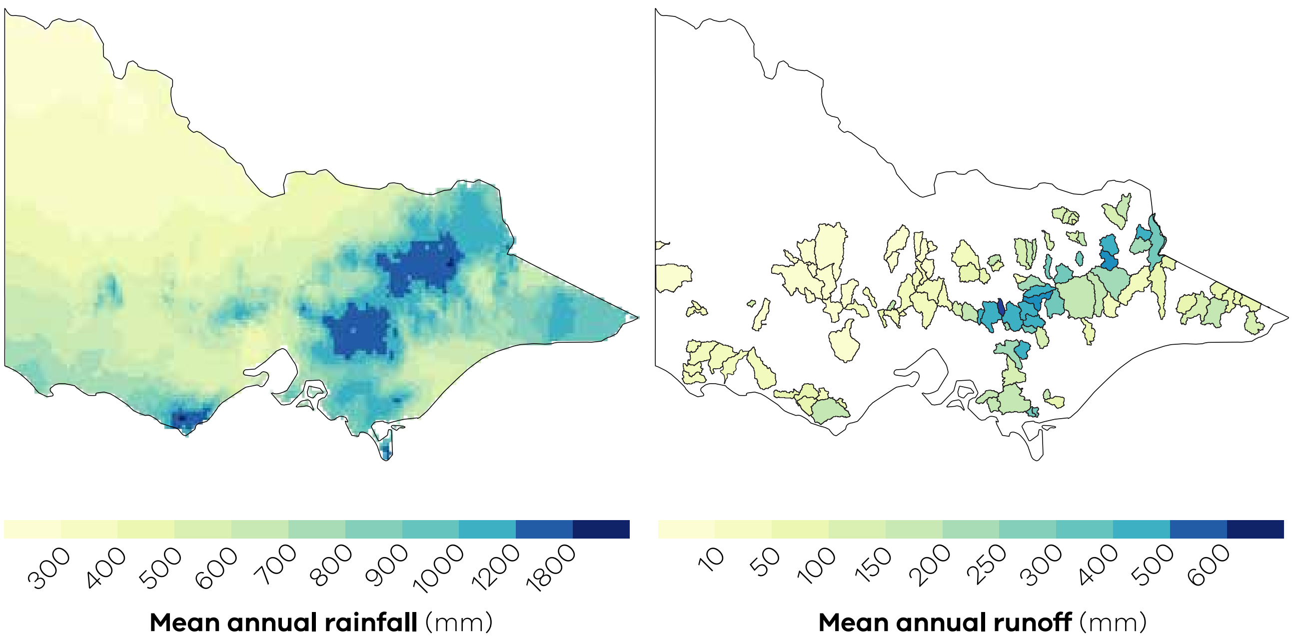


FIGURE 3.2 Mean annual rainfall and runoff averaged over 1976–2023. The gridded rainfall data comes from Australian Gridded Climate Data. Observed streamflow data from the Hydrological Reference Stations were used to estimate catchment runoff. Darker shades of blue represent higher amounts of mean annual rainfall (left) and runoff (right).

FIGURE 3.2 KEY TAKEAWAY

Large amounts of runoff come from the Victorian slopes, as well as from coastal catchments.

3.2 Past changes and trends

Victoria's rainfall and runoff vary between years and at different locations. Significant decreases in streamflow have been observed since the 1990s, particularly in central and western Victoria. A significant reduction in rainfall and runoff occurred during the 1997–2009 Millennium Drought, with less annual runoff generated from a given amount of rainfall during the drought compared to before the drought.

3.2.1 Variability in average annual conditions

Rainfall and runoff in Victoria vary considerably from year to year and across multiple years and decades. Runoff across Victoria was considerably higher from 1950 to 1980 compared to pre-1945 and post-1995, with a significant reduction in rainfall and runoff during the 1997–2009 Millennium Drought (Figure 3.3). Rainfall characteristics and variability and their drivers are discussed in detail in sections 2.2 and 2.3 of this report.

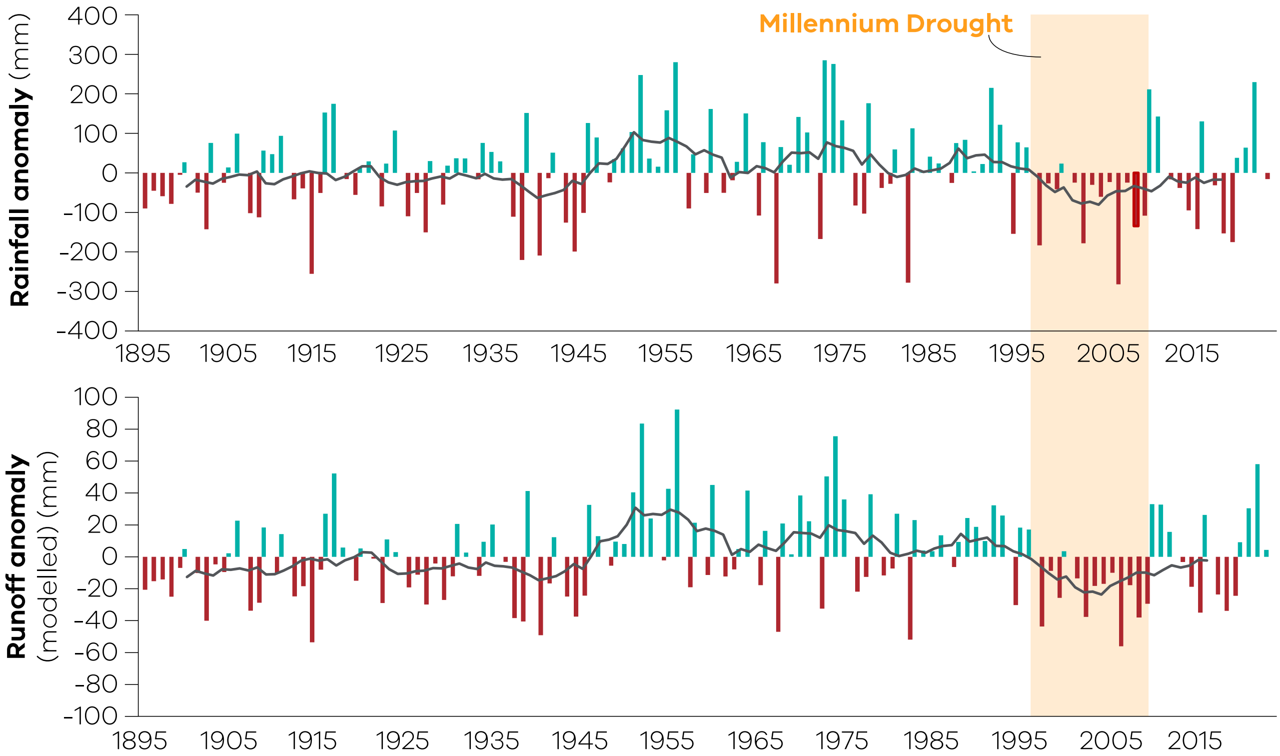


FIGURE 3.3 Annual rainfall (top) and modelled runoff (bottom) averaged across Victoria from 1895 to 2023. The time series is presented as an anomaly relative to the long-term average. The black line shows the 11-year moving average. Teal bars show years that are above the average, and red bars show years below the average.

FIGURE 3.3 KEY TAKEAWAY

There is high interannual and decadal variability in Victoria's rainfall and runoff, with very low runoff during the Millennium Drought.

There are large differences in the pattern of annual streamflow across Victoria (Figure 3.4). A decreasing trend in annual streamflow has been observed in many locations, particularly in central and western catchments. In addition, many catchments in central and western Victoria have experienced changes in annual variability, with many low flow years, interspersed with occasional high flow years.

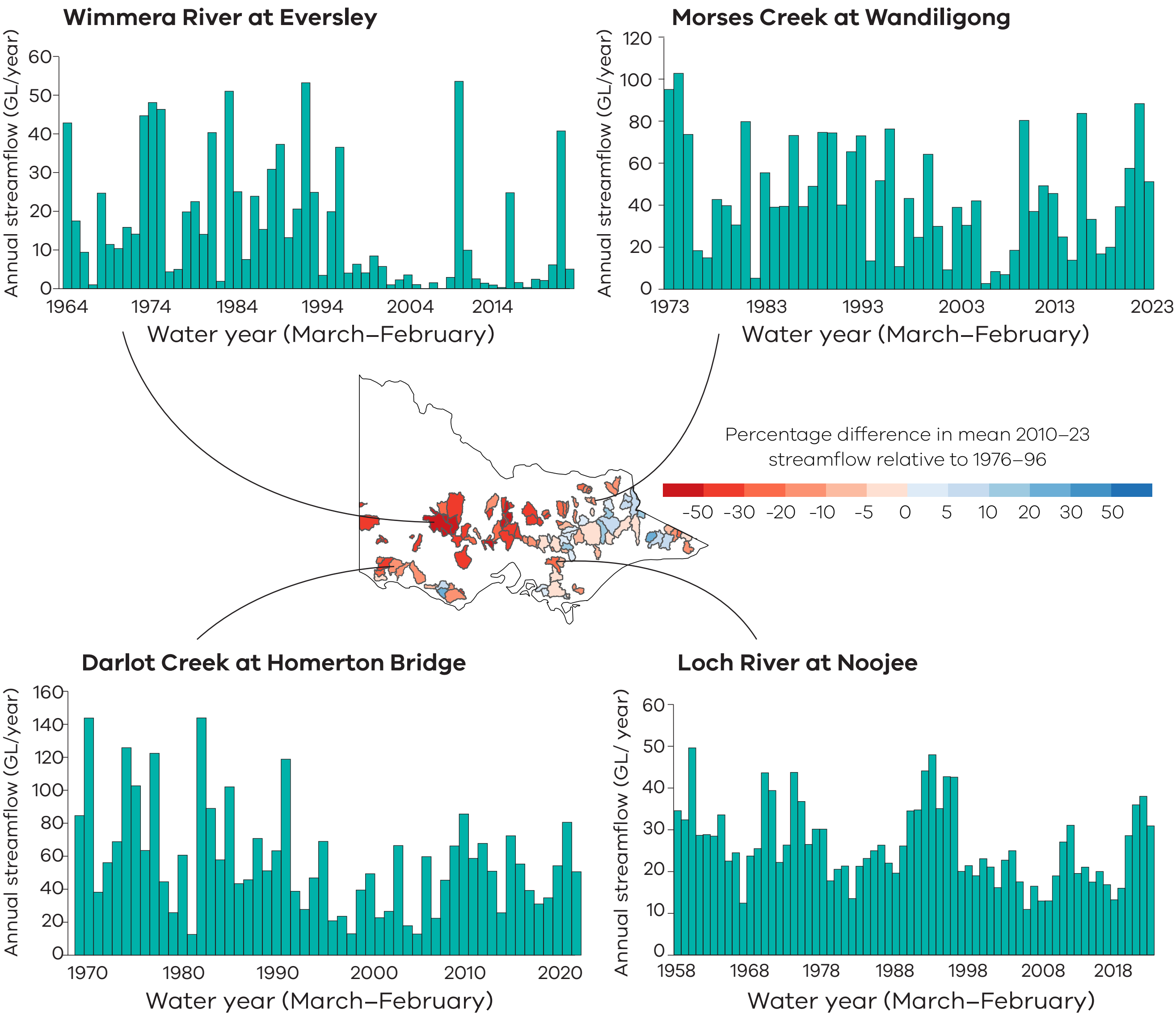


FIGURE 3.4 Year to year streamflow variability across Victoria. Annual streamflow (GL/year) for Wimmera River (top left), Morses Creek (top right), Darlot Creek (bottom left) and Loch River (bottom right).

FIGURE 3.4 KEY TAKEAWAY

There are large differences in the variability of annual streamflow across different regions in Victoria.

3.2.2 The Millennium Drought and its impact

Lower rainfall was experienced during the Millennium Drought, which amplified into significantly lower catchment runoff. The rainfall reduction occurred largely over the cool season (and has continued after the drought), while most of the runoff in Victoria occurs in winter and spring (Potter & Chiew, 2011). Of the catchments that experienced reduced runoff during the Millennium Drought (Figure 3.5b, left), approximately one-third continue to receive less streamflow in the post-drought period, particularly in central and western Victoria (Figure 3.5b, right).

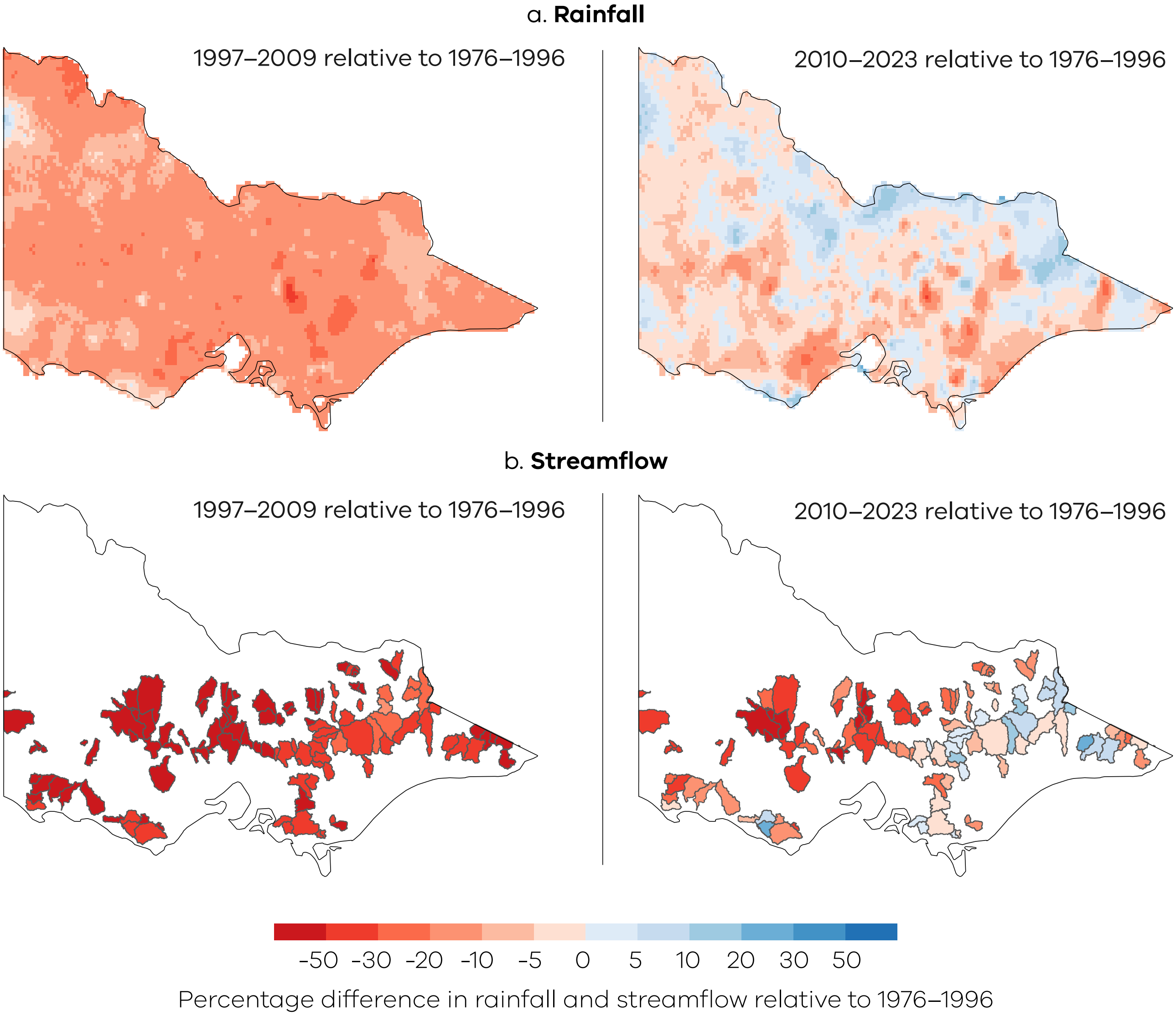


FIGURE 3.5 Percentage change in observed mean rainfall (a) and mean streamflow (b) in 1997–2009 during the Millennium Drought (left column) and in 2010–2023 after the drought (right column) relative to 1976–96 (pre-drought). Blue colours represent increased rainfall and streamflow, while red colours represent a reduction.

FIGURE 3.5 KEY TAKEAWAY

Rainfall decline during the Millennium Drought resulted in a significantly greater decline in streamflow. About one-third of catchments (particularly in the central and west) have not fully recovered from the Millennium Drought.

The runoff reductions in many catchments were much larger than expected from the reduced rainfall, with less annual runoff generated from a given amount of annual rainfall during the Millennium Drought compared to pre-drought conditions. This change in the rainfall-runoff relationship has persisted after the drought in some catchments (such as those observed with reduced runoff in Figure 3.5b), despite the relatively high rainfall over recent years (Figure 3.6).

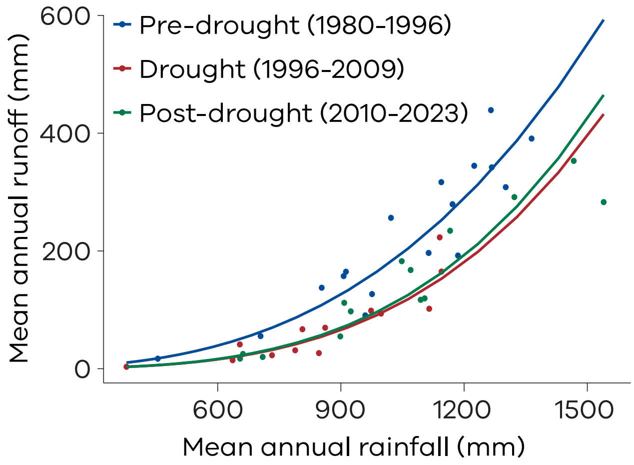


FIGURE 3.6 Comparison of the annual rainfall-runoff relationship between pre-drought (blue), during the drought (red) and post-drought (green) for the Holland Creek catchment (404207) in north central Victoria.

> **FIGURE 3.6 KEY TAKEAWAY**
> In some catchments, runoff decreased more than expected for the given amount of rainfall during and after the Millennium Drought.

This change (shift) in catchment runoff response due to severe or prolonged drought has been described in terms of multiple runoff states (Peterson et al., 2021; Wasko et al., 2024c). Catchments that experienced a shift in the rainfall-runoff relationship may have switched from a normal runoff state into a low (very low) runoff state. In these two-state catchments, it is hypothesised that the threshold of rainfall deficit required to shift into a low runoff state may be lower than the rainfall amount required to shift back (recover) to a normal runoff state (Wasko et al., 2024c). Therefore, returning to a normal runoff state may require an extended wet period in order to meet the recovery threshold amount of rainfall. Ongoing research continues to investigate the two-state concept and thresholds for runoff state changes.

Changes to streamflow characteristics

During and since the Millennium Drought, changes to streamflow characteristics (regime), such as frequency, duration, and timing of peak and low flows, have been observed in some catchments (Bende-Michl et al., *in review*). The nature of these changes was explored using data from 116 unimpaired hydrological reference station (Zhang et al., 2014) catchments in Victoria. Multiple flow indicators were compared across three time periods: before (1970–1997), during (1998–2010) and after (2010–2020) the drought. Flow intermittency (Sauquet et al., 2021) was selected as the key indicator to analyse streamflow regime change. Catchments with a non-perennial (NP) streamflow regime were characterised by an average of five days or more of no (zero) flow per year during the full period of records (1970–2021). Intensification of non-perennial streamflow regime (NPi) described a regime with an increase of 20% or more in the average number of zero flow days per year than before the drought. Five types of streamflow regime changes were identified and described based on their state during each period (Figure 3.7):

- No change in perennial (P) flow during pre-drought, drought and post-drought periods (P-P-P, observed in 53% of the assessed catchments).
- Temporary change from perennial flow during the pre-drought period to non-perennial (NP) intermittent flow during the drought, then returning to perennial flow post-drought (P-NP-P, 5% of the assessed catchments).
- Persistent change from perennial flow during the pre-drought period to intermittent flows during the drought and post-drought (P-NP-NP, 12% of the assessed catchments).
- Temporary change in non-perennial flow with more than 20% increase in the duration of intermittence (NPi) during the drought, with a return to their pre-drought non-perennial regime after the drought (NP-NPi-NP, 4% of the assessed catchments).

- Persistent change in non-perennial flow with more than 20% increase in the duration of intermittence during and after the drought (NP-NPi-NPi, 26% of the assessed catchments).

Catchments with a persistent change in streamflow regime were generally found at lower altitudes, in dry-sub-humid to semi-arid climates, and on flatter terrain with less forest cover. This is broadly consistent with findings from other studies that have investigated changes to the rainfall-runoff relationship (Fowler et al., 2022; Saft et al., 2015; van Rensch et al., 2023). These catchments have smaller rainfall-runoff ratios (< 0.14) due to lower rainfall amounts and similar potential evapotranspiration. This means there is less available water to generate runoff than catchments that did not experience a change in flow regime.

The drought impacted all aspects of flow, with a reduction in magnitude across all flow frequencies, resulting in a downward shift in the flow duration curves (Figure 3.8). Catchments with a persistent change in streamflow regime had the largest proportional reduction in flow. Median flow was reduced on average by 50 to 75%, while high flows were affected to a lesser extent, indicating that major storms still contributed to runoff.

The most impacted flows were low to extreme-low flows, which experienced reductions of up to 100%. This suggests that the drought impacted catchment processes that generate and sustain baseflow, particularly in late summer and early autumn. During this period, perennial catchments became intermittent and non-perennial catchments experienced increased frequency of intermittent flow.

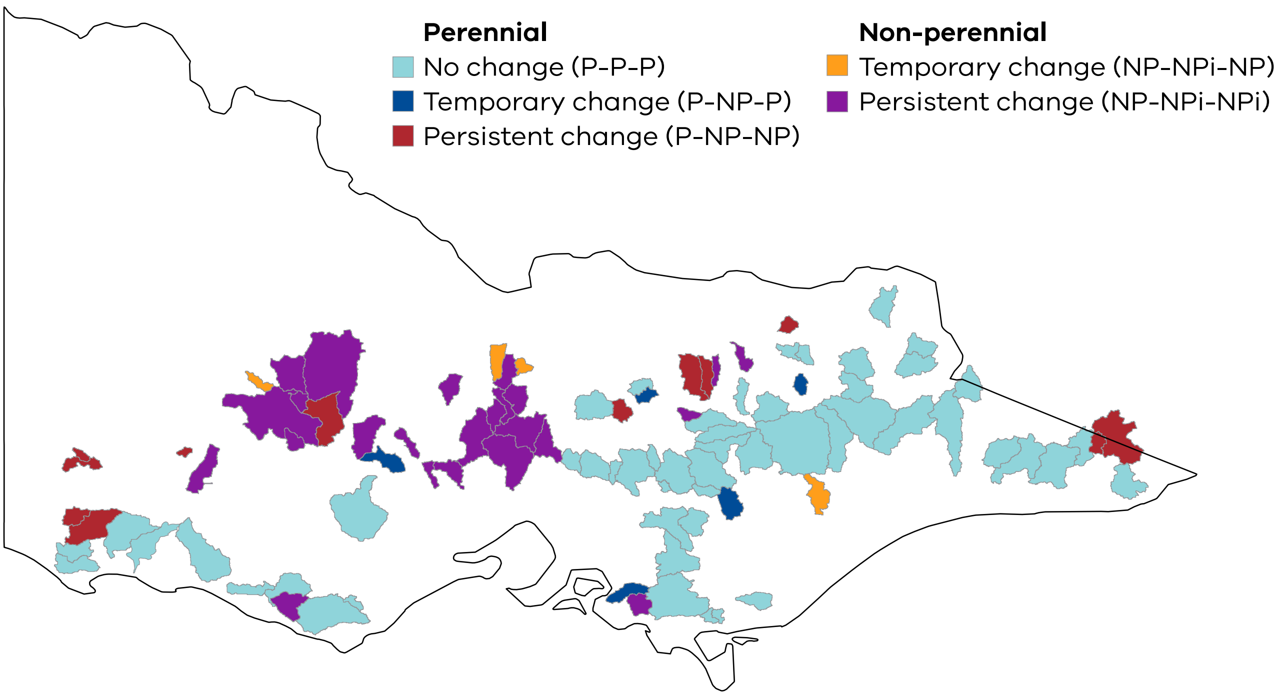


FIGURE 3.7 Map showing changes in streamflow regime in perennial and non-perennial catchments during and after the Millennium Drought. P = perennial flow, NP = non-perennial flow, NPi = longer duration (intensification) of intermittent flow.

FIGURE 3.7 KEY TAKEAWAY

Persistent changes to streamflow characteristics (regime), such as a change from perennial to intermittent flows or intensification of intermittent flows, were experienced in some catchments during and after the Millennium Drought.

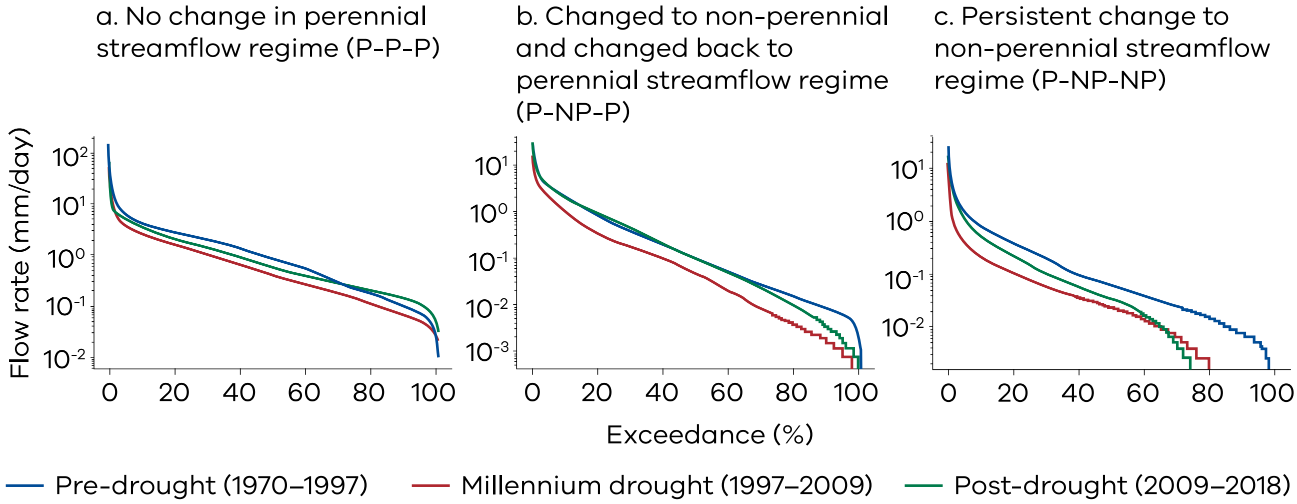


FIGURE 3.8 Flow duration curves showing flow exceedance of streamflow before (blue), during (red) and after (green) the drought for three representative catchments. a) no change in streamflow regime (Catchment 235202); b) temporary change from perennial to non-perennial flows during the drought (Catchment 227231); c) persistent change from perennial to non-perennial streamflow regime during and post-drought (Catchment 238229).

FIGURE 3.8 KEY TAKEAWAY

Flow magnitude was reduced across the full flow range during the Millennium Drought, with low to extreme-low flows particularly affected.

Changes to groundwater

There was a persistent decline in groundwater levels during the Millennium Drought (LeBlanc et al., 2009; Fowler et al., 2020). Decreasing groundwater levels were observed between 2001 and 2007 in groundwater bores across the Murray-Darling Basin (LeBlanc et al., 2009). In addition, a multi-year trend of decreasing groundwater was observed from 1994 to 2009 in groundwater bores that were not affected by groundwater extraction in eastern and western Victoria.

Recent groundwater research has found variations in groundwater sensitivity to rainfall and potential evapotranspiration across Victoria (Fan et al., 2023). This is similar to the observed variability in catchment runoff responses (and variability in whether they recover) to changing rainfall conditions. When considering groundwater levels, bores in northern Victoria were found to be more sensitive to precipitation changes than bores in central Victoria. For recharge, the temperate regions in southern Victoria (south of the Great Dividing Range) were found to be more sensitive to rainfall changes. This highlights that the relationship between climate and groundwater is more nuanced than previously assumed.

3.3 Factors influencing changes to catchment response during the Millennium Drought

The unprecedented length of the Millennium Drought is the primary climatic driver of shifts in Victoria's catchment response during and after the drought. Hydrological processes that are related to surface-groundwater interactions and increased evaporative demand may have also contributed to this shift.

The observed change in catchment response during multi-year droughts suggests that the interaction between hydrological processes and their influence on runoff generation may be different from non-drought or shorter drought periods. The post-drought persistence of this response in some catchments has made it more challenging to identify factors that may contribute to the changes.

In addition to Victoria, changes in catchment response to long droughts have been observed in far south-west Australia (Petrone et al., 2010), and to a lesser extent in parts of NSW and southern Queensland (Saft et al., 2015).

Significant research efforts are focused on identifying factors that may influence or explain the change in catchment response and its persistence. The findings of recent research from a range of perspectives are outlined in the sections below.

3.3.1 Understanding potential drivers of change

Research to investigate and characterise the drivers of change in catchment response has included identifying plausible causes such as climatic forcing, vegetation, soil moisture dynamics, groundwater and human influences (Fowler et al., 2022b). Assessment of these hypotheses against a large body of evidence points to the unprecedented length of the Millennium Drought as the primary climatic driver, paired with groundwater processes, including declines in groundwater storage, altered recharge associated with a deepening of sub-surface unsaturated zone (vadose zone), and reduced connection between sub-surface and surface water processes (Figure 3.9). Increased evaporative demand may also play a role.

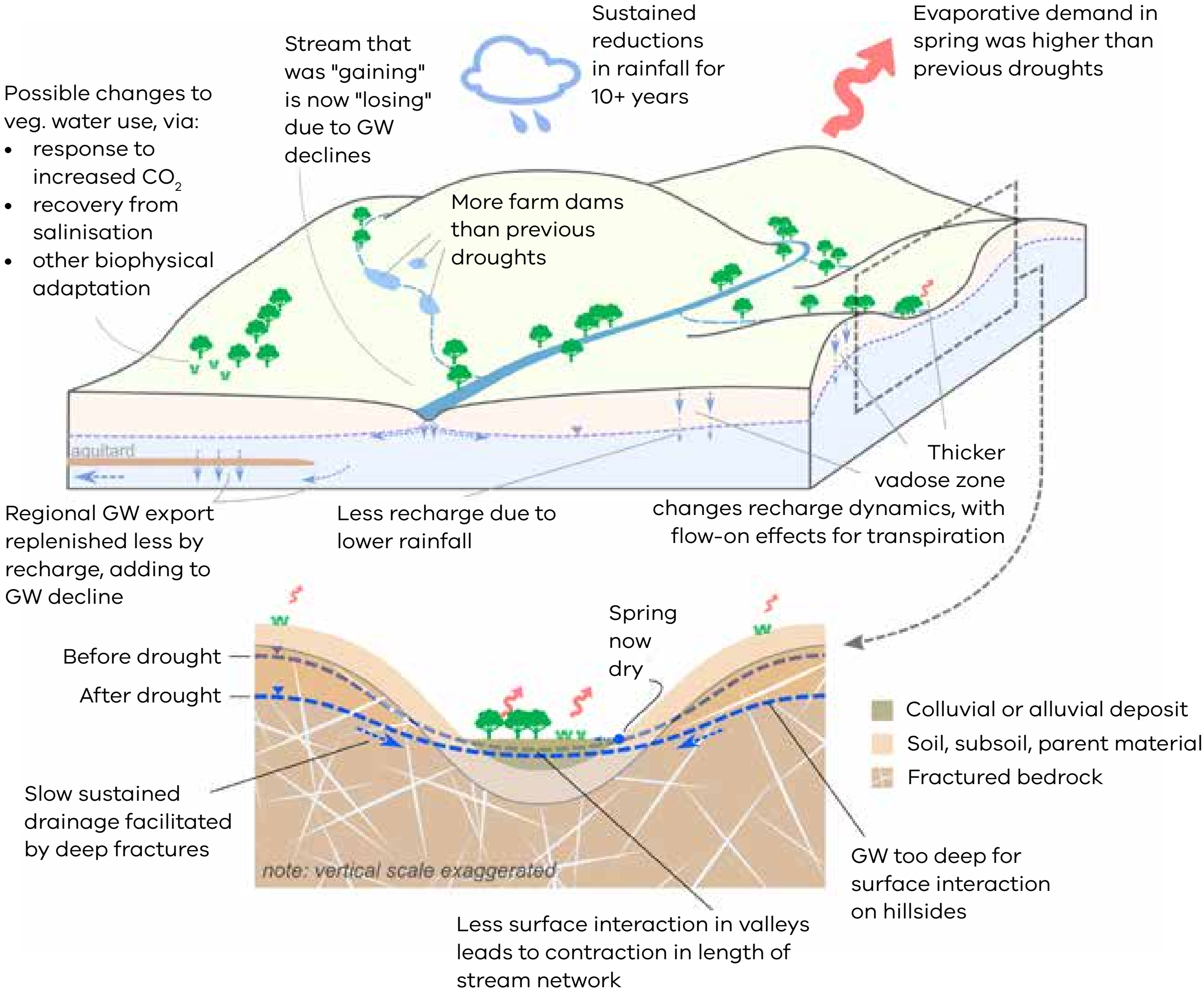


FIGURE 3.9 Synthesis of selected processes that may explain why the Millennium Drought had less streamflow than expected relative to other droughts since the 1950s. The illustration describes catchment-scale (top) and selected hillslope (bottom) processes of a typical catchment in central or western Victoria. Source: Fowler et al., 2022b

FIGURE 3.9 KEY TAKEAWAY

The unprecedented length of the Millennium Drought is likely the primary climatic driver of catchment response shifts, combined with a number of plausible physical processes.

3.3.2 Rainfall characteristics

Annual streamflow is strongly correlated to annual rainfall, but the relationship between rainfall and streamflow changes across different periods. Other rainfall characteristics, like the number of rainfall days and the mean length of wet spells, may be able to more consistently predict annual streamflow over different hydroclimate periods (Fu et al., 2021 and 2023).

The influence of post-drought seasonal rainfall patterns and intensity on streamflow regime were examined across different catchments (Bende-Michl et al., *in review*). Cool season rainfall has increased across most catchments after the Millennium Drought (see section 2 of this report), except for September and October rainfall, which remains lower than the pre-drought totals. This has shifted the timing of post-drought peak streamflow earlier – from September to August.

In catchments with a persistent change in streamflow regime, post-drought streamflow from May to August has remained lower than pre-drought streamflow. Analysis using the Bureau's AWRA-L model shows that incomplete recovery of spring runoff is aligned with depleted soil moisture during these months. These catchments also received less rainfall during the second wet La Niña year in 2011–12 while experiencing higher actual evapotranspiration in spring, resulting in more rapid soil moisture depletion. Intense rainfall (>15 mm per day) has occurred less frequently post-drought in these catchments. This suggests that more frequent higher-intensity rainfall events may be needed for some catchments to return to their pre-drought streamflow regime.

3.3.3 Evapotranspiration and vegetation

The streamflow missing from some catchments during the drought period was most likely directed towards increased evapotranspiration per unit of rainfall relative to pre-drought conditions (Peterson et al., 2021; Stephens et al., 2023). This implies that pre-drought vegetation transpiration rates were maintained during the drought, given the Leaf Area Index did not decline despite reduced rainfall.

Regional water balance approaches that consider the absolute volume of evapotranspiration show that the volume of water lost to actual evapotranspiration remained mostly unchanged during the Millennium Drought. With the actual evapotranspiration volume unchanged, rainfall reductions during the drought were partitioned into reductions in streamflow and sub-surface storage (Weligamage et al., 2023). The results suggest that, in the water-limited context of a multi-annual drought, vegetation has the first use of available water and may even supplement its use from groundwater (hence the reduction in sub-surface storage). Streamflow receives the remaining available water from this process, if any.

Potential greening due to higher carbon dioxide (CO_2) is another factor to be considered, with the Leaf Area Index across Victoria trending upwards over time (i.e. increasing greening in Victoria). This trend only marginally stalled during the Millennium Drought. Higher CO_2 may have influenced the efficiency of water use in recent decades, with flow-on effects on streamflow generation (Liu et al., 2020; Ukkola et al., 2016).

3.3.4 Groundwater–surface water interaction

The occurrence of intermittent flows has increased in some catchments during the drought, with this behaviour persisting post-drought in some catchments (Bende-Michl et al., *in review*). This may result from drought-induced changes in catchment storage and subsequent contributions to streamflow. These processes can be associated with reduced soil moisture replenishment and groundwater recharge, leading to a decrease in baseflow. Interruptions in baseflow can occur when there are changes in the interaction between surface water and groundwater, such as a disconnection between the two from a prolonged period of drying (Kinal & Stoneman, 2012; Fuchs et al., 2019).

A study of a few catchments in Victoria (Bonotto et al., 2022) suggests a weakening of surface-groundwater interactions occurred in some catchments during and after the Millennium Drought compared to the previous wet periods. Trotter et al. (2024) found steeper streamflow recession curves (the rate of change in flow following peak flow being reached) for catchments with a persistent rainfall-runoff shift. The steeper recession curve is likely caused by reduced connectivity between sub-surface moisture storage and surface runoff and increased transmission losses through the streambed.

Box B: Understanding hydrological responses in the Wimmera region

The hydrological response of catchments in north-west Victoria to the Millennium Drought, particularly in the Wimmera region, differed from other areas of the state. While rainfall-runoff relationships have returned to their pre-drought conditions in much of the state, in north-west Victoria, the proportion of rainfall that becomes streamflow remains considerably lower than before the drought (see Figure 3.5). The various factors that may contribute to this behaviour in this region were investigated.

The characteristics of the hydrological changes in the Wimmera region suggest there have been changes in hydrological connectivity, with streams transitioning from a predominantly perennial state to an intermittent stream. One form of hydrological connectivity is when areas of inundation provide pathways for surface water to travel across catchments. Remote sensing imagery indicates there was a large decline in the areas permanently and temporarily inundated by water during the Millennium Drought and that inundation is considerably more variable after the drought than before it. However, declines in surface water inundation across the region are primarily associated with the region's many shallow lakes rather than runoff-generating parts of the catchment.

Remote sensing imagery also shows that while there have been changes in rainfall and streamflow between the three periods (before, during and after the drought), estimates of actual evapotranspiration show little change. Changes in actual evapotranspiration are due to a combination of increasing temperatures leading to increases in the atmospheric demand for water (i.e. potential evaporation) and a gradual greening of the landscape (as indicated by an increasing trend in the Leaf Area Index).

Observations also show that catchment water balances in the Wimmera Region (water balance = rainfall minus streamflow and actual evapotranspiration) have changed from a net rainfall surplus before the drought to a much smaller surplus during the drought, and a small net rainfall deficit after the drought. This reduction in the net rainfall surplus and changing to a rainfall deficit suggests that the amount of water stored in the region is declining (Figure 3.10).

Annual water balance models were used to understand the plausibility of changes in sub-surface water storage within catchments in the Wimmera region. While standard annual water balance models were generally able to simulate streamflow well across Victoria, simulations of catchments in the Wimmera region were relatively poor. Good simulation performance could only be achieved in the region by allowing actual evaporation to draw down conceptual water stores, and by explicitly representing the disconnection between catchment water stores and catchment runoff.

The findings indicate that catchments in the Wimmera region behave differently from other Victoria regions. Connectivity between streams and catchment moisture stores appears to have greatly decreased during the Millennium Drought and is yet to recover. This diminished connectivity appears to be related to the conversion of a net rainfall surplus before the drought to a small net rainfall deficit during and after the drought.

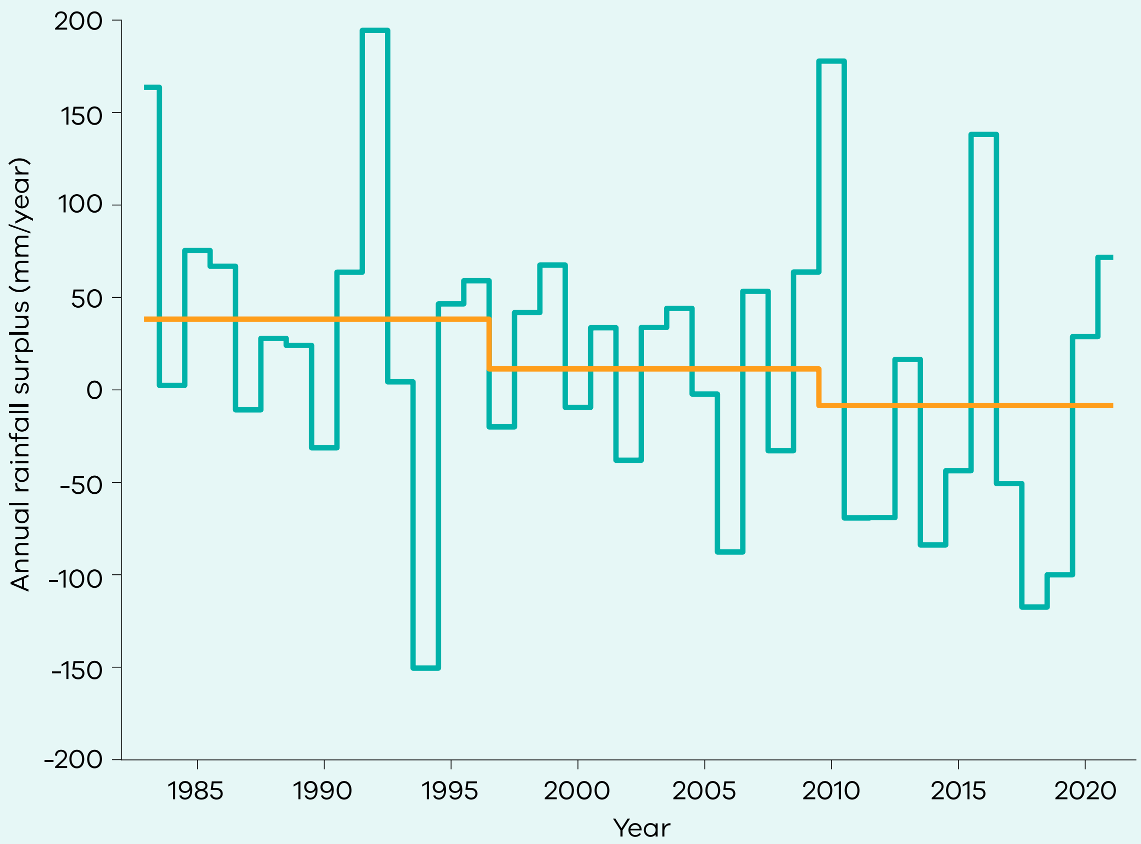


FIGURE 3.10 Annual surface water balance expressed as rainfall surplus (mm/year) for Wimmera River at Glenorchy Weir (Catchment 415201). The green line represents the difference between catchment moisture input (rainfall) and output (runoff and actual evapotranspiration). The yellow line represents average values before, during and after the Millennium Drought.

FIGURE 3.10 KEY TAKEAWAY

Catchment water balances in the Wimmera region have changed from a net rainfall surplus before the Millennium Drought to a small net rainfall deficit during and after the drought.

Box C: Victorian Drought Inference Project

The Victorian Drought Inference Project was an interdisciplinary project that involved hydrologists, climate scientists and water managers from the Victorian Department of Energy, Environment and Climate Action, Melbourne Water, the University of Melbourne, CSIRO, Bureau of Meteorology and Monash University. The project investigated the history and future risk of decadal to multi-decadal droughts in south-eastern Australia (Freund et al., 2017) – information that is highly relevant to the Victorian water sector.

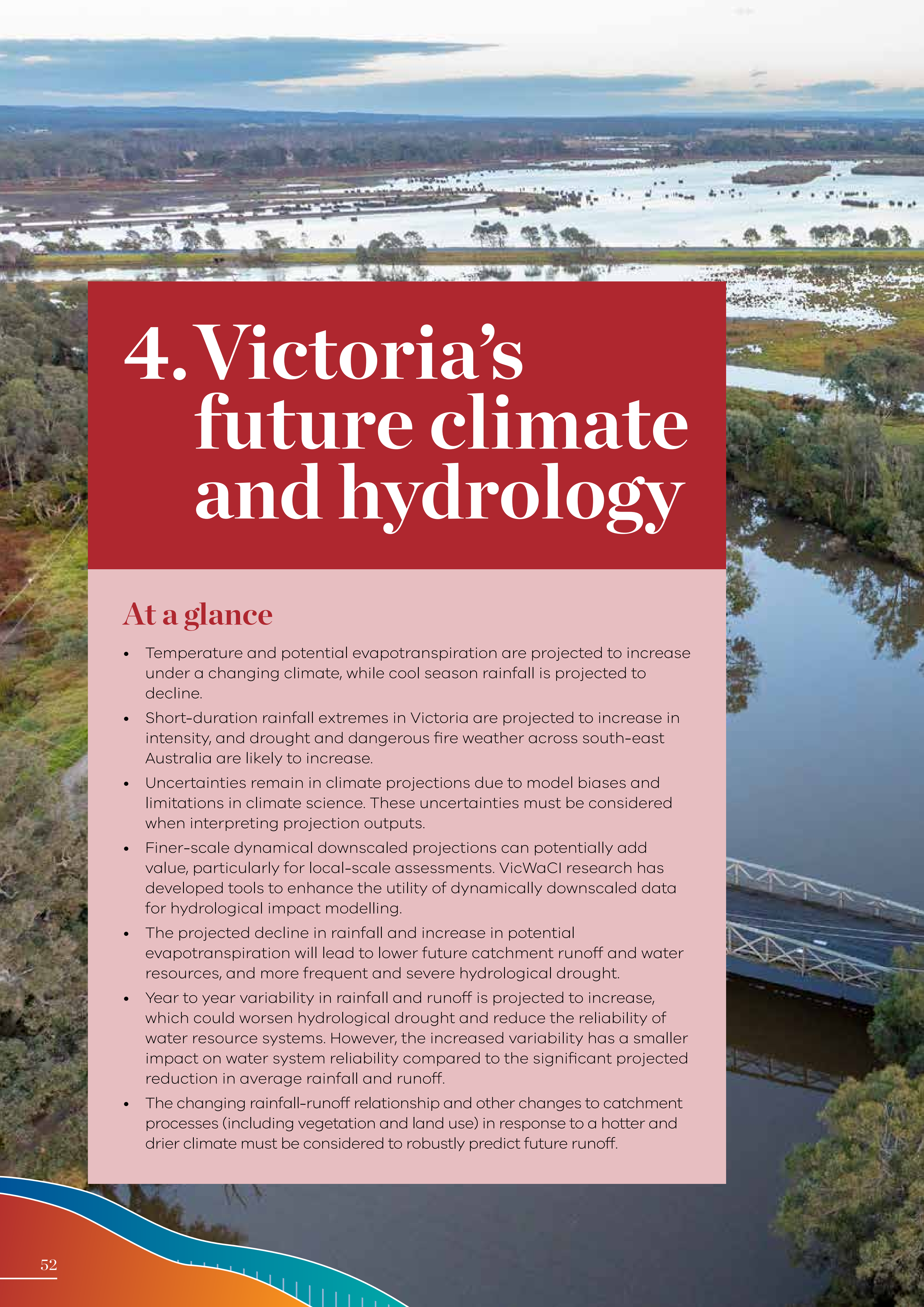
The project collated all published, high-resolution (at least annual), publicly available paleoclimate records for the Australasian region that met the requirements of the study, drawing on tree ring, coral and ice core archives. This consolidated resource is now available to researchers and other interested parties. The collation process highlighted the temporal and spatial limitations of paleoclimate records suitable for high-skill hydroclimate reconstructions for Victoria. The closest suitable multi-century published records were found to be based on tree rings from Tasmania and New Zealand.

Research under the project considered whether the available paleoclimate records were suitable for use in developing streamflow reconstructions for Victorian water industry applications. Remote proxies were found to contribute positively to the skill of reconstructions, likely via the impacts of large-scale climate features, but the challenge of teleconnection non-stationarity led to reduced confidence in the use of remote proxies. The project explored the shortcomings in previous approaches to reconstruction evaluations and developed a comprehensive approach to the tests used to evaluate reconstructions.

Inflows into two major Victorian water systems were considered as case studies. While the work helped to improve our understanding of past climatic conditions, similar to hydroclimate reconstructions performed in other regions of Australia, these case study streamflow reconstructions based on remote proxy records had only modest skill (Henley et al., 2019). The results indicated that to develop high-confidence, high-skill reconstructions of the hydroclimate of recent centuries for Victoria, new local, high-resolution, accurately dated, multi-centennial, well-replicated, hydroclimate-sensitive paleoclimate records would need to be developed. The project spurred a pilot-scale project that demonstrated the strong potential for new records.

The project also developed a method to stochastically simulate streamflow data, accounting for observed variability, the uncertainty in the case study reconstructions and the seasonal mean changes in future precipitation in Victoria projected by climate models. However, the study also recommended that high-skill paleoclimate reconstructions be developed before their direct use in water industry applications in Victoria.

The Victorian Drought Inference Project helped to increase our understanding of the existing network of remote paleoclimate records for developing streamflow reconstructions for Victoria. The project highlighted the importance of rigorous evaluation of reconstructions and statistical approaches to the simulation of variability in the presence of uncertainty. Despite approaches being applied in other Australian jurisdictions to incorporate lower-skill reconstructions based on remote proxies, this project recommended that high-skill paleoclimate reconstructions, likely based on new local proxy records, be developed before their direct use in water industry applications in Victoria.



4. Victoria's future climate and hydrology

At a glance

- Temperature and potential evapotranspiration are projected to increase under a changing climate, while cool season rainfall is projected to decline.
- Short-duration rainfall extremes in Victoria are projected to increase in intensity, and drought and dangerous fire weather across south-east Australia are likely to increase.
- Uncertainties remain in climate projections due to model biases and limitations in climate science. These uncertainties must be considered when interpreting projection outputs.
- Finer-scale dynamical downscaled projections can potentially add value, particularly for local-scale assessments. VicWaCI research has developed tools to enhance the utility of dynamically downscaled data for hydrological impact modelling.
- The projected decline in rainfall and increase in potential evapotranspiration will lead to lower future catchment runoff and water resources, and more frequent and severe hydrological drought.
- Year to year variability in rainfall and runoff is projected to increase, which could worsen hydrological drought and reduce the reliability of water resource systems. However, the increased variability has a smaller impact on water system reliability compared to the significant projected reduction in average rainfall and runoff.
- The changing rainfall-runoff relationship and other changes to catchment processes (including vegetation and land use) in response to a hotter and drier climate must be considered to robustly predict future runoff.

4.1 Future climate

4.1.1 Temperature, rainfall and dry and wet extremes

Victoria's temperatures will continue to increase and cool season rainfall will continue to decline, while changes to warm season rainfall are less certain.

Victoria's climate is expected to continue warming through the 21st century (DEECA, 2024; Grose et al., 2020). The projected amount of warming depends on the emissions scenario, as well as the climate models and baseline period used.

Rainfall during the cool season is projected to decrease further, especially under moderate to high emissions scenarios (Figure 4.1). Cool season rainfall since 1997 has been tracking at the drier end of projections.

Warm season rainfall does not show a significant change; however, climate models indicate that both wet and dry conditions are plausible from year to year (Figure 4.1c, shaded range).

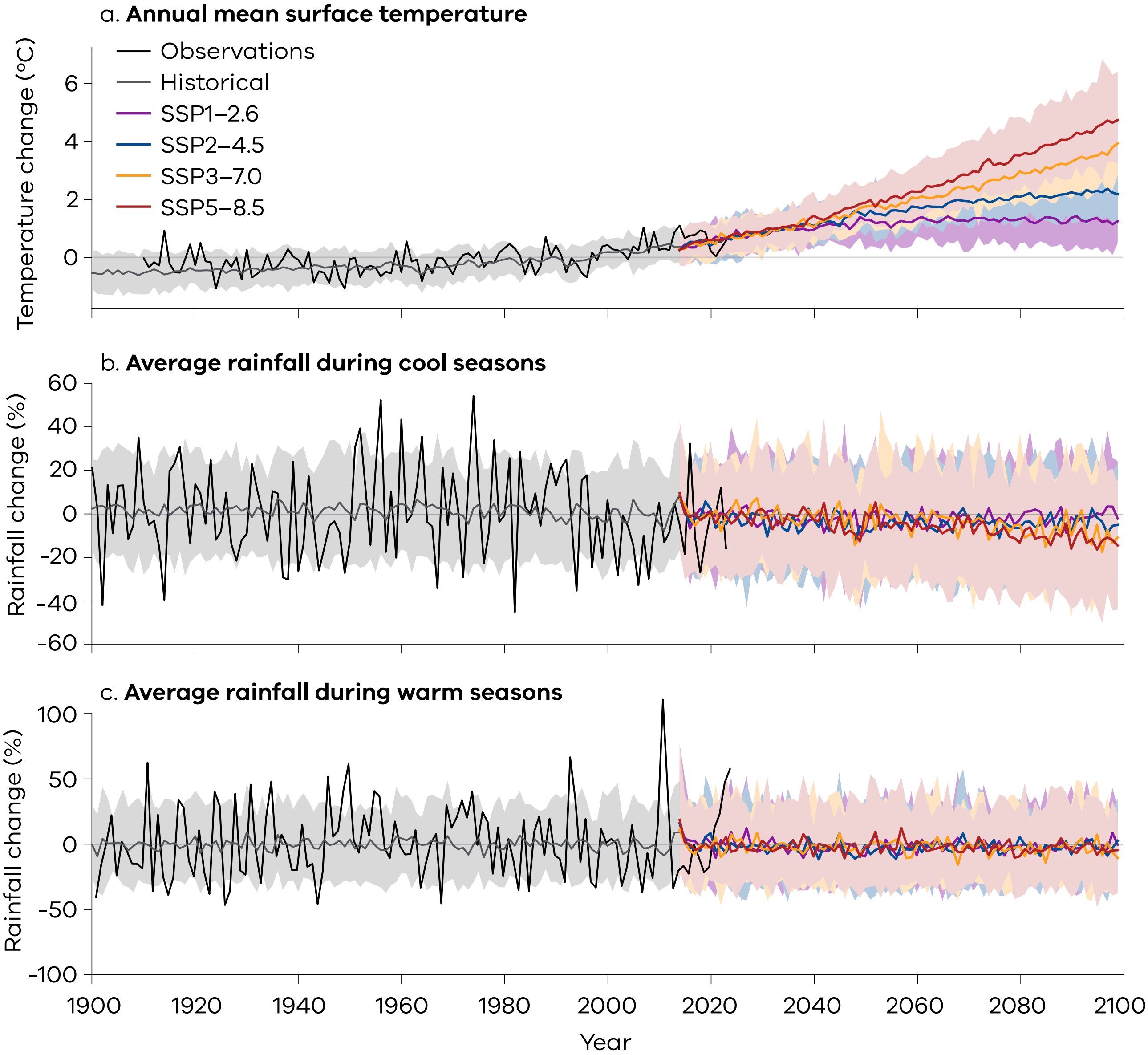


FIGURE 4.1 Observed and projected change in Victoria's (a) annual mean surface temperature, and averaged rainfall during (b) cool and (c) warm seasons from 1900 to 2100. CMIP6 historical model average and range to 2015 are shown in grey. Future change is projected from CMIP6 models and shown for SSP1-2.6 (low emissions scenario), SSP2-4.5 (moderate emissions scenario), SSP3-7.0 (high emissions scenario) and SSP5-8.5 (very high emissions scenario) as °C change for temperature and % change for rainfall, all relative to the baseline period (1986–2005). Observations are shown in black, historical simulations from models in grey and future scenarios in colours. Thick lines show the multi-model mean while shading shows the 10th to 90th percentile spread across models. The multi-model mean smooths out the year-to-year variability and represents the average change at that time. Source: AGCD observations and CMIP6 models.

FIGURE 4.1 KEY TAKEAWAY

Victoria's temperatures will continue to increase and cool season rainfall will continue to decline. Changes in warm season rainfall are less certain.

Step changes in rainfall

Victoria experienced two shifts in cool season rainfall in the observational record: an increase in 1945 and a decrease after 1996 (see Figure 2.4). These step changes require water managers to adapt their strategies and operations to ensure the sustainable and effective management of water resources to meet the needs of people and the environment. Understanding the likelihood of future step changes is important for planning.

The likelihood of future step changes in rainfall was estimated using CMIP5 models, specifically assessing whether the next 20 years will be wetter or drier than the previous 20 years. Past step changes were identified in simulations of past rainfall to assess if the models can accurately represent observed abrupt rainfall changes. The likelihood of step changes in a very high emissions scenario (RCP8.5) was assessed and the frequency of step changes in historical and future simulations was compared with pre-industrial control simulations to determine the impact of climate change on the step change.

Historical model simulations show that the observed change in Victorian rainfall in the mid-20th century did not correspond with an increased likelihood of a step change in CMIP5 historical outputs. Instead, models suggest a higher probability of a step-up change between the late 1960s and 1980. In contrast, the decrease in Victorian rainfall after 1996 corresponds with a period when CMIP5 models suggest an increased likelihood of step-down changes. This suggests that only the most recent step change (decreased rainfall after 1996) was likely influenced by climate change.

CMIP5 projections indicate a future dramatic rise in the likelihood of step-down rainfall changes under a very high emissions scenario (RCP8.5) towards the end of the 21st century. Based on the historical period, models cannot predict the exact timing of a decrease in rainfall. However, there is high confidence that step-down changes in cool season rainfall will become more frequent in future.

The main influence on projected cool season rainfall declines is a decrease in the frequency of extratropical lows in Victoria during the cool season at the end of the century compared to 1979–2005 (Pepler & Dowdy, 2022). Projected changes in anticyclones are less clear (Pepler, 2023). There is also a projected decline in the frequency of cyclone-anticyclone dipole events linked with heavy drought-breaking rainfall for the 2050–2100 period relative to 1980–2005 (Holgate et al., 2023). However, the average intensity of rainfall from cyclones is projected to increase, so the frequency of cyclones with very heavy rain (equal to the current annual maximum daily rainfall) may remain unchanged or even increase (Pepler & Dowdy, 2022).

Wet extremes

Daily rainfall extremes that occur on average once a year or less are projected to become more intense in a warmer climate due to increased moisture in the atmosphere. The best estimate of changes in daily rainfall for the wettest day of the year (annual maxima) is for an 8% increase per 1 °C of warming (Wasko et al., 2024a).

Short-duration (less than a day) rainfall extremes, including those linked to thunderstorms, are projected to increase more significantly. The best estimate of changes in short-duration rainfall extremes is for a 15% increase per 1 °C of warming (Wasko et al., 2024a). Intense hourly and sub-hourly rainfall have already increased in Victoria (Osburn et al., 2020; Tolhurst et al., 2023), which may be contributing to more frequent flash flooding.

The projected increase in rainfall intensity is likely to be smaller for long-duration (multi-day) rainfall events (Wasko et al., 2024a), particularly in regions such as Victoria where total rainfall is projected to decline.

The increase in rainfall intensity is likely to be larger for rarer extreme events, such as those with less than 5% chance of occurring in any given year, compared with more frequent extremes that occur multiple times per year.

Extreme event case study: Victoria's flood risk

The historical trend of small floods becoming smaller and large floods becoming larger is projected to continue at a greater rate in future, depending on the emissions scenario followed. In general, future floods in urban areas are likely to increase in line with future changes in extreme rainfall.

Victoria experiences large year to year variability in rainfall and streamflow conditions (see sections 2 and 3 of this report for more details). This variability impacts the occurrence and severity of flood events, where the frequency of extreme wet and dry periods is largely controlled by large-scale climate drivers related to sea surface temperatures.

As described in section 2 of this report, the intensity of extreme rainfalls has increased over recent decades. However, observed changes in the associated flood response are not always in the same direction.

Analysis of historical streamflow data from rural catchments across Australia shows that the magnitude of very large floods, such as an event with a 1-in-20 chance of occurring or being exceeded in any given year (1-in-20 Annual Exceedance Probability (AEP)), has increased by approximately 3% per decade. This is generally consistent with the magnitude of increases in associated extreme rainfall. In contrast, smaller floods have decreased in magnitude despite increases in extreme rainfall (Wasko & Nathan, 2019).

This trend in observed flood behaviour is due to the drying of soils in rural catchments, caused by a reduction in average annual rainfall, warming temperatures and increased evapotranspiration.

Similar trends occur in projections of future flooding in rural catchments across Australia. Projections indicate that by the end of the century, frequent floods (such as 1-in-5 year events) will continue to get smaller but larger rural floods are projected to increase in magnitude (Wasko et al., 2023).

Floods in urban environments are influenced by the large area of hard surfaces, such as roads and drains, which are impermeable and rapidly transport water through the catchment. As a result, floods in urban areas tend to be larger and rise more quickly than those in rural catchments for a given amount of rainfall. In the future, floods in urban areas are likely to increase in line with future changes in extreme rainfall, as these areas tend to have a relatively small proportion of porous surfaces to absorb some of the rainfall and moderate the associated runoff.

Floods may also be exacerbated by rising sea levels in coastal and estuarine areas.

A systematic review and meta-analysis of recent peer-reviewed science identified some of the findings about changes to extreme rainfall noted above and other influences of climate change relevant to design flood techniques (Wasko et al., 2024a). This analysis has informed an update to the climate change advice in the national guideline for estimating design flood characteristics in the Australian Rainfall and Runoff (refer to Book 1, Chapter 6 of the Australian Rainfall and Runoff; Wasko et al., 2024b). This updated guidance provides practitioners with contemporary guidance on how to account for changing flood behaviour in the assessment of current and future flood risks.

This case study is based on information presented in Victoria's Climate Science Report 2024 (DEECA, 2024), which contains further information about Victoria's flood history and future flood risk.

Droughts

In a warmer climate, droughts are likely to occur more frequently in south-east Australia. However, different global climate models provide varying projections for the severity, duration and specific location of droughts (Ukkola et al., 2024; Kirono et al., 2020).

A decrease in cool season rainfall combined with warmer temperatures will likely cause future droughts in eastern Australia to be significantly longer and more intense than those observed in the 20th century (Falster et al., 2024).

Extreme event case study: Understanding the drivers of meteorological droughts in Victoria

Large-scale climate drivers and weather systems that influence Victoria's rainfall variability are also important in the onset and recovery of drought.

Meteorological drought is generally defined as a period of rainfall deficiency relative to the long-term average conditions. Extended periods of rainfall deficit can often be attributed to the influence of large-scale climate drivers and changes in local weather patterns.

ENSO and IOD account for up to 30% of the interannual variance in Victorian rainfall in winter and spring, and much less in other seasons (Risbey et al., 2009). Both El Niño and positive IOD events have been associated with significant reductions in Victorian rainfall and droughts, particularly during winter and spring (Freund et al., 2017; Risbey et al., 2009). While drought can occur during individual El Niño or positive IOD events, the simultaneous occurrence of these climate drivers tends to produce a stronger rainfall response over Victoria than would occur from the influence of just one of the drivers (Meyers et al., 2007; Gallant et al., 2012).

SAM can also influence Victoria's rainfall variability, especially in summer when negative SAM events produce westerly flow promoting drier conditions, particularly in Victoria's east (Hendon et al., 2007; Risbey et al., 2009).

Cool season Victorian rainfall variability is closely linked to the frequency and intensity of mid-latitude low-pressure systems (Pepler et al., 2020; Jin et al., 2024). The majority of rainfall reductions during drought can largely be attributed to a reduction in heavy rainfall days (Holgate et al., 2023; Devanand et al., 2024). The accumulated rainfall from these heavy rainfall days tends to decline during drought development and increase during recovery (Parker and Gallant, 2022; Jin et al., 2024).

Alongside a reduction in the frequency and intensity of rain-bearing weather systems, an increase in rain-suppressing systems, such as anticyclones, has been observed during dry years in south-east Australia (Pepler, 2023; Jin et al., 2024). On monthly timescales, prolonged drought conditions over Victoria have been linked to the southward movement and intensification of the sub-tropical ridge.

Information in this case study has been compiled from various sources. Further information about drought in Victoria is presented in Victoria's Climate Science Report 2024 (DEECA, 2024).

Extreme event case study: The impact of post-fire debris flow on water quality

Following a severe bushfire, debris flows (the mass movement of materials from the landscape) can occur, damaging water infrastructure and affecting water quality in streams and storage. Higher bushfire risk could lead to more debris flow events in future.

The term 'debris flows' describes the mass movement of material, including rock, soil, vegetation, boulders and trees, from the landscape. The material moved by these debris flow events is usually more significant than a typical landslide and can cut off roads, damage infrastructure and even cause death.

The water sector has a particular interest in debris flow events due to the potential impacts these events may have on water supply systems. Large and rapidly moving debris materials can cause physical damage to water supply infrastructure and can cause sediment and nutrients to enter waterways and reservoirs, affecting water quality. For example, significant water quality contamination occurred in Canberra's main water supply reservoir as a result of post-fire debris flows in 2003. As a result, the reservoir was closed for six months and required a new water treatment plant to be built.

Post-fire debris flow events are more likely to occur in certain catchment and climate conditions. For example, they tend to occur in steep, forested catchments following a severe bushfire when the removal of vegetation and exposure of the soil surface makes the catchment more susceptible to erosion. Landscape aridity and productivity are also important indicators of risk, as these are strongly correlated with post-fire soil hydrologic properties (van der Sant et al., 2018; Noske et al., 2024).

In high-risk locations, an intense short-duration rainfall event (with a return interval of around 2–5 years) in the year immediately following a fire can initiate the movement of landscape materials into debris flows. The resulting sediment yields can be up to three orders of magnitude higher than annual background erosion rates from undisturbed forests (Nyman et al., 2015). More than 300 post-fire debris flows were identified after the 2009 Black Saturday bushfires alone (Nyman et al., 2015).

The threat of debris flow initiation is greatest when there are frequent shifts between wet and dry extremes (Nyman et al., 2019). The frequency of compound drought and heatwave events has significantly increased in recent years, with higher bushfire risk in the areas that are affected. Given the overall drying trend across Victoria and the associated projected increase in future bushfire frequency and severity, combined with expected increases in rainfall intensity, post-fire debris flows will likely become more frequent and widespread in future (Nyman et al., 2019).

Through a partnership between the Victorian Department of Energy, Environment and Climate Action (DEECA), the University of Melbourne and Melbourne Water, debris flow risks in Melbourne's major water supply catchments were investigated and tools developed to help predict and mitigate impacts on water quality. This includes Hydro*Fire*, a model specifically designed to identify high-risk catchment headwaters to support planning, risk mitigation, and management and strategic investment (Nyman et al., 2020). Hydro*Fire* is used widely by DEECA. Engineering structures and hillslope treatments are also being trialled across multiple water supply catchments.

Continued investment in research and tools will help to reduce the risk of debris flow and mitigate its impact.

Engineering works to mitigate debris flow risks in the Thomson catchment, 2019. Photo credit: University of Melbourne

Extreme event case study: The impact of bushfires on water quantity

Research continues to improve our understanding of the impacts of bushfires on streamflow yield in Victoria's forested catchments.

Water yield is influenced by the mix of tree age and species across the entire catchment as well as the local climate conditions. As multiple bushfires have burnt large areas of Victoria's forested catchments over recent decades, our forests are made up of trees with diverse ages and composition of regrowth species. Quantifying the streamflow impacts following a fire in such environments can be complex given the range of variables involved. However, ongoing research by the Victorian Government's Integrated Forest Ecosystem Research (IFER) program and Melbourne Water continues to refine our understanding of these impacts. This is important for the Victorian water sector as many of the state's water supply catchments remain forested.

The impact of bushfires on water yield has a long history of research based on generalised response behaviours, particularly the 'Kuczera curve' (Kuczera, 1987). The Kuczera curve provides a simple and useable model for predicting the long-term impact of fire in Mountain Ash forests based on the age of the forests. It was established using observational data following the 1939 fires in Victoria's Mountain Ash forests but has since been applied rather indiscriminately to estimate the hydrological impact of forest disturbance.

Despite the widespread application of the Kuczera curve in hydrological studies, experiments in Mountain Ash catchments have not been able to faithfully replicate the Kuczera response. This has prompted researchers to consider whether the Kuczera curve is only one example of the recovery profile, very specific to the catchment conditions and forest characteristics at the time of the 1939 fire, rather than a general response.

Recent research has identified an alternative streamflow response model based on observed changes in self-thinning after disturbance (Inbar et al., 2022; Benyon et al., 2023). Self-thinning describes the forest regeneration process of moving from an initial dense stand of small trees to a forest of fewer larger trees due to the competition for light and other resources. This model can replicate the Kuczera curve based on assumed conditions during the 1939 fire. However, it also indicates that the Kucera response may have resulted from one of several possible forest density 'states'. Much smaller or neutral long-term streamflow impacts may occur under other regeneration trajectories, climates and catchment conditions. This hypothesis is the subject of ongoing research.

Many of Victoria's forests are populated with mixed eucalypt species rather than Mountain Ash, which are more fire-tolerant species. Lower tree mortality and post-fire bud sprouting in these forests result in a different post-fire water yield response compared to Mountain Ash. Investigations suggest that the hydrological response following a fire in mixed species forest is smaller, and recovery occurs far more rapidly compared to Mountain Ash forest fires (Nolan et al., 2014a and 2014b, 2015; Heath et al., 2016; Guo et al. 2021). The net streamflow impact in these fire-tolerant forests may be neutral or increase due to a variety of fire severity.

Recent studies have also found that climate variables (such as rainfall and potential evapotranspiration) and climate drivers (such as ENSO and SAM) have a greater influence on regenerated forest evapotranspiration than the relationship between forest age and water use (Khaledi et al., 2021 and 2022). This indicates that streamflow impacts from fire can be lower compared to the influence of climate.

4.1.2 Modelling large-scale climate drivers

While climate models are essential tools for understanding future changes to large-scale drivers that influence Victoria's climate, uncertainties caused by model bias and limitations do exist. These uncertainties need to be considered when interpreting projection outputs.

The variability of Victoria's rainfall can partly be explained by large-scale climate drivers (see section 2 of this report). Therefore, assessing if models can simulate the relationship between these large-scale drivers and the climate is important.

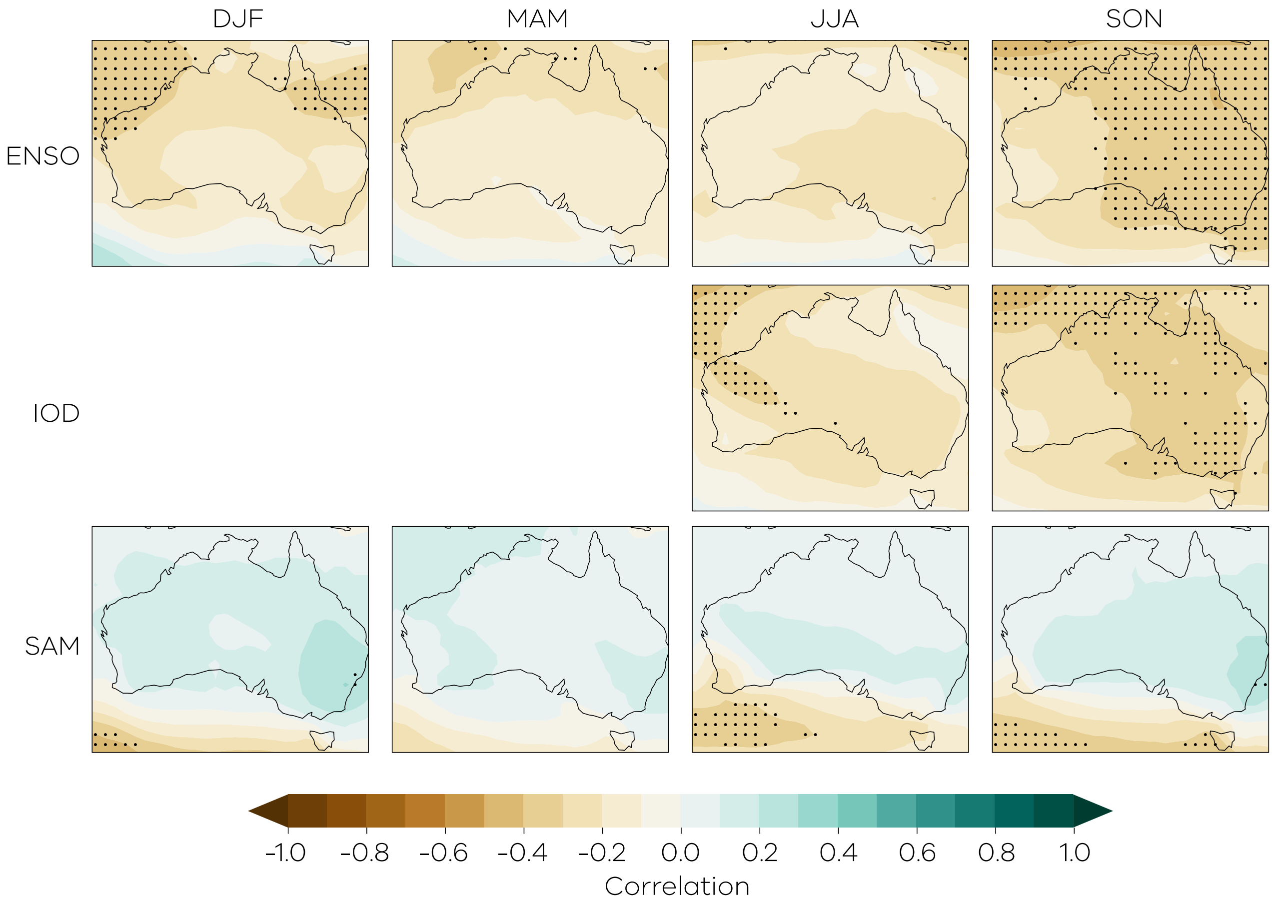


FIGURE 4.2 Seasonal correlation between the ENSO, IOD and SAM indices and precipitation in CMIP6 models. The magnitude of the correlation (colour shading) shows the strength of the relationship between each driver and rainfall, with stippling indicating where this relationship is statistically significant, and the sign is consistent across 70% of the models. Green areas indicate that the rainfall change is in the same direction as the climate driver phase (e.g. the positive climate mode is correlated with rainfall increases). Brown areas indicate that the rainfall change is in the opposite direction to the climate phase (e.g. the positive climate mode is correlated with rainfall decreases).

FIGURE 4.2 KEY TAKEAWAY

Climate models simulate the relationship between ENSO and IOD and Victorian rainfall reasonably well, especially in spring.

The influence of large-scale drivers on observed Victorian rainfall is most pronounced in spring (see Figure 2.7). CMIP6 models effectively capture the relationship between Victorian rainfall and ENSO and IOD (Chung et al., *in press*). However, they are less effective at representing the relationship with SAM (Figure 4.2).

In winter, the main influence on rainfall variability in Victoria is the IOD. The models show a negative correlation with IOD in winter, but this relationship is weaker than observed. Therefore, models may understate the sensitivity of the Victorian climate to the winter IOD. The models also simulate a correlation between rainfall and ENSO and SAM in winter that is similar to those seen in spring. However, the observations do not clearly show this winter correlation. Therefore, the models may overstate the sensitivity of the Victorian climate to these large-scale influences compared with real-world conditions.

The influence of climate drivers on future rainfall variability in Victoria

In our current climate, variations in Victorian rainfall can be at least partly explained by its relationship with large-scale drivers. Changes in these drivers are therefore likely to affect future variations in Victoria's rainfall, along with changes in external forcings (such as increasing greenhouse gas emissions or changes in ozone).

A primary influence on Victorian rainfall variability is SAM. Numerous studies have shown that an increase in greenhouse gases will lead to a positive trend in SAM. This will strengthen the jet stream and shift it south. However, this change is expected to be partially offset by ozone recovery during the 21st century (World Meteorological Organization, 2022), which could weaken the jet stream and shift it north. Despite climate models underestimating SAM trends, particularly in autumn and spring (Chung et al., 2023), they confidently project a positive trend in SAM in summer.

In addition, the Antarctic stratospheric vortex in spring is projected to increase and persist longer in future due to increased greenhouse gases causing stratospheric cooling (Butler et al., 2010; Jucker et al., 2021). This is expected to contribute to the positive trend in SAM, although models do not simulate the evolution of the Antarctic stratospheric vortex well. If the trend towards a more positive SAM in future is weaker than expected, there may not be more rainfall in spring, potentially impacting late-season run-off in the east of the state.

A decrease in IOD variability is possible (Kim et al., 2024; Chung et al., *in press*), but there is little consensus on changes in the IOD. A decrease in IOD variability could lead to less drying in Victoria during positive IOD years and less wetting during negative IOD years. However, this is still an ongoing topic of research.

Some models suggest an increase in ENSO-driven sea surface temperature variability (Cai et al., 2023) and an increase in ENSO teleconnections to rainfall and temperature over most of the world (McGregor et al., 2022). In Australia, El Niño years are generally projected to dry further, while only strong La Niña years are expected to get wetter (Delage & Power, 2020).

The triple La Niña of 2020–23 had significant impacts on climate across the globe. In Victoria, La Niña is typically associated with wet conditions in winter and spring. As a result, the third wet spring in a row led to flooding events in Victoria. Rainfall progressively increased throughout the event (Huang et al., 2024), with the highest rainfall occurring in the summer of 2022–23. This progressive increase occurred without an intensification of La Niña, suggesting that the accumulation of soil moisture may have contributed to the enhanced rainfall observed in the final year.

Multi-year La Niña are rare. Triple La Niña's have only occurred twice since 1950, in 1973–75 and 1998–2001, following strong El Niño's. The projected increase in triple La Niña events is uncertain, however, under a high emissions scenario, the frequency of two-year La Niña events will increase from approximately occurring once every 12 years in 1900–99 to once every nine years in 2000–99 (Geng et al., 2023). Despite large uncertainties in future projections (see Box D), models suggest that extreme La Niña events will occur almost twice as often in the 21st century compared with the 20th century (Cai et al., 2021). This is partly due to an expected increase in extreme El Niño events, which provides favourable conditions for an extreme La Niña to develop.

Box D: Understanding climate model limitations to improve confidence in climate projections

Global climate models are essential tools for assessing and understanding future changes in hydroclimate. However, the magnitude and the direction of future changes strongly depend on the region and the emissions scenario. In addition, climate models may have limitations in representing some climate processes. The combination of these factors can affect the confidence level in future climate projections.

How a model represents different climate parameters can introduce systematic errors, called biases. Global climate models have biases in their representation of the observed climate in Victoria (Grose et al., 2020). For example, results from VicWaCI research indicate that CMIP6 temperature simulations show the largest biases in summer (representing the climate about 2 °C warmer than observed), while rainfall simulations show the largest bias in spring (representing the climate about 10 mm drier than observed). Despite improvements in the latest generation of climate models used in CMIP6, including a reduction in the spread of model results, these biases have not significantly improved.

Climate models simulate the positive summer SAM trend accurately and more frequent El Niño, La Niña, and positive IOD events under climate change (Cai et al., 2021). However, biases in other large-scale climate drivers reduce the accuracy of climate projections.

VicWaCI and other research have shown why these biases exist and ways to account for them. For example, compared with observations, climate model simulations show:

- cooler temperatures over the tropical central to eastern Pacific, caused by the misrepresentation of various dynamic and thermodynamic processes (Lee et al., 2022)
- warmer temperatures over the Southern Ocean and tropical eastern Pacific, caused by inaccuracies in cloud representation (Hartmann, 2022; Kang et al., 2023)
- a stronger equatorial sea surface temperature gradient and a deeper thermocline in the east of the tropical Indian Ocean, which leads to large uncertainties in IOD projections (Wang et al., 2024)
- greater warming in the tropical eastern Pacific, caused by underrepresented interactions between the three oceans in the tropics (Cai et al., 2019)
- a lack of relationship between ENSO and SAM in spring and summer (Lim et al., 2016)
- overestimated strengthening of the spring Antarctic stratospheric vortex and associated positive SAM due to poleward bias in the location of the winter stratospheric jet.

These biases can be addressed in several ways by using:

- a selection of models with smaller biases to improve accuracy, rather than relying on the full range of models
- statistical modelling (which incorporates observations) to constrain projections and improve accuracy
- a forecast-based attribution system initialised with observed conditions that constrain bias growth, paired with carefully designed experiments
- storyline approaches to examine model outputs based on specific scenarios, such as comparing El Niño-like versus La Niña-like changes, to understand the range of possible climate futures.

4.2 Future hydrology and water resources

4.2.1 Hydroclimate projections for Victoria

Average annual runoff and water resources across Victoria are projected to decrease in future, with more frequent and severe hydrological droughts expected.

Climate models project future changes based on our understanding of how large-scale global and regional climate drivers will change as the world warms (see section 2.1 of this report). For example, projected higher temperatures will increase potential evapotranspiration and demand for water from people, agriculture and the environment, and the projected decline in cool season rainfall will be amplified in the reduction of catchment runoff and water resources.

VicWaCI research compared climate projections from newer CMIP6 global climate models (used in the IPCC Sixth Assessment Report) and those from CMIP5 (used in the IPCC Fifth Assessment Report) (Zheng et al., 2024). Most CMIP6 and CMIP5 models project drier conditions in the cool season across most of Australia. However, the direction of change in warm season rainfall is uncertain. The majority of global climate models (more so in the CMIP6 models) show increases in the intensity of very high extreme rainfall. A larger proportion of models (again, more so in CMIP6) project higher rainfall variability from year to year in future.

Hydrological modelling under VicWaCI, based on climate change simulations from CMIP6 models (Zheng et al., 2024), suggests that mean annual runoff and water resources averaged across Victoria will likely decrease by about 25% by 2060, relative to 1976–2005 (Figure 4.3). This decrease is mainly due to less rainfall in the cool season (as most of the runoff in Victorian catchments occurs in winter and spring) and is accentuated by the increase in potential evapotranspiration.

Long (multi-year) wet periods and long dry periods observed in the past will continue to occur. This will occur against a background trend of declining streamflow. With lower mean annual runoff, hydrological droughts will become more severe and occur more often (Zheng et al., 2024; Prosser et al., 2021). These results are similar to those informed by climate change projections from CMIP5 global climate models.

There is a large range in the runoff projections, mainly due to the range or uncertainty in the rainfall projections. The wet (90th percentile) and dry (10th percentile) ends of the projection range vary from little change to more than a 40% reduction in runoff under the extreme dry scenario.

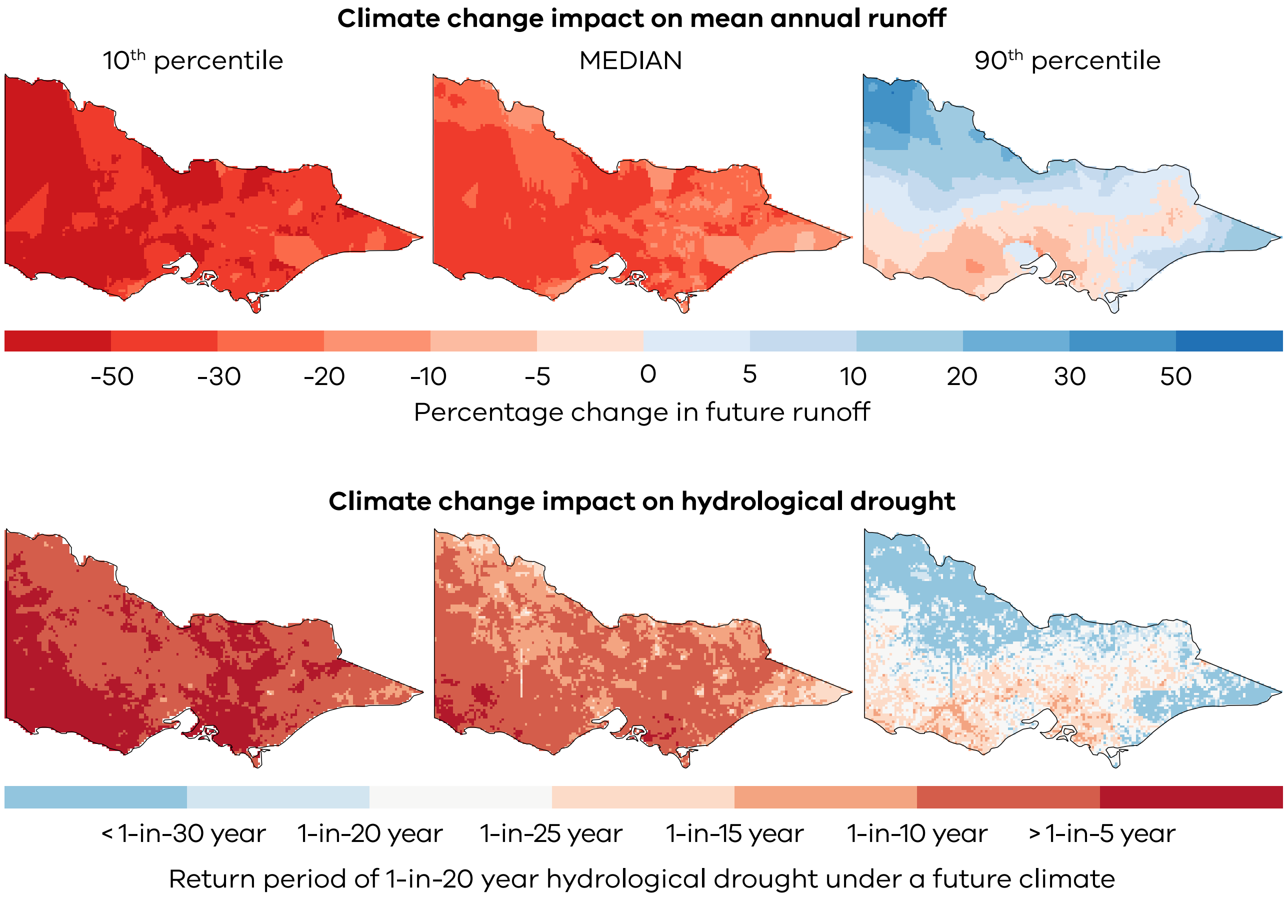


FIGURE 4.3 Projected change in future mean annual runoff (top) and hydrological drought (bottom) for 2046–75 (relative to 1976–2005) under a high emissions scenario. There is a large range of runoff projections, which is represented here as dry (10th percentile), median, and wet (90th percentile) projections. Red shades indicate locations projected to experience the most severe runoff reductions and where the historical 1-in-20 year hydrological drought is projected to occur more frequently in the future. Blue shades show runoff increases and reduced occurrence of drought.

FIGURE 4.3 KEY TAKEAWAY

By 2060, annual runoff is projected to decline across Victoria by about 25% (ranging from little change to more than 40% reduction), and hydrological drought is projected to become more frequent and severe.

4.2.2 Future impacts of rainfall and runoff variability on water security

The projected increase in year to year rainfall and runoff variability could further increase hydrological drought and reduce the reliability of water resource systems. However, the increase in rainfall and runoff variability has a smaller impact on water system reliability compared to the significant projected reduction in average rainfall and runoff.

Most global climate models project an increase in rainfall variability from year to year under climate change (Pendergrass et al., 2017). This is generally consistent with observations and climate change science that indicate that El Niño and La Niña, and the persistence of ENSO, is likely to be stronger under climate change (Cai et al., 2021; Geng et al., 2022; see section 4.1.2 of this report).

The higher interannual rainfall variability will lead to higher interannual runoff variability and a slight increase in mean annual runoff. The increase in interannual rainfall and runoff variability will further heighten hydrological drought and reduce the reliability of water resource systems (see Figure 4.4, vertically upwards for zero change in mean annual rainfall).

However, VicWaCI research has shown that the effect of changing rainfall and runoff variability on water security is smaller than the significant reduction in mean annual rainfall and runoff projected for Victoria (Figure 4.4, vertically upwards for a -10% change in rainfall). Other research (Ren et al., 2024) also shows that the reliability of water resource systems is influenced more by the change in mean annual streamflow than the projected increase in interannual streamflow variability.

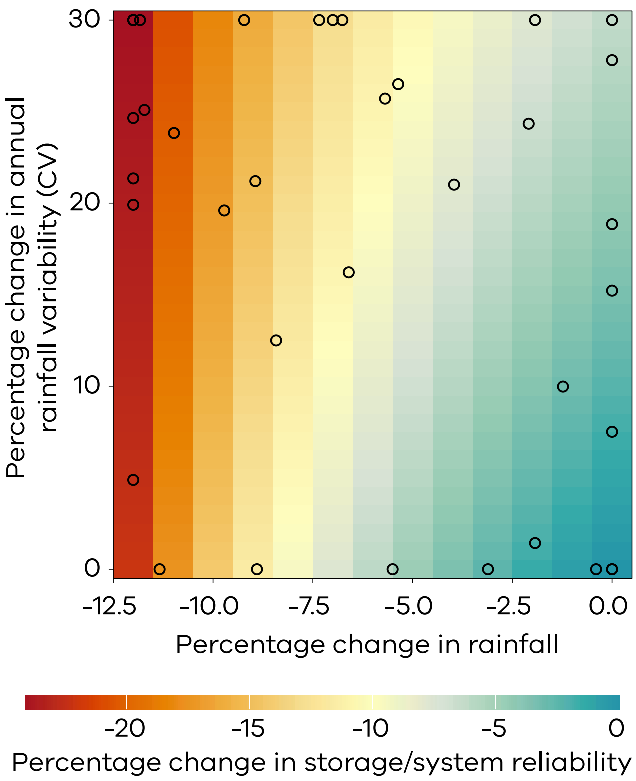


FIGURE 4.4 Change in storage or system reliability resulting from the change in mean rainfall and interannual rainfall variability. Results are from sensitivity modelling and storage analysis using rainfall and streamflow data from a Goulburn River basin catchment. Red and orange shades represent a greater decrease in storage/system reliability than shades of green. The dots show global climate model projected changes in rainfall mean and variability.

FIGURE 4.4 KEY TAKEAWAY
A reduction in rainfall and an increase in interannual rainfall variability (combined with increased potential evapotranspiration) will cause more frequent hydrological drought, making water resource systems less reliable.

Case study: Impact of climate change and natural variability on the reliability of Maryborough's water supply

Maryborough is a town of about 11,700 people in north-central Victoria. Water to the town is mainly supplied by the Evansford and Talbot reservoirs, with potential augmentation during dry periods from the Tullaroop reservoir and Moolort groundwater.

VicWaCI researchers developed models to assess the reliability of the water supply system. They used two approaches: (i) historical climate (rainfall and potential evaporation) and modelled runoff, and (ii) 1,000 replications of stochastic (random) climate and modelled runoff data to account for internal climate variability. Three periods were considered: 1900–2020, 1975–2020 and 1993–2020.

Modelling based on the entire historical period (1900–2020) shows that water restrictions are avoided most (96.7%) of the time (red triangle in Figure 4.5a). The modelling also shows a system yield of 1,224 ML (red triangle in Figure 4.5b), which is the amount that can be supplied to avoid Stage 3 or 4 restrictions and limit Stage 1 or 2 restrictions to less than 5% of the years.

The historical data describes past climate. However, even with similar conditions to those observed, we could have seen different climates depending on, for example, different wet spells and drought length. Stochastic modelling allows us to explore the inherent randomness in climate variability by repeating simulations of climate under similar conditions many times (Chiew et al., 2024). This provides important information for system managers where the security of the water supply is paramount.

The stochastic modelling (and the observations) shows a decline in the system reliability since 1975, as reflected by the percentage of years without any restrictions. The decline is even more significant since 1993 (Figure 4.5a). This is because autumn rainfall declined post-1975, and cool season rainfall significantly declined post-1993, both of which impact system yield.

Using data for the full 1900–2020 period, restrictions occur in less than 5% of the years in 99.8% of the stochastic model runs. In the stochastic modelling using post-1975 and post-1993 data, restrictions occur less than 5% of years only in 76% and 15% of the model runs, respectively.

To ensure no Stage 3 or 4 restrictions, and to limit Stage 1 or 2 restrictions to less than 5% of the years, the median in the stochastic simulations indicates that the average annual volume of water (system yield) that can be supplied to Maryborough is 1,719 ML, 1,331 ML and 1,009 ML for the 1900–2020, post-1975 and post-1993 simulations, respectively (Figure 4.5b). The potential range of water supply can be large; for example, the system yield ranged from 1,078 to 2,428 ML in the 2.5th to 97.5th percentiles of stochastic replicates based on 1900–2020 data (Figure 4.5b).

System yield simulated for 1900–2020 historical data is lower than most yields simulated from the 1,000 stochastic replicates (red dot in Figure 4.5b). This is partly because of the limitations in the stochastic model used here, and partly because most stochastic scenarios do not have a drought as severe as the Millennium Drought, which triggered long restrictions, but have more frequent, less severe droughts that did not trigger as many restrictions.

This case study demonstrates the value of using stochastic data to assess water resource system reliability arising from random uncertainty in hydroclimate variability. Other examples of stochastic modelling in this region include Wang et al. (2018), which explores the vulnerability of ecological conditions from different sequencing of wet and dry spells in the Murray–Darling Basin.

Stochastic models can also generate plausible futures using knowledge from paleoclimate and can be used to consider climate change and natural variability, such as changes in ENSO and ENSO-rainfall teleconnections (Potter et al., 2023). This enables water managers to explore options to increase water supply and the timing of strategies relative to risk to water supply reliability under plausible future climates and increasing demand.

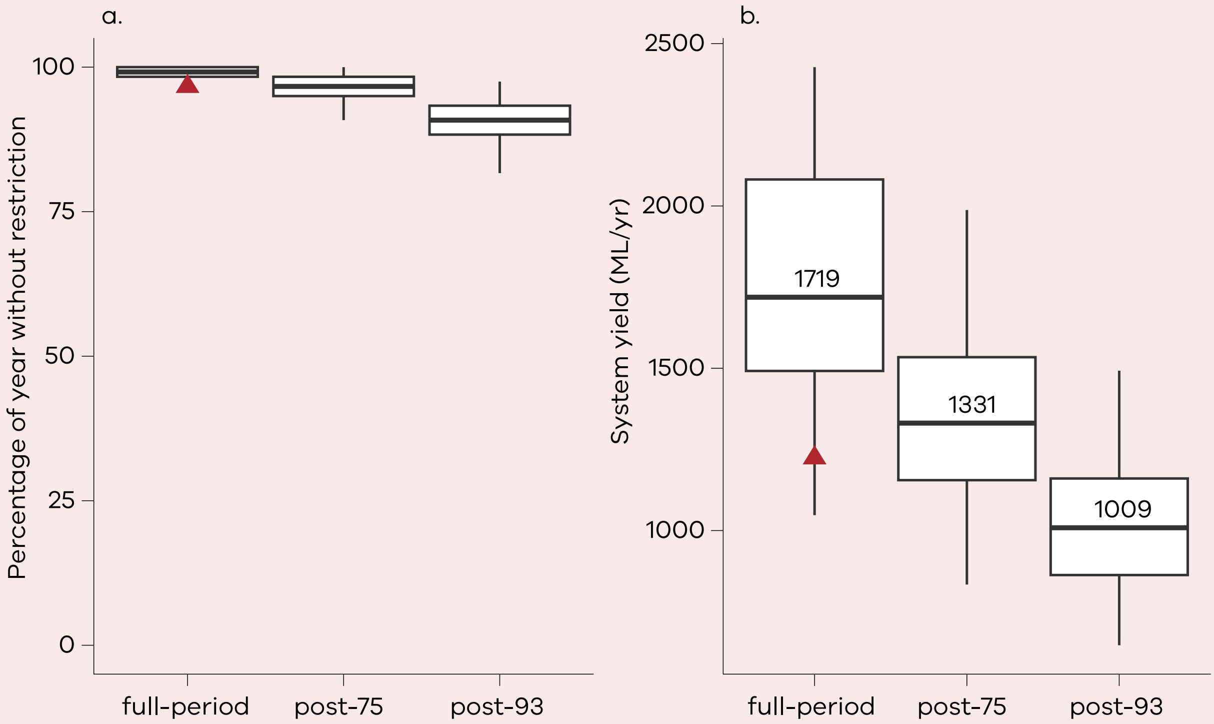


FIGURE 4.5 Performance indicators (percentage of years with restrictions (a) and system yield (b)) of the Maryborough water supply system modelled with historical and stochastic data for three periods: full period (1900–2020), post-1975 (1975–2020), and post-1993 (1993–2020). a) Plots shows the median, 25th to 75th percentile, and the 2.5th to 97.5th percentile of the 1,000 stochastic simulations. Red triangles show results from the one simulation with the historical data. b) System yield is defined as the average annual volume of water supplied so that Stage 3 or 4 restrictions never occur, and Stage 1 or 2 restrictions occur in less than 5% of years.

FIGURE 4.5 KEY TAKEAWAY

The application of stochastic modelling supports an understanding of the range of plausible system outcomes under different climate variability and change scenarios.

Case study: Future long-term streamflow outlook for catchments that have experienced large declines in streamflow

Catchments in some parts of Victoria, including many in central and western Victoria, have experienced a large decline in streamflow since the end of last century (Figure 3.4 and Figure 4.6).

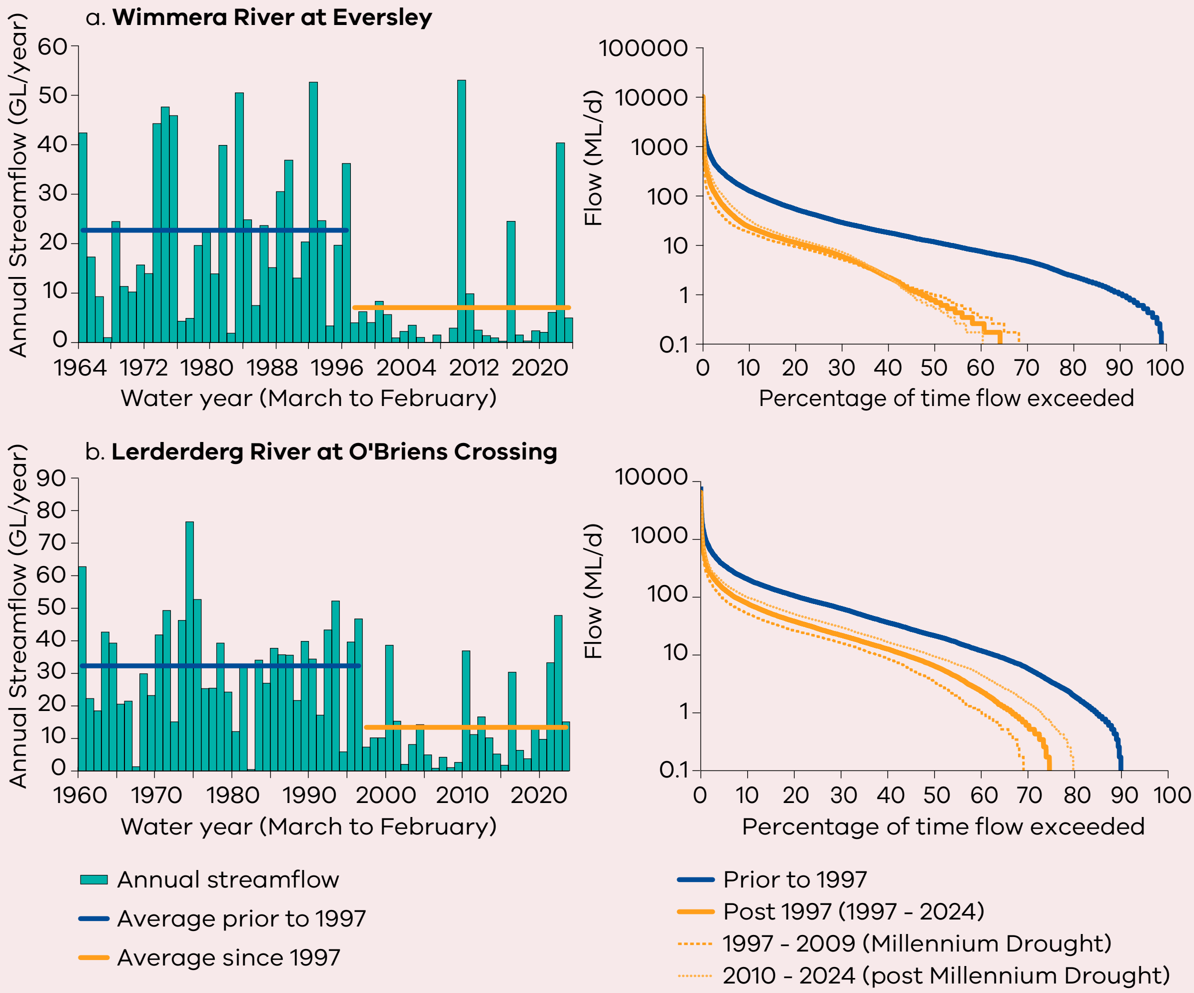


FIGURE 4.6 Gauged streamflow records for two streams in central and western Victoria. a) Wimmera River (1964–2024) and b) Lerderderg River (1960–2024). Annual streamflow for each river is shown in the graphs on the left, with the horizontal lines showing the average annual flow before (blue line) and after (orange line) 1997. The graphs on the right show the percentage of time the stream is at different flow rates, based on daily streamflow data. The blue line shows conditions before 1997 and the orange lines show conditions for different periods after 1997.

FIGURE 4.6 KEY TAKEAWAY

Since the end of last century, some catchments in Victoria have experienced large declines in streamflow, along with changes in streamflow patterns.

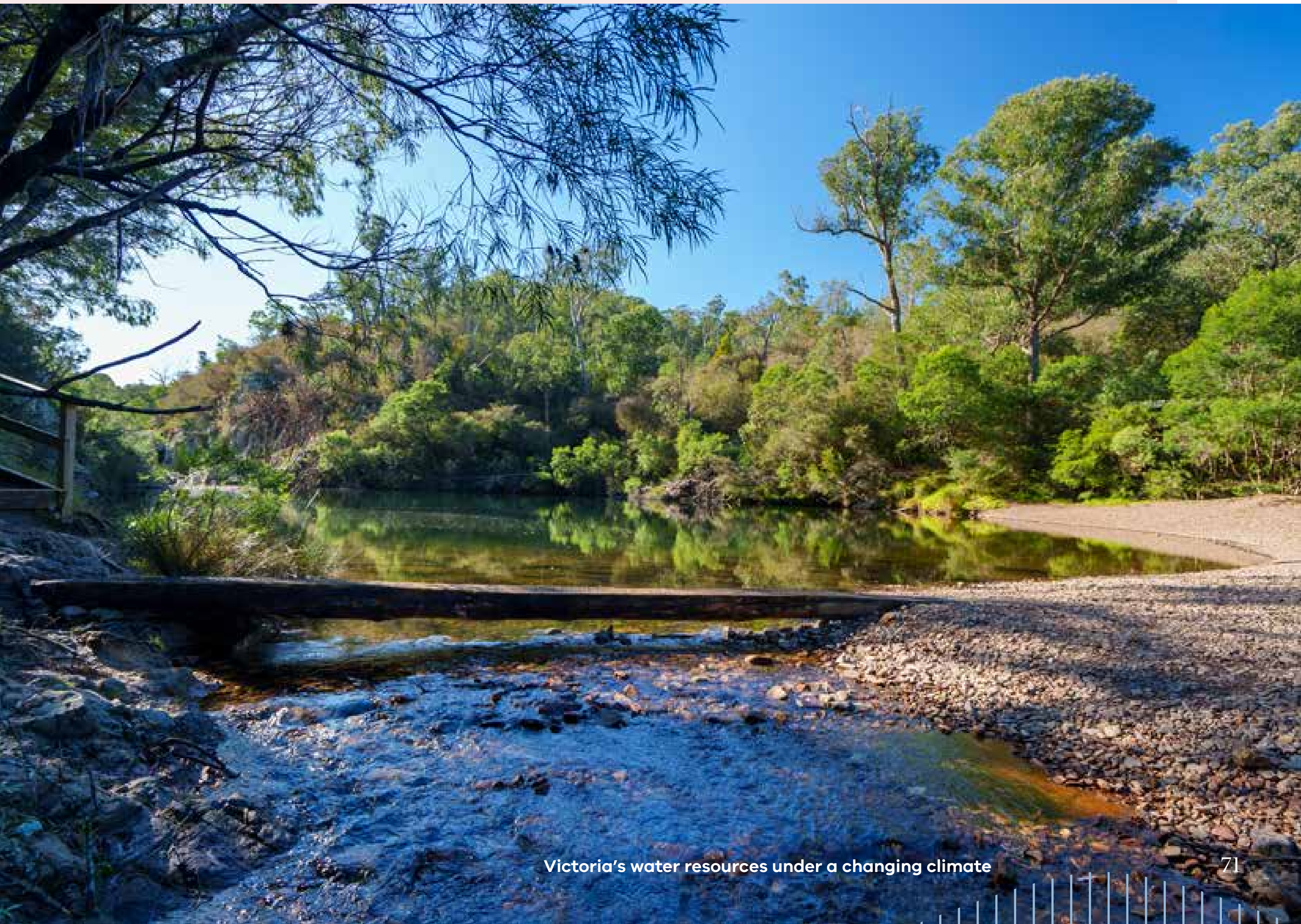
Many of the catchments that have experienced these changes are in parts of Victoria with lower annual rainfall, with streams in these areas often not flowing all year round.

Factors contributing to these changes include changes in rainfall patterns (with less cool season rainfall and fewer very wet days) and temperature increases, driving greater evaporative demand from landscapes and vegetation. These areas also include catchments where streamflow has become intermittent or intermittency has intensified during the drought, and these altered conditions have persisted (Figure 3.8).

These factors have often been compounded by the shift in the runoff response to rainfall. Many catchments that have experienced a significant declining trend in streamflow have also experienced a shift in the runoff response to rainfall – with less runoff resulting from any given rainfall event than last century (Peterson et al., 2021). Of the catchments that experienced the shift in the rainfall-runoff relationship, this condition has persisted despite the relatively high rainfall in recent years (see Figure 3.5).

Future climate projections show increases in evaporative demand, along with likely reductions in the average amount of rainfall received, particularly during the cool season. Catchments in lower rainfall areas are more vulnerable to significant reductions in streamflow in response to rainfall declines, as they already have less surplus moisture available to generate streamflow.

The combination of the influence of increasing temperatures and evaporative demand, along with projected reductions in cool season rainfall, means that catchments that have experienced large declines in streamflow may not return to the conditions experienced last century.



4.2.3 Developing and improving hydroclimate projections

Uncertainties exist in both climate and hydrological modelling that need to be considered when interpreting results. Efforts to improve hydroclimate projections are continuing, including correcting bias in climate variables from dynamical regional models and improving rainfall-runoff models so they can better model prolonged dry periods.

Hydrological models use projections from global and regional climate models to estimate climate change impacts on streamflow (Zheng et al., 2024) (Figure 4.7). Regional climate models or dynamical downscaling (Grose et al., 2023) simulate rainfall at a much finer spatial resolution and can be useful in complex terrain like the mountainous areas in south-east Australia (Grose et al., 2019; Di Virgilio et al., 2020).

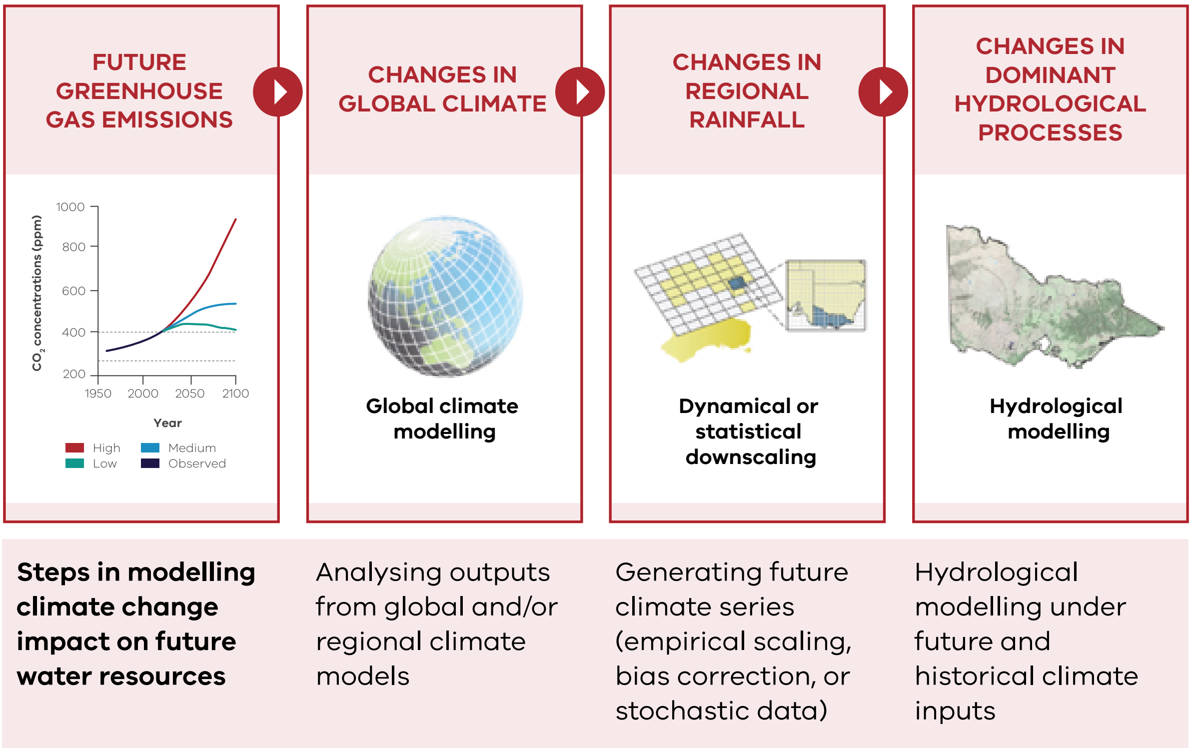


FIGURE 4.7 Components in modelling climate change impact on streamflow.

FIGURE 4.7 KEY TAKEAWAY
Projections of future catchment runoff are developed using hydrological models informed by climate change projections from global and regional climate models.

Dynamical downscaling that combines model data with observations can simulate observed rainfall characteristics, except for the variability from year to year (Teng et al., 2024). However, any uncertainty in global climate model data is also reflected in the dynamically downscaled rainfall model data.

Correcting model bias in dynamically downscaled rainfall from hydrological impact models is challenging, particularly as the bias can be much larger than the magnitude of the change. Dynamical downscaling also underestimates the connection in rainfall from one day to the next (autocorrelation), which underestimates multi-day rainfall accumulations and leads to underestimation of the streamflow (Potter et al., 2020; Charles et al., 2020). However, a new bias correction method from VicWaCI research can better reproduce the autocorrelation in the observed rainfall (Robertson et al., 2023), improving the simulation of historical and future runoff.

Despite the potential advantages of dynamical downscaling, it can be confusing to interpret the varying projections from different dynamical downscaling products and hydrological impact modelling methods. Quantifying the similarities and differences between these shows they all generally indicate a hotter and drier climate in Victoria, leading to reduced water resources and more frequent hydrological droughts (Chiew et al., 2022).

4.2.4 Improving hydrological modelling techniques

Limitations in hydrological modelling of historical conditions, such as prolonged severe drought, are likely to propagate in modelling of future runoff reductions under a drier climate. Improvements are being investigated by adapting hydrological model conceptualisation and modelling techniques.

The largest uncertainty in hydrological modelling of future streamflow is from rainfall projections. However, there are also limitations in extrapolating hydrological models to predict a future with different climates (higher temperature and atmospheric CO_2), catchment conditions, and hydrological processes not seen in the past. This is a key challenge identified by the international hydrological community (Bloschl et al., 2020).

Rainfall-runoff models calibrated against historical data, such as the wetter pre-1997 data, tend to overestimate runoff (and therefore underestimate the reduction in runoff) during the Millennium Drought (Chiew et al., 2014; Saft et al., 2016). It is expected that rainfall-runoff models developed and calibrated against historical data will also tend to underestimate the projected reduction in future runoff under a drier climate (Vaze et al., 2010; Trotter et al., 2023). This is because model calibration tends to lead to simulations that underestimate very high runoff years and overestimate very low runoff years (Figure 4.8).

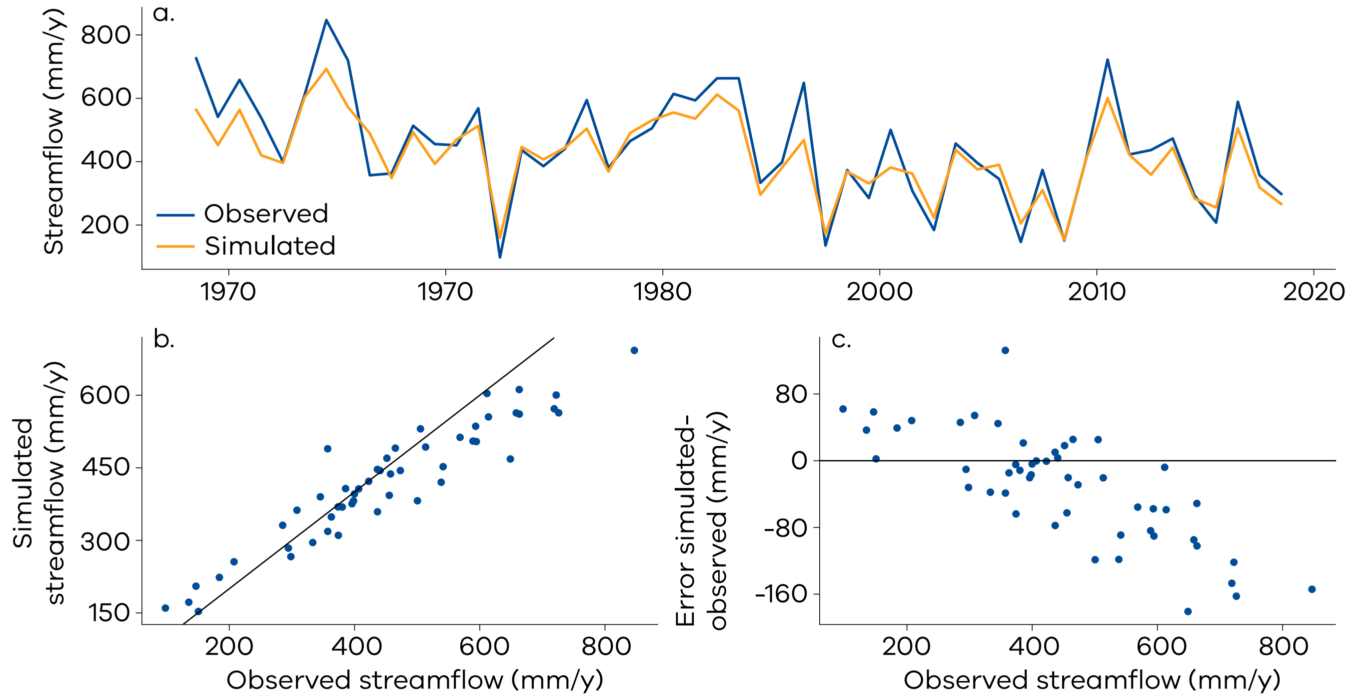


FIGURE 4.8 Comparison of observed and simulated runoff for Goulburn River at Dohertys. a) Annual modelled and observed streamflow series. b) Annual modelled versus observed streamflow. c) Error (modelled minus observed annual streamflow) versus observed streamflow.

FIGURE 4.8 KEY TAKEAWAY

Rainfall-runoff models tend to overestimate runoff during historical dry periods and are therefore likely to underestimate future runoff reductions under a drier climate.

It is often assumed that once a model is calibrated against a variety of climate conditions, it will perform better under future climate variability and change. VicWaCI researchers tested this assumption, finding that calibrating models against a wide range of hydroclimatic data slightly improves model performance, but much more improvement is required (Trotter et al., 2021). This suggests that more sophisticated model calibration techniques and improvements in model structure are required to enhance runoff modelling under changing climate conditions. Therefore, using existing models and calibration techniques to predict streamflow in changing and unknown climate conditions should be used cautiously.

VicWaCI research has attempted to overcome this calibration problem by more robustly calibrating rainfall-runoff models against simulations under both wet and dry conditions (Fowler et al., 2018; Zheng et al., 2022) and by adapting rainfall-runoff models to better conceptualise dominant hydrological processes during long droughts (Fowler et al., 2021 and 2022b). This research has had some success in improving the runoff simulations of the Millennium Drought but only showed slight differences in modelled projections of future runoff.

A new method to help identify improvements in rainfall-runoff models, called Data Assimilation Informed model Structure Improvement (DAISI) (Lerat et al., 2024), was developed by VicWaCI. The method automatically corrects the model behaviour to fit the streamflow simulations with observations, improving the model results. The approach was applied to more than 100 catchments in south-east Australia, resulting in improved model performance while also increasing sensitivity to changes in rainfall inputs. The latter is crucial to ensure that models can capture a large range of potential conditions under climate change.

These improvements and other findings noted in section 3.3 of this report help prioritise future research to improve rainfall-runoff modelling. For example, model results may be further improved by developing new ways to represent soil moisture storage in rainfall-runoff models (Fowler et al., 2021), improving the representation of groundwater–surface water connectivity under dry conditions (Fowler et al., 2022a; Trotter et al., 2024), and assessing the realism of rainfall-runoff models (e.g. Weligamage et al., 2023).

How do changes in hydrological processes impact future runoff projections?

Changes in dominant hydrological processes can occur over different time scales. They may affect future runoff projections directly or combine with other climate changes, contributing to the non-stationarity (or changing rainfall-runoff relationship) of long-term runoff. Traditional rainfall-runoff modelling does not account for many types of non-stationarities (apart from the change in future climate inputs, such as less rainfall and higher potential evapotranspiration). This often leads to an underestimation of how much runoff will decline under a future drier climate. Some non-stationarities in hydrological processes are summarised below (Robertson et al., 2024).

Farm dams

Farm dams will collect proportionally more water under a drier hydroclimate. Models that do not model farm dams directly will underestimate (by up to 10%) the future runoff reduction (Robertson et al., 2023).

Fire

Bushfires are likely to be more frequent under hotter and drier catchment conditions. Fires can acutely affect erosion and water quality and increase runoff for several years immediately after the fire. However, averaged over large regions, the long-term impact of fires on water resources is likely to be relatively small (Lane et al., 2023; Robertson et al., 2024; Chiew et al., 2008). See section 4.1 of this report for further information.

Changing rainfall-runoff relationship

The relationship between rainfall and runoff is changing. By not directly modelling these changes, rainfall-runoff models tend to underestimate the projected reduction in future catchment runoff, particularly in catchments with low runoff (see sections 3.2 and 4.2 of this report).

Vegetation response to higher CO_2

With higher CO_2 concentrations in the air, trees are expected to use water more efficiently. This could increase runoff. However, in water-limited regions such as Victoria, trees can use the additional available water to increase growth, decreasing runoff. This example demonstrates the considerable uncertainty in how vegetation will respond to higher CO_2, higher temperature and potential evapotranspiration, and changing rainfall (Yang et al., 2021; Cheng et al., 2017). Nevertheless, the net impact of higher CO_2 concentrations on future runoff is likely to be relatively small compared to the impact of changes in climate inputs. However, the effect of higher temperature and potential evapotranspiration on runoff is uncertain due to differences in how hydrological models simulate evapotranspiration.

Landscape change

Transitioning from forest to grassland (or vice versa) and other landscape changes can affect catchment runoff. While there is an understanding of the hydrological response to land-use changes (Zhang et al., 2001), it is difficult to predict future landscape or land-use change under climate change.

5. Research implications and applications for water resource management

At a glance

- A future warmer and drier climate is likely to result in a decline in water availability and may exacerbate Victoria's variable climate conditions.
- Research findings can inform management and planning activities to ensure sustainable water availability and supply for the future.
- VicWaCI and other related research investments inform guidance on how to assess the impact of climate change on water availability, ensuring evidence-based guidance is provided to Victorian water managers.
- Outputs from Victoria's investment in climate and hydrological research have supported a range of water management strategies, policies and plans.

5.1 Implications of research for water resource management

Management of Victoria's water resources will need to consider a decline in water availability as well as the risk of more extreme dry and wet periods under a warmer and drier climate future.

VicWaCI research, combined with broader research across Australia, provides critical information on Victoria's changing climate and hydrology. Research findings can inform decisions, plans and activities to sustainably manage Victoria's water resources under a changing climate. Research findings that may have implications for water resource management include the following.

- The decline in cool season rainfall leads to a disproportionately large decline in streamflow, as most runoff in Victoria occurs in winter and spring.
- In addition to the impact of seasonal rainfall changes, the reduction in light to moderate rainfall and the increase in heavy and extreme rainfall can influence catchment wetness and streamflow generation.
- The ability to predict seasonal Victorian rainfall is greatest for spring. During other seasons, many of the large-scale climate drivers that can be predicted are not strongly correlated with Victorian rainfall.
- Although climate variability has played a role in past decreases in cool season rainfall, drier cool seasons are likely to occur more frequently in future due to the influence of human-caused climate change.
- The reduction in the runoff response to rainfall first observed during the Millennium Drought has persisted in parts of central and western Victoria since the drought ended more than 14 years ago. Although an extended wet period in the future could return these catchments to their pre-drought runoff state, the likelihood of this occurring may decrease over time, given the projected future increases in temperatures and decreases in rainfall.
- Changes in streamflow patterns, like the increasing occurrence of low flows in some unregulated catchments over recent decades, can significantly impact a range of values, including the functioning of freshwater ecosystems.
- The projected warmer and drier climate through the 21st century means that water availability in Victoria's streams, lakes and storages is likely to decline over coming decades.
- Projected increases in year to year rainfall and runoff variability could further increase risks to the reliability of water supplies. However, the impact of the overall reduction in rainfall and runoff will likely have a more significant effect on water supply reliability than the increases in variability.

- There is a large range of uncertainty in future hydroclimate projections. This remains a challenge in adapting water resources systems to cope with climate change.
- Although dynamical downscaled regional climate models produce projections of climate variables at high spatial resolution, there are limitations that must be considered or addressed when applying their output for hydrological applications. Robust bias correction needs to be applied to rainfall projections used for hydrological modelling. Outputs from a range of global and regional climate models should be considered together to ensure the range of plausible futures is represented.
- Current hydrological modelling approaches tend to underestimate the reduction in future streamflow as they do not adequately account for shifting rainfall-runoff relationships and conditions under a future climate. Understanding the hydrological drivers and adapting models to account for these drivers is a significant challenge and area of continuing research. Until streamflow projections can more robustly represent these changes, the risk of projections underestimating future streamflow reductions should be considered in water resource planning.

5.2 Using projections in decision-making

Understanding the projected impacts of climate change on water availability enables us to assess and sustainably manage and secure Victoria's water resources.

Assessments of long-term water availability, supply and demand underpin water management strategies and policy. The *Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria* (the Guidelines) provide practical guidance on applying climate change scenarios to those assessments. The Guidelines also provide fit-for-purpose projected hydrological and climate (hydroclimate) variables important to water resource management in Victoria.

The Guidelines have been applied to assess:

- long-term urban water security
- the reliability of water supply for town, agriculture, industry, environmental and cultural uses
- environmental flow requirements and management
- catchment, waterway and wetland management
- risk assessment for water infrastructure.

VicWaCI and other related research investments inform the Guidelines by:

- providing context to understand uncertainties in the output of climate models
- identifying and testing robust methods to develop and apply hydroclimate projection data
- advancing understanding of the impacts of recent and future extreme events, including the Millennium Drought and the increased intensity of extreme rainfall.

5.3 Application of research to policy and management

Knowledge from climate and hydrological science informs water resource management, policies, and adaptation plans.

Climate and hydrology research outputs identify and explain recent trends, as well as the drivers of those trends. Climate projections enable us to prepare and plan our adaptation strategies.

Examples of how research output has been incorporated into water policy and management include:

- The projected decrease in cool season rainfall, warmer temperatures and decrease in streamflow have led to greater investment in climate-independent water sources to ensure future water security as part of the Central and Gippsland Region Sustainable Water Strategy 2022.
- Improved information about potential changes to the frequency and intensity of extreme events, such as bushfires and floods, informs adaptation plans and emergency management, including the Water Sector Adaptation Action Plan.
- The impact of projected changes to streamflow on water-based ecosystem functions and responses are considered in management plans for environmental water and waterway health, such as the Victorian Waterway Management Strategy and Environmental Water Management Plans.

5.4 Research application case studies

Victoria's investment in climate and hydrological research is vital for the sustainable management of the state's water resources. The research is used by various Victorian water sector stakeholders, including for assessments of groundwater availability and environmental flow recommendations.

5.4.1 Case study 1. Groundwater Management 2030

Groundwater is a valuable water resource that meets about 15% of Victoria's water needs. It interacts with rivers, lakes and wetlands, playing an important role in supporting healthy waterways and environments. As Victoria becomes warmer and drier, groundwater availability and quality may change.

Groundwater is recharged by rain or surface water that seeps through the open pore spaces of overlying soil or rock in an unconfined aquifer. Decreased rainfall is likely to reduce groundwater recharge. Elevation of the water table (groundwater level) will also decrease if groundwater recharge becomes lower than discharge.

Groundwater and surface water can be highly connected in some areas, including the Victorian highlands. Contribution from groundwater to streamflow supports baseflow and drought refuges in waterways during low streamflow periods. When groundwater levels decrease below the water level in a stream (or other water bodies), the contribution from groundwater to streamflow will decrease (Figure 5.1). In extreme cases, groundwater levels can fall lower than the streambed so that water from the stream seeps into groundwater.

Groundwater Management 2030 (GM2030) is a set of priorities for groundwater management in Victoria. The first priority action of GM2030 is a commitment to study groundwater availability and review limits of take. Projected climate change scenarios from the guidelines (DELWP, 2020b) and the latest knowledge from hydrological and climate research have been incorporated into the assessment of groundwater availability. This helps to ensure groundwater will continue to support Victorian agriculture, communities and environments into the future.

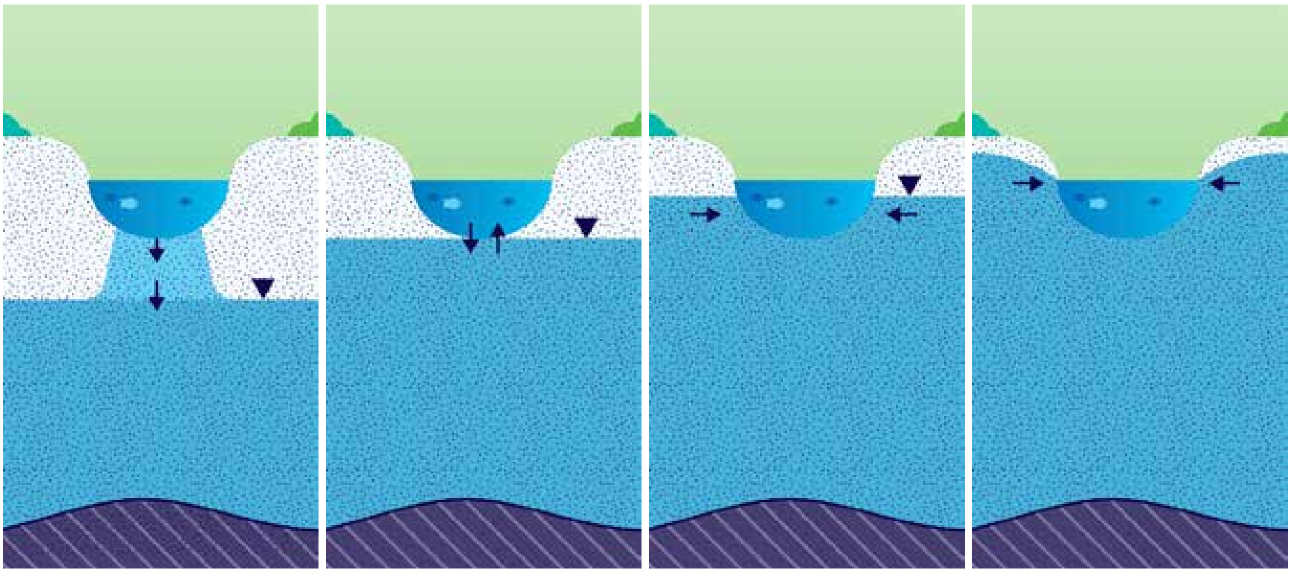


FIGURE 5.1 Interaction between groundwater and surface water, such as streamflow, as groundwater level decreases and surface water level remains stable. Arrows show the direction of flow from groundwater to surface water and vice versa. Inverted triangles show groundwater levels relative to surface water levels.

5.4.2 Case study 2. Updating the Lower Ovens flow recommendations under a changing climate

In May 2024, the North East Catchment Management Authority finalised an update to environmental flow recommendations for the Lower Ovens River system (NECMA, 2024). The previous environmental flow study (Cottingham et al., 2008) was completed using the 2002 Victorian FLOWS method. The 2013 FLOWS method is Victoria's current statewide approach for determining the environmental water requirements of waterways. It provides a process for developing flow-dependent environmental objectives and the flow regime required to meet these objectives and maintain the waterway's environmental values at a low level of risk. These objectives and recommendations feed into a variety of planning activities, including environmental water recovery targets and sustainable water strategies. They are a key reference for the long-term watering plans prepared for the Murray–Darling Basin Plan.

Ahead of the 2024 review of the FLOWS method, the Lower Ovens environmental flow update acknowledged that climate variability and climate change pose a significant challenge for environmental water managers. In the Lower Ovens, environmental water allocations are relatively small compared to unregulated mean annual flow, and changes in runoff and groundwater levels affect streamflow and, therefore, the ability to meet recommended environmental flows. The update also endeavoured to include cultural perspectives.

The updated environmental flow recommendations were developed with a consideration for potential climate change impacts through an iterative process using hydrological compliance and vulnerability assessments. Using the 2022 Ovens River eWater SOURCE hydrological model, the characterisation of streamflow and changes to specific environmental flow components could be considered under a range of future climatic conditions. Projected climate scenarios for 2040 and 2065 were adopted to model future streamflow regimes and characterise the vulnerability of environmental objectives and the likelihood of the availability of the required flows in future. By specifically considering climate change alongside the FLOWS framework for setting objectives and flow recommendations, the study forms a scientifically robust resource to support decision-making in relation to environmental water management and operational plans.

Lower Ovens River. Photo credit: NECMA

5.4.3 Case study 3. Learning from stakeholder engagement on compound events

Victoria has recently experienced a range of extreme events, from droughts and catastrophic bushfires to widespread flooding. Climate projections point towards a volatile future where weather-driven extreme events become more severe, resulting in societal and economic impacts (Stevenson et al., 2022). These effects can be exacerbated when extreme events or hazards occur in combination, either temporarily or spatially – known as compound events. The potential impacts of compound events can be significant across many sectors and different timescales.

To better understand water sector needs regarding compound events and climate extremes, general and targeted stakeholder engagement was conducted during 2023. The objective of the engagement was to:

- capture insights into which extreme events are most relevant and impactful to stakeholders
- understand current knowledge gaps
- determine how future research may help inform stakeholders' climate adaptation and mitigation strategies.

The engagement activities highlighted that stakeholders' roles and functions within their organisations influence their exposure and response to climate risks. Stakeholders understand the risks associated with extreme events, but compound events are often not adequately considered. Some challenges in communicating and identifying the potential impacts of compound events relative to the effects of other extreme events were also identified.

As a result of these activities, a collaboration with a joint stakeholder-research group was developed to explore the risk of intense rainfall following bushfires, which may trigger post-fire debris flows and adversely affect stream water quality.

Other learnings from the stakeholder engagement activities include:

- Alongside high-intensity, short-duration events, longer-duration events can have a cumulative impact on water resource management.
- Consistent event definition and climate variable thresholds can improve warnings and preparation.
- Events may affect service continuity and asset management directly or through sector interdependencies (e.g. energy, transport).

The potential for stakeholder engagements in guiding compounding extreme events research is a valuable approach for yielding relevant outcomes to support effective adaptation and mitigation strategies.

Glossary

Term	Definition
Antarctic stratospheric vortex	A stratospheric wind pattern that blows strongly at about the latitude of the Antarctic coast (around 10–30 km above the surface). It is driven by the temperature differences between the cold pole and the warm regions closer to the equator.
Australian Gridded Climate Data (AGCD)	The Australian Bureau of Meteorology's official dataset for monthly gridded rainfall and temperature.
Climate driver	The large-scale, natural ocean and atmospheric processes that influence climate at seasonal to decadal timescales.
Climate projection	Simulations of the climate system based on a scenario of future emissions or concentrations of greenhouse gases and aerosols, generally from climate models.
Climate variability	Variations in the average climate on all space and time scales beyond that of individual weather events. The variability may be due to natural processes in the climate system (internal variability) or to variations in natural or anthropogenic external forcing (external variability).
Compound extremes	Refers to two or more extreme events that occur simultaneously or successively; or a combination of extreme events that amplify the impact of the individual events; or a combination of events that are not themselves extreme but lead to an extreme event or impact when combined.
Cool season	The cooler months, from April to October in Victoria.
Coupled Model Intercomparison Project (CMIP)	A project that coordinates and archives climate model simulations from modelling groups around the world. Global climate models in the sixth phase of the project, CMIP6, were used to inform the IPCC Sixth Assessment Report.
Cyclone and anticyclone	A cyclone is a low-pressure system of the atmosphere, with winds rotating in a clockwise direction in the Southern Hemisphere. For the purposes of this report, the term cyclones refers to extratropical cyclones. An anti-cyclone is a high-pressure system that rotates in an anti-clockwise direction in the Southern Hemisphere.
Debris flow	A hazardous moving mass of loose mud, sand, soil, rock and water that travels down a slope and into adjacent valleys and streams (such as a landslide).
Downscaling	A method to develop local to regional-scale climate information from larger-scale (coarse resolution) models or data analyses. Downscaling methods include dynamical, statistical and empirical.

Term	Definition
El Niño Southern Oscillation (ENSO)	Year to year fluctuations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. El Niño usually brings below-average rainfall, and La Niña usually brings above average rainfall to much of Australia.
Emissions scenario	A plausible representation of the future development of greenhouse gas emissions and aerosols. They are based on a set of assumptions, such as socioeconomic development and technological change. Examples include shared socioeconomic pathways, SSPs (used in the IPCC Sixth Assessment Report) or representative concentration pathways, RCPs (used in the IPCC Fifth Assessment Report).
Evapotranspiration	The transfer of water vapour to the air directly from the soil or through plants. Actual evapotranspiration (AET) is the evapotranspiration that occurred while potential evapotranspiration (PET) is the evapotranspiration that would occur from a fully saturated surface.
Global climate model (GCM)	A numerical representation of the global climate system based on its physical, chemical and biological properties, their interactions and feedback processes. Resolution of global climate models usually range between 100 to 200 km.
Greenhouse gas	Natural and human-caused gases that trap heat in the atmosphere and warm the planet. Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the primary greenhouse gases in the Earth's atmosphere.
Indian Ocean Dipole (IOD)	A climate driver defined by the difference in sea surface temperatures between the eastern and western tropical Indian Ocean. When positive, there is cooler than normal water in the tropical eastern Indian Ocean and warmer than normal water in the tropical western Indian Ocean.
Interannual variability	The magnitude of year to year change in climate.
Intergovernmental Panel on Climate Change (IPCC)	The United Nations body for assessing climate change science. It provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. The IPCC Sixth Assessment Report was released in 2021–23.
Madden-Julian Oscillation (MJO)	The major fluctuation in tropical weather on weekly to monthly timescales, characterised as an eastward moving pulse of cloud and rainfall near the equator that typically recurs every 30 to 60 days.
Millennium Drought	Extreme dry climate that occurred during 1997–2009 in southern mainland Australia due to a combination of low rainfall and low river inflows.
Natural variability	Variations in climate that are caused by processes other than human influences. This includes variability that is internally generated within the climate system and variability that is driven by natural external factors.
Palaeoclimate	Indirect measurements of climate from geologic (e.g. sediment cores) and biologic (e.g. tree rings) materials that preserve evidence of past changes in climate. Palaeoclimate research looks at changes in climate beyond the timeline of instrumental records.

Term	Definition
Regional climate model (RCM)	A climate model used to generate higher-resolution results from a global climate model. Like a global climate model, a regional climate model is a numerical representation of the climate system based on its physical, chemical and biological properties, their interactions and feedback processes, but it produces results at a regional or local scale.
Representative concentration pathway (RCP)	An emissions scenario that includes changes in concentrations of greenhouse gases and land use over time. These are used as inputs to climate models.
Runoff	The flow of water over land before reaching a stream, river or other watercourse. Once in a watercourse, runoff is referred to as streamflow. It is a major component of the hydrological cycle.
Shared socioeconomic pathways (SSPs)	Scenarios used to explore the consequences of greenhouse gases accumulating in the atmosphere. Each SSP outlines ways the world may change in future, including different types of energy generation, rates of population growth, economic development and land uses. These lead to different levels of greenhouse gas emissions over time.
Southern Annular Mode (SAM)	The north–south movement of the westerly wind belt that circles Antarctica. When positive, the jet is displaced poleward. The changing position of the westerly wind belt influences the strength and position of atmospheric fronts and mid-latitude weather systems, and is an important driver of rainfall variability in southern Australia.
Streamflow	The flow of water in streams, rivers and other channels. Water flowing in channels comes from surface runoff from adjacent hillslopes, from groundwater flow out of the ground, and from water discharged from pipes. Perennial streamflow occurs year-round, while intermittent streamflow occurs during certain times of the year or under different hydroclimate conditions.
Sub-tropical ridge	A belt of high-pressure that encircles the globe in the sub-tropical latitudes. It is part of the global circulation of the atmosphere. The exact latitude of the sub-tropical ridge changes between seasons and plays an important role in the way Australian weather varies from season to season.
Teleconnections	Significant relationships or links in the climate system, such as between a climate driver (such as ENSO or IOD) and another driver or regional climate (rainfall or temperature).
Tropical and extratropical circulation	The large-scale atmospheric circulation in different parts of the Earth's atmosphere. *Tropical circulation* refers to the circulation pattern that occurs in low latitudes (within 30 °N and 30 °S) and is dominated by the rising motion around the equator and subsidence in the subtropics. *Extratropical circulation* refers to the atmospheric circulation in the middle and polar latitudes. The key features of the extratropical circulation are westerlies and weather systems such as cyclones, anticyclones and fronts.

Term	Definition
Uncertainty	Uncertainty refers to a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can be represented by qualitative statements (e.g. reflecting the judgment of a team of experts).
Victoria's Climate Science Report 2024	A report, completed every five years under the Victorian *Climate Change Act 2017*, that summarises the best available scientific evidence on Victoria's changing climate.
Victorian Water and Climate Initiative (VicWaCI)	A research program to improve understanding of Victoria's climate and water resources. It focuses on working with the Victorian water sector to apply this knowledge to water resource management. This report presents findings from phase 2 of the initiative (2020–24).
Warm season	The warmer months, from November to March in Victoria.

References

Abram, N.J., Henley, B.J., Sen Gupta, A., Lippman, T.J.R., Clark, H., Dowdy, A.J., Sharples, J.J., Nolan, R.H., Zhang, T., Wooster, M.J., Wurtzel, J.B., Meissner, K.J., Pitman, A.J., Ukkola, A.M., Murphy, B.P., Tapper, N.J., & Boer, M.M. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment, 2*, 8. https://doi.org/10.1038/s43247-020-00065-8.

Ball, J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., & Testoni, I. (Eds.). (2019). *Australian rainfall and runoff: A guide to flood estimation*. Commonwealth of Australia.

Bende-Michl, U., Bahramian, K., Thomas, S., Kociuba, G., Rudeva, I., Sharples, W., Bonotto, G., Carrara, E., Azarnivand, A., Tolhurst, G., Rauniyar, S., & Sharmila, S. (*in review*). Streamflow regime shifts in a drying climate: insights from multi-year Millennium Drought on Victorian river systems.

Benyon, R.G., Inbar, A., Sheridan, G.J., Lyell, C.S., & Lane, P.N.J. (2023). Variable self-thinning explains hydrological responses to stand replacement in even-aged forests. *Journal of Hydrology, 618*. https://doi.org/10.1016/j.jhydrol.2023.129157.

Bilish, S.P., Callow, J.N., & McGowan, H.A. (2020). Streamflow variability and the role of snowmelt in a marginal snow environment. *Arctic, Antarctic, and Alpine Research*, *52*(1). https://doi.org/10.1080/15230430.2020.1746517.

Blöschl, G., Bierkens, M.F.P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., … Zhang, Y. (2019). Twenty-three unsolved problems in hydrology (UPH) – A community perspective. *Hydrological Sciences Journal, 64*(10). https://doi.org/10.1080/02626667.2019.1620507.

Bonotto, G., Peterson, T.J., Fowler, K., & Western, A.W. (2022). Identifying causal interactions between groundwater and streamflow using convergent cross-mapping. *Water Resources Research, 58*. https://doi.org/10.1029/2021WR030231.

Boschat, G., Purich, A., Rudeva, I., & Arblaster, J. (2023). Impact of Zonal and Meridional Atmospheric Flow on Surface Climate and Extremes in the Southern Hemisphere. *American Meteorological Society*. https://doi.org/10.1175/JCLI-D-22-0251.1.

Burls, N.J., Blamey, R.C., Cash, B.A., Swenson, E.T., al Fahad, A., Bopape, M-J.M., Straus, D.M., Reason, C.J.C. (2019). The Cape Town "Day Zero" drought and Hadley cell expansion. NPJ *Climate and Atmospheric Science, 2*, 27. https://doi.org/10.1038/s41612-019-0084-6.

Butler, A.H., Thompson, D.W.J., & Heikes, R. (2010). The steady-state atmospheric circulation response to climate change-like thermal forcings in a simple general circulation model. *Journal of Climate, 23*(9). https://doi.org/10.1175/2010JCLI3228.1.

Cai, W., Van Rensch, P., Cowan, T., & Hendon, H.H. (2012). An asymmetry in the IOD and ENSO teleconnection pathway and its impact on Australian climate. *Journal of Climate*, *25*(18). https://doi.org/10.1175/JCLI-D-11-00501.1.

Cai, W., Wu, L., Lengaigne, M., Li, T… Change, P. (2019). Pantropical climate interactions. Science, 363. https://www.science.org/doi/10.1126/science.aav4236.

Cai, W., Ng, B., Geng, T., Jia, F., Wu, L., Wang, G., Liu, Y., Gan, B., Yang, K., Santoso, A., Lin, X., Li, Z., Liu, Y, Yang, Y., Jin, F-F, Collins, M., & McPhaden, M.J. (2023). Anthropogenic impacts on twentieth-century ENSO variability changes. *Nature Reviews Earth & Environment*, *4*(6). https://doi.org/10.1038/s43017-023-00427-8.

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J-S., Lengaigne, M., McPhaden, M.J., Stuecker, M.F., Taschetto, A.S., Timmerman, A., Wu, L., Yeh, S-W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X-T., & et al. (2021). Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment, 2*. https://doi.org/10.1038/s43017-021-00199-z.

Charles, S.P., Chiew, F.H.S., Potter, N.J., Zheng, H., Fu, G., & Zhang, L. (2020). Impact of dynamically downscaled rainfall biases on projected runoff changes. *Hydrological and Earth System Sciences, 24*. http://dx.doi.org/10.5194/hess-24-2981-2020.

Cheng, L., Zhang, L., Wang, Y.P., Canadell, J.G., Chiew, F.H.S., Beringer, J., Li, L., Miralles, D.G., Piao, S., & Zhang, Y. (2017). Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nature Communications, 8*, 110. https://doi.org/10.1038/s41467-017-00114-5.

Chiew, F.H.S. & McMahon, T.A. (2002). Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. *Hydrological Sciences Journal*, 47 (3). https://doi.org/10.1080/02626660209492950.

Chiew, F.H.S., Zheng, H., Potter, N.J., Charles, S.P., Thatcher, M., Ji, F., Syktus, J., Robertson, D.E., & Post, D.A. (2022). Different hydroclimate modelling approaches can lead to a large range of streamflow projections under climate change: Implications for water resources management. *Water, 14*. http://dx.doi.org/10.3390/w14172730.

Chiew, F.H.S., Robertson, D.E., Potter, N.J., Post, D.A., Devanand, A., Zheng, H., & Khan, Z. (2024). Climate variability, climate change and baselines: considerations for water resources management and planning. *Hydrology and Water Resources Symposium*, Melbourne, November 2024.

Chiew, F.H.S., Potter, N.J., Vaze, J., Petheram, C., Zhang, L., Teng, J., & Post, D.A. (2014). Observed hydrological non-stationarity in far south-eastern Australia: Implications and future modelling predictions. *Stochastic Environmental Research and Risk Assessment, 28*(1). https://doi.org/10.1007/s00477-013-0755-5.

Chung, C., Boschat, G., Taschetto, A., Narsey, S., McGregor, S., Santoso, A., & Delage, F. (2023). Evaluation of seasonal teleconnections to remote drivers of Australian rainfall in CMIP5 and CMIP6 models. *Journal of Southern Hemisphere Earth Systems Science, 73(3)*. https://doi.org/10.1071/ES23002.

Chung, C.T.Y., Power, S.B., Boschat, G., Gillett, Z.E., & Narsey, S. (*in press*). Projected Changes to Characteristics of El Niño-Southern Oscillation, Indian Ocean Dipole, and Southern Annular Mode Events in the CMIP6 models. *Earth's Future*.

Cottingham, P., Gawne, B., Gigney, H., Koehn, J., Roberts, J., Stewardson, M., & Vietz, G. (2008). Lower Ovens Environmental Flows Project: Environmental flow recommendation. Report prepared for the North Eastern Catchment Management Authority. Peter Cottingham & Associates and the Murray Darling Freshwater Research Centre. Access via: https://www.vewh.vic.gov.au/__data/assets/pdf_file/0003/357537/Ovens-flow-study-Final-report-of-flow-recommendations-17032008.pdf.

Delage, F.P.D., & Power, S.B. (2020). The impact of global warming and the El Niño-Southern Oscillation on seasonal precipitation extremes in Australia. *Climate Dynamics, 54*. https://doi.org/10.1007/s00382-020-05235-0.

Department of Environment, Land, Water and Planning (DELWP). (2016). *Water for Victoria*. https://www.water.vic.gov.au/about-us/water-for-victoria.

Department of Environment, Land, Water and Planning (DELWP). (2019). *Victoria in Future 2019*. https://www.parliament.vic.gov.au/49c5b5/contentassets/1e833e26d6a4491f9b7488a2ef553b28/vpa-further-info-victoria_in_future_2019.pdf.

Department of Environment, Land, Water and Planning (DELWP). (2021). *Water Cycle Climate Change Adaptation Action Plan 2022–2026*. https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0025/558421/WaterCycleAdaptationActionPlan.pdf.

Department of Environment, Land, Water and Planning (DELWP), Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation, & The University of Melbourne. (2020a). *Victoria's Water in a Changing Climate*. https://www.water.vic.gov.au/our-programs/climate-change-and-victorias-water-sector/hydrology-and-climate-science-research/victorian-water-and-climate-initiative.

Department of Environment, Land, Water and Planning (DELWP). (2020b). *Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria* (Final, November 2020). https://www.water.vic.gov.au/__data/assets/pdf_file/0027/663327/guidelines-for-assessing-the-impact-of-climate-change-on-water-availability-in-victoria-2020-edition.pdf.

Department of Energy, Environment and Climate Action (DEECA). (2024). *Victoria's Climate Science Report 2024*. https://www.climatechange.vic.gov.au/victorias-changing-climate.

Devanand, A., Falster, G.M., Gillett, Z.E., Hobeichi, S., Holgate, C.M., Jin, C., Mu, M., Parker, T., Rifai, S.W., Rome, K.S., Stojanovic, M., Vogel, E., Abram, N., Abramowitz, G., Coats, S., Evans, J.P., Gallant, A.J.E., Pitman, A.J., Power, S.B., Rauniya, S.P, Taschetto, A.S., & Ukkola, A.M. (2024). Australia's Tinderbox Drought: An extreme natural event likely worsened by human-caused climate change. *Science Advances*, 10(10). https://www.science.org/doi/10.1126/sciadv.adj3460.

Di Virgilio, G., Evans, J.P., Blake, S.A., Armstrong, M., Dowdy, A.J., Sharples, J., & McRae, R. (2019). Climate change increases the potential for extreme wildfires. *Geophysical Research Letters, 46*(14). https://doi.org/10.1029/2019GL083699.

Di Virgilio, G., Evans, J.P., Clarke, H., Sharples, J., Hirsch, A.L. & Hart, M.A. (2020). Climate change significantly alters future wildfire mitigation opportunities in southeastern Australia. *Geophysical Research Letters*, 47(15). https://doi.org/10.1029/2020GL088893.

Dowdy, A.J., Ye, H., Pepler, A., Thatcher, M., Osbrough, S.L., Evans, J.P., Di Virgilio, G. & McCarthy, N. (2019). Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-46362-x.

Falster, G.M., Wright, N.M., Abram, N.J., Ukkola, A.M., & Henley, B.J. (2024). Potential for historically unprecedented Australian droughts from natural variability and climate change. *Hydrology and Earth System Sciences, 28*(11). https://doi.org/10.5194/hess-28-1383-2024.

Fan, X., Peterson, T.J., Henley, B.J., & Arora, M. (2023). Groundwater sensitivity to climate variations across Australia. *Water Resources Research, 59*. https://doi.org/10.1029/2023WR035036.

Fiddes, S.L., Pezza, A.B. & Barras, V. (2015). A new perspective on Australian snow. *Atmospheric Science Letters, 16*(3). https://doi.org/10.1002/asl2.549.

Fiddes, S., Pepler, A., Saunders, K., Hope, P. (2021). Redefining southern Australia's climatic regions and seasons. *Journal of Southern Hemisphere Earth Systems Science* 71. https://doi.org/10.1071/ES20003.

Fowler, K.J.A., Coxon, G., Freer, J.E., Knoben, W.J.M., Peel, M.C., Wagener, T., Western, A.W., Woods, R.A., & Zhang, L. (2021). Towards more realistic runoff projections by removing limits on simulated soil moisture deficit. *Journal of Hydrology, 600*. https://doi.org/10.1016/j.jhydrol.2021.126505.

Fowler, K., Knoben, W., Peel, M., Peterson, T., Ryu, D., Saft, M., Seo, K-W., & Western, A. (2020). Many commonly used rainfall-runoff models lack long, slow dynamics: Implications for runoff projections. *Water Resources Research, 56*(5). https://doi.org/10.1029/2019WR025286.

Fowler, K., Peel, M., Saft, M., Nathan, R., Horne, A., Wilby, R., McCutcheon, C., & Peterson, T. (2022b). Hydrological shifts threaten water resources. *Water Resources Research*, *58*(8). https://doi.org/10.1029/2021WR031210.

Fowler, K., Peel, M., Saft, M., Peterson, T., Western, A., Band, L., Petheram, C., Dharmadi, S., Tan, K.S., Zhang, L., Lane, P., Kiem, A., Marshall, L., Griebel, A., Medlyn, B., Ryu, D., Bonotto, G., Wasko, C., Ukkola, A., Stephens, C., Frost, A., Weligamage, H., Saco, P., Zheng, H., Chiew, F., Daly, E., Walker, G., Vervoort, R.W., Hughes, J., Trotter, L., Neal, B., Cartwright, I., & Nathan, R. (2022a). Explaining changes in rainfall-runoff relationships during and after Australia's Millennium Drought: A community perspective. *Hydrology and Earth System Sciences, 26*. https://doi.org/10.5194/hess-26-6073-2022.

Fowler, K., Peel, M., Western, A., & Zhang, L. (2018). Improved rainfall-runoff calibration for drying periods: Choice of objective function. *Water Resources Research, 54*(5). https://doi.org/10.1029/2017WR022466.

Freund, M., Henley, B.J., Karoly, D.J., Allen, K.J., & Baker, P.J. (2017). Multi-century cool- and warm-season rainfall reconstructions for Australia's major climatic regions. *Climate of the Past*, *13*(12). https://doi.org/10.5194/cp-13-1751-2017.

Freund, M.B., Henley, B.J., Karoly, D.J., McGregor, H.V., Abram, N.J., & Dommenget, D. (2019). Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries. *Nature Geoscience, 12*. https://doi.org/10.1038/s41561-019-0353-3.

Frost, A.J., Ramchurn, A., & Smith, A. (2018). The Australian Landscape Water Balance model (AWRA-L v6). Technical Description of the Australian Water Resources Assessment Landscape model version 6. Bureau of Meteorology Technical Report. https://awo.bom.gov.au/assets/notes/publications/AWRALv6_Model_Description_Report.pdf.

Fu, G., Chiew, F.H.S., Zheng, H., Robertson, D.E., Potter, N.J., Teng, J., Post, D.A., Charles, S.P., & Zhang, L. (2021). Statistical analysis of attributions of climate characteristics to non-stationary rainfall-streamflow relationships. *Journal of Hydrology, 603*. https://doi.org/10.1016/j.jhydrol.2021.127017.

Fu, G., Chiew, F.H.S., & Post, D.A. (2023). Trends and variability of rainfall characteristics influencing annual streamflow: A case study of south-east Australia. *International Journal of Climatology, 43*(3). https://doi.org/10.1002/joc.7645.

Fu, G., Chiew, F.H.S., Post, D.A., Pepler, A., & Rudeva, I. (2024). Attributions of rainfall changes to weather systems in southeast Australia. *International Journal of Climatology*. https://doi.org/10.1002/joc.8644.

Fuchs, E.H., King, J.P., & Carroll, K.C. (2019). Quantifying disconnection of groundwater from managed-ephemeral surface water during drought and conjunctive agricultural use. Water Resources Research, 55. https://doi.org/10.1029/2019WR024941.

Gallant, A.J.E., Kiem, A.S., Verdon-Kidd, D.C., Stone, R.C., & Karoly, D.J. (2012). Understanding hydroclimate processes in the Murray–Darling Basin for natural resources management. *Hydrology and Earth System Sciences*, *16*(7). https://doi.org/10.5194/hess-16-2049-2012.

Geng, T., Cai, W., Wu, L., Santoso, A., Wang, G., King, Z., Gan, B., Tand, Y., Li, S., Wang, S., Chen, Z., & McPhaden, M.J. (2022). Emergence of changing central Pacific and eastern Pacific El Niño-Southern Oscillation in a warming climate. *Nature Communications, 13*. https://doi.org/10.1038/s41467-022-33930-5.

Geng, T., Jia, F., Cai, W., Wu, L., Gan, B., Jing, Z., Li, S., & McPhaden, M. J. (2023). Increased occurrences of consecutive La Niña events under global warming. *Nature, 619*. https://doi.org/10.1038/s41586-023-06236-9.

Grose, M.R., Narsey, S., Delage, F.P., Dowdy, A.J., Bador, M., Boschat, G., Chung, C., Kajtar, J.B., Rauniyar, S., Freund, M.B., Lyu, K., Rashid, H., Zhang, X., Wales, S., Trenham, C., Holbrook, N.J., Cowan, T., Alexander, L., Arblaster, J.M., & Power, S. (2020). Insights From CMIP6 for Australia's Future Climate. *Earth's Future*, *8*(5), https://doi.org/10.1029/2019EF001469.

Grose, M.R., Narsey, S., Transoco, R., Mackallah, C., Delage, F., Dowdy, A., Di Virgilio, G., Watterson, I., Dobrohotoff, P., Rashid, H.A., Rauniyar, S., Henly, B., Thatcher, M., Syktus, J., Abramowitz, G., Evans, J.P., Su, C-H., & Takbash, A. (2023). A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia. *Climate Services, 30*. https://doi.org/10.1016/j.cliser.2023.100368.

Grose, M.R., Syktus, J., Thatcher, M., Evans, J.P., Ji, F., Rafer, T., & Remenyi, T. (2019). The role of topography on projected rainfall change in mid-latitude mountain regions. *Climate Dynamics, 53*(7–8), 3675–3690. https://doi.org/10.1007/s00382-019-04736-x.

Guo, Y., Zhang, L., Zhang, Y., Wang, Z. & Zheng, H.X. (2021). Estimating Impacts of Wildfire and Climate Variability on Streamflow in Victoria, Australia. *Hydrological Processes, 35*(12). https://doi.org/10.1002/hyp.14439.

Hartmann, L.D. (2022). The Antarctic ozone hole and the pattern effect on climate sensitivity. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.2207889119.

Heath, J.T., Chafer, C.J., Bishop, T.F.A., & Van Ogtrop, F.F. (2016). Post-fire recovery of eucalypt dominated vegetation communities in the Sydney basin, Australia. *Fire Ecology*, *12*(3). https://doi.org/10.4996/fireecology.1203053.

Hendon H.H., Lim, E-P,. & Abhik, S. (2020). Impact of Interannual Ozone Variations on the Downward Coupling of the 2002 Southern Hemisphere Stratospheric Warming. *Journal of Geophysical Research: Atmosphere*, *125*(16). https://doi.org/10.1029/2020JD032952.

Hendon, H.H., Thompson, D.W., & Wheeler, M.C. (2007). Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *Journal of Climate*, *20*(11). https://doi.org/10.1175/JCLI4134.1.

Henley, B.J., Peel, M.C., Nathan, R., King, A.D., Ukkola, A.M., Karoly, D.J., & Tan, K.S. (2019). Amplification of risks to water supply at 1.5 °C and 2 °C in drying climates: a case study for Melbourne, Australia. *Environmental Research Letters*, *14*(8). https://iopscience.iop.org/article/10.1088/1748-9326/ab26ef/meta.

Holgate, C.M., Pepler, A.S., Rudeva, I., & Abram, N.J. (2023). Anthropogenic warming reduces the likelihood of drought-breaking extreme rainfall events in southeast Australia. *Weather and Climate Extremes, 42*. https://doi.org/10.1016/j.wace.2023.100607.

Hope, P., Timbal, B., Hendon, H., Ekström, M., & Potter, N. (2017). *A Synthesis of Findings from the Victorian Climate Initiative*. Bureau of Meteorology. http://www.bom.gov.au/research/projects/vicci/docs/2017/VicCI-SynR-MR.pdf.

Huang, A.T., Gillet, Z.E. & Taschetto, A.S. (2024). Australian Rainfall Increases During Multi-Year La Niña. *Geophysical Research Letters*, *51*(9). https://doi.org/10.1029/2023GL106939.

Huf, B., & McLean, H. (2020). Parliament of Victoria, 2019–20 Bushfires: Quick guide. Research Note No. 1, February 2020. https://www.parliament.vic.gov.au/495ff4/globalassets/sections-shared/about/publications/research-papers/2019-20-bushfires_rn_2020_1.pdf.

Inbar, A., Trouvé, R., Benyon, R.G., Lane, P.N.J., & Sheridan, G.J. (2022). Long-term hydrological response emerges from forest self-thinning behaviour and tree sapwood allometry. *Science of The Total Environment*, *852*. https://doi.org/10.1016/j.scitotenv.2022.158410.

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport.pdf.

Jin, C., Reeder, M.J., Gallant, A.J., Parker, T., & Sprenger, M. (2024). Changes in weather systems during anomalously wet and dry years in southeastern Australia. *Journal of Climate*, 37(4). https://doi.org/10.1175/JCLI-D-23-0305.1.

Jucker, M., Reichler, T., & Waugh, D.W. (2021). How frequent are Antarctic sudden stratospheric warmings in present and future climate? *Geophysical Research Letters, 48*. https://doi.org/10.1029/2021GL093215.

Kang, S.M., Yu, Y., Deser, C., Zhang, X., Kang, I., Lee, S., Rodgers, K.B., & Ceppi, P. (2023). Global impacts of recent Southern Ocean cooling. *Proceedings of the National Academy of Sciences of the United States of America, 120*(30). https://doi.org/10.1073/pnas.2300881120.

Khaledi, J., Lane, P.N.J., Nitschke, C.R., & Nyman, P. (2022). Wildfire contribution to streamflow variability across the Australian temperate zone. *Journal of Hydrology, 609*. https://doi.org/10.1016/j.jhydrol.2022.127728.

Khaledi, J., Nitschke, C., Lane, P.N.J., Penman, T., & Nyman, P. (2021). The influence of atmosphere-ocean phenomenon on water availability across temperate Australia. *Water Resources Research*, 5(1). https://doi.org/10.1029/2020WR029409.

Kim, S-K., Park, H-J., An, S-I., Liu, C., Cai, W., Santoso, A., & Kug, J-S. (2024). Decreased Indian Ocean Dipole variability under prolonged greenhouse warming. *Nature Communications, 15*. https://doi.org/10.1038/s41467-024-47276-7.

Kinal, J., & Stoneman, G.L. (2012). Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia. Journal of Hydrology. https://doi.org/10.1016/j.jhydrol.2012.09.013.

Kirono, D.G., Round, V., Heady, C., Chiew, F.H., & Osbrough, S. (2020). Drought projections for Australia: Updated results and analysis of model simulations. *Weather and Climate Extremes*, 30. https://doi.org/10.1016/j.wace.2020.100280.

Kuczera, G. (1987). Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology*, 94. https://doi.org/10.1016/0022-1694(87)90054-0.

Leblanc, M.J., Tregoning, P., Ramillien, G., Tweed, S.O., & Fakes, A. (2009). Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia, *Water Resources Research, 45*. https://doi.org/10.1029/2008WR007333.

Lee, S., L'Heureux, M., Wittenberg, A.T., Seagar, R., O'Gorman, P.A., & Johnson, N.C. (2022). On the future zonal contrasts of equatorial Pacific climate: Perspectives from observations, simulations, and theories. *NPJ Climate and Atmospheric Science, 5*(82). https://doi.org/10.1038/s41612-022-00301-2.

Lerat, J., Chiew, F.H.S., Robertson, D.E., Andréassian, V., & Zheng, H. (2024). Data assimilation informed model structure improvement (DAISI) tor robust prediction under climate change: application to 201 catchments in southeastern Australia. *Water Resources Research*, 60. https://doi.org/10.1029/2023WR036595.

Lim, E-P., Hendon, H.H., Arblaster, J.M., Chung, C., Moise, A.F., Hope, P., Young, G., & Zhao, M. (2016). Interaction of the recent 50-year SST trend and La Niña 2010: Amplification of the Southern Annular Mode and Australian springtime rainfall. *Climate Dynamics, 47*. https://doi.org/10.1007/s00382-015-2963-9.

Lim, E-P., Hudson, D., Wheeler, M.C., Marshall, A.G., King, A., Zhu, H., Hendon, H.H., de Burgh-Day, C., Trewin, B., Griffiths, M., Ramchyrn, A., & Young, G. (2021). Why Australia was not wet during spring 2020 despite La Niña. *Scientific Reports, 11*. https://doi.org/10.1038/s41598-021-97690-w.

Lim, E-P., Zhou, L., Young, G., Abhik, S., Rudeva, I., Hope, P., Wheeler, M.C., Arblaster, J.M., Hendon, H.H., Manney, G.L., Son, S-W., Oh, J., & Garreaud, R.D. (2024). Predictability of the 2020 strong vortex in the Antarctic stratosphere and the role of ozone. *Journal of Geophysical Research: Atmospheres*, *129*. https://doi.org/10.1029/2024JD040820.

Lim, E-P., & Hendon, H.H. (2015). Understanding the Contrast of Australian Springtime Rainfall of 1997 and 2002 in the Frame of Two Flavors of El Niño. *Journal of Climate*, *28*(7). https://doi.org/10.1175/JCLI-D-14-00582.1.

Lim, E-P., Narsey, S., Chung, C.T.Y., Boschat, G., Hope, P., Marshall, A., & Wheeler, M.C. (2023). The Southern Annular Mode and Large-Scale Circulations: How understanding largescale linkages can provide insights into improving seasonal forecasts and regional projections. Climate Systems Hub, National Environment Science Program, Australia. https://nesp2climate.com.au/wp-content/uploads/2023/12/The-Southern-Annular-Mode_5.2-1.pdf.

Liu, N., Kala, J., Liu, S., Haverd, V., Dell, B., Smettem, K.R.J., & Harper, R.J. (2020). Drought can offset potential water use efficiency of forest ecosystems from rising atmospheric CO_2. *Journal of Environmental Sciences, 90*. https://doi.org/10.1016/j.jes.2019.11.020.

McGregor, S., Cassou, C., Kosaka, Y., & Phillips, A.S. (2022). Projected ENSO teleconnection changes in CMIP6. *Geophysical Research Letters, 49*(11). https://doi.org/10.1029/2021GL097511.

Meyers, G., McIntosh, P., Pigot, L., & Pook, M. (2007). The years of El Niño, La Niña and interactions with the tropical Indian Ocean. *Journal of Climate*, *20*(13). https://doi.org/10.1175/JCLI4152.1.

Nolan, R.H., Lane, P.N.J., Benyon, R.B., Bradstock, R., & Mitchell, P.J. (2014b). Changes in evapotranspiration following wildfire in resprouting eucalypt forests. *Ecohydrology,* 7(5). https://doi.org/10.1002/eco.1463.

Nolan, R.H., Mitchell, P.J., Bradstock, R., & Lane, P.N.J. (2014a). Structural adjustments in resprouting trees drive differences in post-fire transpiration. *Tree Physiology*, *34*(2). https://doi.org/10.1093/treephys/tpt125.

Nolan, R.H., Lane, P.N.J., Benyon, R.B., Bradstock, R., & Mitchell, P.J. (2015). Trends in evapotranspiration and streamflow following wildfire in resprouting eucalypt forests. *Journal of Hydrology,* 524. https://doi.org/10.1016/j.jhydrol.2015.02.045.

North East Catchment Management Authority (NECMA). (2024). Lower Ovens Environmental Flow Recommendation update. *Available from NECMA by request.*

Noske, P.J., Nyman, P., Lane, P.N.J., Rengers, F.K., & Sheridan, G.J. (2024). Changes in soil erosion caused by wildfire: A conceptual biogeographic model. *Geomorphology,* 459. https://doi.org/10.1016/j.geomorph.2024.109272.

Nyman, P., Rutherfurd, I.D., Lane, P.N.J., & Sheridan, G.J. (2019). Debris flows in southeast Australia linked to drought, wildfire, and the El Niño–Southern Oscillation. *Geology*, 47(5). https://doi.org/10.1130/G45939.1.

Nyman, P., Smith, H.G., Sherwin, C.B., Langhans, C., Lane, P.N.J., & Sheridan, G.J. (2015). Predicting sediment delivery from debris flows after wildfire. *Geomorphology, 250*. https://doi.org/10.1016/j.geomorph.2015.08.023.

Nyman, P., Yeates, P., Langhans, C., Noske, P.J., Peleg, N., Scharer, C., Lane, P.N.J., Haydon, S., & Sheridan, G.J. (2020). Probability and consequence of postfire erosion for treatability of water in an unfiltered supply system. *Water Resources Research, 57*. https://doi.org/10.1029/2019WR026185.

Osburn, L., Hope, P., & Dowdy, A. (2020). Changes in hourly extreme precipitation in Victoria, Australia, from the observational record. *Weather and Climate. Extremes, 31*. https://doi.org/10.1016/j.wace.2020.100294.

Parker, T., & Gallant, A.J.E. (2022). The role of heavy rainfall in drought in Australia. *Weather and Climate Extremes*, *38*. https://doi.org/10.1016/J.WACE.2022.100528.

Peace, M., & McCaw., L. (2024). Future fire events are likely to be worse than climate projections indicate–these are some of the reasons why. *International Journal of Wildland Fire*, *33*(7). https://doi.org/10.1071/WF23138.

Peel, M.C., MacMahon, T.A., & Finlayson, B.L. (2004). Continental differences in the variability of annual runoff: Update and reassessment. *Journal of Hydrology, 295*. https://doi.org/10.1016/j.jhydrol.2004.03.004.

Pendergrass, A.G., Knutti, R., Lehner, F., Deser, C., & Sanderson, B.M. (2017). Precipitation variability increases in a warmer climate. *Scientific Reports, 7*. http://dx.doi.org/10.1038/s41598-017-17966-y.

Pepler, A.S., Dowdy, A.J. & Hope, P. (2021). The differing role of weather systems in southern Australian rainfall between 1979–1996 and 1997–2015. *Climate Dynamics, 56*. https://doi.org/10.1007/s00382-020-05588-6.

Pepler, A. (2023). Projections of synoptic anticyclones for the twenty-first century. *Climate Dynamics*, 61. https://doi.org/10.1007/s00382-023-06728-4.

Pepler, A.S., & Dowdy, A.J. (2022). Australia's future extratropical cyclones. *American Meteorological Society*. https://doi.org/10.1175/JCLI-D-22-0312.1.

Pepler, A.S., Dowdy, A.J., van Rensch, P., Rudeva, I., Catto, J.L., & Hope, P. (2020). The contributions of fronts, lows and thunderstorms to southern Australian rainfall. *Climate Dynamics*, 55. https://doi.org/10.1007/s00382-020-05338-8.

Pepler, A., Trewin, B., & Ganter, C. (2015). The influences of climate drivers on the Australian snow season. *Australian Meteorological and Oceanographic Journal,* 65(2). http://www.bom.gov.au/jshess/docs/2015/pepler.pdf.

Pepler, A.S., & Rudeva, I. (2023). Anomalous subtropical zonal winds drive decreases in southern Australian frontal rain. *Weather and Climate Dynamics, 4*. https://doi.org/10.5194/wcd-4-175-2023.

Peter, J., Vogel, E., Sharples, W., Bende-Michl, U., Wilson, L., Hope, P., Dowdy, A., Kociuba, G., Srikanthan, S., Duong, V.C., Roussis, J., Matic, V., Khan, Z., Oke, A., Turner, M., Baron-Hay, S., Johnson, F., Mehrotra, R., Sharma, A., Thatcher, M., Azarvinand, A., Thomas, S., Boschat, G., Donnelly, C., & Argent, R. (2024). Continental-scale bias-corrected climate and hydrological projections for Australia. *Geoscientific Model Development, 17*(7). https://doi.org/10.5194/gmd-17-2755-2024.

Peterson, T.J., Saft, M., Peel, M.C., & John, A. (2021). Watersheds may not recover from drought. *Science,* 372. https://doi.org/10.1126/science.abd5085.

Petrone, K.C., Hughes, J.D., Van Niel, T.G., & Silberstein, R.P. (2010). Streamflow decline in southwestern Australia, 1950–2008. *Geophysical Research Letters, 37*. https://doi.org/10.1029/2010GL043102.

Potter, N.J., & Chiew, F.H.S. (2011). An investigation into changes in climate characteristics causing the recent very low runoff in the southern Murray-Darling Basin using rainfall-runoff models. *Water Resources Research, 47.* https://doi.org/10.1029/2010WR010333.

Potter, N.J., Chiew, F.H.S., Charles, S.P., Fu, G., Zheng, H., & Zhang, L. (2020). Bias in downscaled rainfall characteristics. *Hydrology and Earth System Sciences*, 24. http://dx.doi.org/10.5194/hess-24-2963-2020.

Potter, N.J., Chiew, F.H.S., & Robertson, D.A. (2023) Stochastic generation of plausible futures using climate teleconnections for South-Eastern Australia. *Journal of Hydrometeorology*, 24. https://doi.org/10.1175/JHM-D-22-0206.1.

Prosser, I.P., Chiew, F.H.S., & Stafford Smith, I.M. (2021). Adapting water management to climate change in the Murray–Darling Basin, Australia. *Water*, 13. http://dx.doi.org/10.3390/w13182504.

Rauniyar, S.P., & Power, S.B. (2020). The impact of anthropogenic forcing and natural processes on past, present, and future rainfall over Victoria, Australia. *Journal of Climate*, 33(18). https://doi.org/10.1175/JCLI-D-19-0759.1.

Rauniyar, S.P., & Power, S.B. (2023). Past and future rainfall change in sub-regions of Victoria, Australia. *Climatic Change, 176*, 92. https://doi.org/10.1007/s10584-023-03562-9.

Raut, B.A., Reeder, M.J., & Jakob, C. (2017). Trends in CMIP5 rainfall patterns over southwestern Australia. *American Meteorological Society*. https://doi.org/10.1175/JCLI-D-16-0584.1.

Reid, K.J., Barnes, M.A., Gillett, Z.E., Udy, D.G., Ayat, H., Boschat, G., Bowden, A., Grosfeld, N.H., King, A.D., Parker, T., Richardson, D., Shao, Y., Teckentrup., L., Trewin, B., Hope, P., Zhou, L., Borowiak, A.R., Holgate, C.M., & Isphording, R. (*in press*). A multiscale evaluation of the wet 2022 in eastern Australia. *Journal of Climate*.

Reinfelds, I., Swanson, E., Cohen, T., Larsen, J., & Nowlan, A. (2014). Hydrospatial assessment of streamflow yields and effects of climate change: Snowy Mountains, Australia. *Journal of Hydrology, 512*. https://doi.org/10.1016/j.jhydrol.2014.02.038.

Ren, P., Stewardson, M., Peel, M., Turner, M., & John, A. (2024). Assessing climate change impacts on yield of "dual-priority" water rights in carryover systems at catchment scale. *Water Resources Research, 60*(1). https://doi.org/10.1029/2023WR035376.

Risbey, J.S., Pook, M.J., McIntosh, P.C., Wheeler, M.C., & Hendon, H.H. (2009). On the Remote Drivers of Rainfall Variability in Australia. *Monthly Weather Review*, *137*(10). https://doi.org/10.1175/2009MWR2861.1.

Robertson, D.E., Chiew, F.H.S., & Potter, N.J. (2023). Adapting rainfall bias corrections to improve hydrological simulations generated from climate model forcings. *Journal of Hydrology, 619*. https://doi.org/10.1016/j.jhydrol.2023.129322.

Robertson, D.E., Chiew, F.H.S., Zheng, H., Pena Arancibia, J., Lal Shrestha, D., & Post, D.A. (2024). How do hydrological non-stationarities impact future runoff projections. Hydrology and Water Resources Symposium, Melbourne, November 2024.

Saft, M., Peel, M.C., Western, A.W., Perraud, J-M., & Zhang, L. (2016). Bias in streamflow projections due to climate-induced shifts in catchment response. *Geophysical Research Letters, 43*. https://doi.org/10.1002/2015GL067326.

Saft, M., Western, A.W., Zhang, L., Peel, M.C., & Potter, N.J. (2015). The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective. *Water Resources Research, 51.* https://doi.org/10.1002/2014WR015348.

Sauquet, E., Shanafield, M., Hammond, J.C., Sefton, C., Leigh, C., & Datry, T. (2021). Classification and trends in intermittent river flow regimes in Australia, northwestern Europe and USA: A global perspective. *Journal of Hydrology, 597*. https://doi.org/10.1016/j.jhydrol.2021.126170.

Santoso, A., Hendon, H., Watkins, A., Power, S., Dommenget, D., England, M.H., Frankcombe, L., Holbrook, N.J., Holmes, R., Hope, P., Lim, E-P., Luo, J-J., McGregor, S., Neske, S., Nguyen, H., Pepler, A., Rashid, H., Sen Gupta, A., Taschetto, A.S., Wang, G., Abellán, E., Sullivan, A., Huguenin, M.F., Gamble, F., & Delage, F. (2019). Dynamics and predictability of El Niño–Southern Oscillation: An Australian perspective on progress and challenges. *Bulletin of the American Meteorological Society, 100*(3). https://doi.org/10.1175/BAMS-D-18-0057.1.

Sharmila, S., Pepler, A., Reddy, J.P., & Sharples, W. (*in prep,* a) What drives summertime compound dry-hot to wet extreme events in southeastern Australia?

Sharmila, S., Pepler, A., Reddy, J.P., & Sharples, W. (*in prep,* b). Variability and drivers of compound drought and heatwave events in southeastern Australia.

Stephens, C.M., Band, L.E., Johnson, F.M., Marshall, L.A., Medlyn, B.E., De Kauwe, M.G., & Ukkola, A.M. (2023). Changes in blue/green water partitioning under severe drought. *Water Resources Research, 59*. https://doi.org/10.1029/2022WR033449.

Stevenson, S., Coats, S., Touma, D., Cole, J., Lehner, F., Fasullo, J., & Otto-Bliesner, B. (2022). Twenty-first century hydroclimate: A continually changing baseline, with more frequent extremes. *Proceedings of the National Academy of Sciences, 119*(12). https://doi.org/10.1073/pnas.2108124119.

Teng, J., Bennett, J.C., Charles, S.P., Chiew, F.H.S., Ji, F., Potter, N., Fu, G., Thatcher, M., & Remenyi, T. (2024). Trend and inter-annual variability in regional climate models: Validation and hydrological implications in southeast Australia. *Journal of Hydrology, 642*. https://doi.org/10.1016/j.jhydrol.2024.131817.

Timbal, B., & Fawcett, R. (2013). A Historical Perspective on Southeastern Australian Rainfall since 1865 Using the Instrumental Record. *American Meteorological Society*. https://doi.org/10.1175/JCLI-D-12-00082.1.

Tolhurst, G., Hope, P., Osburn, L., and Rauniyar, S. (2023). Approaches to Understanding Decadal and Long-Term Shifts in Observed Precipitation Distributions in Victoria, Australia. *Journal of Applied Meteorology Climatology, 62*. https://doi.org/10.1175/JAMC-D-22-0031.1.

Tory, K.J., Cruz, M.G., Matthews, S., Kilinc, M. & McCaw, W.L. (2024). On the sensitivity of fire-weather climate projections to empirical fire models. *Agricultural and Forest Meteorology*, *348*. https://doi.org/10.1016/j.agrformet.2024.109928.

Trotter, L., Saft, M., Peel, M., & Fowler, K. (2021). "Naïve" inclusion of diverse climates in calibration is not sufficient to improve model reliability under future climate uncertainty. In *Proceedings of the International Congress on Modelling and Simulation, MODSIM.*

Trotter, L., Saft, M., Peel, M.C., & Fowler, K.J.A. (2023). Symptoms of performance degradation during multi-annual drought: A large-sample, multi-model study. *Water Resources Research, 59*. https://doi.org/10.1029/2021WR031845.

Trotter, L., Saft, M., Peel, M.C., & Fowler, K.J.A. (2024). Recession constants are non-stationary: Impacts of multi-annual drought on catchment recession behaviour and storage dynamics. *Journal of Hydrology, 630*. https://doi.org/10.1016/j.jhydrol.2024.130707.

Ukkola, A.M., De Kauwe, M.G., Roderick, M.L., Abramowitz, G., & Pitman, A.J. (2020). Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation. *Geophysical Research Letters*, 47(11). https://doi.org/10.1029/2020GL087820.

Ukkola, A.M., Prentice, C., Keenan, T.F., van Dijk, A.I.J.M., Viney, N.R., Myneni, R.B., & Bi, J. (2016). Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation. *Nature Climate Change, 6*(1), 75–78. https://doi.org/10.1038/nclimate2831.

Ukkola, A.M., Thomas, S., Vogel, E., Bende-Michl, U., Siems, S., Matic, V., & Sharples, W. (2024). Future changes in seasonal drought in Australia. *EarthArXiv* [pre-print]. https://doi.org/10.31223/X56110.

van Rensch, P., Turner, M., Saft, M., Peel, M.C., Peterson, T.J., Hope, P., & Pepler, A. (2023). The Role of Weather System Changes and Catchment Characteristics in the Rainfall-Runoff Relationship Shift in Victoria, Australia. *Water Resources Research*, *59*(6). https://doi.org/10.1029/2022wr033692

van der Sant, R.E., Nyman, P., Noske, P.J., Langhans, C., Lane, P.N.J., & Sheridan, G.J. (2018). Quantifying relations between surface runoff and aridity after wildfire. *Earth Surface Processes and Landforms, 43*(10). https://doi.org/10.1002/esp.4370.

Vaze, J., Post, D.A., Chiew, F.H.S., Perraud, J.M., Viney, N.R., & Teng, J. (2010). Climate non-stationarity: Validity of calibrated rainfall-runoff models for use in climate change studies. *Journal of Hydrology, 394*. https://doi.org/10.1016/j.jhydrol.2010.09.018.

Wang, G., & Hendon, H. (2007). Sensitivity of Australian Rainfall to Inter-El Niño Variations. *American Meteorological Society*. https://doi.org/10.1175/JCLI4228.1.

Wang, G., Cai, W., Santoso, A., Abram, N., Ng, B., Yang, K., Geng, T., Doi, T., Du, Y., Izumo, T., Ashok, K., Li, J., Li, T., McKenna, S., Sun, S., Tozuka, T., Zheng, X., Liu, Y., Lixin, W., Jia, F., Hu, S., & Li, X. (2024). The Indian Ocean Dipole in a warming world. *Nature Reviews: Earth & Environment, 5*. https://doi.org/10.1038/s43017-024-00573-7.

Wang, J., Horne, A., Nathan, R., Peel, M., & Neave, I. (2018). Vulnerability of ecological condition to the sequencing of wet and dry spells prior to and during the Murray-Darling Basin Millennium Drought. *Journal of Water Resources Planning and Management*, *144*(8). https://doi.org/10.1061/(ASCE)WR.1943-5452.0000963.

Wasko, C., Guo, D., Ho, M., Nathan, R., & Vogel, E. (2023). Diverging projections for flood and rainfall frequency curves. *Journal of Hydrology*, *620*. https://doi.org/10.1016/j.jhydrol.2023.129403.

Wasko, C., & Nathan, R. (2019). Influence of changes in rainfall and soil moisture on trends in flooding. *Journal of Hydrology, 575*. https://doi.org/10.1016/j.jhydrol.2019.05.054.

Wasko, C., Westra, S., Nathan, R., Pepler, A., Raupach, T.H., Dowdy, A., Johnson, F., Ho, M., McInnes, K.L., Jakob, D., Evans, J., Villarini, G., & Fowler, H.J. (2024a). A systematic review of climate change science relevant to Australian design flood estimation. *Hydrology and Earth System Sciences: Discuss*. https://doi.org/10.5194/hess-28-1251-2024.

Wasko, C., Westra, S., Nathan, R., Jakob, J., Nielson, C., Evans, J., Rodgers, S., Ho, M., Babister, M., Dowdy, A., & Sharples, W. (2024b). Climate Change Considerations, Book 1 Chapter 6 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia.

Wasko, C., Stephens, C., Peterson, T., Nathan, R., Pepler, A., Hettiarachchi, S., Vogel, E., Johnson, F., & Westra, S. (2024c). Understanding the implications of climate change for Australia's water resources: Challenges and future directions. *Journal of Hydrology, 645*. https://doi.org/10.1016/j.jhydrol.2024.132221.

Weligamage, H.G., Fowler, K., Peterson, T., Saft, M., Peel, M.C., & Ryu, D. (2023). Partitioning of precipitation into terrestrial water balance components under a drying climate. *Water Resources Research, 59*. https://doi.org/10.1029/2022WR033538.

Wilson, L., Bende-Michl, U., Sharples, W., Vogel, E., Peter, J., Srikanthan, S., Khan, Z., Matic, V., Oke, A., Turner, M., Duong, V.C., Loh, S., Baron-Hay, S., Roussis, J., Kociuba, G., Hope, P., Dowdy, A., Donnelly, C., Argent, R., Thomas, S., Kitsios, A., & Bellhouse, J. (2022). A national hydrological projections service for Australia. *Climate Services, 28*. https://doi.org/10.1016/j.cliser.2022.100331.

World Meteorological Organization. (2022). *Executive summary: Scientific assessment of ozone depletion: 2022* (GAW Report No. 278). WMO, Geneva. https://ozone.unep.org/system/files/documents/Scientific-Assessment-of-Ozone-Depletion-2022-Executive-Summary.pdf.

Yang, Y., McVicar, T.R., Yang, F., Zhang, Y., Piao, S., Peng, S., & Beck, H.E. (2021). Low and contrasting impacts of vegetation CO_2 fertilisation on global terrestrial runoff over 1982–2010: accounting for aboveground and belowground vegetation CO_2 effects. *Hydrology and Earth System Sciences, 25*. https://doi.org/10.5194/hess-25-3411-2021.

Zhang, S.X., Bari, M., Amirthanathan, G., Kent, D., MacDonald, A., & Shin, D. (2014). Hydrologic Reference Stations to Monitor Climate-Driven Streamflow Variability and Trends. *Hydrology and Water Resources Symposium 2014*. Barton, ACT. Engineers Australia, 2014: 1048-1055. http://www.bom.gov.au/water/hrs/media/static/papers/SophieZhang_et_al_HWRS_2014_Perth_24-27_February.pdf.

Zhang, L., Dawes, W.R., & Walker, G.R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37. http://dx.doi.org/10.1029/2000WR900325.

Zheng, H., Chiew, F.H.S., Post, D.A., Robertson, D.E., Charles, S.P., Grose, M.R., & Potter, N.J. (2024). Projections of future streamflow for Australia informed by CMIP6 and previous generations of global climate models. *Journal of Hydrology, 636*. http://dx.doi.org/10.1016/j.jhydrol.2024.131286.

Zheng, H., Chiew, F.H.S., & Zhang, L. (2022). Can model parameterisation accounting for hydrological non-stationarity increase robustness in future runoff projection? *Journal of Hydrometeorology, 23*. http://dx.doi.org/10.1175/JHM-D-21-0102.1.

Zhou, L., Lim, E-P., Hope, P., Young, G., Pepler, A., & Simmonds, I. (*submitted*). Understanding the drivers of extreme wet over south-eastern Australia in spring 2022.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., & Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews: Earth & Environment,* 1. https://doi.org/10.1038/s43017-020-0060-z.