Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria

Final

November 2020

Victoria State Government | Environment, Land, Water and Planning

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Acknowledgment

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.

We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Acknowledgements

DELWP acknowledges the contribution to these guidelines from a range of researchers and water industry participants, including:

- Water Corporation representatives who provided technical perspectives and water sector expertise through participation in the workshops that informed the development of the draft guidelines, and other water sector experts who provided input into the development of the guidelines, including staff from the Department of Environment, Land, Water and Planning;
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Any questions on these guidelines should be directed to the Hydrology and Climate Science team, Water Resource Assessment Branch, Water Resource Division, Water & Catchments Group, Victorian Department of Environment, Land, Water and Planning. Email the Hydrology and Climate Science team at HCS.team@delwp.vic.gov.au

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Summary

Victoria's climate is changing, and this poses many challenges for the water sector as well as Victorian businesses, industries and communities that rely on water.

Our water resources are largely climate dependent, so planning for climate change is extremely important for Victorian water resource management. Multiple lines of evidence indicate that Victoria will be hotter and drier in the future and this has clear implications for Victoria's water security. Climate change also impacts how we assess and understand our water resource availability right now and in the future. With a changing climate, we need to prepare for climate conditions that lie beyond conditions experienced in the past.

Although the body of scientific knowledge on climate change continues to mature, future climate projections reflect modelling uncertainty and uncertainty around future greenhouse gas emissions. It is therefore important that a range of possible climate scenarios are considered when planning for the sustainability of Victoria's water future.

These guidelines present a consistent approach for applying climate change scenarios for temperature, potential evapotranspiration, rainfall, runoff and groundwater recharge to be used across Victoria for assessing the impact of climate change on water availability. These guidelines also include information on changes to climate variability associated with climate change.

These guidelines were developed by the Victorian Department of Environment, Water, Land and Planning (DELWP) and build on the 2016 edition of the guidelines. Feedback on the 2016 edition of the guidelines was sought from organisations that used them, including Victorian Water Corporations. The guidelines have also been updated in response to new and updated legislation and water policy, and new research findings, including those from the Victorian Water and Climate Initiative.

The guidelines support Water Corporations to discharge their responsibilities under Clause 6-A of the Statement of Obligations (General) issued by the Minister for Environment, Climate Change and Water in December 2015, that requires Water Corporations to 'comply with any guidelines for forecasting the impact of climate change on water supplies' issued by DELWP.

In addition to urban and rural water impact assessments, the guidelines can be used to assess future water availability for integrated water cycled management, environmental water assessments and other purposes.

The key benefits of these guidelines include:

(i) **Providing tailored guidance on how to apply the climate science** for water resource planning applications. Applying the science can be complex, and the guidelines describe how to do this in a manner consistent with current research findings.

(ii) **Promoting a consistency in approach to climate change impact assessment for water supplies.** This enables comparisons of current and future water availability and use for shared water resources across Victoria.

(iii) **Enabling more efficient climate change impact assessments** by pre-generating a standard set of climate change information, thereby removing the burden for individual Water Corporations or other users to generate their own climate change projections in an area of complex science.

Key features

Key features of the guidelines include:

- Clarification of the role of these guidelines relative to other climate change and water supply planning guidance issued by DELWP.
- A how-to guide for using these guidelines for various applications.
- An overview of observed climate change to date.
- An overview of the methods used by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to generate climate change projections for the guidelines and their associated uncertainties and limitations.
- Information and methods for undertaking climate change impact assessment for water availability and supply.

- Guidance on when to consider additional assessment techniques and/or planning approaches to manage near-term planning risks.

Recommended approaches

The guidelines present recommended approaches to climate change impact assessment based on scenario planning within the context of Victoria's adaptive management framework for water supply planning. These recommended approaches include:

1. Establishment of a post-1975 historic climate reference period and a post-1997 historic climate reference period from which to generate a range of projected climate change scenarios (referenced from the post-1975 period) and a step climate change scenario (referenced from the post-1997 period). These historic climate reference periods can be used (if desired) to communicate streamflow characteristics and supply system performance under historic climate conditions.

2. Extension of those historic climate reference periods to incorporate a broader range of natural climate variability using either scaling techniques or stochastic data generation.

3. The use of low, medium and high climate change scenarios (in addition to the post-1997 step climate change scenario — see below) to represent current and projected future climate and streamflow. These scenarios are derived using average annual climate change projections, applied to the post-1975 historic climate reference period, for temperature, potential evapotranspiration, rainfall and runoff. These are applied by river basin for the years 2040 and 2065, under a high Representative Concentration Pathway (RCP8.5). The RCP8.5 scenario incorporates high rates of greenhouse gas emissions and is suitably precautionary for water supply planning applications. It considers global climate modelling uncertainty and uncertainty around future greenhouse gas emissions and concentrations. These scenarios (low, medium and high) represent the 10^{th}, 50^{th} and 90^{th} percentile outcome from the 42 available global climate models (GCMs).

4. Linear interpolation of the low, medium and high climate change projections between global climate model time slices in 1995, 2040 and 2065, and linear extrapolation of global climate model projections up to 2075 to support applications over a 50-year planning horizon.

5. The use of the post-1997 step climate change scenario (in addition to low, medium and high climate change scenarios — see above) to represent current and future climate and streamflow. This scenario is derived by projecting the post-1997 historic climate reference period and is independent of global climate modelling. This scenario assumes that the dry conditions experienced since 1997 represent a permanent step-change in climate from that experienced prior to 1997.

6. Adjustments to peak daily and sub-daily rainfall and runoff (if applicable for the given application) to reflect projected increases in rainfall intensity under global warming, in conjunction with changes to average annual rainfall and runoff.

7. Application of climate change scenarios to estimate:

> **a) changes in demand** under climate change, using climate dependent demand models. The use of the medium climate change projection only is recommended in the case of urban water demands. This is because of the lower sensitivity of urban water demand to climate change impacts relative to projected changes to long term water availability, and other potential demand sensitivities such as population and water-use behaviours.
>
> **b) changes in groundwater recharge** under climate change, using a risk-based approach that considers aquifer type and depth.
>
> **c) additional changes in runoff due to changes in snow cover**, for water supply catchments in alpine areas.
>
> **d) changes in water supply availability**, such as changes in supply system yield, reliability, or other metrics relevant to water supply systems and river systems.

8. Identification of near-term risks where a water supply planning decision must be made now about actions to occur over the next ten years, and the planning decisions are both vulnerable to the climate change impact assessment assumptions and could be regretted if those assumptions were subsequently found to be incorrect. In the case that a risk is identified, there are additional methods and information available to assess the vulnerability of water resource planning decisions to the guideline assumptions.

9. Optional application of additional information and techniques that can be utilised to further assess the sensitivity of planning outcomes to the assumptions in the guidelines. These include:

> **a) The option to also utilise a more moderate RCP scenario (RCP4.5)** that reflects lower rates of greenhouse gas emissions that could occur under greenhouse gas mitigation measures pledged by the world's governments. Up to the year 2040, projected rainfall changes for most river basins in Victoria are not materially different for RCP4.5 and RCP8.5. In the latter half of the 21st century, the range of projected rainfall changes in Victoria under the RCP4.5 scenario falls within the bounds of that for the RCP8.5 scenario.
>
> **b) Additional climate change projections**, such as the downscaled projections available from a subset of six GCMs in the Victorian Climate Projections 2019 (VCP19). This includes specific advice on whether the VCP19 projections are wetter, drier or about the same for any given river basin in the year 2065.
>
> **c) Additional climate change impact assessment techniques**, including but not limited to sensitivity testing and/or stress testing. This includes specific advice on how to undertake sensitivity testing to seasonal shifts in rainfall in each river basin.

Future updates

These guidelines will be updated from time to time to refine the guidance and incorporate new research as it becomes available. The next major update of these guidelines will likely occur after the Intergovernmental Panel on Climate Change publishes its assessment of the next update of global climate modelling (CMIP6) in 2022.

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1. Introduction

Victoria's climate is changing, and this poses many challenges for the water sector as well as Victorian businesses, industries and communities that rely on water. Our water resources are largely climate dependent, so planning for climate change is extremely important for Victorian water resource management. Although the body of scientific knowledge on climate change continues to mature, future climate projections reflect modelling uncertainty and uncertainty around future greenhouse gas emissions. It is therefore important that a range of possible climate scenarios are considered when planning for the sustainability of Victoria's water future.

1.1 Scope and purpose of the guidelines

1.1.1 Scope and purpose

These guidelines update and replace the previous guidelines issued in 2016 (DELWP, 2016a).

The purpose of these guidelines is to set out climate change scenarios for temperature, potential evapotranspiration, rainfall, runoff and groundwater recharge for use across Victoria for assessing the impact of climate change on water availability, supply and demand. These guidelines also include information on changes to climate variability associated with climate change.

These guidelines were developed by the Victorian Department of Environment, Water, Land and Planning (DELWP) and informed by feedback from users of the 2016 edition of the guidelines, including Victoria's Water Corporations. The primary audience of the guidelines is Victoria's Water Corporations, and water resource managers and planners within the department. It is recognised, however, that there is a wide range of other potential users of the guidelines, including other government agencies, consultants, businesses, researchers and others who have a need to consider the impact of climate change on water availability in Victoria.

The key benefits of these guidelines include:

(i) To provide tailored guidance on how to apply the climate science for water resource planning applications. Applying the science can be complex, and the guidelines describe how to do this in a manner consistent with current research findings.

(ii) To promote a consistency in approach to climate change impact assessment for water supplies. This enables comparisons of current and future water availability and use for shared water resources across Victoria.

(iii) To enable more efficient climate change impact assessment by pre-generating a standard set of climate change information, thereby removing the burden for individual Water Corporations or other users to generate their own climate change projections in an area of complex science.

The scope of the guidelines includes the provision of annual climate change projections for the years 2040 and 2065 for temperature, potential evapotranspiration, rainfall, runoff and recharge, for each river basin in Victoria. These are provided for two Representative Concentration Pathways (RCPs) incorporating different scenarios of greenhouse gas emissions and concentrations over time. The guidelines also include a range of other supporting information including the establishment of historic climate reference periods, discussion of climate change projection uncertainties, supporting data for sensitivity testing for seasonal climate change impacts, an overview of the influences on Victoria's climate and how they are changing, and a range of other practical considerations for when applying these guidelines.

The guidelines are expected to be suitable for a broad range of assessments on the impact of climate change on water availability, but there may be some applications where other scenarios or methods may be more appropriate. The scope of the guidelines does not cover aspects of water planning covered by other guidance documents or expert processes, including the projected impacts of climate change on water quality, sewerage planning, floodplain management, asset management, and ecosystem behaviour. However, these guidelines do support a range of water planning activities in Victoria, as outlined below in Sections 1.1.2 and 1.1.3.

1.1.2 Role of the guidelines within Victoria's water planning framework

These guidelines perform an important role in delivering on commitments under Victoria's policy and legislative framework. It is stated in Victoria's *Climate Change Act 2017* (the Act) that "decision makers must have regard to climate change", including the potential impacts of climate change (Parliament of Victoria, 2017). The guidelines are consistent with a core guiding principle stated within the Act, namely that decisions, policies, programs or processes should be based on informed decision making, using "the best practicably available information about the potential impacts of climate change" (Parliament of Victoria, 2017). The guidelines also support the other guiding principles within the Act by (i) providing information on uncertainties that aligns with a risk management approach, and (ii) presenting long-term projections that can help to assess equity across generations. By publishing the guidelines, they support the principles of (iii) community engagement and (iv) compatibility of information across policies and programs. The role of the guidelines is acknowledged in Action 2.3 of *Water for Victoria* (DELWP, 2016b), Victoria's strategic water management plan, namely that:

> *"In the short-term, water corporations will apply the Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria".*

This obligation is also embedded within the Statement of Obligations (General) to Victorian Water Corporations that was issued by the Minister for Environment, Climate Change and Water in December 2015. Clause 6-A requires Water Corporations to comply with these guidelines (Minister for Environment, Climate Change and Water, 2015).

The role of the guidelines within directly related water resource programs and planning activities is illustrated in Figure 1. The guidelines feed directly into the *Urban Water Strategy Guidelines* (DELWP, 2020a) for urban Water Corporations to develop a 50-year water supply and demand management strategy. The information in the guidelines also contributed to DELWP guidance notes for the (typically) 12-month supply and demand forecasts in the annual water outlooks by all Water Corporations (DELWP, 2019b; DELWP, 2019c). The information in the guidelines can potentially also help to inform a range of other plans and strategies, including but not limited to Water Corporation annual operating plans and drought preparedness plans. The information presented in these guidelines is compatible with the parallel climate change guidance provided to Water Corporation Board members and executives (DELWP, 2019a). At a national level, the guidelines are consistent with climate change adaptation guidance from the Water Services Association of Australia (WSAA, 2016).

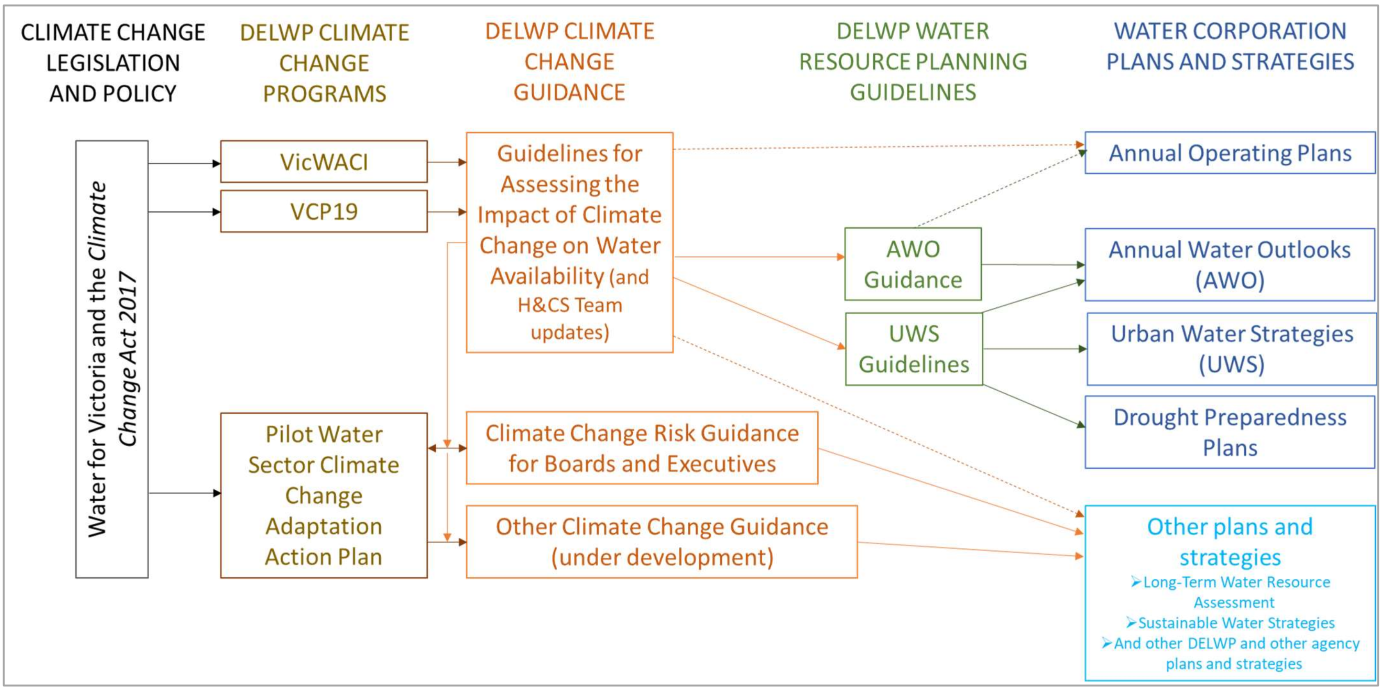

Figure 1 Climate change guidance in the context of Victoria's regulatory and planning framework for water resources

As part of initiatives under Victoria's Pilot Water Sector Climate Change Adaptation Action Plan (DELWP, 2018), other climate change guidance is under development by DELWP. This includes the *Guidelines for Assessing the Impact of Climate Change on Sewerage Systems* (DELWP, in development), which should be referred to for sewerage planning applications, such as the effect of climate change on sewerage generation and sewer infiltration rates.

The guidelines have drawn upon the climate science research generated from Victorian Government funded research under the Victorian Water and Climate Initiative (VicWaCI) and the Victorian Climate Projections 2019 (VCP19) regional climate modelling exercise.

1.1.3 Planning approaches supported by the guidelines

The guidelines provide information on observed historical changes and projected future changes in Victoria's climate. This is just one consideration when undertaking water resource modelling. This section outlines other considerations, and the role of climate change impact assessments within the broader context of Victoria's water planning framework.

Climate change impact assessments take place within a planning and decision-making context and, as such, is a tool to inform those planning and decision-making processes. Climate change impacts are only one of many uncertainties that water resource managers and water users must plan for. Other uncertainties that can be relevant to water resource planning include climate variability, future population change, land use change, technology change, ecosystem behaviour, and changes to the size and nature of local, national and global economies.

The information provided in the guidelines is designed to directly support scenario planning within an adaptive management framework. This approach is embedded within Victoria's water planning framework. For example, for urban Water Corporations, long-term planning actions over a 50-year planning horizon are developed in urban water strategies, but the timing and nature of these actions can be adapted to suit the prevailing climate conditions through an Annual Water Outlook. Similarly, the Long-Term Water Resource Assessment (DELWP, 2020b) and Sustainable Water Strategy process includes regular reviews to consider changes in our understanding of climate behaviour over time. This adaptive management approach is particularly important given the uncertainty in the climate change projections in these guidelines, including uncertainties not only about the magnitude of the impacts, but also about how these impacts may evolve through time (e.g. gradual and/or step change occurring within the context of a highly variable climate).

Climate change is recognised as a problem of "deep uncertainty" (Marchau et al., 2019), and, as such, the guidelines are designed to support other analytical and planning approaches. These other approaches can be utilised, in conjunction with scenario planning, to further assess imminent decisions that are perceived to be at high risk from climate change uncertainty.

The guidelines provide information to support water resource modelling, but they are not water resource modelling guidelines. National and multi-jurisdictional guidance on surface water resource modelling can be found in Black et al. (2011) and Murray-Darling Basin Authority (MDBA, 2019) and on groundwater modelling in Barnett et al. (2012).

The guidelines provide information on observed historical changes and projected future changes in climate variability under climate change. However, the guidelines do not provide prescriptive advice on information and analysis techniques for managing climate variability, other than where they intersect with issues related to climate change. Areas of intersection covered in these guidelines include (see also Section 2.5):

(i) defining climate variability and climate change;

(ii) guidance on the selection of climate scenarios for drought and operational planning that are consistent with the climate reference period assumptions in the guidelines; and

(iii) guidance on suitable methods for extending climate and streamflow reference period information for water resource applications.

For guidance on responding to climate variability for the purposes of urban drought preparedness planning, refer to the *Urban Water Strategy Guidelines* (DELWP, 2020a).

1.2 The process for updating the guidelines

DELWP has developed these guidelines in consultation with existing users of the guidelines, predominantly Victorian Water Corporations. The process began with a review of past applications, which led to the identification of opportunities to improve and clarify existing guidance. A series of discussion papers were then produced, and workshops hosted in 2019 and 2020. Past users have provided valuable input to the guidelines update by articulating user needs and exploring the implications of climate change on effective water planning and management.

1.3 What has changed since the last update?

1.3.1 New science, new policies and lessons learnt from applying the guidelines

Various changes have been made to this update of the guidelines, relative to the previous version (DELWP, 2016a). These include:

- **Lessons learnt from applying the 2016 guidelines** — Water Corporations and other users of the 2016 edition of the guidelines provided valuable feedback on areas for improvement in both formal and informal reviews conducted for the guidelines.
- **New science** — DELWP has drawn upon the latest climate research in preparing the guidelines, which users can refer to for more detailed information. These include:
    - The Victorian Water and Climate Initiative (VicWaCI) and its predecessor research program, the Victorian Climate Initiative (VicCI), which concluded in 2017. Both were Victorian Government funded research programs. The four-year VicWaCI program has operated since 2017 and is conducted by the Bureau of Meteorology (BoM), Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the University of Melbourne. VicWaCI research is focused on the impacts of climate change on Victorian water resources and has delivered new findings to provide stronger evidence about the nature of observed climate change in Victoria. The latest VicWaCI findings are summarised in Section 3 in these guidelines, and are sourced from *Victoria's Climate Science Report 2019* (DELWP, 2019d), *Victoria's Water in a Changing Climate: Insights from the Victorian Water and Climate Initiative* (DELWP et al., 2020), *A Synthesis of Findings from the Victoria Climate Initiative* (Hope et al., 2017), and Hydroclimate projections for Victoria at 2040 and 2065 (Potter et al., 2016), among others.
    - The Victorian Climate Projections 2019 (VCP19), which provide downscaled climate change projections for Victoria from a regional climate model using inputs from a subset of six global climate models (GCMs) (Clark et al., 2019a).
    - A range of other relevant findings from research organisations in Australia and overseas.
- **New legislation and parallel policy development** – Victoria's Climate Change Act 2017 was passed, spawning additional policy initiatives that are related to the guidelines, such as the Pilot Water Sector Climate Change Adaptation Action Plan (DELWP, 2018) and the Guidelines for Assessing the Impact of Climate Change on Sewerage Systems (DELWP, in development); and
- **The Paris Agreement** (UNFCCC, 2016) – The majority of the world's governments have committed to reduce greenhouse gas emissions, which will influence future emissions trajectories. These guidelines draw upon the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (IPCC, 2015), which summarises the latest global climate trends and updated GCM projections, and more recent modelling on the Paris Agreement targets (IPCC, 2018);

1.3.2 DELWP response

DELWP has responded to these changes by updating the guidelines in consultation with Water Corporations and other users of the 2016 guidelines, and by seeking additional information from climate and hydrology research scientists. Key changes to the guidelines to incorporate this new information include:

- **Additional information on a more moderate emissions scenario** (RCP4.5) that would be more consistent with the implementation of emissions reductions under the Paris Agreement, and additional discussion on the suitability of the nominated emissions scenario (RCP8.5) in the context of the Paris Agreement.
- **Clarification of the approach to interpolating GCM projections between now and 2040**. This clarification addresses an information gap in the guidelines. The recommended approach will have the effect of (i) representing current water availability as a range with respect to GCM projection uncertainty from 1995 to date, and (ii) potentially bringing forward actions anticipated to occur over this period prior to 2040.
- **Further discussion of seasonal scaling factors for the climate change projections**. In response to greater certainty about the seasonal nature of observed climate changes to date, and a greater understanding of the seasonal nature of the influences on Victoria's climate into the future, DELWP commissioned CSIRO to provide cool season (April to October) and warm season (November to

March) projections. These projections have been used to generate a plausible range of cool season and warm season rainfall projections for sensitivity testing of planning outcomes.

- **Development of guidance on the impacts of climate change on snow cover**. This was identified as a knowledge gap in the previous guidelines, which has now been addressed with practical advice for alpine catchments.
- **Update of the guidance on the impacts of climate change on peak rainfall and streamflow**. In addition to the design guidance in Australian Rainfall and Runoff (Bates et al., 2019), the guidelines provide additional information from recent climate and hydrology research and advice on how that knowledge can be practically applied for the purpose of modelling peak rainfall and streamflow for water supply purposes.
- **Update of the guidance on the impacts of climate change on groundwater recharge.** Guidance on historic recharge rates from recent studies has been included. Direct and indirect impacts of climate on groundwater resources have also been discussed to inform assessment of availability during periods of drought. The advice provided supports risk-based decision making that is fit-for-purpose for urban groundwater supply systems, without limiting use of more complex assessments for groundwater resources assessments.
- **Additional guidance on assessing shifts in rainfall-runoff behaviour during and after prolonged drought**. The guidelines now incorporate practical advice on additional uncertainty in the runoff projections under climate change, arising from the University of Melbourne research into historical changes in rainfall-runoff behaviour, particularly during and after the Millennium Drought.
- **Additional information that can support alternative impact assessment approaches.** This is in addition to the scenario assessment approach outlined in the body of the guidelines, which is typically applied within an adaptive management framework within Victoria. The additional information includes guidance on supplementary downscaled GCM results for Victoria, and a range of assessment techniques that can make use of this (and related) information.

1.4 What has not changed since the last update?

Some of the fundamental assumptions and approaches of the guidelines have not changed. These include:

- **A post-1975 historic climate reference period**, to which the GCM projections can be applied to generate low, medium and high climate change scenarios.
- **A post-1997 historic climate reference period**, which can be used to project a post-1997 step climate change scenario derived independently of the GCMs. This scenario assumes that the dry conditions experienced since 1997 represent a permanent step-change in climate from that experienced prior to 1997.
- **The presentation of low, medium and high climate change impacts** representing the 10th, 50th and 90th percentile results from the suite of 42 available GCMs.
- **The use of CMIP5 climate change projections** from the Intergovernmental Panel on Climate Change's (IPCC) Fifth assessment report. Projections may be updated after the IPCC publishes its assessment of the next update of global climate modelling (CMIP6). The IPCC sixth assessment report has been delayed by the COVID-19 disruption but is expected to be delivered in mid-2021 to mid-2022.

2. How to Use These Guidelines

2.1 Introduction

These guidelines seek to distil complex climate change science into practical guidance for the Victorian water industry and other water resource planners across Victoria. It is recommended that practitioners read the guidelines in their entirety to gain a broad appreciation of the assumptions being made and their implications for climate change impact assessment and subsequent decision making.

Practitioners with a sound understanding of climate change science or with previous experience (i.e. after your first application) working with this edition of the guidelines may wish to proceed directly to the information needed to apply the guidelines.

The following sub-sections provide a brief how-to guide for accessing items of particular relevance to different user types, including for bulk urban and rural water impact assessment (Section 2.2), integrated water cycle management (Section 2.3) and environmental water management (Section 2.4). The ways in which the guidelines address issues related to climate variability are briefly discussed in Section 2.5.

Climate change science, including the availability of application-ready datasets, is continually evolving. Section 7.1 provides a reference to any emerging updates to the guidelines, and any newly available datasets or research outcomes identified by DELWP to complement these guidelines. It is recommended that practitioners revisit this section prior to undertaking new impact assessments.

2.2 For bulk urban and rural water impact assessment

For bulk urban and rural water supply systems, Figure 2 provides an overview of where to find information in the guidelines of relevance for different aspects of your climate change impact assessment.

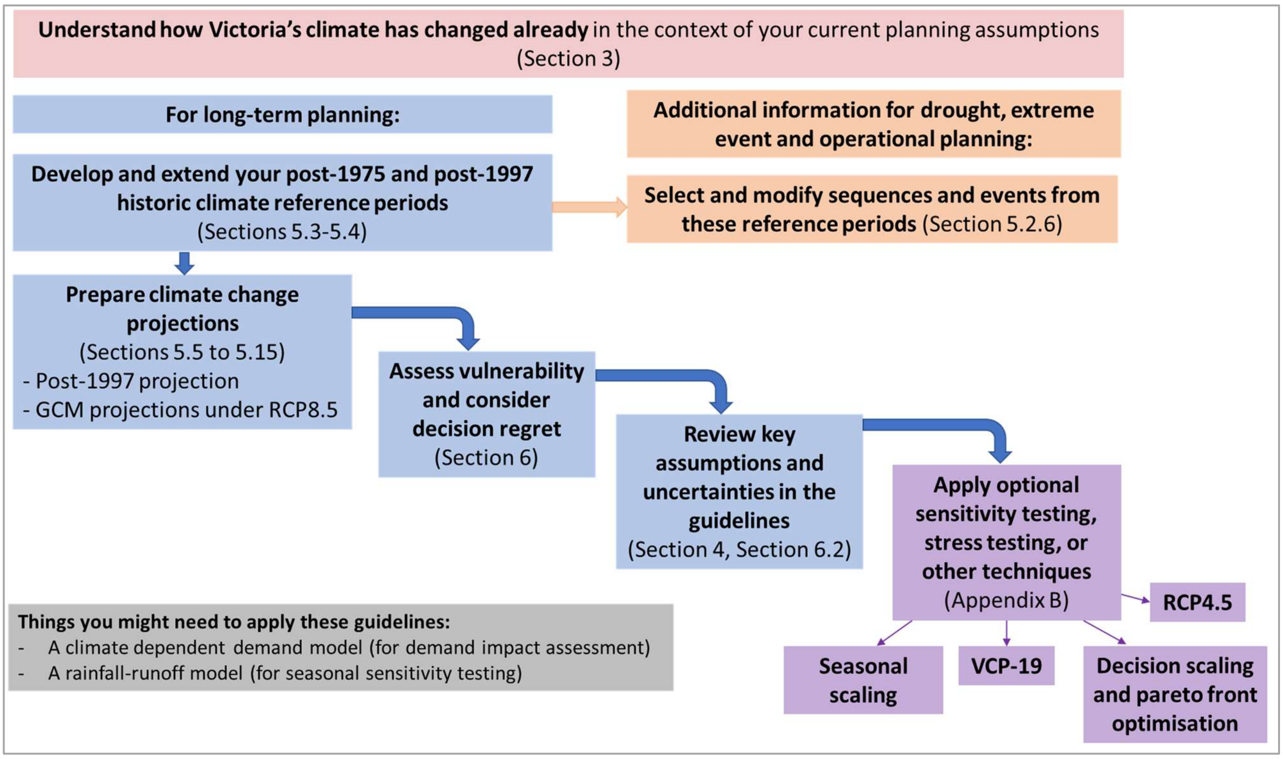

Figure 2 Overview of impact assessment process for bulk urban and rural water supply systems

2.3 For integrated water cycle management

For integrated water cycle management, some additional information in the guidelines can potentially help to refine your water supply impact assessment, in addition to the advice for bulk water supply systems above. This additional advice is highlighted in colour and in bold in Figure 3.

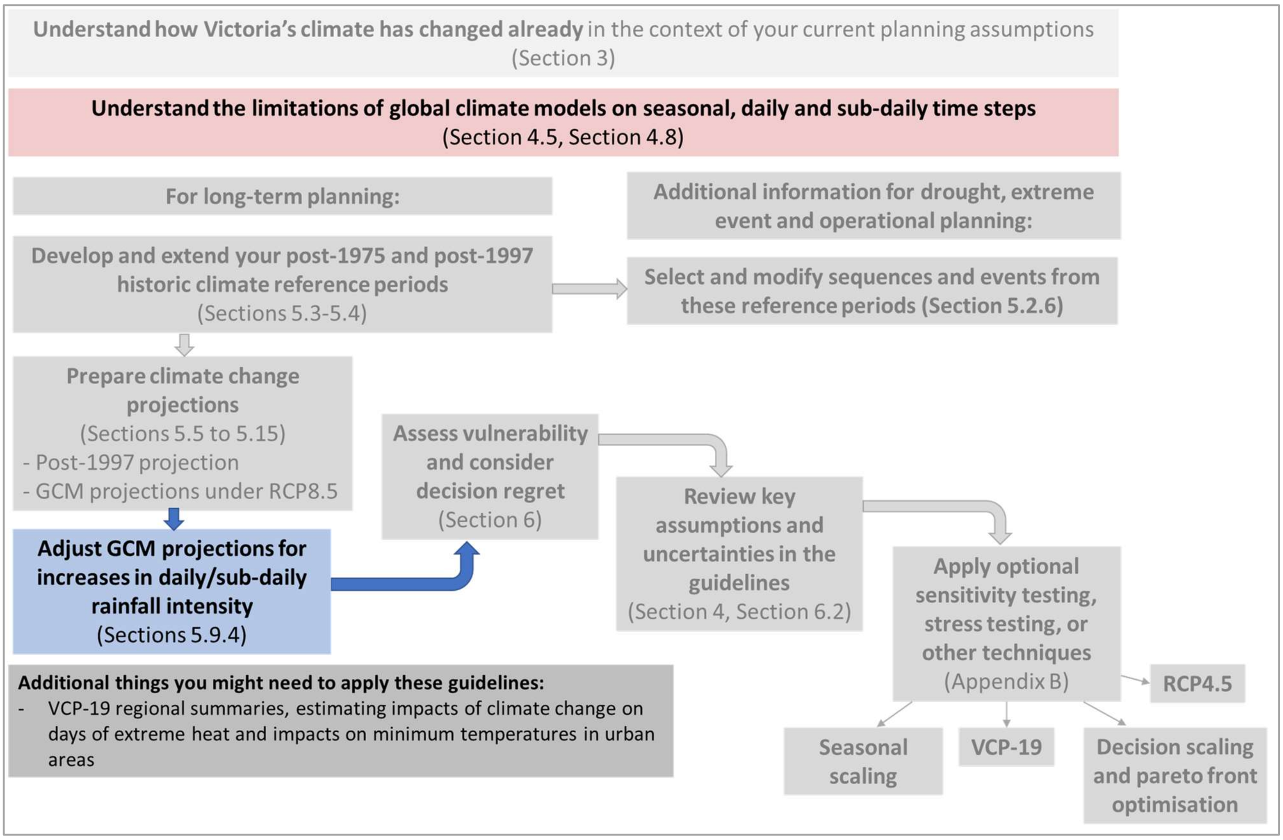

Figure 3 Overview of additional sections of high relevance for integrated water cycle management

2.4 For environmental water management

For environmental water management, some additional information in the guidelines can potentially help to refine your water supply impact assessment, in addition to the advice for bulk water supply systems above. This additional advice is highlighted in colour and in bold in Figure 4.

For environmental water managers, it is no longer recommended that CSIRO's seasonal climate change projections be applied. This advice is replaced by the range of projected changes to cool season and warm season rainfall provided in Appendix B.6.2, which can be used for sensitivity testing to explore the impacts of climate change on seasonal streamflows.

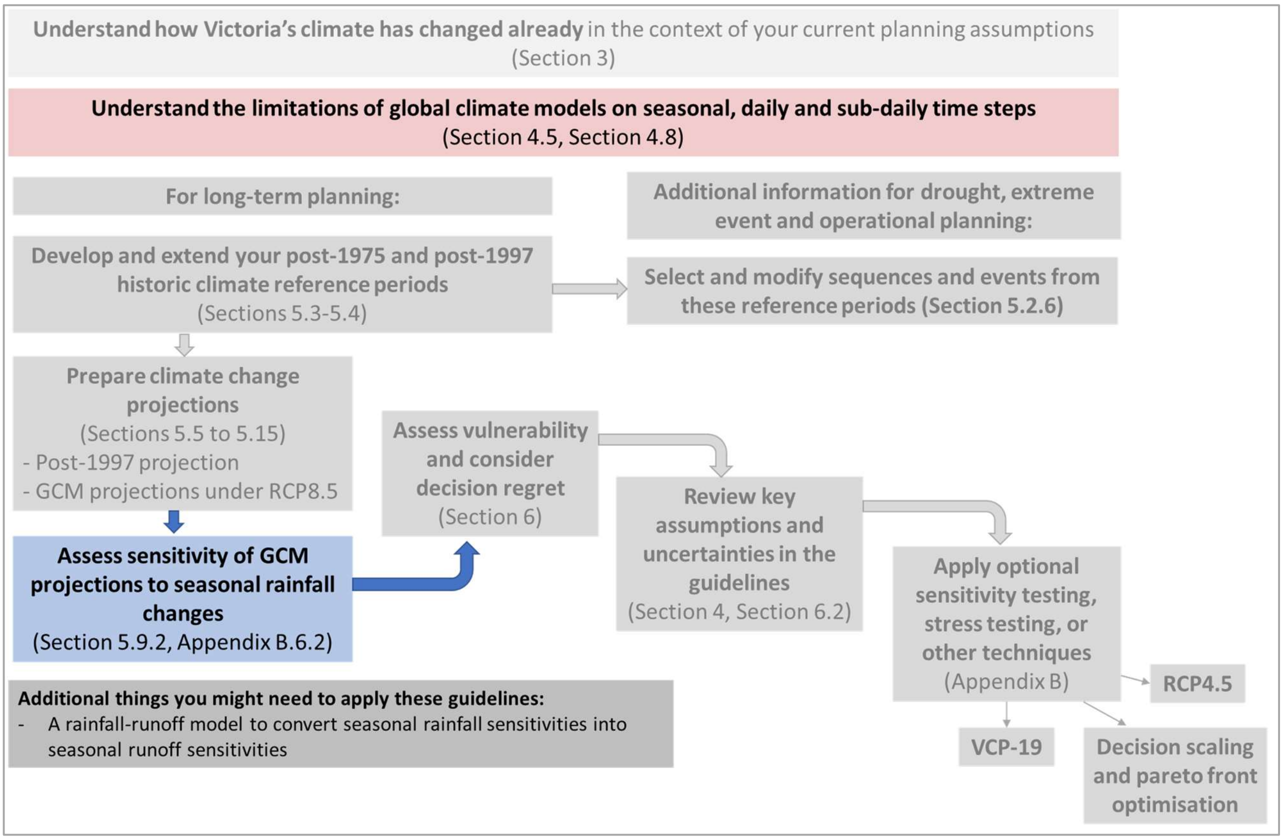

Figure 4 Overview of additional sections of high relevance for environmental water management

2.5 Guidance on climate variability versus climate change

Victoria has a highly variable climate, both spatially across the state, and over time. Climate variability is represented by fluctuations in temperature, evapotranspiration, rainfall and other climate variables on sub-daily, daily, seasonal, annual and decadal time scales. Climate variability can be chaotic or cyclical in nature. For the purposes of these guidelines, natural climate variability is regarded as a phenomenon of the earth's climate system at equilibrium under pre-industrial levels of greenhouse gas concentrations in the atmosphere. In contrast, climate change represents a change in climate behaviour, including changes in climate variability, associated with an underlying shift in the drivers of the Earth's climate system.

The scope of these guidelines is to provide guidance on climate change impact assessment. The scope of these guidelines does not cover how to undertake impact assessment for climate variability, which is addressed in national best practice modelling guidelines (Black et al., 2011; Barnett et al., 2012), the *Urban Water Strategy Guidelines* (DELWP, 2020a) and a long-established best practice through past applications. Climate variability was nevertheless an important consideration in the development of these guidelines and will be an important consideration in their application.

Aspects of climate variability that are covered in these guidelines include:

- Historic changes in climate variability, such as seasonal rainfall shifts, and changes in daily and sub-daily rainfall intensity (Section 3.4).
- Difficulties in attributing observed historical changes in climate to natural climate variability or anthropogenic climate change (Section 4.4).
- Establishment of climate reference periods that capture a wide range of climate variability (Sections 5.2 and 5.3).
- Extension of climate reference periods to capture additional climate variability (Section 5.4), including stochastic data generation methods (Section 5.4.3).
- Projected changes in climate variability, including changes in seasonal, daily and sub-daily behaviour (Section 4, Section 5 and Appendix B.6.2).

Water availability assessments based on historic climate records are unlikely to contain the full range of climate variability that can be expected to occur in Victoria's future. Events that fall outside of the range of climate experienced over the observed record can be experienced in the future, even without the influence of climate change. Stochastic data generation methods can help to expand our understanding of the potential range of climate variability that could be expected.

The extent to which this increased investment in data preparation is warranted will depend upon factors including (i) the ability to communicate the outputs to decision makers and stakeholders, (ii) the likely risk associated with additional climate variability for a given river or supply system and (iii) the ability to reasonably assess desired performance metrics using only the period covered by historical records (e.g. if minimum standards for a given application were to require assessment against say a 1-in-1,000-year drought event, then historical records alone would be unable to reasonably assess performance against this metric). Further discussion of stochastic data preparation methods is provided in Section 5.4.3.

3. Observed Climate Change to Date

3.1 Introduction

Victoria's climate and hydrology has changed over recent decades. This section provides an overview of those changes to set the context for defining and interpreting Victoria's climate change projections (Section 4) and the methods for assessing climate change impacts on water supplies (Section 5). It includes information about observed changes in global greenhouse gas emissions and global air temperature, observed changes in the regional influences on Victoria's climate, observed changes in Victoria's climatology (i.e. the type of rain-bearing and non-rain-bearing weather events), and observed changes in rainfall, runoff, evaporation and recharge.

More detailed information about observed climate change to date can be found in *Victoria's Climate Science Report 2019* (DELWP, 2019d), the *A Synthesis of Findings from the Victorian Climate Initiative* (Hope et al., 2017) and VicWaCI's research synthesis report, *Victoria's Water in a Changing Climate* (DELWP et al., 2020). These reports were the source of information for the following overview.

3.2 Observed global changes in emissions, greenhouse gas concentrations and air temperature

Greenhouse gas emissions continue to increase, but the rate of increase is slowing. Greenhouse gas concentrations today are fundamentally different to pre-industrial concentrations, or anything over the last million years. This was taken into consideration when selecting climate reference periods for the guidelines.

Global greenhouse gas emissions from fossil fuels have continued to increase over time; however, the rate of increase has been slowly reducing, as shown in Figure 5. This is primarily due to slower growth in the use of coal (GCP, 2020). The Global Carbon Project (2020), which is a United Nations funded greenhouse gas emissions tracking project, estimates that emissions have increased on average by 0.9% per year from 2010-2018, compared to an average growth of 3.0% per year in the decade from 2000–2009.

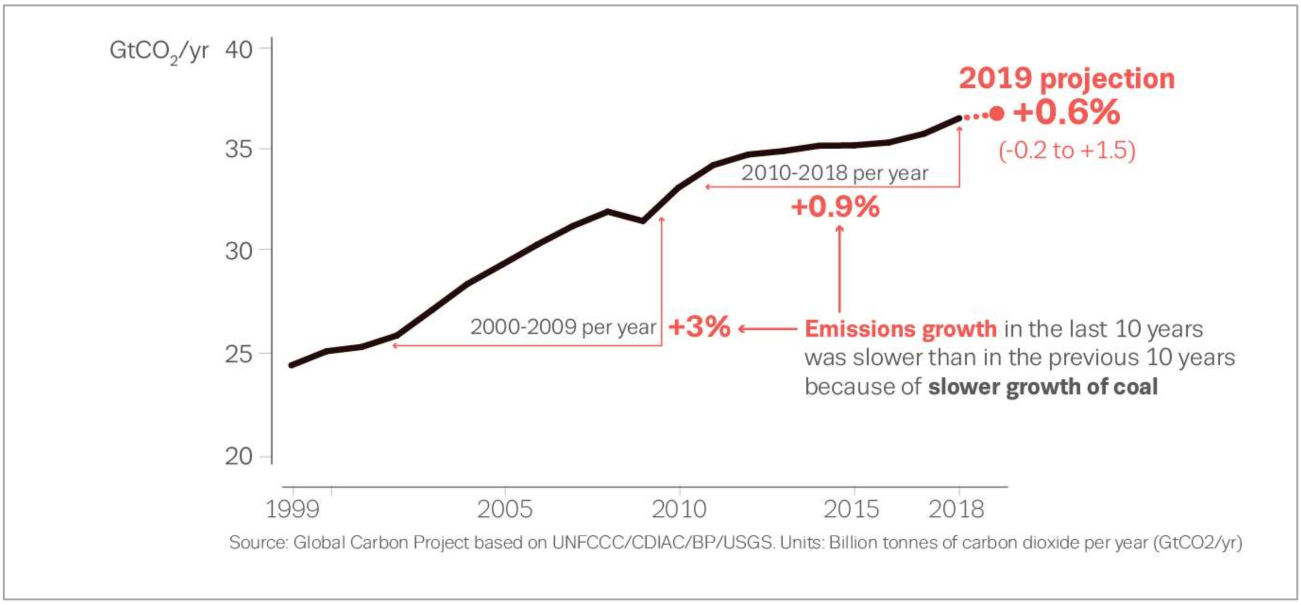

Figure 5 Recent Historical Growth in Carbon Dioxide Emissions from Fossil Sources, as estimated by the Global Carbon Project (GCP, 2020)

Greenhouse gas levels in the atmosphere today are fundamentally different to conditions experienced over the last million years, as illustrated by estimated atmospheric carbon dioxide concentrations derived from ice cores in Figure 6 (NASA, 2020). Fluctuations in greenhouse gas concentrations do occur naturally over many decades; however, current rates of increase and current concentrations are both well outside of the range of estimated values over the last million years. Concentrations of other greenhouse gases, such as nitrous oxide and methane, have similarly increased.

Greenhouse gas emissions can be influenced by events from year to year. For example, the United Kingdom's Met Office (2020) — the equivalent of the Bureau of Meteorology in the UK — forecast in early 2020 that 20% of the projected increase in carbon dioxide emissions in 2020 would be due to Australia's bushfires of that year. Equally, forced lockdowns in many countries of the world during the COVID-19 pandemic have reduced emissions. Le Quéré et al. (2020) found that global emissions at their peak reduction in April 2020 (17% below April 2019 value) were similar to 2006 levels, and if emissions stayed at this level throughout lockdown, the world would meet its Paris Agreement targets. However, Le Quéré et al. (2020) estimate the annual reduction in emissions in 2020 will be much smaller (4–8% below 2019) and do not believe the current reductions are likely to be sustained.

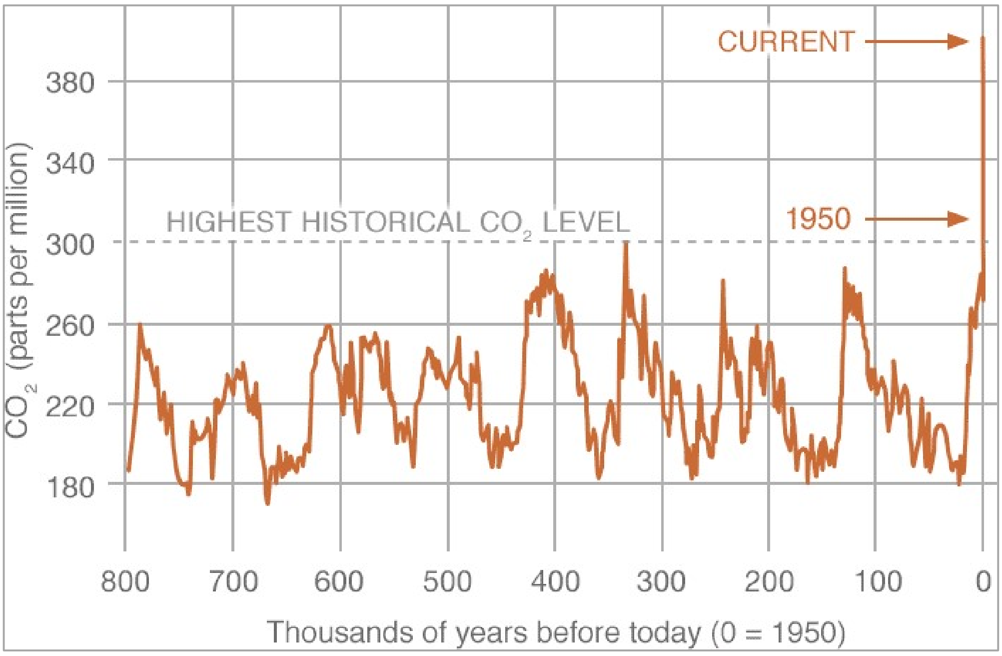

Figure 6 Trends in global atmospheric carbon dioxide over the last 800,000 years (NASA, 2020)

> The global mean temperature for 2019 was 1.1 ± 0.1 °C above pre-industrial (1850–1900) levels. Note that for subsequent chapters, projected changes are expressed relative to greenhouse gas concentrations in the year 1995 (the reference year for the global climate modelling), not pre-industrial levels.

Global air temperature has been trending upwards since the start of the 20th century. The calendar year following the 2015–16 El Niño (2016) was the hottest year on record. Furthermore, most global climate datasets (up to the year 2019) indicate that 2019 was the second hottest year on record (WMO, 2020). The global mean temperature for 2019 was 1.1 ± 0.1 °C above pre-industrial (1850-1900) levels. Observations in Victoria are consistent with those at a global level (DELWP, 2019d). As shown in Figure 7, most of this warming has occurred from the 1970s onwards. In addition to increases in average air temperatures, the frequency of days of extreme heat has increased (DELWP, 2019d), with 24 sites around the State recording their hottest temperature on record in 2019 (BoM, 2020).

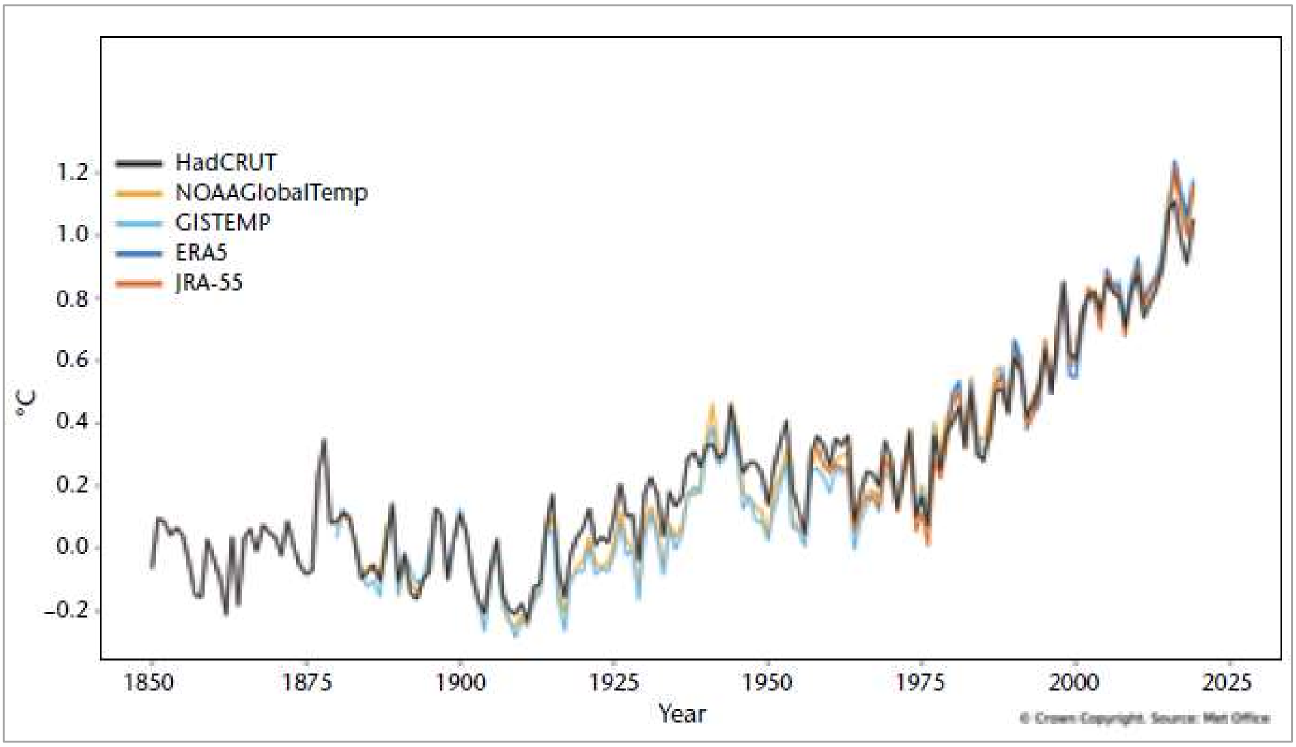

Figure 7 Global annual temperature anomaly relative to pre-industrial (1850-1900) levels, from three observed and two re-analysed datasets (WMO, 2020)

Global and local air temperatures have increased historically as step changes. The identification of past step changes was an important consideration when establishing historic climate reference periods for the guidelines.

Unlike the increases in greenhouse gas concentrations (Figure 6), temperature can be interpreted as exhibiting discrete periods of rapid warming (or steps) followed by periods of stable global temperatures (Figure 7). Observed step changes in temperature for the south-east Australian region include:

- Statistically significant step changes in temperature in 1968 for minimum temperature, and in 1973 and 1997 for maximum temperature (Jones, 2012; Jones and Ricketts, 2017).
- Statistically significant step changes in the relationship between annual maximum and minimum temperature in 1968, 1973 and 1997 (Jones, 2012).
- Statistically significant step changes in the relationship between annual maximum temperature and annual precipitation from 1968–1973 (Jones, 2012).

According to Jones (2012) this behaviour is also evident in GCM outputs, with statistically significant step changes in the modelled climate variables being identified over historical periods. These step-like changes can arise when an underlying trend combines with natural year-to-year variability.

3.3 Observed regional changes in climate influences and Victoria's climatology

Victoria's Climate Science Report 2019 (DELWP, 2019d) describes the factors influencing Victoria's climate and how our climate is shaped by different weather systems, seasonal influences and large-scale climate drivers. The complex interplay of these influences makes Victoria's climate highly variable. At a continental scale, Australia's climate is influenced by atmospheric circulation patterns that transfer excess heat from the tropics to the poles. At the southern end of the continent, Victoria's climate is also influenced by circulation patterns around Antarctica. These circulation patterns are affected by changes in sea surface temperature, wind speeds and pressure in the Indian, Pacific and Southern Oceans (Risbey et al. 2009) and the upper atmosphere over Antarctica (Lim et al. 2019). The behaviour of these variables in each of these regions gives rise to the various climate indicators that can be used to forecast climate conditions in Victoria and to understand longer-term climate variability, including the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM), the Inter-decadal Pacific Oscillation (IPO) and the rare but important sudden stratospheric warmings as seen in 2019.

Various changes in the influences on Victoria's climate have been observed over recent decades. Changes that have been linked to global warming include (DELWP, 2019d):

- A change in the storms that bring rainfall to Victoria in the cooler months of the year (Hope et al., 2015a; Pepler et al. 2020).
- An intensification of the sub-tropical ridge that is linked to drier conditions over Victoria and has an influence on the amount of Victoria's rain associated with the mid-latitude storm track (Grose et al., 2015b).
- An expansion of the Hadley Cell circulation pattern (Nguyen, 2015) that draws warm air from the tropics and delivers it closer to the poles. This expansion is possibly contributing enhanced summer rain (Hope et al., 2017).
- A trend towards a positive Southern Annular Mode (SAM) in winter that has contributed to reduced cool-season rainfall (Hope et al., 2017). SAM describes the north–south movement of the westerly wind belt that circles Antarctica.

The changes in these large-scale circulation patterns are not necessarily gradual. For example, the expansion of the Hadley Cell and associated sub-tropical ridge displayed "abrupt jumps following the major El Niño (ENSO) event of 1997-98 and the major volcanic eruption of Mt Pinatubo in 1991" (Hope et al., 2015b).

Observed changes in the regional influences on Victoria's climate have contributed to observed changes in seasonal and annual rainfall and have been linked to global warming. By improving our understanding of these observed atmospheric changes through recent research, our understanding of both historical and projected climate change has improved.

3.4 Observed local changes in air temperature, evaporation, rainfall, runoff and recharge

Changes in Victoria's climate and water resources have been observed over recent decades. These changes are likely to be a combination of both anthropogenic climate change and climate variability which extends beyond that which has been previously observed. Key changes include:

- Victoria's **annual recorded rainfall** has seen a downward trend from the early 1900s to date, but it is not statistically significant over this period as a whole (Grose et al., 2015a; Timbal et al., 2016).
- Over the past thirty years, there has been a decrease in **cool season rainfall** (defined as April to October for Victoria) (Timbal et al., 2016). This is shown across Victoria in Figure 8. This decrease has persisted after the end of the Millennium Drought, and is consistent with the observed changes in regional climate influences and Victoria's climatology, previously described in Section 3.3. The chance of occurrence of the observed decline in cool season rainfall for the post-1997 period due to natural internal climate variability alone is very unlikely (Rauniyar and Power 2020).
- **Warm season rainfall** has declined in southern Victoria, and remained about the same or increased in central and northern Victoria over the past few decades (see Figure 8).
- Across the state, there have been significant reductions in **annual streamflow** over recent decades (DELWP, 2019d). An analysis conducted in the Victorian Climate Initiative (VicCI) (Hope et al., 2017) found that the declines varied between about 25% and 75% (1997–2014 compared to 1975–1997), with relative declines typically larger in western Victoria, and smaller in the alpine areas;

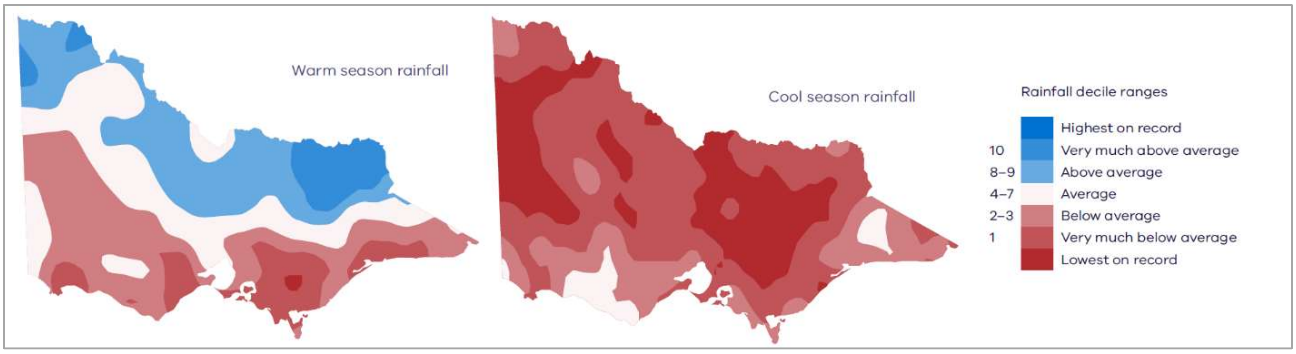

Figure 8 Observed rainfall in Victoria for the last 30 years (1989/90-2018/19) for the warm season (Nov-Mar) and cool season (Apr-Oct) relative to all other 30 year periods in the historical record (source: Bureau of Meteorology in DELWP (2019d).

- Changes in annual rainfall are amplified when translated into changes in **catchment runoff**. Historical declines in Victorian streamflows, particularly over the Millennium Drought, have been well documented (e.g. DELWP, 2019d). By way of example, Figure 9 illustrates this for inflows to the GWMWater headworks, which is an area where streamflow declines have been greater than other parts of Victoria. Inflows into the GWMWater headworks since 1975 have been around 22% lower than the long-term average, and around 56% lower since 1997; only twice within the last twenty years has the long-term annual average inflow been exceeded in this storage system.
- Many catchments in Victoria have exhibited shifts in **rainfall-runoff behaviour** during extended droughts such as the Millennium Drought (Saft et al., 2015; Saft et al., 2016; Fowler et al., 2016; Tan and Neal, 2018). That is, annual runoff is lower during and (in some cases) for many years after drought for a given annual rainfall. This issue is explained in further detail in Appendix B.9, with DELWP's approach to addressing this issue for practitioners in Section 5.10.3.
- **Peak hourly and peak daily rainfalls** across Victoria have increased. For sub-daily durations, this rate of increase is higher than anticipated by increases in the water holding capacity of the atmosphere under higher temperatures (Guerreiro et al., 2018).
- **Peak runoff** may or may not have increased in any given catchment, depending on catchment size, level of urbanisation and the interplay between increases in peak rainfall and decreases in soil moisture (due to lower average rainfall) for a given recurrence interval. Decreases in soil moisture tend to have had a greater influence on peak runoff in rural catchments up to around the 1 in 10-year average recurrence interval event, leading to lower peak flows for common flood events (Wasko and Nathan, 2019). After about the 1 in 40-year threshold, increases in peak flows tend to resemble increases in rainfall intensities.
- **Pan evaporation** data now indicates a stable or increasing trend across southern Australia due to increasing vapour pressure deficits (i.e. decreasing humidity) since the mid-1990s, consistent with increases in temperature and decreases in rainfall over this period (Stephens et al., 2018).
- For groundwater systems, changes in **historical recharge** are influenced by local recharge mechanisms. Where there has been no observed groundwater level response to changes in rainfall over recent decades, direct recharge is very low to negligible. In aquifers connected to the surface, groundwater recharge is a 'threshold' process with a minimum amount of rainfall required to generate any recharge. Empirical evidence in some Victorian catchments indicates that approximately 350 mm/yr of rainfall is required for significant recharge to occur, with some studies suggesting minimum monthly or minimum daily thresholds for given minimum periods. Further information on the conceptual understanding of the impact of changes in rainfall on changes in recharge is provided in Appendix B.10.

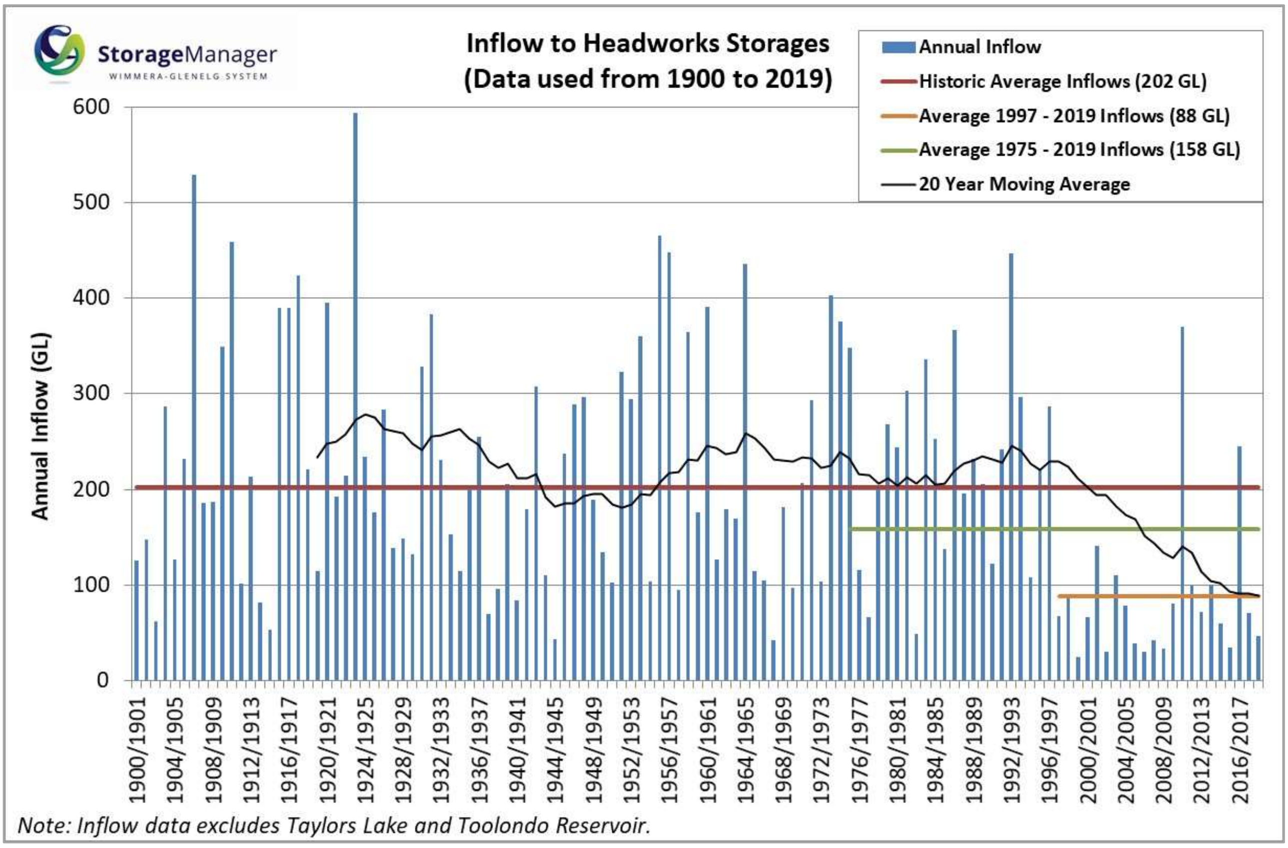

Figure 9 Annual inflows to GWMWater headworks storages (Source: Grampians Wimmera Mallee Water)

4. How the Future Climate Projections for Victoria Were Developed

4.1 Introduction

Projections of runoff and related climate variables were prepared for Victoria's river basins by CSIRO as part of the Victorian Climate Initiative (VicCI) (Potter et al, 2016), with supplementary projections available from the Victorian Climate Projections 2019 (VCP19) project (Clarke et al., 2019a). This chapter provides a brief overview of the modelling approach, including the emissions scenarios adopted, the downscaling approach, the selection of output parameters, and the distillation of the results into three representative climate change projections for each emissions scenario. To ensure appropriate use of these projections, key limitations in their applicability are also discussed. The final projection tables for each river basin in Victoria are subsequently presented in Section 5.

4.2 Overview of climate modelling approaches

4.2.1 Global climate modelling

The earth's climate system is a highly complex set of interactions between not only the sun and the atmosphere, but also between the atmosphere and the oceans, the land surface, the land sub-surface, the natural environment and human activities. The Intergovernmental Panel on Climate Change (IPCC) last collated global climate model (GCM) results from research organisations around the world for its Fifth Assessment Report in 2014 (IPCC, 2015). This set of 42 GCMs is known as the CMIP5 suite of models. Since the publication of the Fifth Assessment Report, these models have been progressively refined and updated, with the assessment of the next round of model results (the CMIP6 suite of models) due for release by the IPCC from mid-2021 to mid-2022. These guidelines, published in 2020, utilise the CMIP5 model results.

4.2.2 Process for deriving climate change projections for the guidelines

The overall process for deriving climate change projections for the guidelines is illustrated in Figure 10.

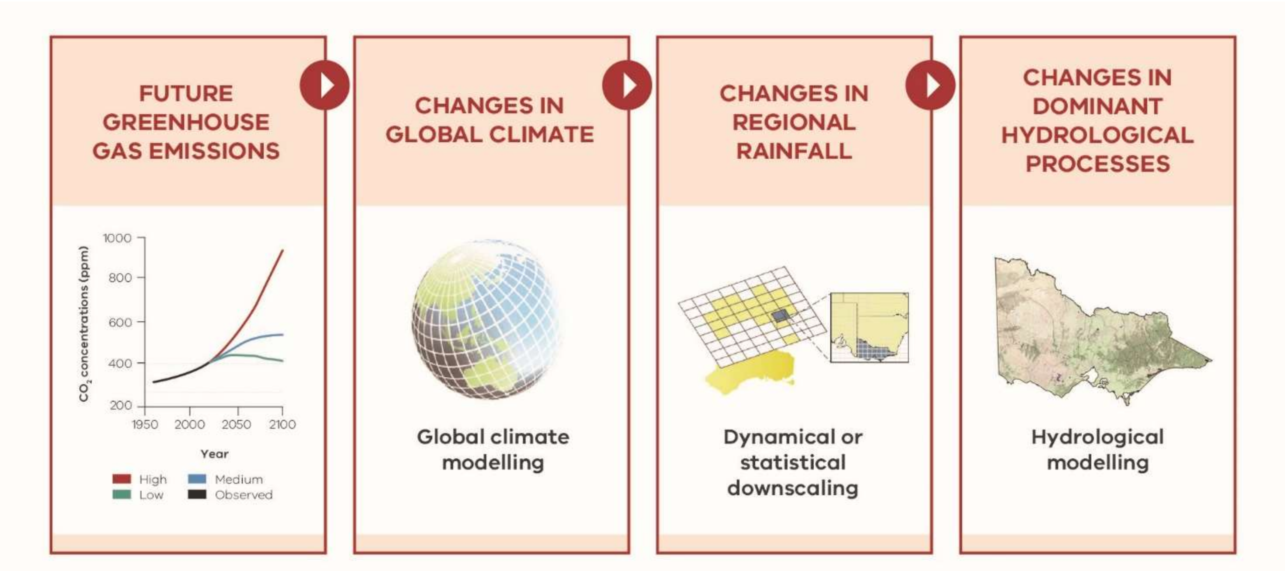

Figure 10 Overview of modelling process to derive climate change projections from global climate models (Potter et al., 2016)

The steps involved in this process are as follows:

1. **Selection of reference climate period and future time slices:** The reference climate period for the global climate modelling was a 20-year climate window over the period 1986–2005, consistent with the reference climate period adopted in the IPCC's Fifth Assessment Report (IPCC, 2015). This period is centred on the year 1995. The two future time slices selected from the GCMs were 20-year climate windows centred on the year 2040 (2031–2050) and year 2065 (2056–2075). These future periods were selected to provide an approximate 50-year planning horizon from 2015 onwards (the

year these projections were developed), and an interim value to explore whether projection trajectories were non-linear.

2. **Selection of an emissions scenario(s):** Representative Concentration Pathway (RCP) scenarios represent plausible changes in greenhouse gas and aerosol emissions and concentrations over time, as well as land use/land cover changes. For water supply planning, these guidelines recommend the use of the RCP8.5 scenario, with the RCP4.5 scenario available for testing the robustness of planning outcomes. The selection of emissions scenarios for the guidelines is discussed in further detail in Section 4.3.
3. **Selection of global climate models:** The range of future climate conditions is derived from the 42 GCMs (the CMIP5 model ensemble) used in the IPCC's Fifth Assessment Report (IPCC, 2015). All 42 models were included in the analysis after extensive consideration of alternative approaches to model choice and sampling. This is discussed further in Section 4.4.
4. **Downscaling of GCM results:** Downscaling provides projections at a finer resolution than that of the output of the GCMs (typical resolution in the order of 200 km x 200 km grid cells). Many techniques exist for this process, ranging from simple scaling to complex dynamical and statistical modelling. The empirical delta scaling method was adopted for the VicCI projections in the guidelines because it is robust, computationally less complex than other methods (allowing consideration of projections from the full range of 42 GCMs), and represents changes in average climate conditions well (Ekström, 2015). In this method, annual and seasonal scaling factors were derived based on output from the GCMs in the selected time periods (differences between future and current time period). For rainfall, a more complex daily scaling, which accounts for changes in the future daily rainfall distribution, was also implemented.
5. **Hydrological modelling:** The SIMHYD rainfall-runoff model was calibrated to 90 unregulated river catchments across Victoria over the period 1975–2014. A 'nearest neighbour' regionalisation method was used to obtain parameter sets for 5 km grid cells to simulate runoff across Victoria. Modelled future runoff (using the above future climate input) was then compared to the modelled historical runoff to estimate the change in future runoff.
6. **Selection of low, medium and high climate change projections for each emissions scenario:** The results from the GCMs with the 10th percentile, median and 90th percentile runoff response to the climate projections were selected in the guidelines to define the low, medium and high climate change scenarios. The median of the model ensemble is the result that is projected to be exceeded by 50% of the 42 GCMs. The 90th percentile GCM result (high climate change) is drier than the 10th percentile GCM result (low climate change). It is important to note that because the 10th and 90th percentiles have been used, there are a small number of GCMs that sit outside of the wet and dry range — so the future may be wetter or drier than the range covered by the low and high scenarios. There is also the possibility that our future might lie outside the modelled range due to limitations in the models, feedbacks that are not modelled, and low-likelihood high impact events such as a major meteorite strike or an on-going global pandemic. These scenarios represent a low, medium and high climate change impact on water availability from climate dependent sources. Projections (10th, 50th and 90th percentiles) can be drawn from different GCMs for different climate parameters and basins. This is discussed further in Section 5.6.2.
7. **Projected changes for each river basin in Victoria:** Results are presented as state-wide maps and tables for each river basin in Victoria in the relevant parts of Section 5.

The VicCI projections are based on all 42 CMIP5 GCM results. GCM outputs have been downscaled using an empirical scaling method, except for runoff impacts, which have been calculated using rainfall-runoff modelling. The 10th, 50th and 90th percentile results are presented at a basin scale in these guidelines as low, medium and high climate change projections.

4.2.3 Regional climate modelling (VCP19)

High resolution stretched-grid climate modelling is an alternative downscaling technique to that adopted in the VicCI projections for the guidelines. This process, known as dynamic downscaling, involves running GCM outputs through a finer scale climate model that incorporates the influence of topography and coastlines on climate behaviour. This potentially has a number of benefits over the downscaling method used for the VicCI projections. These include capturing changes in variability in the projected climate, and a better understanding of local climate behaviour, particularly in alpine areas.

The Victorian Climate Projections 2019 (VCP19) utilised the CSIRO Conformal Cubic Atmospheric Model (CCAM) to dynamically downscale projections to a 5 km resolution across Victoria. These projections were released in October 2019 (Clarke et al., 2019a). A primary justification for preparing the projections was to extend Victoria's climate change projection information by utilising an approach that was different to the downscaling approach used in the VicCI projection modelling. Other reasons for developing an alternative set of projections were to output additional climate parameters not directly related to water resources, and to potentially gain insights into climate projections at a local scale after considering the effects of local mountain ranges. A brief comparison of the key features of VCP19 relative to the VicCI projections is presented in Table 1. The key differences are:

- The VicCI projections present a range of outputs after considering the outputs from all 42 available CMIP5 GCMs, but the VCP19 projections only utilise six of those 42 GCMs. These six GCMs were chosen to represent a range of projected changes in temperature and rainfall, as well as having realistic representations of large-scale drivers of the Australian climate, but they do not cover the full range of available projections in each river basin, as explored further in Appendix B.2.1.
- The VCP19 projections provide a range of other outputs not directly related to water supply impact assessment, in addition to those available from the VicCI projections.
- The VCP19 projections represent changes in daily, monthly, seasonal and annual climate behaviour and variability, whereas the VicCI projections only present annual (and seasonal) projected changes (although changes in the daily rainfall distribution are accounted for in the modelling).
- The VCP19 projections extend over a longer time period, up to 2090, given their potential use in other applications beyond a 50-year planning horizon, whereas the VicCI projections only extend to 2065.

Table 1 Comparison of VCP19 and Victorian Climate Initiative (VicCI) Guideline Projections

Projection Feature	VCP19	VicCI
Global Climate Models	Subset of 6 GCMs from the suite of 42 CMIP5 GCMs.	10th, 50th and 90th percentile projections from the suite of 42 CMIP5 GCMs.
Emissions Trajectories	RCP4.5, RCP8.5.	RCP4.5, RCP8.5.
Downscaling and bias correction	Downscaled to 5 km grids using a dynamic downscaling model. The VCP19 application-ready datasets apply percentile-percentile scaling to AWAP data from 1980–2010 for bias correction.	Statistical downscaling using empirical delta scaling.
Parameters	Mean, maximum and minimum air temperature (average and extreme), rainfall (average and extreme), relative humidity, potential evapotranspiration, wind speed, solar radiation and days above/below temperature thresholds.	Average annual rainfall, average annual potential evapotranspiration, average annual temperature, average annual runoff, average annual recharge.
Temporal scale	Time series of bias corrected data provided on a daily, monthly, seasonal and annual time step in the application-ready datasets. Bias-corrected time slices at year 2030, 2050, 2070 and 2090. Raw model outputs also available over simulation period from 1960 to 2100 for advanced users.	Data provided as average annual (and seasonal) projections. Time slices of change at year 2040 and 2065 relative to 1995.

When using the application-ready datasets available from VCP19, it is important to note that these datasets were bias-corrected using a percentile-percentile scaling method. That is, application-ready data was derived using a percentile-percentile scaling approach on a time-slice of observed data to reproduce the changes in the probability distribution projected by the CCAM simulations relative to the baseline period. Hence the application-ready datasets will still have, for example, the same number of rain days, and the same timing of extreme temperature days, as the observed data. The Climate Change in Australia website, which houses the VCP19 datasets, advises against using the raw outputs without applying bias correction.

The VCP19 projections offer some additional insights into projected climate change behaviour in Victoria. Notably, these include projected enhanced drying on the western windward slopes of mountain ranges (notionally above 1,000 metres elevation) and the effect of climate change on urban heat islands. However, the VCP19 projections also have a number of shortcomings, such as a significant warm bias along the east coast of Victoria, poorer representation of mean sea level pressures than their host GCMs, and an over-estimation of wind speeds in winter for a given level of pressure (Clarke et al., 2019a).

These guidelines support the use of VCP19 projections to gain additional insights for specific water planning applications (e.g. in alpine areas and for examining projected changes in urban heat islands), and for use in sensitivity testing of streamflow characteristics or supply system performance to climate change projections at a very local (finer than river basin) scale or outside the range of VicCI projections.

Other regional climate modelling results were also considered for their potential use in the guidelines but were not considered to offer significant benefits for most applications. Appendix B.2 provides further references for these other downscaled datasets and their potential use in additional stress testing of water supplies.

4.3 Emissions scenarios and the Paris Agreement

Introduction to Representative Concentration Pathways (RCPs)

A key input to GCMs are greenhouse gas concentrations scenarios, which are developed from scenarios of greenhouse gas, Antarctic ozone and aerosol emissions and concentrations over time, as well as land use/land cover changes. These factors provide the drivers for change in climate response in the models. The IPCC Fifth Assessment Report provides four such scenarios, known as representative concentration pathways (RCPs) (IPCC, 2015). For ease of communication, “emissions scenarios” is sometimes used within these guidelines to describe RCP scenarios.

RCP scenarios are labelled according to their assumed radiative forcing in the year 2100. For example, the RCP8.5 trajectory assumed a radiative forcing of 8.5 W/m^2 in the year 2100, while the RCP2.6 trajectory assumed a radiative forcing of 2.6 W/m^2 in the year 2100. Recent (2019) radiative forcing is estimated to be approximately 2.6 W/m^2 (IPCC, 2018).

RCP8.5 is the highest concentration scenario of the four RCP scenarios available (Figure 11). It is broadly described by the IPCC as “a scenario with very high greenhouse gas emissions […] without additional efforts to constrain emissions” (IPCC, 2015). RCP2.6 was described as a stringent mitigation scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures, while RCP4.5 and RCP6.0 are described as intermediate concentration scenarios between these two bookends. RCP2.6 is broadly consistent with the goals of the Paris Agreement (UNFCCC, 2016) to hold the increase in global average temperature to well below 2°C above pre-industrial levels and also pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

Our understanding of climate change is continually improving, but the future climate remains uncertain. For this reason, Victorian water resource planning needs to consider a range of possible future climate conditions, reflecting a range of potential emissions trajectories. From the four available RCP scenarios presented in the IPCC’s Fifth Assessment Report, these guidelines have adopted the RCP8.5 scenario for water supply impact assessment, with projections for the RCP4.5 scenario provided for optional sensitivity testing.

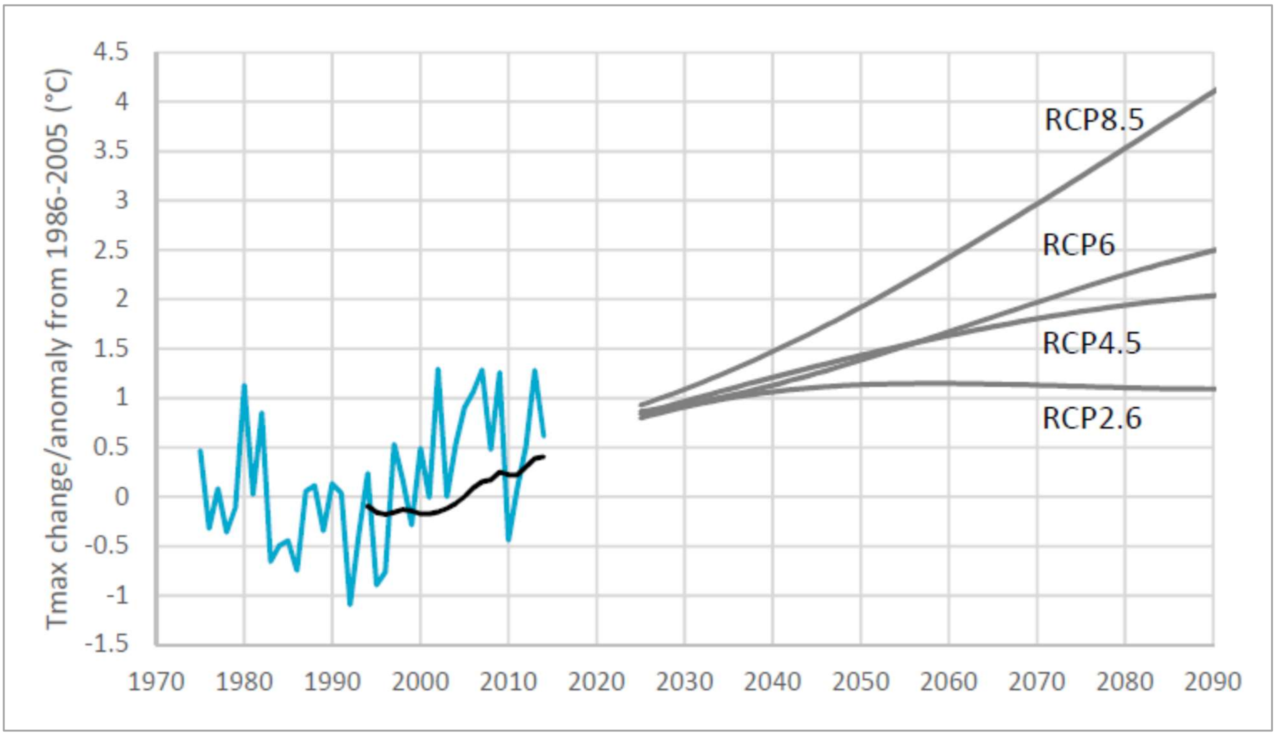

Figure 11 Temperature projections across the whole of the Murray-Darling Basin (Potter et al., 2016). Observations are shown in blue with a 20-year trailing moving average shown in black (i.e. the last value of the black line represents the average of the last twenty years of the blue line).

RCP8.5 scenario for water supply impact assessment

The following information was considered in adopting the RCP8.5 scenario for water supply impact assessment.

- Due to the lag in response between global greenhouse gas concentrations and the global temperature response, **different emissions scenarios do not result in substantially different temperature projections (and hence rainfall and runoff projections) over the near-term**. For example, Figure 11 indicates that all RCP scenarios generate a similar temperature response up to around 2030, in which case RCP8.5 is representative of all scenarios up to this point.
- The RCP8.5 scenario generates both the wettest and driest projections for Victoria under the range of GCM results, and therefore **encapsulates a broader range of both wet and dry outcomes** than other emissions scenarios for assessing the robustness of planning decisions (Potter et al., 2015).
- Depending on the parameter of interest, RCP8.5 has approximately **double the number of GCM simulations** available relative to RCP6.0 (CSIRO and Bureau of Meteorology, 2015) and will therefore capture a broader range of possible outcomes for the given emissions scenario.
- When GCMs that perform less well over southern Australia (based on four particular model criteria) are excluded from modelling results, this tends to remove the wettest projections, thereby increasing the likelihood of a drier climate future for Victoria relative to the full suite of results (Grose et al., 2017). See also Section 4.4.
- Since the mid-1990s, surface air temperature projections and wet season (Apr–Nov) rainfall projections for Victoria have both been tracking along the warmest and driest GCM projections (Clarke et al., 2019a; DELWP, 2019d), as shown in Figure 12, notwithstanding the influence of natural climate variability over this period.
- The VCP19 regional climate model projections suggest that projected temperature change could be higher than estimated in some GCMs, particularly over spring and summer, due to enhanced response of the land surface to drying compared to that in low resolution GCMs (Clarke et al., 2019a).

- There is a possibility of climate change feedback loops that further enhance global warming and which are not explicitly accounted for in the GCMs. The increasing frequency of major bushfires in Australia and its impact on global greenhouse gas emissions has been cited as one example of such a feedback loop (Mann, 2020).
- While preliminary in nature, early indications from the raw results from the CMIP6 suite of global climate modelling suggests that some of the updated models tend to be producing warmer outcomes than their equivalent CMIP5 versions (Hausfather, 2019), although the two sets of results may become consistent when the CMIP6 model outputs are constrained to better match observed warming to date (Tokarska et al., 2020).

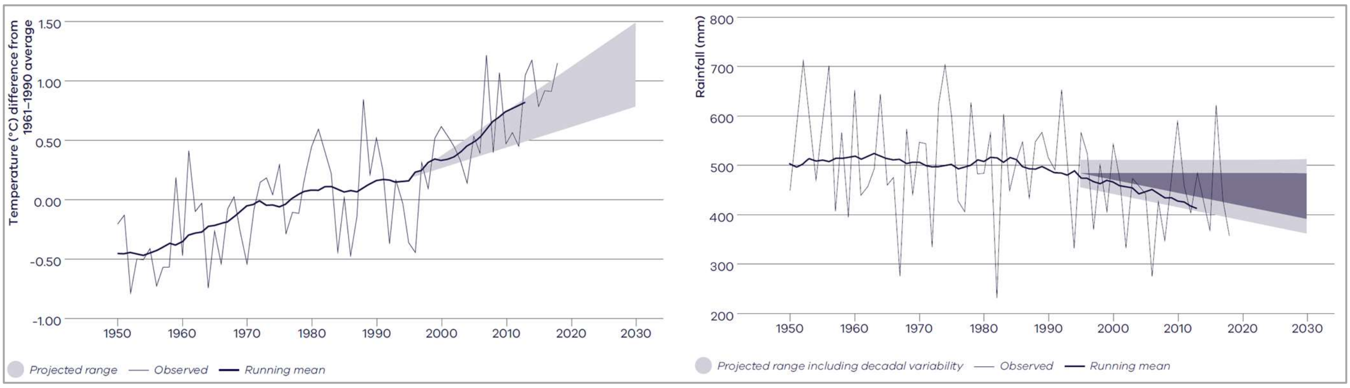

Figure 12 Comparison of observed annual temperature (left) and April to November rainfall (right) for Victoria relative to GCM projections (shaded area) for all emissions scenarios (DELWP, 2019d). Bold line is a running twenty-year average of observations.

These guidelines adopt the RCP8.5 scenario for water supply impact assessment. The RCP8.5 scenario encapsulates a broad range of wet and dry projections, allowing for robust decision making, and is precautionary in nature, which is appropriate considering GCM uncertainty.

RCP4.5 scenario for optional sensitivity testing

The following information was considered in recommending the RCP4.5 scenario for optional sensitivity testing:

- RCP4.5 generates a similar temperature response to RCP2.6 and RCP6.0 until around 2040 (and hence is representative of both achieving and not achieving the Paris Agreement targets). In some river basins of Victoria, the high climate change projections for rainfall for the year 2040 under RCP4.5 are greater than under RCP8.5, again re-enforcing that these two projections are not materially different up to the year 2040 in the context of GCM uncertainty. Up to around 2065, RCP4.5 generates a similar temperature response to RCP6.0 and is therefore representative of all available emissions scenarios involving moderate greenhouse gas mitigation.
- The only emissions trajectory not covered by RCP4.5 and RCP8.5 is therefore for the period after 2040 under a scenario where the Paris Agreement targets are met by mid-century (i.e. without overshooting the target and coming back to it by the end of the 21st century). However, the United Nations Environment Programme's *Lessons from a decade of emissions gap assessments* report (Christensen and Olhoff, 2019) concluded that even current commitments under the Paris Agreement, let alone actual progress towards their realisation, are insufficient to limit global warming to either 1.5^{o}C or 2.0^{o}C by the end of the 21st century.
- Depending on the parameter of interest, RCP4.5 has approximately double the number of GCM simulations available relative to RCP2.6 and RCP6.0 (CSIRO and Bureau of Meteorology, 2015) and will therefore capture a broader range of possible outcomes for the given emissions scenario.

These guidelines recommend the RCP4.5 scenario for optional sensitivity testing. The RCP4.5 scenario represents moderate rates of greenhouse gas emissions broadly consistent with greenhouse gas reduction commitments by the world's governments, up to 2040.

4.4 Which global climate model is the best for Victoria?

Rainfall and runoff under current greenhouse gas concentrations could be either over- or under-estimated, depending on which GCM from the available ensemble is the most correct. While we know the historical temperature trajectory, it is difficult to separate the influence of historical climate variability and historical anthropogenic climate change on observed changes. If there were no natural climate variability since the mid-1990s, then Figure 12 (in the previous section) would suggest that the models that generate the driest projections are the most accurate for Victoria. However, we know that Victoria's climate is highly variable, and that the Millennium Drought, in large part, was a manifestation of that natural climate variability. This is because wetter years have occurred since the end of the Millennium Drought.

Hope et al. (2016) reported on the evaluation of model performance of 41 GCMs based on a range of evaluation criteria including the ability of models to simulate current climate and to capture the behaviour of key climate influences. The analysis highlighted that models that do well on some criteria do not necessarily do well on others and that there is no easy way to select a set of "best" models. Although there clearly are a number of models that are more consistently "poor" performers. The systematic removal of poorly performing models has the potential to shift the ensemble projected rainfall mean.

Grose et al. (2017) reported that after excluding GCMs (from the suite of 42 GCMs) that clearly do not reflect four key changes in observed climate features since 1995 (e.g. sub-tropical jet stream behaviour, Southern Ocean storm track behaviour, etc.), projected rainfall increases for southern Australia by the end of the 21st century are less likely than indicated by the whole GCM ensemble. Grose et al. (2017) also noted that because all of the currently utilised GCMs under-estimate the southward movement of the sub-tropical ridge of high pressure across Australia, all models may under-estimate the impact of anthropogenic forcing on projected drier rainfall conditions in southern Australia. Rauniyar and Power (2020) found that all these GCMs underestimate both interannual and decadal observed rainfall variability during the cool season. These conclusions suggest that the GCMs that project a drier future for Victoria are more likely to be accurate.

These examples (Hope et al. 2016; Grose et al., 2017) and other examples within the literature (e.g. CSIRO and Bureau of Meteorology, 2015) highlight that different assessment criteria can lead to the exclusion of different models.

We know that some GCMs represent the systems linked to Victoria's rainfall better than others. However, we don't know which GCM is the most accurate, so the guidelines draw from all available 42 GCMs to present a range of climate change projections.

4.5 Seasonal versus annual global climate model projections

When considered in isolation from the projected annual changes in rainfall, seasonal changes in rainfall display a distinct spatial pattern, as shown in Figure 13. This figure displays projected 10th, 50th and 90th percentile cool and warm season changes across Victoria for RCP8.5 in the year 2065. These results are drawn from the full suite of 42 CMIP5 GCMs. Similar patterns are shown for the four seasons in Potter et al. (2016) for a wider range of time slices. Trends in projected changes in seasonal rainfall are further described in Hope et al. (2015a).

When the spread of projections for any given season is considered in relation to the other season(s) and the annual projections, it becomes apparent that there is no consistency in the magnitude (and in some cases the direction) of cool season changes relative to warm season changes. This is illustrated in Figure 14, using the Werribee Basin as an example. In this figure, for models with a projected annual change similar to the median model estimate, it can be seen that the warm season change could be higher or lower than the annual change, depending on which model is selected. This is similarly the case for the 10th and 90th percentile annual changes. For Victoria, the cool season is assumed to run from April to October and the warm season is assumed to run from November to March.

When considering whether to provide tables of seasonal rainfall projections in the guidelines, consistency with the annual projections was regarded as a high priority. This would ensure that any application of the seasonal projections would generate results that are consistent with those applied using the annual projections. It was found that this was not currently possible because:

- When selecting seasonal scaling factors independently of annual scaling factors, the 10th percentile projection for each season is often sourced from a different GCM than that which generates the 10th percentile annual projection. Similarly, when selecting seasonal scaling factors independently from each season, the 10th percentile projection for one season is often sourced from a different GCM than that which generates the 10th percentile projection in another season. Therefore, adopting the 10th and 90th percentile seasonal projections would result in more extreme annual values when compared against the equivalent annual projection (but the median projection would be similar).
- When selecting seasonal scaling factors from models that generate the annual projected changes in any given river basin, the projected seasonal changes are not spatially consistent. This is because different GCMs can generate quite different seasonal changes, and the GCMs that generate the 10th, 50th and 90th percentile models can be different in each river basin.
- The seasonal scaling factors are not consistent in any given river basin for small tolerances in the projected annual change. That is, if say the GCM that generates the 85th percentile annual change was adopted instead of the GCM that generates the 90th percentile annual change, the projected seasonal changes from these two models could be quite different, despite having similar annual projected changes.

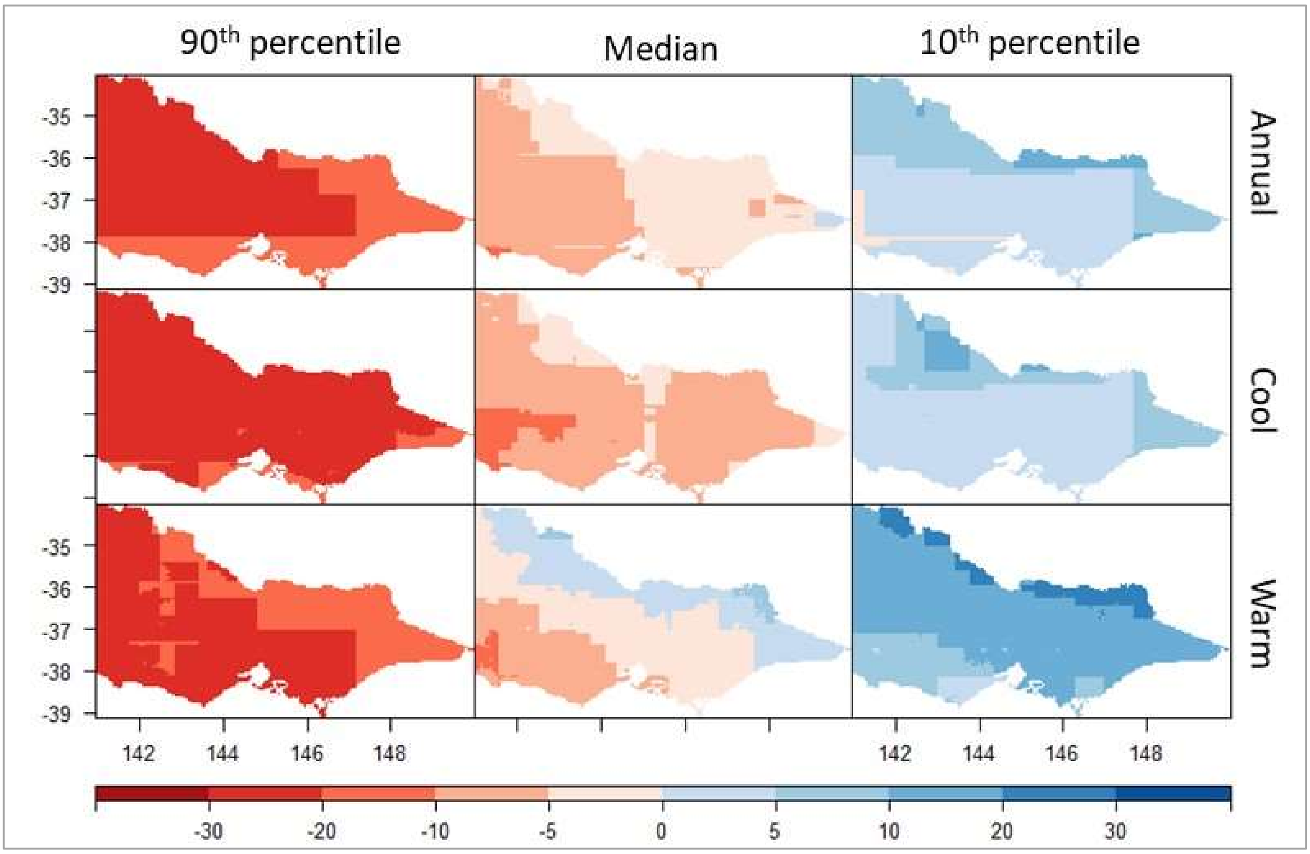

Figure 13 Projected 10th, 50th and 90th percentile cool and warm season rainfall changes (% change from 1995 value) across Victoria for RCP8.5 in the year 2065 (source: CSIRO)

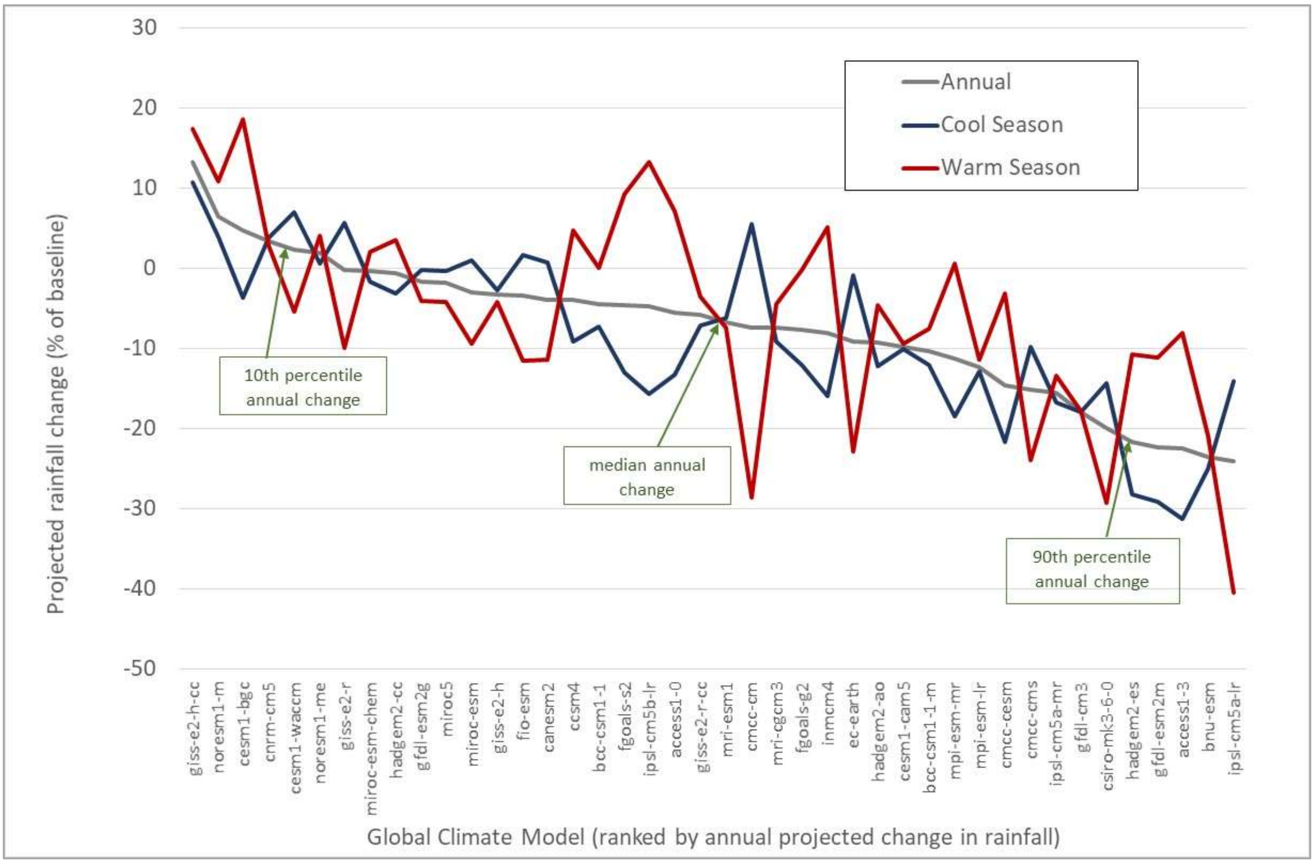

Figure 14 Projected change in cool and warm season rainfall for the Werribee Basin by ranked global climate model, RCP8.5 for the year 2065 (Source: data provided by CSIRO in 2020, based on analysis for Potter et al, 2016).

In consideration of the above, Appendix B.6.2 provide seasonal scaling factors for testing the **sensitivity** of the impact assessment to potential seasonal changes in climate.

The consistency of seasonal and annual projections will be revisited when the next round of global climate modelling results (CMIP6) are released.

4.6 Spatial resolution of GCM projections

Projected changes in climate and runoff are provided in these guidelines for each Victorian river basin. They are considered appropriate for use at this scale for water supply planning purposes in most Victorian water supply systems. This spatial resolution of the adjustment factors may be considered too coarse for some applications. However, the use of finer scale information may imply false precision in its accuracy, as indicated in the *Victorian Climate Initiative Annual Report 2014-15*, which concluded that (Hope et al., 2015b):

> *"When conducting impact studies, users should recognise that the apparent precision in currently available relatively fine-resolution (in time and space) data sets does not necessarily imply a 'better' answer, but rather only provides one realisation of all possible outcomes."*

If finer spatial resolution in the GCM projections is desired by practitioners for a given application, two options are available. These include (i) processing the VicCI downscaled projections, which are available at a 5 km by 5 km grid size, for your area of interest or (ii) processing the bias corrected VCP19 application-ready datasets, which are also available at 5 km by 5 km grids, for your area of interest. Both options potentially involve significant additional processing time and expense, relative to utilising the readily available information at a river basin scale in the guidelines. Preliminary details on the opportunities and challenges in bias correcting VCP19 outputs for hydrological applications, and comparison of rainfall and hydrologically modelled runoff projections with VCP19 against the VicCI projections, can be found in the VicWaCI's *Victoria's Water in a Changing Climate* report (DELWP et al., 2020), Potter et al. (2020) and Charles et al. (2020).

As noted previously in Section 4.2.3, the VCP19 projections are only available for a subset of six GCMs, so would still need to be interpreted in the context of the broader suite of GCM model results. Further guidance on how climate change adjustment factors can be generated for regions other than river basins is provided in Appendix B.3.

4.7 Selection of output parameters

Parameters output from the VicCI climate change projections for use in these guidelines were average annual temperature, average annual potential evapotranspiration, and average annual rainfall, with downscaled outputs run through rainfall-runoff models to project changes in average annual runoff. Projected changes in groundwater recharge are inferred from projected changes in rainfall and runoff. These datasets have been selected because they are the datasets of most direct relevance to water supply and river system behaviour.

A range of other datasets are available from the VCP19 downscaled datasets, as previously listed in Table 1 in Section 4.2.3, which may be useful for niche applications. For example, days with air temperature above and below particular thresholds could be useful for the management of peak daily demands in water supply distribution systems, or for asset protection.

4.8 Global climate model limitations

GCMs are the best tools available for projecting changes in climate resulting from increases in greenhouse gas concentrations. There is a high level of confidence associated with GCM projections of increases in temperature; however, the level of confidence about the nature and magnitude of projected changes decreases for other variables (rainfall, potential evapotranspiration and runoff), and at finer temporal and spatial scales.

As stated in Section 4.2 and in the associated technical report (Potter et al., 2016), there are a number of assumptions made throughout the modelling process that can generate significant uncertainties in the estimation of future impacts on the regional climate under increased greenhouse gas concentrations. These uncertainties are partly captured in the use of three GCM projections (10th percentile, median and 90th percentile) from the ensemble of 42 models.

The most significant sources of uncertainty in the preparation of global climate modelling results are:

- Uncertainty about how emissions may change into the future. These values depend on many socio-economic factors as well as the feedbacks in bio-physical systems.
- Uncertainty in the representation of climate processes in the GCMs. The 42 GCMs are all considered plausible futures. Shortcomings in all models occur at finer temporal scales, as illustrated when examining seasonal projections. A handful of GCMs perform poorly in some aspects of modelling at a regional scale, as listed in Grose et al. (2015a), Timbal et al. (2015, 2016), Hope et al. (2016) and Grose et al. (2017).
- Uncertainty in the downscaling process. The GCMs operate at coarse spatial scales (typically in the order of 200 km x 200 km grid cells) and downscaling is required to represent these coarse scale climate changes locally. Many different downscaling methods exist with different capabilities of adding regional detail to the coarser resolution GCM output. Thus, different downscaling methods can result in differences in the magnitude of changes projected locally.
- Bias correction methods used to prepare GCM or downscaled output for use by rainfall-runoff models can introduce further uncertainties.
- Uncertainty in the rainfall-runoff modelling process, including calibration uncertainty, the transposition of rainfall-runoff models to ungauged areas, and the potential for bias in rainfall-runoff models when applied outside of their range of calibrated conditions.

Grose et al. (2015a) and Timbal et al. (2015) assessed the level of confidence of a given modelled change in climate conditions from the GCMs. This level of confidence was based on the rating method used in the IPCC's Fifth Assessment Report, whereby confidence in a projected change is based on the type, amount, quality and consistency of different lines of evidence (which can be process understanding, theory, model output or expert judgement). The confidence ratings are described as being low, medium, high or very high. The level of confidence is summarised in Table 2, with an emphasis on the level of confidence associated with projected within-year climate change.

Table 2 Level of confidence in seasonal and daily time step changes in climate from global climate models (GCMs), for water resource planning applications (adapted from Grose et al. (2015a) and Timbal et al. (2015))

Modelled seasonal or daily time step climate change	Level of confidence that this change will occur	Comments
Increase in the temperature reached on the hottest days, the frequency of hot days and the duration of warm spells.	Very High	Confidence in the magnitude of the temperature increase, particularly at a local scale, is low.
Increase in potential evaporation rates in all seasons.	High with regard to direction of change, but medium confidence in magnitude of the change	Potential for increases in the short-term in frosts/frost risk with cool, clear nights (DELWP, 2019d).
Decrease in the frequency of frost-risk days.	High	
Rainfall decreases in winter and spring.	High	Hope et al. (2015b) states that, “there are a number of reasons to expect that projected cool season rainfall deficits may be under-estimated by current climate models, particularly for the winter months”, notably that the models, “do not capture the magnitude of the observed trends in the sub-tropical ridge” that are associated with cool season rainfall changes in Victoria.
Little change in autumn rainfall.	Low for southern Victoria	Grose et al. (2015a) states that substantial decreases in autumn rainfall are also plausible. Timbal et al. (2015) does not specifically comment on the level of confidence in changes in autumn rainfall for northern Victoria.
Intensity of heavy rainfall events will increase.	High with regard to direction of change, but medium confidence in the magnitude of the change	The magnitude of the change cannot reliably be projected as some smaller scale processes associated with extreme events are not well represented by GCMs.
Time spent in drought (rainfall deficiencies) will increase over the course of the 21st century and the frequency and duration of extreme droughts will increase.	Medium	Hope et al. (2015b) states drought durations in the GCM outputs over the 21st century are all shorter than the Millennium Drought.

Of relevance to water resource planning in Victoria are projected changes to prolonged droughts such as the Millennium Drought, which recently tested the state’s water supply system performance. When looking at modelled future long-duration droughts, Hope et al. (2015b) note that the Millennium Drought recorded 121 months without any ‘wet’ months, and that GCMs, “do not capture spells of this duration; nor do they indicate any likely change in frequency of these prolonged no 'very wet' month spells over the coming century.”

Projected changes at a daily time step are dependent upon the downscaling technique applied. The spatial downscaling technique applied by CSIRO for these guidelines (Potter et al., 2016) has the advantage that it is robust, computationally less complex than other methods, and represents changes in average climate conditions well (Ekström, 2015). However, because it involves scaling a historical dataset, it assumes no changes to the number or sequencing of rain days under future climate change.

With respect to projected daily and seasonal changes, this overview of model limitations makes the following conclusions:

- The projected changes reasonably reflect changes in rainfall intensity identified in the GCMs, particularly the increase in intensity for higher rainfall events. However, there is still a wide range of uncertainty in the projected changes from the GCMs.

- The projected changes do not reflect changes in the number of rain days and/or their sequencing, which can be important for understanding changes to within-year drought severity and duration and multi-year drought and variability.
- There is considerable variance in seasonal rainfall projections for any given annual rainfall projection. The magnitude of changes in cool season (Apr–Oct) rainfall may be under-estimated (since GCMs tend to underestimate trends in key climate influences relative to recent observations) and the projected negligible change in autumn rainfall does not match the significant declines recently observed.

It is important to re-iterate that the modelling approach used by CSIRO utilises the latest GCM results and utilises them to create locally relevant information in a robust manner that has been peer reviewed. Model limitations reflect the considerable challenges faced by climate scientists and hydrologists in making projections about our future climate and water availability. These limitations of the model projections need to be recognised during their application. In the case of within-year climate changes, the model projections do not yet provide all the information needed by water resource managers in Victoria at a suitable level of confidence.

GCMs are the best tools available for projecting changes in climate resulting from increases in greenhouse gas concentrations. There is a high degree of confidence in projected annual changes in near-surface air temperature and potential evapotranspiration; however, greater uncertainty exists for the projection of rainfall.

5. Climate Change Impact Assessment

5.1 Introduction

This section presents the procedures and reference information for assessing the impact of climate change on water availability and demands. This guidance is applicable to water supply systems and river systems at local and regional scales. An overview of the impact assessment process is presented in Figure 15.

A: Creating reference period conditions	
1. Select your climate reference periods (Section 5.3)	Post-1975 for near-term and long-term assessments plus post-1997 to allow for possibility of more rapid climate change to date
2. Extend your climate reference periods (Section 5.4)	Historical data scaling or stochastic data generation
B: Selecting, understanding and working with the climate change scenarios	
3. Select your climate change scenario(s) (Section 5.5)	RCP8.5 plus projection of post-1997 historic climate reference period. Option to test robustness under milder RCP4.5 scenario
4. Understand projection uncertainty (Section 5.6)	Consider the implications of high, medium and low projections representing global climate model uncertainty for the given RCP scenario(s)
5. Interpolate and extrapolate projections (Section 5.6.3)	Methods to interpolate between 1995, 2040 and 2065, and to extrapolate beyond 2065
C: Source and apply the climate change scaling factors	
6. Source and apply tabulated projections (Sections 5.7 to 5.13)	Tables and associated methods for projecting temperature, potential evapotranspiration, rainfall, runoff, recharge and demands under climate change
7. Special considerations (Sections 5.14 to 5.15)	Special considerations for alpine areas and bushfire prone areas
D: Interpret the climate change scenario outcomes	
8. Interpret the outcomes (Section 6)	Examine outcomes and consider need for additional sensitivity/stress testing to address near-term decision risks
E: Optional sensitivity / stress testing	
9. Optional sensitivity testing (Section 6.4 and Appendix B)	Tables, information sources and techniques for optional sensitivity/stress testing

Figure 15 Overview of impact assessment process

5.2 Overview of climate reference periods and climate change scenarios

When describing the various reference periods and scenarios presented in these guidelines, the following labelling has been adopted.

If assessing river or supply system behaviour under observed conditions, **two historic climate reference periods** should be adopted, namely:

- A post-1975 historic climate reference period.
- A post-1997 historic climate reference period.

These historic climate reference periods can be used (if desired) to communicate streamflow characteristics and supply system performance under historic climate conditions, including historic greenhouse gas concentrations.

If representing river or supply system behaviour under a plausible range of current and future conditions, several **climate change scenarios** can be used, namely:

- Low, Medium and High climate change scenarios, which are projected from the post-1975 historic climate reference period, with the projected changes commencing from 1995.
- Post-1997 step climate change scenario, which is projected as a continuation of the post-1997 historic climate reference period.

Using 2020 as an example, application of the above approach means that the current river or supply system behaviour is expressed as a range under projected climate change scenarios at 2020. This range reflects the uncertainty in climate change modelling in the context of a non-stationary climate.

The above concepts are illustrated by Figure 16, which depicts historic annual streamflow and climate change projections applied to average annual streamflow. The historic climate reference periods are described further in Section 5.3 and the climate change scenarios are described further in Section 5.6.

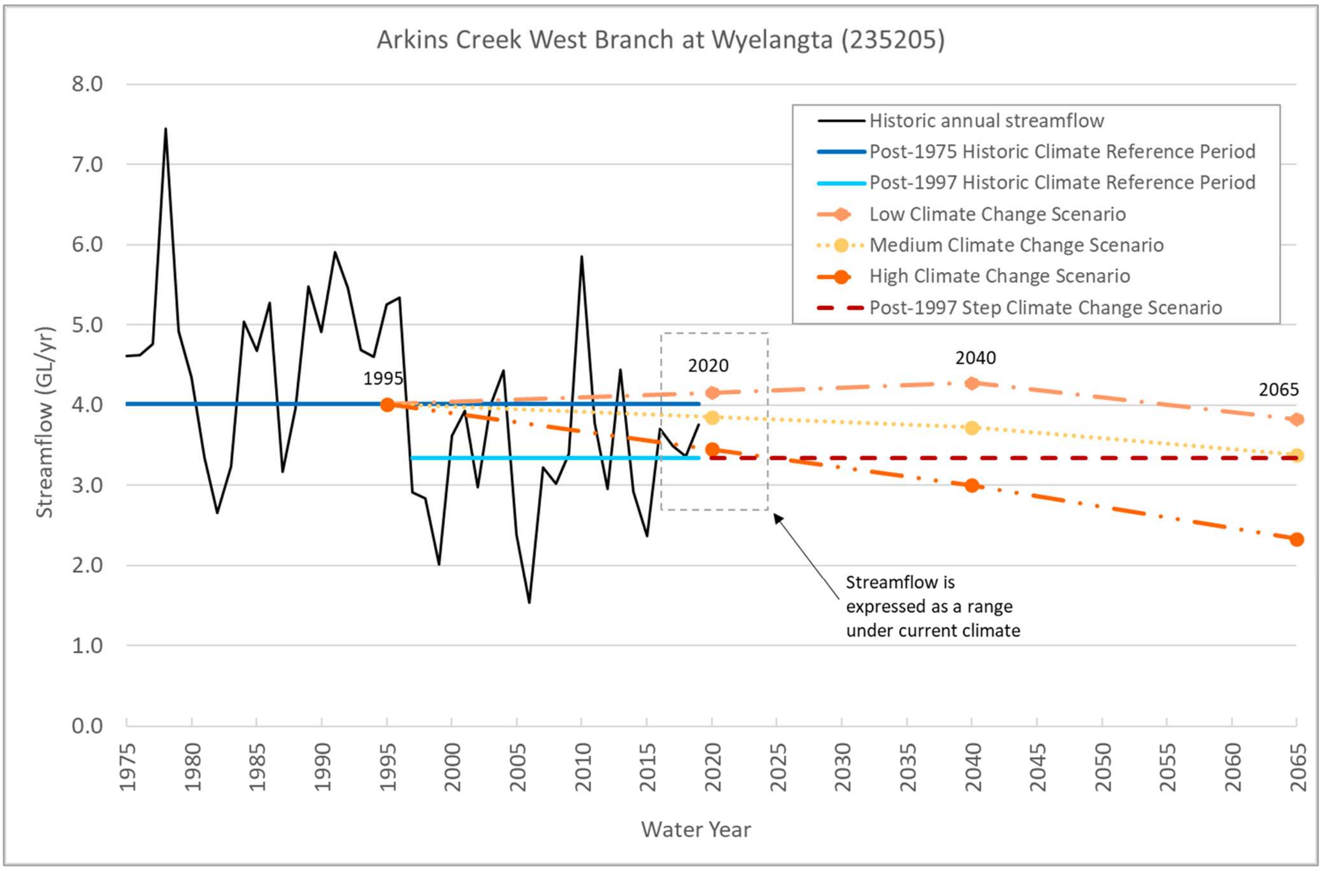

Figure 16 Example application of climate reference period and climate change scenario nomenclature illustrating projected changes in average streamflow conditions at a streamflow monitoring site in the Otway Coast Basin.

5.3 Develop your historic climate reference period datasets

5.3.1 Why are climate reference periods important?

Climate reference periods provide a reference point from which to project climate change impacts. Climate reference periods are required to present an understanding of historic and current river or supply system behaviour, and are important for accounting purposes when comparing available resources over time, across different climate change scenarios and across different parts of Victoria.

5.3.2 How the climate reference periods were selected for the guidelines

The selection of a suitable climate reference period(s) is a trade-off between being long enough to capture natural climate variability (droughts, floods and everything in between), but short enough to avoid the confounding effects of trends over the reference period, such as those driven by changes in greenhouse gas concentrations. The desired characteristics of a climate reference period are:

- It includes a wide range of natural climate variability.
- It is reasonably stationary with respect to greenhouse gas induced climate change.
- It is comparable across supply systems and river basins.

A range of factors were considered when selecting climate reference periods. These included the availability of observed climate and hydrology data, the variability of that observed data, the presence of trends and steps in the observed data, the availability of suitable paleoclimate information, and the likely minimum requirements for procedures that can extend the reference period to incorporate more climate variability. DELWP also consulted with Water Corporations and research scientists on this issue.

5.3.3 Historic climate reference periods (post-1975 and post-1997)

The purpose of the historic climate reference periods is to enable (i) the generation of estimates of historic climate and water availability under historic greenhouse gas concentrations and (ii) the generation of current and future climate scenarios. These reference periods are simply the historic climate record over the period July 1975 (or July 1997) to June of the most recent year of available data. The most recent year of available data should ideally extend to the current year, or to within a few years of the current year where it is not feasible to obtain or extend the historic climate record to the current year.

> The historic climate reference periods are simply the historic climate record over the period July 1975 (or July 1997) to June of the most recent year of available record.

5.3.4 Rationale for selecting the post-1975 historic climate reference period

The rationale for selecting the post-1975 historic climate reference period for use in these guidelines was:

- **It incorporates a wide range of natural climate variability**, including the Millennium Drought, the 1982–83 drought and several relatively wet years.
- **It is long enough to reasonably apply data extension techniques,** such as historical data scaling or stochastic data generation, that can incorporate greater natural climate variability.
- **It aligns with the reference periods adopted by CSIRO when estimating the projected changes in temperature, rainfall, potential evaporation and runoff from global climate models**. It is noted that CSIRO (Potter et al., 2016) utilised periods centred on 1995 (1986-2005 for GCM scaling and 1975-2014 for runoff estimation) based on available data at the time. The reference period being adopted in the 2020 guidelines differs marginally from this (i.e. it is centred on ~1998) because of the additional data available since 2014. However, the arguments presented by CSIRO in choosing their post-1975 reference period for runoff estimation remain valid despite the availability of additional data. CSIRO (Potter et al., 2016) argued that their adoption of a post-1975 reference period was appropriate because:

- It is consistent with World Meteorological Organisation conventions of a 30-year reference period, but with an additional 10 years to take into account Victoria's greater climate variability relative to other areas of the world in similar climate zones.
  - It is centred around the same year (1995) as the reference period used in the downscaling of future climate changes from the GCMs, but was extended from 20 years to 40 years for the same reasons above.
  - It aligns with the period used for rainfall-runoff model calibration for the hydrologic models used to estimate projected changes in runoff. This period was selected because it was considered reasonably stationary with respect to land use and water resource management changes.
  - It recognises SEACI and VicCI research findings that highlighted how key climate influences for Victoria have changed since the first half of the 20th century. This has now been further reinforced by VicWaCI research.
- **The start date is broadly consistent with observed step changes in climate behaviour** in the 1970s**,** particularly temperature (Jones, 2012; Jones and Ricketts, 2017), noting, however, that statistically significant step changes have also been detected in the late 1990s.
- **It is consistent with recent research by the Bureau of Meteorology** (Rauniyar and Power, 2020) that has used GCMs to assess the relative contribution of anthropogenic climate change to Victoria's observed cool season rainfall decline since the late 1990s.

On this last point, the Bureau of Meteorology's research (Rauniyar and Power, 2020) is concluding that approximately 20% of the observed cool season rainfall decline in Victoria over recent decades was attributable to external forcing, which includes the impact of greenhouse gas emissions. This value (20%) represents the average of the median rainfall changes under three RCP scenarios (i.e., RCP8.5, RCP4.5, RCP2.6) which consist of 105 GCMs runs in total. The inter-quartile range of results (i.e. the 25th and 75th percentile model projections) indicated an attribution from external forcing of 40% to -4%[1] of observed cool season rainfall decline in Victoria. This suggests that the majority (at least 75%) of GCMs estimate that climate variability has been a stronger driver of the observed drying from the late 1990s to date than anthropogenic climate change. The Bureau of Meteorology noted the caveats on these results, namely that the GCMs upon which they rely have a strong tendency to under-estimate observed drying in Victoria, and that there is a wide range of uncertainty in quantifying the effects of external forcing on Victoria's observed cool season rainfall decline. However, taking the GCMs at face value, and after discussion with a range of climate scientists across different research organisations, it was concluded by those research scientists that a post-1975 climate baseline would be more consistent with those global climate modelling results than a shorter (post-1997) baseline, for the purposes of long-term climate change projections to 2040 and beyond.

The post-1975 historic climate reference period incorporates ~45 years of climate variability. GCM-derived projections can be applied to the post-1975 historic climate reference period to represent future climate change scenarios.

In selecting this historic climate reference period at the current time, it is recognised that Victoria's climate is changing, and that this reference period will need to be reviewed in subsequent revisions to the guidelines over the next decade.

5.3.5 Rationale for selecting the post-1997 historic climate reference period

The previous section outlined the rationale for the selection of the post-1975 historic climate reference period for representing historic river or supply system behaviour. This section outlines the second approach, called the **post-1997 historic climate reference period**, which assumes that the dry conditions experienced since

[1] An attribution of -4% indicates that the 25th percentile GCM result projects conditions that are wetter than observed prior to the observed decline

1997 represent a permanent step-change in climate from that experienced prior to 1997. It allows for the possibility that a step change in climate has already occurred in 1997.

Climate conditions in Victoria have on average been much drier since 1997 than over the long-term. As discussed in Section 5.3.4, our current best advice from climate scientists suggests that the majority (at least 75%) of GCMs estimate that climate variability has been a stronger driver of the observed cool season drying in Victoria from the 1990s to date than anthropogenic climate change (Rauniyar and Power, 2020). However, it is still possible, as projected by a minority of GCMs, that these observed rainfall declines are predominantly attributable to anthropogenic climate change and could therefore represent a permanent shift in Victoria's climate. This viewpoint is supported by the identification of statistically significant step changes in global and southern hemisphere temperature occurring in or around 1997 (Jones, 2012; Jones and Ricketts, 2017). While currently considered less likely, it is nevertheless prudent to plan for the possibility that a step change in climate has already occurred in 1997. This is especially important for near-term applications but is also relevant for long-term planning until such time as the high climate change projection becomes drier than post-1997 conditions.

The post-1997 historic climate reference period allows for the possibility that climate change has occurred earlier than projected by most global climate models.

As the period since 1997 includes less than 30 years of data, it does not include some of the multi-year variability likely to be experienced in Victoria's climate in the long-term. In order to incorporate this variability, if needed for the given application, the post-1997 historic climate reference period can be extended using the extension techniques outlined in Section 5.4. These extension techniques will be less reliable when using a reference period shorter than 30 years, such as the post-1997 period.

5.3.6 Event sampling for near-term drought, extreme event and operational planning

Operational planning decisions are typically focussed on streamflow characteristics and supply system performance over the next week through to the next season or year, and for some systems, up to the next few years. Operational planning decisions are often tested using a sample of climate and runoff events spanning these durations. For most operational planning activities, sampling climate and runoff events from either the post-1975 or post-1997 historic climate reference period will be suitable. This approach of sampling from these reference periods has the advantage that these datasets are easy to prepare and communicate. The decision to sample from either or both of the post-1997 and post-1975 historic climate reference periods should be based on the desirable range of climate conditions under which decisions are to be tested, and should consider the risks of adopting events from only one versus the other reference period for the given application.

For drought and extreme event planning, the historical instrumental record is quite short when considering these events of low historical likelihood. For example, it is possible that a drought could occur over the near-term that is more severe (in terms of magnitude of the rainfall deficit and/or its duration) than that which has occurred historically (Verdon-Kidd and Kiem, 2009), irrespective of whether this is driven by increased greenhouse gas concentrations or natural climate variability. Such a situation occurred during the Millennium Drought.

There is only medium confidence in the projected changes to drought duration and severity from the GCMs and this confidence decreases for extreme drought events. For example, in the 21st century under increased greenhouse gas concentrations, none of the raw GCM outputs anticipate a drought duration near to or longer than the Millennium Drought (Hope et al., 2015b). If the GCMs do not replicate extreme drought events, then any projected changes in the duration of individual droughts of a given likelihood that are derived from the GCMs, and applied to historical drought events like the Millennium Drought, would only be applied with a low degree of confidence. This application of time series outputs from the GCMs to adjust historical drought duration is therefore not recommended by these guidelines.

It is possible to apply GCM projections (interpolating between 1995 and 2040 to the current year) to the post-1975 or post-1997 climate reference period for operational, drought and extreme event planning (as per the guidance for long-term planning in Section 5.6). This would have the advantage, under the high climate change projection, of generating drought events that are more severe than those that occurred historically. It would also ensure consistency in assumptions with long-term planning applications. However, the level of complexity in generating, applying and communicating outcomes from the high, medium and low projections to the year 2020 for operational, drought and extreme event planning purposes is considered unwarranted, given the availability of other more transparent and defensible alternatives discussed below.

There are various techniques available to generate synthetic droughts that are more severe than the worst drought on record. This can include stochastic data generation, as applied for setting very high levels of security for water supplies in some of Australia's capital cities (e.g. Seqwater, 2017) or, more simply, can involve historical sampling (with or without replacement) from the historical record, as is currently adopted by many Water Corporations. This involves scenarios such as running the 2006–07 drought year back to back or running the three driest years from the Millennium Drought back to back. This sampling preserves the within-year characteristics of a real drought event but rearranges each year to meet the scenario objectives of generating a hypothetical multi-year event that is less likely (but more severe) than the Millennium Drought. This is illustrated in Figure 17. In this figure, the extent to which different drought events are sampled and re-shuffled should reflect the organisation's perceived level of risk for the given application. However, the principle of testing the critical functions of river systems and supply systems to the possibility of droughts worse than the worst drought on record remains.

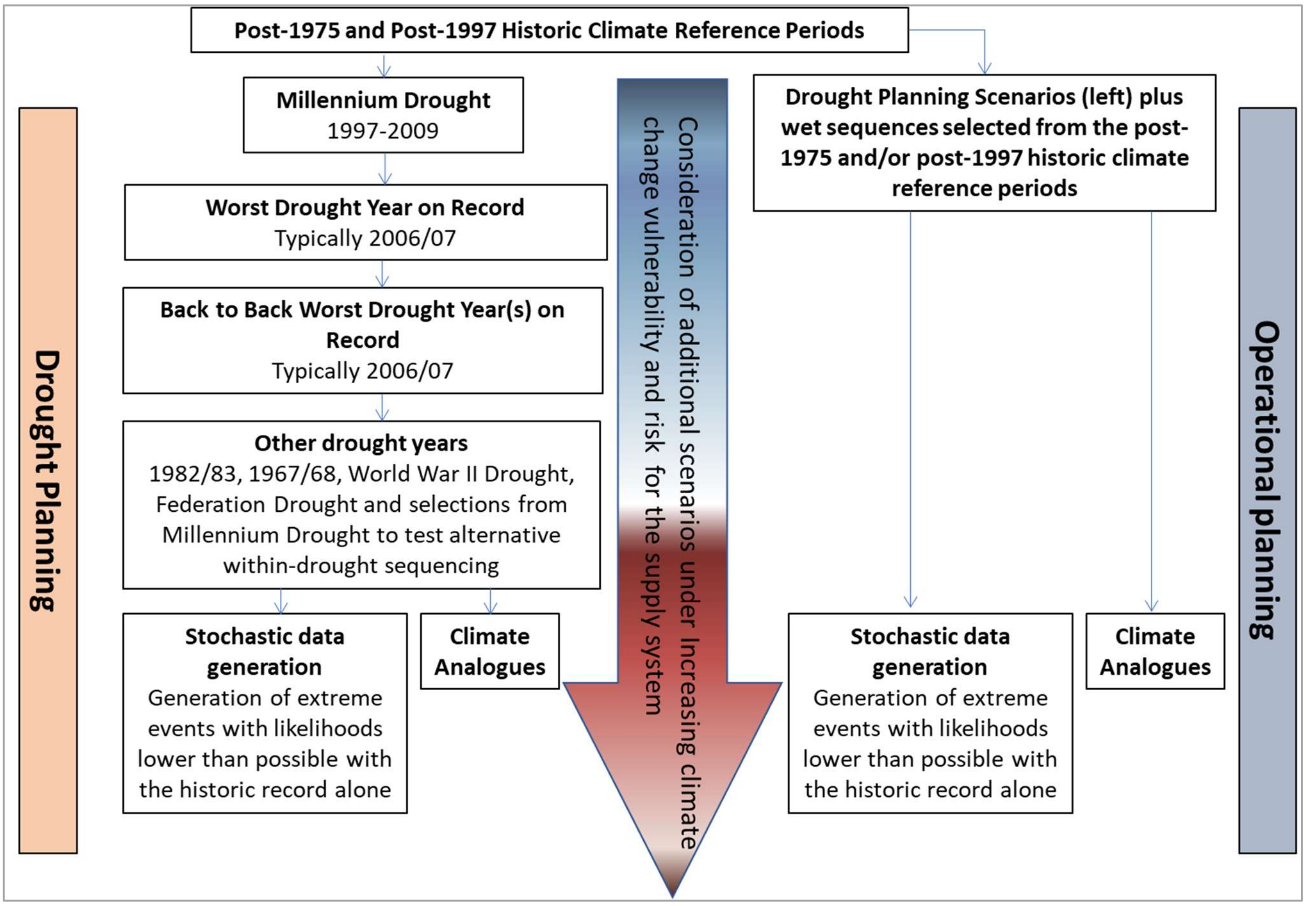

Figure 17 Operational, drought and extreme event sampling consistent with the climate change guidance

In addition to historical sampling, climate analogues from other parts of Australia can also be used, particularly for narratives around potential climate change, as discussed further in Appendix B.4. The use of climate analogues is considered a lower priority approach than both stochastic data generation and historic sampling from at-site drought events.

There may be exceptions to this process for smaller supply systems with less than 12 months of available storage capacity. For these supply systems, changes to within-year drought duration (and severity) are more important for testing supply system resilience than changes to multi-year drought duration. In this case, scaling or otherwise extending within-year historical drought events, including years in the Millennium Drought, is considered appropriate if the higher degree of uncertainty in this process is acknowledged. This form of stress testing is discussed in further detail in Appendix B.6.1.

5.4 Extend your climate reference period datasets

5.4.1 Introduction

Victoria's climate is highly variable and it is therefore arguable whether an historic record spanning 20–25 years (in the case of a post-1997 historic climate reference period) or 45–50 years (in the case of a post-1975 historic climate reference period) contain sufficient climate variability to reasonably assess water availability under a representative range of wet, dry and average conditions. Two techniques are presented below to enable the extension of the historic climate reference period to incorporate more climate variability than observed over that period — namely historical data scaling and stochastic data generation. No single approach is recommended over the other. Historical data scaling requires less effort to apply and interpret than stochastic data generation and takes full advantage of available historical climate and streamflow records, which in Victoria can extend back to the early 20th and late 19th century (Ashcroft et al. 2019). Stochastic data generation, while considerably more complex, has specific advantages in its ability to preserve more of the unique characteristics of the reference period, such as the daily persistence of rainfall, and can create a much wider range of annual rainfall and streamflow sequencing by use of statistical methods. This latter benefit means that it is suitable for generating extreme drought events beyond the notional 1 in 200-year events possible using historical data scaling (i.e. typically up to around a 1 in 10,000-year drought event).

Paleoclimate reconstructions for rainfall and streamflow have been utilised in some other Australian states to extend reference climate and streamflow datasets with additional climate variability. As noted in Appendix B.5, unlike some other states, paleoclimate proxy records for Victoria are not suitable for generating paleoclimate reconstructions of adequate quality for application in Victoria.

5.4.2 Historical data scaling

Historical data scaling is a simple technique to adjust historical data so that it has similar exceedance properties to a shorter reference period, such as the post-1975 or the post-1997 reference period. The recommended approach for these guidelines involves deriving average values for each interval (decile/percentile) of probability exceedance for both the reference period and the earlier historical data. The historical record prior to the reference period (e.g. pre-1975 flow) is then factored by the ratio of the average values in each period (e.g. post- and pre-1975) for the decile in which each value is located. The streamflow transformation tool within the utilities menu of the REALM modelling software automates this calculation for a given input streamflow time series (DELWP, 2008 & 2015). In recent years, a significant amount of water resource modelling has transitioned from using REALM to using eWater Source. The REALM streamflow transformation tool was initially ported with identical functionality to eWater Source (DELWP, 2019e) and is available through the eWater Source community plugin library. To coincide with recommendations of these guidelines, DELWP has released a new version of the plugin in eWater Source re-named to the Hydroclimate Data Transformation Plugin (DELWP, 2020c). This updated plugin offers the original streamflow transformation tool functionality as well as historical data seasonal flow duration curve (FDC) scaling and climate change projection transformations. This scaling can be applied to streamflow, rainfall, evaporation or temperature.

Given the observed changes in cool season versus warm season rainfall noted throughout these guidelines, it would be advantageous to undertake flow duration curve decile scaling on individual seasons (either spring/summer/autumn/winter or cool/warm season), particularly when applying to the post-1997 reference period. The REALM utility tool and eWater Source plugin do not currently allow exceedance curve decile scaling on individual seasons, so datasets would need to be separated into their respective seasons prior to input into the REALM utility tool, and then combined again once the scaling has been completed. Such an approach would allow Water Corporations to consider potential increases in intense warm season rainfall in the post-1997 reference period, as well as the cool season rainfall declines that are more pronounced than what is observed at an annual time step.

Historical data scaling should be applied seasonally rather than annually. Either cool/warm season or spring/summer/autumn/winter scaling are suitable, with a preference for a consistent approach to be adopted regionally. This may require communication across organisations with shared water resources.

Any historical data scaling technique has the potential to create discontinuities in daily time series data. When applying the scaling to deciles using all months of data, discontinuities can occur at the boundary of each decile. For example, with respect to streamflow data, if a baseflow recession passes through a decile boundary, it could result in a step jump up or down for daily flows either side of that boundary. Similarly, when separate flow duration curves are utilised for each season, there is an additional potential for discontinuity from one season to the next (e.g. from the last day of the warm season to the first day of the cool season). The implications of adopting flow duration curve scaling for particular applications should therefore be checked by examining the factored time series output relative to the intended use of that output. This issue is unlikely to arise for monthly time step data, where discontinuities from month to month are unlikely to be evident.

Hydrology and Risk Consulting (HARC, 2020) undertook an analysis of the potential for the scaling of historical data to introduce data anomalies in 150 datasets across Victoria. From this analysis it was concluded that:

- Inconsistent scaling factors across adjacent deciles occurred in less than 5% of datasets.
- It was not uncommon for high, low or the majority of historical streamflows to increase after scaling (e.g. low flows increased in 26% of datasets). The frequency with which this occurred was much lower when using a post-1997 historic climate reference period, relative to a post-1975 historic climate reference period.
- Understanding the quality of the reference period data is important for interpreting the validity of the historical data scaling.

HARC (2020) also investigated some of the potential causes of anomalies introduced by historical data scaling. These included examining differences in a sample of wet and dry catchments, differences when analysing the dataset on different time steps, differences when utilising a shorter period of record in the historical (pre-reference) period, differences when applying annual or seasonal scaling, and differences due to changes in the method of streamflow derivation and differences in the observed flows over time (e.g. due to changes in gauging practices). This analysis did not identify any conclusive patterns for the drivers of potential data anomalies introduced by historical data scaling, with anomalies likely to be unique to individual datasets associated with local quality control or water management issues. Where potential anomalies were identified, an examination of the stationarity of gauged water levels was shown to help identify whether the poor quality of raw data was a cause of the anomaly. See Appendix A.3 for examples of anomalous exceedance curve scaling.

When applying historical data scaling to match exceedance curve behaviour, always check the consistency of the scaling factors across adjacent deciles. Review the quality of your historical data and adopt simpler historical data scaling to match average behaviour if needed.

If anomalies are identified in the historical data scaling process to match exceedance curve behaviour, and it is found to be attributable to the scaling process (rather than the quality of your input data), a simpler scaling approach may be warranted. This could include the use of a single set of decile scaling factors across all months and seasons in a year. A suitable, but less preferred alternative is historical data scaling to match reference period average seasonal (or average annual) behaviour, rather than matching deciles. This approach is less preferred because it does not allow for the different observed historical changes under wet and dry conditions (i.e. that differently affect the high and low end of climate and streamflow exceedance curves) that are attributable to anthropogenic climate change.

Regardless of which historical data scaling method is applied from those discussed above, differences in rainfall and streamflow persistence in the reference period relative to the earlier historical period will be preserved. That is, the interval between high flow events, the number of rain days, or changes in low flow duration observed in the reference period dataset will not be transferred to the earlier historical dataset. If differences in persistence are significant and your river or supply system is sensitive to these changes, then historical data scaling could reinforce climate variability that is no longer applicable to the reference period. In this case, it is recommended that either historical data scaling should not be undertaken and the earlier historical data discarded (but with clear justification as to why). Alternatively, stochastic data generation should be adopted, which has the ability to preserve the persistence characteristics from the reference period.

5.4.3 Stochastic data generation

Definition and purpose of stochastic data

Stochastic data used in modelling water systems are random numbers that are modified so that they have the same statistical characteristics (in terms of mean, variance, skew, long-term persistency, etc.) as the reference period data on which they are based (adapted from Srikanthan et al., 2007).

> *“Using historical climate data as inputs into hydrological models provides results that are based on only one realisation of the past climate. Stochastic climate data provide alternative realisations that are equally likely to occur, and can therefore be used as inputs into hydrological and ecological models to quantify uncertainty in environmental systems associated with climate variability”* (Srikanthan et al., 2007).

Stochastic simulations can be particularly valuable to more accurately characterise the probabilities or risks presented by extreme events. A single simulation, of similar length to the period of historical data, may provide a reasonably accurate and reliable estimate of non-extreme metrics, such as mean annual runoff into a particular reservoir. However, a single simulation of the same length as the historical data (between say 50 and 120 years), is much less likely to provide an accurate assessment of the true probability of a reservoir running dry during an extreme 1 in 100-year drought. This is particularly the case in water resources systems where reservoirs are designed to have the capacity to sustain water supply during multi-year drought periods. Stochastic data methods, when appropriately applied, allow for more accurate assessments of the likelihood of extreme events, such as droughts, bushfires and floods.

In order for stochastic simulations to be useful, the most important statistics produced from the stochastic replicates must be consistent with the statistics of the underlying data. Data from a reference period — such as measured rainfall, streamflow, evaporation or temperature — is normally used as the baseline for preparing the statistics. In this case, “(e)ach stochastic replicate (sequence) is different and has different characteristics compared to the historical data, but the average of each characteristic from all the stochastic replicates is the same as the historical data” (Srikanthan et al., 2007). Recent examples have adjusted the underlying statistics, which are to be matched by the stochastic replicates, to allow for projected climate change (Peel et al., 2015; Henley et al., 2019). For example, the stochastic rainfall replicates might be modified to preserve some statistics from the observed historical rainfall data (e.g. correlation in annual rainfall totals) but with the mean annual rainfall statistic modified to match a climate change projection. The underlying reference period series, as input to the stochastic data generation process, may also be adjusted to be consistent with the statistics from post-1975 or post-1997 periods.

For the generation of stochastic data consistent with these climate change guidelines, stochastic data generation can be undertaken directly on the post-1997 and post-1975 historic climate reference periods. When generating stochastic data for use with GCM-based projections, the adjustment of that data for projected peak (if applicable) and average annual historical climate change from 1995 to date can be undertaken either before or after generating the stochastic data. However, due to the level of effort in generating and checking stochastic data, it is suggested that the stochastic data be generated only once (using the post-1975 historic climate reference period). The adjustment for projected historic low, medium and high climate change from 1995 to date can then be applied to the stochastic dataset.

This section briefly summarises the features of stochastic simulation models and issues to consider when selecting a stochastic data generation model for application. Appendix B.6.4 provides information on specific stochastic data simulation methods for use in water resources modelling, concentrating on methods and tools that are readily available to Australian modellers.

Features of stochastic simulation models

Stochastic data simulation methods can be applied to simulate:

- precipitation
- evaporation and evapotranspiration
- streamflow

- temperature.

Stochastic models can be used to generate data on several different timescales, including:

- annual
- seasonal (where the number of seasons and even length of seasons can vary)
- monthly
- weekly
- daily
- sub-daily (e.g. hourly, or even down to 5-minute resolution).

The variables to be simulated and the time-step required for the model will vary, according to the:

- underlying structure of the water resources model
- computing infrastructure required to run the model for many replicates
- metrics that are to be analysed from the model.

Stochastic data are produced by a statistical model. This statistical model often has its own parameters, such as the mean and variance for each variable and the cross-correlations between the variables. These parameters can be calibrated, to improve the ability of the stochastic model to accurately reproduce the most important statistical properties of the underlying (normally historical) data. Calibration of the stochastic data model is an important step in the process. The calibration process should demonstrate that the statistics of the stochastic replicates are sufficiently close to the statistics in the underlying data sequence.

Calibration should normally be tested by generating replicates that are the same length as the underlying (reference period) data series. For example, if the reference period rainfall sequence at a site is 47 years long, during calibration stochastic replicates should be generated that are also 47 years long. Once an acceptable model calibration has been demonstrated using replicates that are the same length as the reference period data, the calibrated statistical model may then be applied to generate any number of replicates, of any length that is required for simulation.

Some stochastic data simulation models can incorporate uncertainty in the model parameters into the data generation process. Allowing for parameter uncertainty will normally increase the variability between the stochastic data replicates that are produced. Consequently, allowing for parameter uncertainty has been demonstrated to increase the probability (and hence the risk) posed by extreme droughts in some systems (Thyer et al., 2006; Berghout et al., 2015).

Several (but not all) stochastic data generation models first produce stochastic data at annual or seasonal time-steps. These types of stochastic data generation models then have an approach to down-scale, or disaggregate, the annual/seasonal generated data to a finer time-step (monthly, weekly, daily or sub-daily). The practical advantage of this two-step approach is that the annual/seasonal totals are closer to normally distributed and therefore may be generated using a parametric model, which is better able to represent years/seasons that are outside of the range of the underlying (historical) data. A parametric approach may then be applied to the second step (disaggregation or downscaling) and still allow the multi-year dynamics of the system to be appropriately captured (Peel et al., 2011; Steinschneider and Brown, 2013; Kuczera, 2020).

Selection of a stochastic data generation model

There are at least three tools that are readily available to Australian practitioners for generating stochastic climate data: SCL, foreSIGHT and MSSSCAR (in WATHNET5). Within each of these tools, there are several options that are available to generate stochastic data for a system. Further discussion of the details of the approaches are provided in Appendix B.6.4.

In selecting a stochastic data generation method, modellers should consider the following:

- Variables (e.g. rainfall, streamflow, evaporation) that are required to run the water resources model.
- Variables that might be required to generate inputs to the water resources model (e.g. temperature may be required to generate a time series of demand).
- Time-step of the water resources model.

- Time-step of models that might be required to generate inputs (e.g. rainfall runoff models may run on a daily time step, in order to generate a weekly or monthly flow series, as input to the water resources system model).
- Overall number of sites and variables to be generated.
- Importance of seasonality, as a driver of the response of the system, and (if seasonality is important) how many seasons and the start and end months for the seasons.
- Importance of long-term climate drivers on climate in the study area.

Modellers should consider making simplifications to the structure of the water resources model, in order to reduce the effort that may otherwise be required to calibrate a stochastic data model and to generate the stochastic data. Stochastic data should always be calibrated to the underlying (historical) data. If stochastic data is required for a large number of sites and/or variables, there may be considerable effort required to demonstrate that the stochastic data generation model is well calibrated for all these sites and variables.

It may be helpful to simplify the underlying model structure, in order to facilitate stochastic simulations. For example, it may be desirable to increase the time-step of the underlying model (from say daily to monthly) or to reduce the spatial detail in the model, by lumping several catchments together or only representing the largest reservoirs in the system. A relevant recent example of this is the simulation of a simplified representation of the Melbourne water supply system (Henley et al., 2019), which generated inflows using a monthly time-step model and only modelled the four largest reservoirs in the Melbourne system. The Henley et al. (2019) model had considerably less spatial resolution than REALM or eWater Source models, which might normally be used for water resources planning, and which would typically run on a finer time-step (e.g. daily) and typically represent the smaller storages and management rules for many more stream reaches in the system.

In some cases, the only means of testing the sensitivity of outcomes to the stochastic data generation approach may be to apply a few different approaches. To test the sensitivity of the yield of a water resources system to ENSO, it would probably be best to first generate the stochastic data with ENSO as the state driver and then run this through the system, before repeating the process again without using the state driver. Fu et al. (2018) found that applying four different weather generators for stochastic data generation allowed for a broader representation of the influence of climate variability and climate change on outcomes from water resources models.

In summary, stochastic simulation in water resources models will often require trade-offs to be made in what spatial details or features are represented in the model and the model time-step. For example, it may be that explicit modelling of farm dam impacts or modelling environmental flow releases on a daily time-step are traded-off against a model that is better able to capture the probability of extreme multi-year drought events that cause severe restrictions. The modelling team should use their experience, in modelling the system with historical data series, to make informed choices about simplifications that are likely to deliver the most value from stochastically generated data. Improved understanding of probabilities and risks for extreme events may come at the expense of loss of some detail in modelling finer scale spatial and temporal features.

5.5 Select your Representative Concentration Pathway scenarios

As discussed previously in Section 4.3, Representative Concentration Pathway (RCP) scenarios incorporate different assumptions of greenhouse gas and aerosol emissions and concentrations over time, as well as land use/land cover changes. Climate and runoff projections for two RCPs are provided in these guidelines.

RCP8.5 for water supply planning applications

The RCP8.5 scenario is a high emissions scenario that is recommended for water supply planning applications in Victoria. The RCP8.5 scenario spans a wide range of plausible futures and is consistent with a precautionary approach for water supply impact assessment, which is appropriate in the context of GCM uncertainty and uncertainty around future greenhouse gas emissions and concentrations.

RCP4.5 for optional sensitivity testing

In addition to the RCP8.5 scenario, projections for the RCP4.5 scenario are also provided in the guidelines for optional sensitivity testing. The RCP4.5 scenario assumes lower rates of greenhouse gas emissions and concentrations over time. The global temperature response from the RCP4.5 scenario over the ~50 year planning horizon of the guidelines is broadly reflective of the response that could be expected under both current and pledged greenhouse gas emission policies from the world’s governments (Hausfather and Peters, 2020). It is a higher RCP scenario than that which would eventuate if the Paris Agreement targets were to be reached. As discussed in Section 4.3, current greenhouse gas reduction commitments by the world's governments are insufficient to meet the objectives of the UNFCCC Paris Agreement (Christensen and Olhoff, 2019); moreover, many nations are not on track to meet the commitments that they have made (den Elzen et al, 2019).

After assessing the impacts of the RCP8.5 scenario, the role of the RCP4.5 scenario would be to test the robustness of water supply planning decisions under a lower emissions trajectory. **The RCP4.5 scenario could, for example, help to inform decisions around the potential benefits of staging water supply infrastructure investment amidst future emissions uncertainty.**

Due to the lower radiative forcing of the RCP4.5 scenario, we would expect that the RCP4.5 scenario would result in weaker projected future changes compared to the RCP8.5 scenario. However, this is not always the case for the year 2040 projections. In some river basins, the high (90th percentile) climate change projections for rainfall for the year 2040 under RCP4.5 are greater than under RCP8.5. This reinforces the fact that the projections under these two RCP scenarios are not materially different up to the year 2040 in the context of GCM uncertainty. This has also been observed in the analysis of GCM outputs in other parts of the world (e.g. Betts et al., 2013; Kalmarkar and Bradley, 2017). The difference in climate response to the two RCP scenarios is generally small in the year 2040 and greater in the year 2065.

Other approaches

Although the RCP8.5 scenario is recommended by these guidelines, with the option to undertake sensitivity testing with the RCP4.5 scenario, the intent of these guidelines is not to limit the emissions scenarios used in water supply planning in Victoria. Additional emissions scenarios can be adopted for further sensitivity testing or for specific applications as required. For example, RCP scenarios representing lower emissions trajectories could be used to explore the implications of a future where more aggressive emissions reductions are pursued by the world's governments.

The next assessment report by the IPCC will be delivered from around mid-2021 to mid-2022 and will consider updates of these RCP scenarios, as well as a broader range of emissions scenarios that are more closely tied to specific socio-economic outcomes (Shared Socio-Economic Pathways) and greenhouse gas emissions policy settings. The guideline recommendation to adopt RCP8.5, with the option of testing the robustness of planning decisions with RCP4.5, should therefore be regarded as an interim recommendation that is likely to be updated after 2022.

> The RCP8.5 scenario must be adopted as a suitably precautionary emissions scenario for water supply planning. In addition, the RCP4.5 scenario can be adopted to test the robustness of planning decisions under a lower emissions trajectory. For near-term decision risks, the potential role of the RCP4.5 scenario is further explored in Section 6, alongside the consideration of other uncertainties.

5.6 Develop your climate change scenarios

5.6.1 Introduction

These guidelines recommend the use of the following four climate change scenarios to represent river or supply system behaviour under plausible future conditions:

- Low, medium and high climate change scenarios, which are projected from the post-1975 historic climate reference period (with projected changes commencing from 1995). These scenarios make use of climate change projections derived from GCMs.
- Post-1997 step climate change scenario, which is projected as a continuation of the post-1997 historic climate reference period. This scenario is derived independent of global climate modelling. It assumes a continuation of climate and runoff experienced from July 1997 to date.

These guidelines assume that all scenarios are equally plausible. No scenario is recommended in preference to another.

5.6.2 Representing global climate model uncertainty

There are 42 GCMs that were used to produce the low, medium and high climate change projections under the RCP8.5 emissions scenario, and a slightly lower number of models for the RCP4.5 emissions scenario. Each of these models assume different ways of representing the complex physics of global atmospheric circulation and are generally all considered equally plausible. At a regional scale, a minority of models have been assessed as less plausible (e.g. Grose et al., 2017; CSIRO and Bureau of Meteorology, 2015). However, when the criteria by which to assess this plausibility are altered, different models can be included or excluded for different reasons, which makes it difficult to definitively exclude any models at the current time.

The approach adopted by CSIRO for the guidelines (Potter et al., 2016) adopts the 10th, 50th and 90th percentile model outputs as being representative of the range of climate change that could be expected. This provides a wide spread of model results but excludes outlying model results from the wettest (or coolest) and driest (or hottest) 10% of projections.

The 10th (low), 50th (medium) and 90th (high) percentile climate change projections provide a wide range of projections that are all equally plausible. A small number of wetter and drier model projections lie outside of this range.

When planning for climate change, there is a tendency to only utilise the high climate change projection that generates the driest outcome. While this may be suitable for defining a notional upper bound on impacts, water supply planning decisions should ideally be sufficiently robust to perform well under the wide range of future climate possibilities. If a fully robust solution cannot be identified, then decision makers should be informed about the performance of particular supply system options under the range of projections, so that the trade-offs involved in choosing one solution over another can be understood.

There is also a tendency to interpret the medium projection as the most likely projection. **The medium projection is not the most likely projection, because at the current time, all projections are equally likely**. As more information is collected on the global climate response to greenhouse gas emissions over time, it is possible that either the driest projection could be the most likely, or the wettest projection, or any projection in between.

The runoff projections have been derived using the 10th, 50th and 90th percentile rainfall projections, and hence the high, medium and low projections for runoff are consistent with those for rainfall. The high, medium and low projections for temperature, potential evapotranspiration (PET), and rainfall have been derived independently. Temperature and evapotranspiration are highly correlated, so it is likely that the 10th percentile temperature and the 10th percentile evapotranspiration will be from the same model. However, the GCM that produces the 10th percentile temperature or evapotranspiration value may not be the model that produces the 10th percentile rainfall.

The above approach of deriving the range of projections independently for each variable is considered suitable for most water supply impact assessments. This is because it ensures that information is being sourced from all 42 available GCMs, rather than being dependent on any single GCM. Also, when models (such as water demand models) use multiple parameters as input, use of a median value for temperature or PET can often be justified as water planning outcomes are typically far less sensitive to climate change impacts on demand than to climate change impacts on rainfall and runoff.

In an instance where changes in temperature and PET are estimated to have as great, or greater, impact on planning outcomes as changes in rainfall and runoff, then this would be a trigger to consider using a range of temperature or PET values either side of the median value, such as the 10th and 90th percentile values presented in the guidelines. This is likely to be a reasonable sensitivity test for most applications. However, if adopting the 10th and 90th percentile temperature values alongside the 10th and 90th percentile rainfall and runoff projections, this could generate combinations of variables that lie outside those in any individual GCM. In these instances, it may be appropriate to draw all projections from a single GCM. Such an approach would be applicable, for example, for research applications. Where such an approach is desirable, it is recommended that the user seek the advice of climate scientists for information on appropriate model selection and data sources, with the use of results from all 42 GCMs usually being preferable to just adopting one or a few models.

For a broader understanding of the degree of consensus between any two projected variables across different models for major regions of Australia, see the Climate Futures Tool on the Climate Change in Australia website (https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/projections/).

5.6.3 Projecting the low, medium and high climate change scenarios

The process for estimating climate and runoff under projected low, medium and high climate change involves applying GCM-derived factors to the post-1975 historic climate reference period. Subsequent sections 5.7–5.10 provide tabulated factors for average annual change in temperature, potential evapotranspiration, rainfall and runoff, to represent current (i.e. 2020) conditions and future conditions under climate change in the years 2040 and 2065. These projections are provided for each river basin.

Interpolation from 1995 to 2020

The process of estimating current (i.e. 2020) climate and water availability from the post-1975 historic climate reference period and the year 2040 climate change projections is illustrated in Figure 18. The top panel of this figure shows the scaling factors derived from comparison of GCMs over 20-year periods centred on 1995 and 2040. These are the values presented for the year 2040 in the climate projection tables in sections 5.6.4–5.10. The bottom panel of Figure 18 shows the assumed linear interpolation of projected impacts over this period to generate the projected current (~2020) climate and runoff under the low, medium and high climate change scenarios.

In summary, projected climate change from 1995 to date is a linearly interpolated change factor for each of the high, medium and low projections (or only the medium projection if that is all that is provided in the guidelines for that given variable) as follows:

Projected climate change from 1995 to date (i.e. 2020)

= (Current year - 1995) / (2040-1995) * (Projected change in 2040)

Equation 1

By assuming a linear interpolation between 1995 and 2020, it is possible that the assumed level of greenhouse gas concentrations in 2020 could be either over-estimated or under-estimated, because climate change impacts are likely to increase non-linearly over time.

Interpolation from now to 2040

Interpolation of GCM projections for climate and streamflow after 2020 can be undertaken in the same manner as for generating the current (i.e. 2020) climate and streamflow, as described above. This is shown in Figure 19. This figure provides an example calculation for an interpolation of the high climate change projection for the year 2030, as per Equation 2.

Projected climate change between now and 2040

= (Year of interest - 1995) / (2040-1995) * (Projected change in 2040)

Equation 2

Interpolation from 2040 to 2065

Linear interpolation of climate change projections from the year 2040 to the 2065 can be undertaken in a similar manner to the above. The method of calculation is as per Equation 3.

Projected climate change between 2040 and 2065

= (Year of interest - 2040) / (2065-2040) * (Projected change in 2065 - Projected change in 2040)

Equation 3

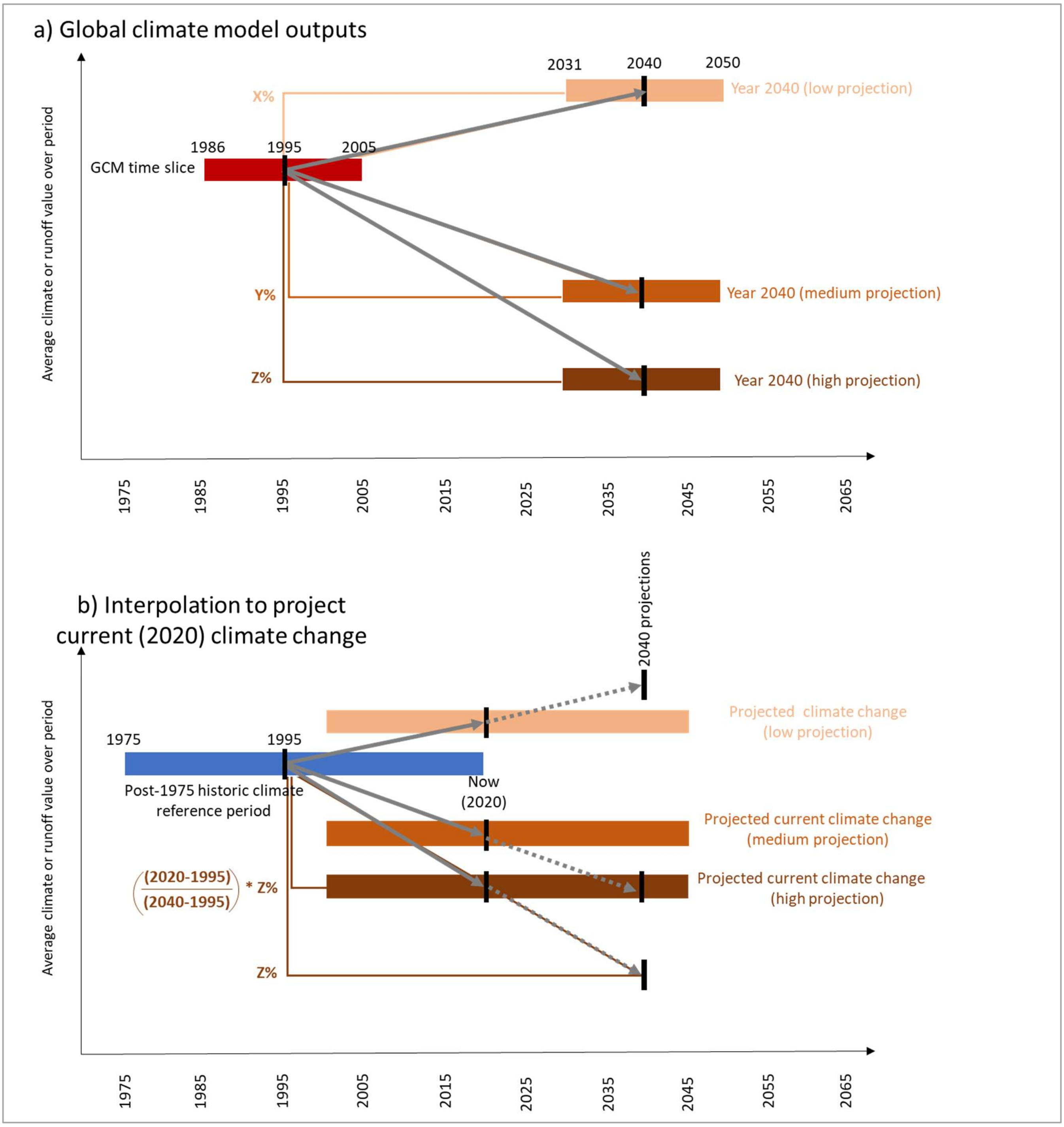

Figure 18 Interpolation to generate projected low, medium and high climate and runoff at 2020

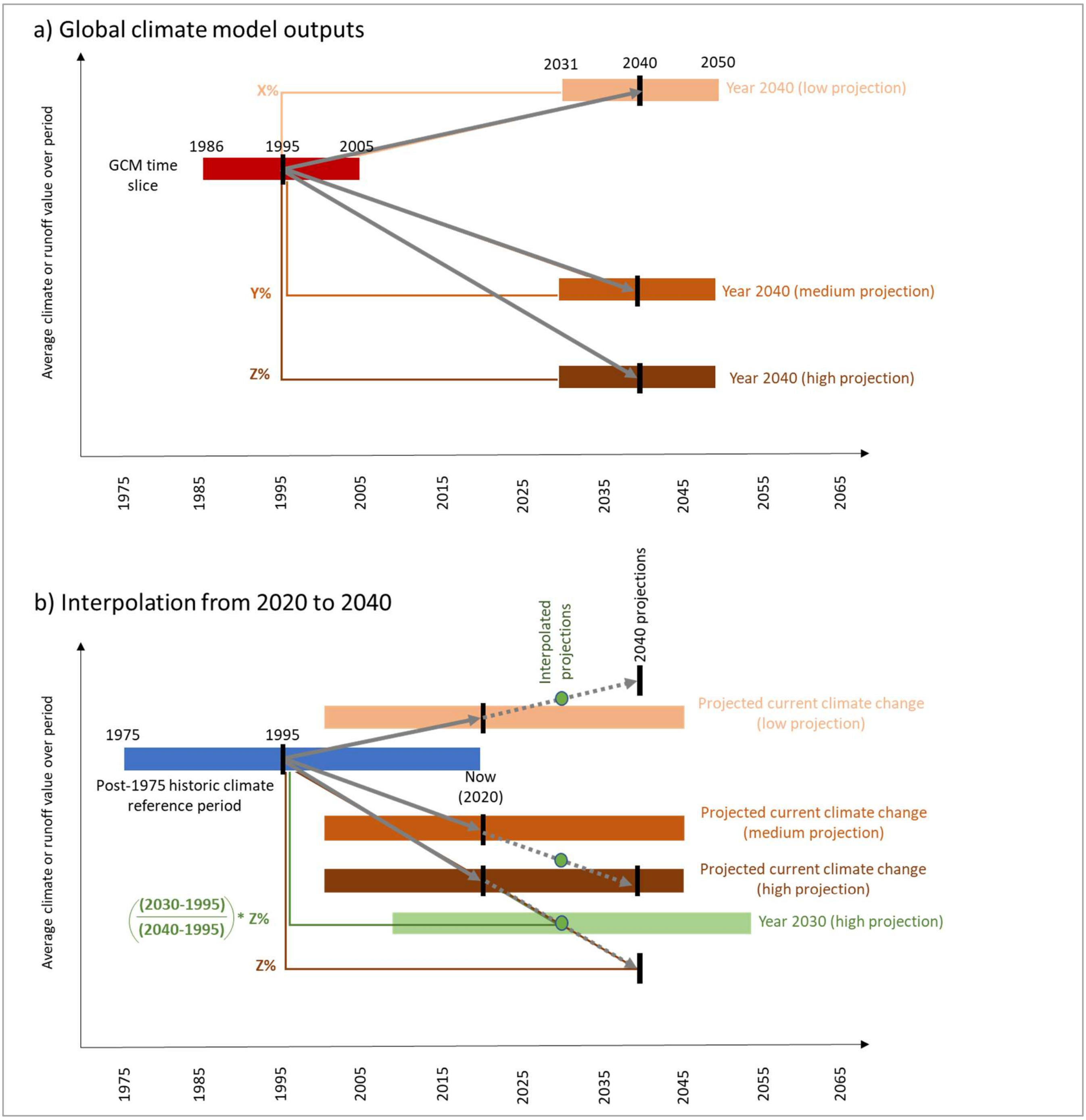

Figure 19 Interpolation of global climate model projections between 2020 and 2040

Extrapolation from 2065 to 2075

Beyond 2065, the linear trend from 2040 to 2065 can be linearly extrapolated up to the year 2075 as per Equation 4. This will enable a 50-year projection to be made for urban water strategies over the anticipated life of these guidelines. Based on the temperature projections up to 2100 previously presented in Figure 11 (Section 4.3), for RCP8.5 this extrapolation method is expected to marginally under-estimate the projected change beyond 2065, and for RCP4.5 it is expected to marginally over-estimate the projected change beyond 2065.

> **Projected climate change between 2065 and 2075**
>
> **= Projected change in 2065 +**
>
> **[(Projected change in 2065 - Projected change in 2040) / (2065-2040)] * (Year of interest – 2065)**

Equation 4

Extrapolation beyond 2075

If climate change projections are required beyond the year 2075 up to the year 2100, it is recommended that the relative change in projections from the year 2070 to the year 2090 be obtained from alternative projections, such as VCP19 (Clarke et al., 2019a) or the Climate Change in Australia projections for Australia's NRM regions (Grose et al., 2015a; Timbal et al., 2015), noting that these projections are available for rainfall, but not runoff, at the time of publishing these guidelines in 2020. Beyond 2100, it is recommended that specific advice from climate scientists should be obtained.

5.6.4 Projecting the post-1997 step climate change scenario

The post-1997 step climate change scenario is projected from the post-1997 historic climate reference period, but without the use of GCM-derived projections. It assumes that the climate and streamflow experienced post-1997 will continue into the future. This scenario is especially important for near-term applications but is also relevant for long-term planning until such time as the high climate change scenario becomes drier than observed post-1997 conditions. This scenario assumes that (i) projected climate change has already occurred as a step change in 1997, (ii) no further climate change has occurred from 1997 to date, and (iii) no further climate change will occur into the future.

5.6.5 What is the current status of the climate and water availability?

For long-term planning applications, understanding current climate and water availability over a long-term climate sequence is important for assessing current streamflow characteristics or supply system performance, as well as providing an important reference point from which to compare that performance over coming decades under climate change.

As discussed previously in Section 4, the precise rate of historical climate change attributable to anthropogenic forcing is uncertain, as reflected in the range of high, medium and low GCM projections from 1995 to date. Clearly, real-world observations from today are the best representation of current climate and water availability under current levels of greenhouse gas concentrations. However, the further back in time these real-world observations have been recorded, the more likely that they would manifest differently today, given the historical changes in greenhouse gas concentrations that have occurred between the observation being made and today. The adoption of the post-1975 and post-1997 historic climate reference periods allows for these changes prior to 1975 and 1997 respectively. However, it is still quite possible that climate events since these two dates would manifest differently if they were to commence today, rather than in a previous decade, due to the different levels of greenhouse gas concentrations over these reference periods.

For these guidelines, our understanding of a long-term representation of current climate and water availability reflects this uncertainty by representing it in a number of different ways. Firstly, this includes an estimate of current (~2020) climate and water availability under high, medium and low GCM projections from 1995 to date. These provide three alternative, equally plausible realisations of what our current climate and water availability would look like in the long-term. Post-1997 observations are adopted as a fourth, equally plausible, alternative realisation of current long-term climate and water availability, which assumes that historical anthropogenic climate change occurred largely as a step change in 1997.

It may seem counter-intuitive to represent current climate and water availability as a range under climate change, but it is reflective of the non-stationary nature of the current climate. In other words, the current climate is responding to increased and increasing levels of greenhouse gases in the earth's atmosphere. Our understanding of the climate is continuing to improve, but there is still considerable uncertainty associated with global climate modelling, including how much of the current climate is attributable to anthropogenic climate change and how much is attributable to natural climate variability. By expressing current climate and runoff as a range under climate change, this uncertainty is acknowledged.

5.7 Applying climate change projections to temperature

5.7.1 Average annual temperature changes

The GCM-derived projected changes in average annual temperature for each river basin are presented in Table 3. These should only be applied to the post-1975 historic climate reference period (not the post-1997 historic climate reference period).

In the East Gippsland Basin for example, under the RCP8.5 emissions scenario, average annual temperature is projected to increase by 1.0–1.7°C by 2040 relative to 1995, with a median projection of 1.3°C. Projected changes in maximum daily temperature are similar in magnitude to changes in average daily temperature in Victoria (Grose et al., 2015), hence the values in Table 3 can be applied to maximum daily temperature values. The exception is temperatures on days of extreme heat. Changes in peak seasonal temperatures will be higher than these average annual changes (Clarke et al., 2019a), as discussed further in Section 5.7.2. Changes in minimum temperatures will be lower than these average annual changes, which is also considered further in Section 5.7.2.

In this table, the year 2020 projection has been linearly interpolated between the mid-point of the reference period climate reference period used in the global climate modelling (1995) and the year 2040 projection. The year 2040 and 2065 projections have been extracted from the GCMs by CSIRO. These temperature projections are relative to 1995, not pre-industrial temperatures, which are around 0.5°C lower than temperatures in 1995.

For the purposes of demand estimation, only the medium (50th percentile) temperature projections need be applied, as discussed further in Section 5.12. The low (10th percentile) and high (90th percentile) model projections are only provided for reference purposes, if further testing of the sensitivity to projected temperature changes is desired for any given application.

Table 3 Projected change in average annual temperature

River basin (and basin number)	Projection	Change relative to 1995 (°C)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
East Gippsland (221)	Low	0.5	0.4	1.0	0.8	1.9	1.1
	Medium	0.7	0.6	1.3	1.1	2.4	1.5
	High	0.9	0.7	1.7	1.3	2.9	2.0
Snowy (222)	Low	0.6	0.4	1.0	0.8	1.9	1.2
	Medium	0.8	0.6	1.4	1.1	2.5	1.5
	High	0.9	0.8	1.6	1.4	2.9	2.0
Tambo (223)	Low	0.6	0.4	1.0	0.8	1.9	1.2
	Medium	0.7	0.6	1.3	1.1	2.4	1.5
	High	0.9	0.7	1.6	1.3	2.8	1.9
Mitchell (224)	Low	0.6	0.4	1.0	0.7	1.9	1.2
	Medium	0.7	0.6	1.3	1.1	2.4	1.5
	High	0.9	0.7	1.5	1.3	2.9	1.9
Thomson (225)	Low	0.5	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.4	1.5
	High	0.9	0.7	1.5	1.3	2.8	1.9
Latrobe (226)	Low	0.5	0.4	0.9	0.7	1.7	1.0
	Medium	0.7	0.5	1.2	1.0	2.2	1.4
	High	0.8	0.7	1.5	1.2	2.8	1.8

River basin (and basin number)	Projection	Change relative to 1995 (°C)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
South Gippsland (227)	Low	0.4	0.4	0.8	0.7	1.6	0.9
	Medium	0.6	0.5	1.1	0.9	2.1	1.4
	High	0.8	0.7	1.5	1.2	2.7	1.7
Bunyip (228)	Low	0.5	0.4	0.9	0.7	1.7	0.9
	Medium	0.6	0.5	1.2	1.0	2.1	1.4
	High	0.8	0.7	1.5	1.2	2.7	1.8
Yarra (229)	Low	0.5	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.3	1.5
	High	0.9	0.7	1.5	1.3	2.8	1.8
Maribyrnong (230)	Low	0.5	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.3	1.4
	High	0.8	0.7	1.5	1.2	2.8	1.8
Werribee (231)	Low	0.5	0.4	1.0	0.7	1.8	1.1
	Medium	0.7	0.6	1.3	1.0	2.3	1.4
	High	0.8	0.7	1.5	1.2	2.8	1.8
Moorabool (232)	Low	0.5	0.4	0.9	0.7	1.7	1.0
	Medium	0.7	0.5	1.2	1.0	2.2	1.4
	High	0.8	0.6	1.5	1.2	2.6	1.8
Barwon (233)	Low	0.5	0.4	0.8	0.6	1.6	0.9
	Medium	0.6	0.5	1.1	0.9	2.1	1.3
	High	0.8	0.6	1.4	1.1	2.6	1.7
Lake Corangamite (234)	Low	0.5	0.4	0.8	0.6	1.6	0.9
	Medium	0.6	0.5	1.1	0.9	2.0	1.3
	High	0.8	0.6	1.4	1.1	2.6	1.7
Otway Coast (235)	Low	0.4	0.3	0.8	0.6	1.4	0.8
	Medium	0.6	0.5	1.0	0.8	1.9	1.2
	High	0.7	0.6	1.3	1.1	2.5	1.6
Hopkins (236)	Low	0.5	0.4	0.9	0.6	1.6	1.0
	Medium	0.6	0.5	1.1	0.9	2.1	1.3
	High	0.8	0.6	1.4	1.1	2.5	1.7
Portland Coast (237)	Low	0.4	0.3	0.7	0.6	1.3	0.7
	Medium	0.5	0.5	1.0	0.8	1.9	1.2
	High	0.7	0.6	1.3	1.1	2.4	1.6
Glenelg (238)	Low	0.5	0.4	0.8	0.6	1.6	1.0
	Medium	0.6	0.5	1.1	0.9	2.0	1.3
	High	0.8	0.6	1.4	1.1	2.6	1.6
Millicent (239)	Low	0.5	0.4	0.8	0.7	1.7	1.0
	Medium	0.6	0.5	1.1	0.9	2.1	1.3
	High	0.8	0.6	1.5	1.1	2.5	1.7
Upper Murray (401)	Low	0.6	0.4	1.1	0.8	1.9	1.2
	Medium	0.8	0.6	1.4	1.1	2.6	1.6
	High	0.9	0.8	1.7	1.5	3.0	2.1

River basin (and basin number)	Projection	Change relative to 1995 (°C)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kiewa (402)	Low	0.6	0.4	1.1	0.7	1.9	1.2
	Medium	0.8	0.6	1.4	1.1	2.5	1.6
	High	0.9	0.8	1.6	1.5	3.0	2.0
Ovens (403)	Low	0.6	0.4	1.0	0.7	2.0	1.2
	Medium	0.8	0.6	1.4	1.1	2.5	1.6
	High	0.9	0.8	1.6	1.5	3.0	2.0
Broken (404)	Low	0.6	0.4	1.0	0.7	2.0	1.2
	Medium	0.8	0.6	1.4	1.1	2.5	1.6
	High	0.9	0.8	1.6	1.4	3.0	2.0
Goulburn (405)	Low	0.5	0.4	1.0	0.7	2.0	1.1
	Medium	0.8	0.6	1.4	1.0	2.4	1.5
	High	0.9	0.8	1.6	1.4	2.9	1.9
Campaspe (406)	Low	0.5	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.4	1.4
	High	0.9	0.8	1.6	1.4	2.9	1.8
Loddon (407)	Low	0.6	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.4	1.5
	High	0.9	0.8	1.6	1.4	2.9	1.9
Avoca (408)	Low	0.6	0.4	1.0	0.7	1.9	1.2
	Medium	0.8	0.6	1.4	1.1	2.4	1.5
	High	0.9	0.8	1.6	1.4	3.0	1.9
Lower Murray (409)	Low	0.6	0.4	1.1	0.7	2.0	1.2
	Medium	0.8	0.6	1.5	1.1	2.5	1.6
	High	0.9	0.8	1.7	1.4	3.1	2.0
Mallee (414)	Low	0.6	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.1	2.4	1.4
	High	0.9	0.7	1.6	1.3	2.9	1.9
Wimmera (415)	Low	0.6	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.3	1.5
	High	0.9	0.7	1.6	1.3	2.9	1.9
Victoria*	Low	0.5	0.4	1.0	0.7	1.9	1.1
	Medium	0.7	0.6	1.3	1.0	2.3	1.5
	High	0.9	0.7	1.5	1.3	2.8	1.8

* The statewide change is not an average of the changes for each river basin. This is because the river basins vary in size and some basins include areas that fall within New South Wales.

5.7.2 Minimum and peak temperature changes

According to the VCP19 climate change projections, temperatures on days of extreme heat in Victoria are expected to increase to a greater extent than average maximum daily temperature changes (Clarke et al., 2019a). For example, under the RCP8.5 emissions scenario in the Gippsland region, the median climate change projection for the 1 in 20-year hottest day is an increase of around 2.9°C by mid-century (relative to 1995), compared to a 2.0°C increase in average maximum daily temperatures (Clarke et al., 2019b). Increases in the number of days per year above 35°C vary by region, but in Traralgon, for example, the median number of days above this threshold is expected to increase from around 6 to 14 days per year by the mid-21st century, relative to the 1990s under the RCP8.5 emissions scenario (Clarke et al., 2019b).

Urban heat islands will also play a role in peak temperature changes, further adding to both maximum and minimum daily temperatures in urban areas, relative to surrounding rural areas.

Similarly, changes in minimum temperatures will be lower than the average annual changes presented in Table 3 (Clarke et al., 2019a).

For further information about peak and minimum temperature changes from a subset of six GCMs downscaled using regional climate modelling, refer to the relevant VCP19 regional fact sheet, available from https://www.climatechange.vic.gov.au/adapting-to-climate-change-impacts/victorian-climate-projections-2019.

5.8 Applying climate change projections to potential evapotranspiration

The projected changes in average annual potential evapotranspiration for each river basin are presented in Table 4. The values in this table were derived using Morton's (1983) wet area formulation (Potter et al., 2016). These should only be applied to the post-1975 historic climate reference period (not the post-1997 historic climate reference period).

In the East Gippsland Basin for example, under the RCP8.5 emissions scenario, average annual potential evapotranspiration is projected to increase by 2.9-5.9% by 2040 relative to 1995, with a median projection of 4.2%.

In this table, the year 2020 projection has been linearly interpolated between the mid-point of the reference period climate reference period used in the global climate modelling (1995) and the year 2040 projection. The year 2040 and 2065 projections have been extracted from the GCMs by CSIRO.

For the purposes of demand estimation, only the medium (50th percentile) potential evapo-transpiration projections need be applied, as discussed further in Section 5.12. The low (10th percentile) and high (90th percentile) model projections are only provided for reference purposes, if further testing of the sensitivity to projected potential evaporation changes is desired for any given application.

Table 4 Projected change in average annual potential evapotranspiration

		Change relative to 1995 (%)					
River basin (and basin number)	Projection	Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
East Gippsland (221)	Low	1.6%	1.1%	2.9%	1.9%	5.0%	2.8%
	Medium	2.4%	1.9%	4.2%	3.5%	6.9%	5.3%
	High	3.3%	2.7%	5.9%	4.8%	9.7%	6.3%
Snowy (222)	Low	1.7%	1.1%	3.1%	2.0%	5.2%	2.8%
	Medium	2.5%	2.0%	4.5%	3.6%	7.5%	5.5%
	High	3.2%	2.6%	5.8%	4.7%	10.4%	7.2%
Tambo (223)	Low	1.7%	1.2%	3.1%	2.2%	4.6%	2.8%
	Medium	2.5%	2.0%	4.5%	3.6%	7.5%	5.8%
	High	3.3%	2.8%	5.9%	5.0%	11.2%	6.7%
Mitchell (224)	Low	1.7%	0.8%	3.1%	1.4%	5.6%	3.1%
	Medium	2.6%	2.0%	4.7%	3.6%	7.9%	5.6%
	High	3.2%	2.8%	5.7%	5.0%	11.7%	6.5%
Thomson (225)	Low	1.7%	0.8%	3.1%	1.4%	5.6%	3.0%
	Medium	2.6%	2.1%	4.6%	3.7%	7.5%	5.6%
	High	3.1%	2.9%	5.7%	5.3%	11.7%	6.8%
Latrobe (226)	Low	1.4%	0.8%	2.5%	1.5%	4.8%	2.6%
	Medium	2.5%	1.9%	4.5%	3.5%	7.6%	5.3%
	High	3.2%	2.8%	5.8%	5.0%	11.3%	6.5%
South Gippsland (227)	Low	1.3%	0.9%	2.4%	1.6%	4.4%	2.4%
	Medium	2.4%	1.8%	4.2%	3.3%	7.0%	4.9%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
	High	3.0%	2.8%	5.5%	5.0%	10.9%	6.4%
Bunyip (228)	Low	1.5%	0.8%	2.6%	1.5%	4.8%	2.8%
	Medium	2.4%	1.7%	4.3%	3.1%	7.3%	5.3%
	High	3.2%	2.8%	5.7%	5.1%	10.1%	6.6%
Yarra (229)	Low	1.7%	0.8%	3.1%	1.4%	5.6%	3.1%
	Medium	2.5%	2.1%	4.6%	3.7%	7.6%	5.6%
	High	3.3%	3.1%	5.9%	5.5%	12.0%	7.0%
Maribyrnong (230)	Low	1.7%	0.9%	3.0%	1.7%	5.7%	3.2%
	Medium	2.6%	2.2%	4.8%	3.9%	7.7%	5.1%
	High	3.4%	2.8%	6.1%	5.0%	11.1%	6.8%
Werribee (231)	Low	1.6%	1.0%	2.9%	1.8%	5.7%	3.2%
	Medium	2.6%	2.1%	4.7%	3.7%	7.7%	5.1%
	High	3.3%	2.8%	5.9%	5.1%	11.5%	6.8%
Moorabool (232)	Low	1.5%	0.9%	2.8%	1.7%	5.5%	3.0%
	Medium	2.5%	1.7%	4.5%	3.1%	7.7%	5.3%
	High	3.2%	2.8%	5.7%	5.1%	10.5%	6.8%
Barwon (233)	Low	1.3%	0.9%	2.3%	1.7%	4.8%	2.6%
	Medium	2.2%	1.6%	4.0%	2.8%	7.0%	4.8%
	High	3.0%	2.8%	5.4%	5.0%	9.9%	6.2%
Lake Corangamite (234)	Low	1.2%	0.9%	2.1%	1.6%	4.8%	2.7%
	Medium	2.2%	1.6%	3.9%	2.8%	6.9%	4.8%
	High	3.0%	2.8%	5.4%	5.0%	9.8%	6.1%
Otway Coast (235)	Low	1.0%	0.9%	1.8%	1.7%	3.9%	2.3%
	Medium	2.0%	1.5%	3.7%	2.7%	6.4%	4.2%
	High	2.9%	2.6%	5.3%	4.6%	9.5%	5.9%
Hopkins (236)	Low	1.3%	0.8%	2.3%	1.5%	5.1%	2.8%
	Medium	2.3%	1.6%	4.1%	2.9%	6.9%	5.0%
	High	3.1%	2.7%	5.6%	4.9%	10.5%	6.4%
Portland Coast (237)	Low	1.1%	0.8%	2.1%	1.5%	4.2%	2.4%
	Medium	1.9%	1.3%	3.4%	2.4%	6.1%	4.0%
	High	2.8%	2.5%	5.1%	4.5%	9.0%	5.6%
Glenelg (238)	Low	1.4%	1.1%	2.6%	2.0%	5.0%	3.0%
	Medium	2.1%	1.6%	3.8%	2.9%	6.7%	4.5%
	High	3.2%	2.6%	5.7%	4.7%	10.1%	6.4%
Millicent (239)	Low	1.4%	1.1%	2.5%	2.0%	5.1%	2.7%
	Medium	2.1%	1.7%	3.8%	3.0%	6.7%	4.4%
	High	3.1%	2.5%	5.5%	4.5%	9.1%	5.8%
Upper Murray (401)	Low	1.7%	0.9%	3.0%	1.6%	5.3%	2.8%
	Medium	2.6%	2.0%	4.6%	3.6%	8.1%	5.4%
	High	3.2%	2.7%	5.7%	4.9%	10.7%	6.7%
Kiewa (402)	Low	1.8%	0.8%	3.2%	1.4%	5.6%	3.1%
	Medium	2.7%	2.2%	4.8%	3.9%	8.1%	5.7%
	High	3.1%	3.0%	5.7%	5.4%	11.4%	6.8%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Ovens (403)	Low	1.8%	0.8%	3.2%	1.5%	5.6%	3.2%
	Medium	2.7%	2.2%	4.8%	3.9%	8.1%	5.7%
	High	3.2%	2.9%	5.8%	5.2%	11.4%	6.7%
Broken (404)	Low	1.8%	0.9%	3.2%	1.6%	5.7%	3.1%
	Medium	2.8%	2.2%	5.0%	3.9%	8.0%	5.3%
	High	3.1%	2.8%	5.6%	5.0%	11.0%	6.8%
Goulburn (405)	Low	1.8%	0.8%	3.2%	1.5%	5.6%	3.2%
	Medium	2.7%	2.1%	4.9%	3.8%	8.2%	5.5%
	High	3.2%	2.9%	5.8%	5.2%	11.4%	7.0%
Campaspe (406)	Low	1.7%	1.0%	3.0%	1.8%	5.7%	3.0%
	Medium	2.6%	2.1%	4.7%	3.7%	7.8%	5.3%
	High	3.3%	2.8%	5.9%	5.0%	10.3%	6.7%
Loddon (407)	Low	1.7%	0.9%	3.0%	1.6%	5.5%	3.0%
	Medium	2.6%	2.1%	4.6%	3.7%	7.7%	5.2%
	High	3.2%	2.7%	5.7%	4.8%	9.9%	6.8%
Avoca (408)	Low	1.6%	0.9%	2.9%	1.6%	5.5%	3.0%
	Medium	2.4%	1.9%	4.3%	3.4%	7.1%	4.9%
	High	3.0%	2.6%	5.4%	4.6%	9.9%	6.5%
Lower Murray (409)	Low	1.6%	0.9%	2.8%	1.6%	5.4%	2.9%
	Medium	2.5%	1.9%	4.5%	3.5%	7.6%	5.2%
	High	3.0%	2.7%	5.3%	4.9%	10.0%	6.5%
Mallee (414)	Low	1.7%	0.9%	3.0%	1.7%	5.4%	3.2%
	Medium	2.3%	1.8%	4.2%	3.3%	7.0%	4.7%
	High	2.9%	2.5%	5.2%	4.5%	9.5%	6.0%
Wimmera (415)	Low	1.7%	1.0%	3.0%	1.8%	5.4%	3.1%
	Medium	2.3%	1.8%	4.2%	3.2%	7.1%	5.0%
	High	3.1%	2.7%	5.5%	4.9%	9.8%	6.5%
Victoria*	Low	1.7%	0.9%	3.1%	1.7%	5.4%	3.1%
	Medium	2.5%	1.9%	4.5%	3.5%	7.4%	5.2%
	High	3.0%	2.6%	5.5%	4.6%	10.2%	6.5%

* The statewide change is not an average of the changes for each river basin. This is because the river basins vary in size and some basins include areas that fall within New South Wales.

5.9 Applying climate change projections to rainfall

5.9.1 Average annual rainfall changes

The projected changes in average annual rainfall for each river basin are presented in Table 5. These should only be applied to the post-1975 historic climate reference period (not the post-1997 historic climate reference period).

In the East Gippsland Basin for example, under the RCP8.5 emissions scenario, average annual rainfall is projected to increase by up to 6.8% or decrease by up to 10.8% by 2040 relative to 1995, with a median projection of a 1.0% decrease.

In this table, the year 2020 projection has been linearly interpolated between the mid-point of the reference period climate reference period used in the global climate modelling (1995) and the year 2040 projection. The year 2040 and 2065 projections have been extracted from the GCMs by CSIRO.

Table 5 Projected change in average annual rainfall

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
East Gippsland (221)	Low	3.8%	3.1%	6.8%	5.6%	7.9%	6.6%
	Medium	-0.5%	-0.4%	-1.0%	-0.7%	-1.2%	-1.0%
	High	-6.0%	-5.1%	-10.8%	-9.2%	-15.0%	-10.9%
Snowy (222)	Low	4.2%	2.7%	7.6%	4.9%	8.5%	6.7%
	Medium	-0.8%	-0.1%	-1.4%	-0.2%	-4.5%	-1.9%
	High	-5.8%	-5.3%	-10.4%	-9.6%	-14.9%	-12.3%
Tambo (223)	Low	3.3%	3.0%	5.9%	5.4%	7.1%	5.3%
	Medium	-1.4%	-0.4%	-2.6%	-0.7%	-4.5%	-2.2%
	High	-6.0%	-6.1%	-10.8%	-10.9%	-16.6%	-13.2%
Mitchell (224)	Low	2.4%	2.3%	4.3%	4.1%	2.3%	4.0%
	Medium	-1.3%	-0.9%	-2.3%	-1.7%	-4.8%	-3.6%
	High	-5.4%	-6.8%	-9.7%	-12.3%	-18.5%	-14.8%
Thomson (225)	Low	2.3%	2.5%	4.1%	4.5%	2.3%	4.0%
	Medium	-1.1%	-0.8%	-2.0%	-1.5%	-4.1%	-3.0%
	High	-5.9%	-6.5%	-10.6%	-11.7%	-19.9%	-15.1%
Latrobe (226)	Low	1.8%	2.4%	3.3%	4.4%	2.2%	3.9%
	Medium	-2.2%	-0.7%	-4.0%	-1.3%	-4.5%	-3.9%
	High	-6.3%	-6.6%	-11.4%	-11.9%	-16.7%	-14.2%
South Gippsland (227)	Low	1.4%	2.4%	2.6%	4.4%	2.2%	4.0%
	Medium	-2.5%	-0.7%	-4.5%	-1.3%	-4.4%	-4.7%
	High	-6.5%	-7.3%	-11.7%	-13.1%	-15.9%	-13.4%
Bunyip (228)	Low	1.6%	2.4%	2.9%	4.3%	2.1%	3.7%
	Medium	-2.2%	-0.7%	-3.9%	-1.2%	-5.0%	-4.3%
	High	-6.1%	-6.6%	-10.9%	-11.9%	-16.1%	-13.9%
Yarra (229)	Low	2.0%	2.6%	3.7%	4.7%	2.4%	4.0%
	Medium	-1.5%	-0.8%	-2.7%	-1.5%	-4.3%	-2.2%
	High	-5.9%	-6.9%	-10.5%	-12.5%	-20.6%	-14.8%
Maribyrnong (230)	Low	1.5%	2.9%	2.7%	5.2%	2.6%	3.8%
	Medium	-1.3%	-0.7%	-2.4%	-1.2%	-5.5%	-3.3%
	High	-6.7%	-7.7%	-12.0%	-13.8%	-21.6%	-15.3%
Werribee (231)	Low	1.2%	2.9%	2.2%	5.2%	2.4%	3.1%
	Medium	-1.5%	-0.9%	-2.7%	-1.6%	-6.2%	-3.4%
	High	-6.5%	-8.0%	-11.7%	-14.4%	-21.4%	-16.1%
Moorabool (232)	Low	1.1%	2.8%	2.0%	5.0%	1.5%	2.3%
	Medium	-1.9%	-0.8%	-3.4%	-1.4%	-5.9%	-3.2%
	High	-6.4%	-7.9%	-11.6%	-14.3%	-21.4%	-16.1%
Barwon (233)	Low	1.1%	2.1%	2.0%	3.7%	1.2%	1.5%
	Medium	-1.7%	-0.5%	-3.0%	-0.9%	-5.2%	-3.6%
	High	-6.4%	-7.5%	-11.5%	-13.5%	-19.6%	-13.6%
Lake Corangamite (234)	Low	1.1%	2.1%	2.0%	3.7%	-0.2%	1.7%
	Medium	-2.2%	-0.7%	-3.9%	-1.3%	-5.3%	-3.9%
	High	-6.4%	-8.0%	-11.6%	-14.4%	-19.1%	-14.5%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Otway Coast (235)	Low	1.2%	2.3%	2.1%	4.1%	0.5%	1.9%
	Medium	-2.0%	-0.4%	-3.6%	-0.8%	-5.8%	-4.7%
	High	-6.5%	-7.3%	-11.7%	-13.1%	-19.0%	-13.0%
Hopkins (236)	Low	1.2%	2.0%	2.1%	3.6%	1.0%	1.5%
	Medium	-2.4%	-1.2%	-4.4%	-2.1%	-5.7%	-4.9%
	High	-6.5%	-8.3%	-11.6%	-15.0%	-20.9%	-14.7%
Portland Coast (237)	Low	1.5%	1.9%	2.6%	3.5%	-0.2%	2.5%
	Medium	-2.5%	-1.2%	-4.6%	-2.2%	-8.4%	-5.5%
	High	-6.1%	-7.6%	-10.9%	-13.7%	-19.0%	-13.6%
Glenelg (238)	Low	0.6%	1.1%	1.2%	1.9%	1.4%	2.2%
	Medium	-2.8%	-1.3%	-5.0%	-2.3%	-8.4%	-4.7%
	High	-7.1%	-7.8%	-12.7%	-14.1%	-21.7%	-14.9%
Millicent (239)	Low	0.7%	1.3%	1.2%	2.3%	1.1%	2.3%
	Medium	-3.1%	-1.6%	-5.5%	-2.9%	-8.5%	-4.9%
	High	-8.3%	-8.0%	-15.0%	-14.4%	-22.9%	-16.7%
Upper Murray (401)	Low	4.2%	3.1%	7.5%	5.5%	8.2%	6.6%
	Medium	-0.4%	-0.1%	-0.7%	-0.2%	-2.6%	-0.7%
	High	-4.7%	-5.2%	-8.5%	-9.4%	-14.4%	-14.1%
Kiewa (402)	Low	3.1%	2.7%	5.5%	4.9%	4.0%	4.5%
	Medium	-1.4%	-0.8%	-2.5%	-1.4%	-2.1%	-2.3%
	High	-5.3%	-7.1%	-9.5%	-12.8%	-16.0%	-14.6%
Ovens (403)	Low	2.9%	2.7%	5.3%	4.8%	3.8%	4.4%
	Medium	-1.9%	-0.8%	-3.4%	-1.5%	-3.7%	-2.8%
	High	-5.3%	-7.1%	-9.5%	-12.7%	-17.5%	-14.7%
Broken (404)	Low	3.3%	2.9%	6.0%	5.2%	6.8%	4.9%
	Medium	-2.0%	-0.7%	-3.7%	-1.2%	-3.5%	-2.0%
	High	-7.9%	-7.2%	-14.2%	-12.9%	-18.3%	-16.9%
Goulburn (405)	Low	2.2%	2.6%	3.9%	4.7%	2.4%	4.4%
	Medium	-1.4%	-1.0%	-2.5%	-1.8%	-4.0%	-2.4%
	High	-7.6%	-7.3%	-13.6%	-13.1%	-20.7%	-16.3%
Campaspe (406)	Low	1.3%	2.8%	2.4%	5.1%	2.6%	3.8%
	Medium	-1.2%	-0.9%	-2.2%	-1.6%	-6.1%	-3.3%
	High	-8.4%	-8.3%	-15.2%	-15.0%	-23.2%	-17.3%
Loddon (407)	Low	1.4%	3.1%	2.5%	5.5%	3.2%	4.3%
	Medium	-1.6%	-1.6%	-2.8%	-2.9%	-5.6%	-3.1%
	High	-7.9%	-8.3%	-14.3%	-15.0%	-22.9%	-17.1%
Avoca (408)	Low	2.7%	3.1%	4.8%	5.5%	6.9%	6.0%
	Medium	-2.1%	-1.3%	-3.8%	-2.3%	-3.4%	-1.4%
	High	-8.6%	-9.0%	-15.5%	-16.2%	-20.6%	-18.2%
Lower Murray (409)	Low	4.0%	3.4%	7.3%	6.2%	9.1%	7.4%
	Medium	-2.1%	-1.0%	-3.8%	-1.8%	-2.3%	-0.8%
	High	-8.4%	-6.8%	-15.0%	-12.3%	-19.1%	-16.0%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Mallee (414)	Low	2.6%	2.5%	4.7%	4.5%	6.9%	7.1%
	Medium	-3.0%	-1.3%	-5.3%	-2.3%	-6.5%	-2.3%
	High	-9.9%	-9.7%	-17.8%	-17.5%	-23.6%	-19.1%
Wimmera (415)	Low	1.1%	2.7%	2.0%	4.9%	3.9%	4.2%
	Medium	-2.1%	-1.6%	-3.7%	-2.8%	-5.9%	-3.8%
	High	-7.4%	-8.5%	-13.3%	-15.3%	-22.3%	-17.8%
Victoria*	Low	1.3%	2.2%	2.4%	4.0%	2.7%	3.3%
	Medium	-2.0%	-0.9%	-3.6%	-1.6%	-4.7%	-3.0%
	High	-5.8%	-7.6%	-10.4%	-13.6%	-19.4%	-14.9%

* The statewide change is not an average of the changes for each river basin. This is because the river basins vary in size and some basins include areas that fall within New South Wales.

5.9.2 Average seasonal rainfall changes

As discussed previously in Section 4.5, in the GCMs there is no consistency in projected seasonal rainfall changes for a given projected annual change in Victoria. For this reason, seasonal rainfall projections have not been tabulated in the guidelines. When the projected seasonal rainfall changes are considered in isolation from the projected annual changes, some spatial patterns emerge across Victoria. This is shown in Figure 20 and Figure 21 for the four seasons under RCP8.5 in 2040 and 2065, with Figure 21 highlighting the same information for the year 2065 but using the cool and warm season.

Two sources of information are presented below to better understand anticipated seasonal changes in climate under future climate change. These are (i) an overview of the GCM outputs for individual seasons (and the associated plausible range of seasonal changes for sensitivity testing climate change impacts in Appendix B.6.2), and (ii) the analysis of recent historical changes in seasonal climate behaviour. The GCM outputs do not replicate some changes in seasonal behaviour that have recently been observed, as previously discussed in Section 4.8. Recent historical changes in seasonal climate will be most relevant for short- to medium-term projections, while GCM outputs are more relevant for long-term projections.

To test the sensitivity of your river or supply system to the potential range of different seasonal rainfall projections under the RCP scenarios, refer to the tabulated ranges for this purpose in Appendix B.6.2.

GCM outputs for individual seasons

The annual projected changes are considered a reasonable indicator of the projected changes in individual seasons for both temperature and potential evapotranspiration. For example, for potential evapotranspiration, the range of annual projected changes was for a 2–6% increase in potential evapotranspiration, while, for individual seasons, the largest deviation from this range was in summer where projected changes ranged from 1–7%.

Annual projected changes in rainfall are considered a reasonable indicator of the projected direction of rainfall change in individual seasons for the medium and high climate change scenarios, but less so for the low climate change scenario, where there was less model agreement on the direction of seasonal rainfall changes. Relative to the projected annual changes in rainfall for the year 2040 time slice and relative to the post-1975 historic climate reference period:

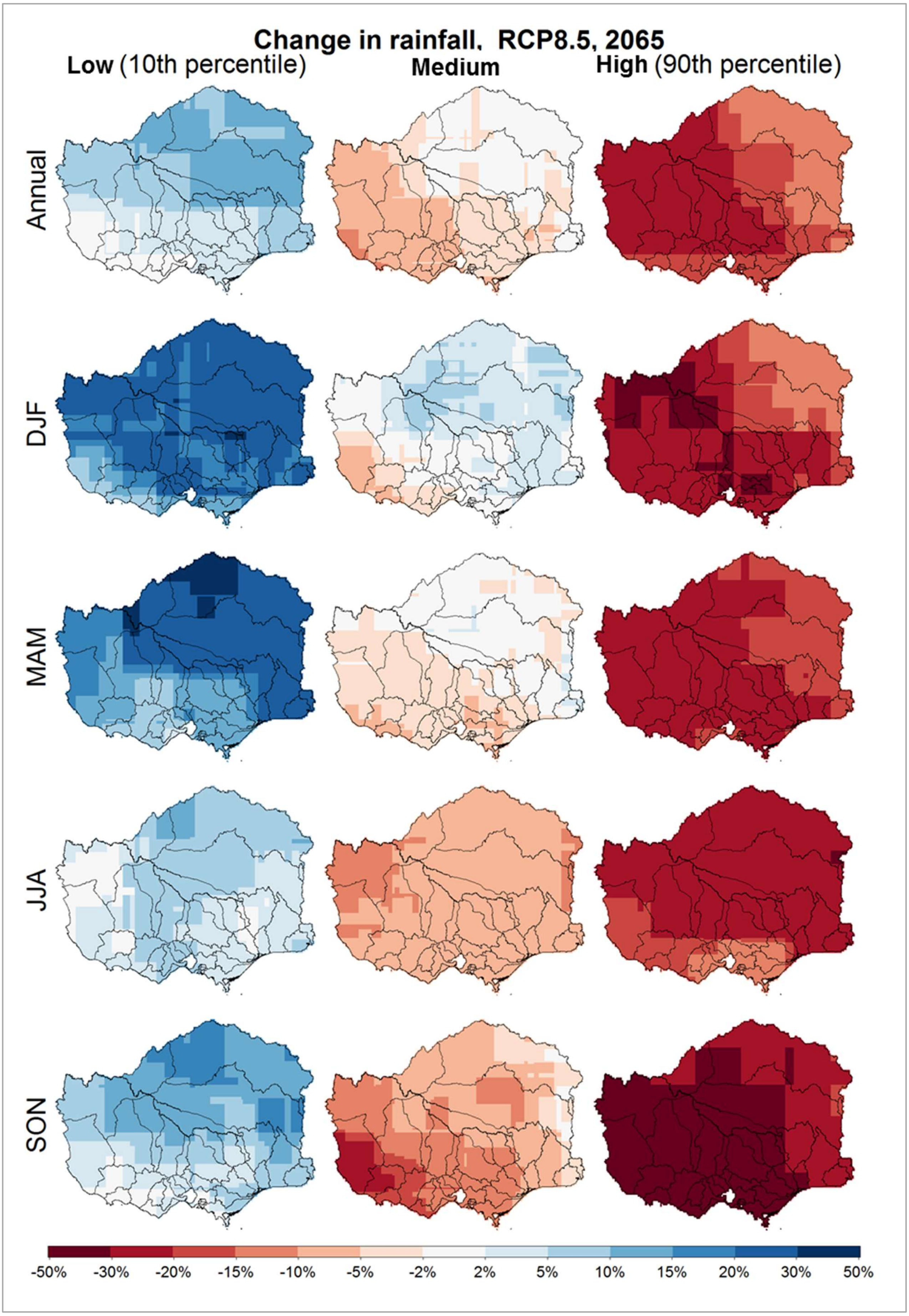

Figure 20 Projected changes in seasonal rainfall under emissions scenario RCP8.5 by 2065 relative to 1995 climate for study region, outlines correspond to Australian river basins (Source: Potter et al., 2016)

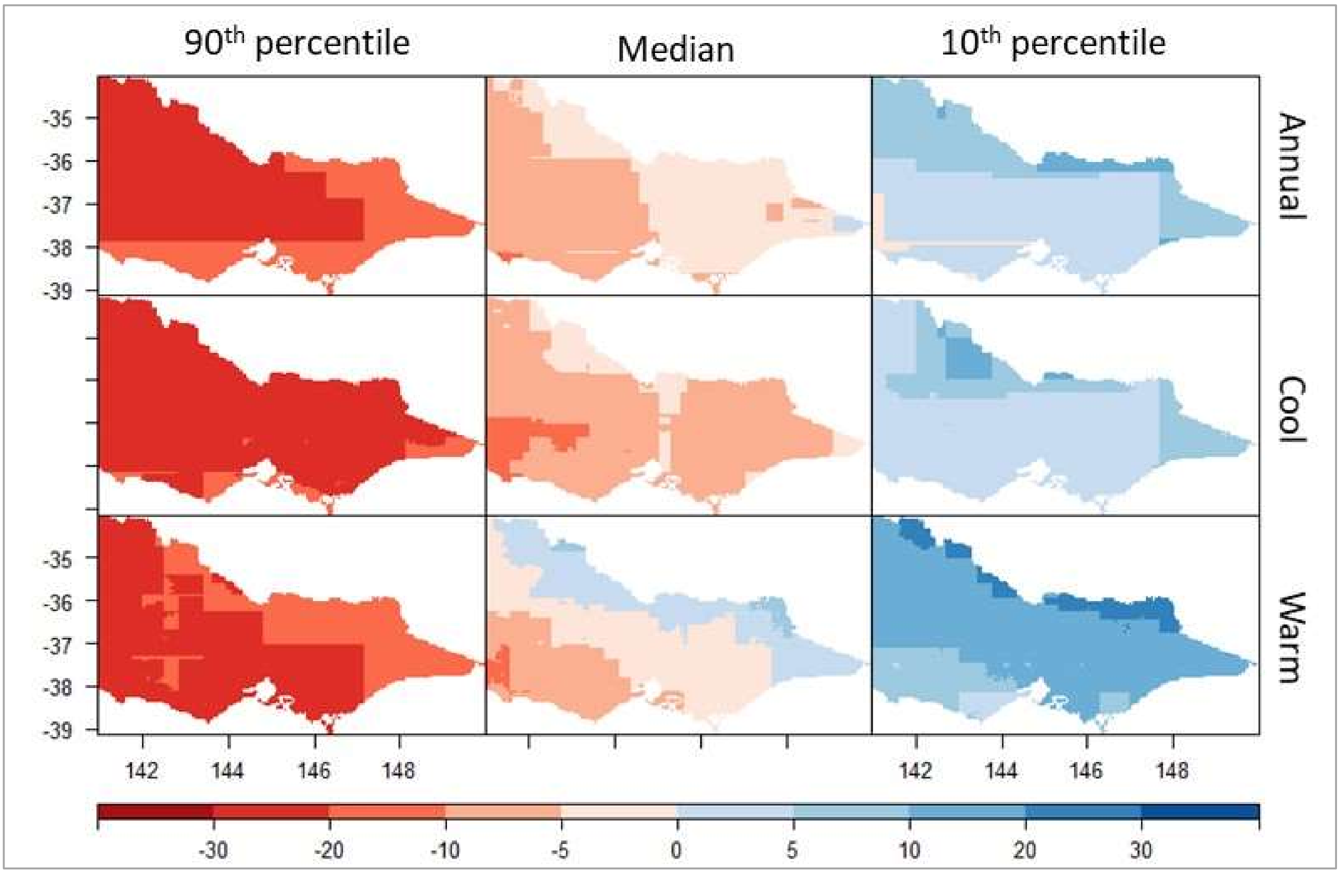

Figure 21 Projected 10th, 50th and 90th percentile cool and warm season rainfall changes (% change from 1995 value) across Victoria for RCP8.5 in the year 2065 (source: CSIRO)

- The spread of GCM results is generally wider for individual seasons than the annual changes, indicating lower model agreement of the projections for individual seasons.
- The projected low climate change scenario (which on an annual basis ranges from 1–8% wetter than the post-1975 historic climate reference period in river basins across Victoria) is estimated to be much wetter in summer (8–21% wetter than the post-1975 historic climate reference period) and autumn (8–23% wetter than the post-1975 historic climate reference period). The projected changes in winter and spring are similar to the annual changes.
- The projected medium climate change scenario (which on an annual basis ranges from 6% drier to no change from the post-1975 historic climate reference period in river basins across Victoria) is estimated to be drier in spring (11–3% drier than the post-1975 historic climate reference period), roughly the same in winter, and slightly wetter or drier in summer (-6% to +4% change relative to the post-1975 historic climate reference period) and autumn (-4% to +3% change relative to the post-1975 historic climate reference period).
- The projected high climate change scenario (which on an annual basis ranges from 18% to 8% drier than the post-1975 historic climate reference period in river basins across Victoria) is estimated to be similar or slightly drier than the annual changes in all seasons except spring, where projected changes are much drier (-26% to -17% change relative to the post-1975 historic climate reference period).
- Summer rainfall changes are generally wetter for the low climate change scenario and less dry for the high scenario in river basins north of the Great Dividing Range and in East Gippsland.

Seasonal changes in rainfall for the year 2065 time slice are similar in nature to those outlined above, but where deviations from the annual changes occur, they are typically larger. Seasonal changes in runoff are similar to those above but are amplified where deviations from the projected annual changes are expected to occur.

Recent historical observation

To gain an appreciation of local seasonal and daily changes under higher greenhouse gas concentrations, the recent historical record can be compared to earlier decades. This could include comparisons between the post-1975 historic climate reference period (1975 to date), the post-1997 historic climate reference period (1997 to date), and the instrumental record prior to the start of the post-1975 historic climate reference period (start of record to 1975). Variables that could be extracted from these datasets include changes in average seasonal values (summer/autumn/winter/spring or cool/warm season) from one period versus another period, or annual seasonal trends within or across these periods.

For example, for a representative long-term rainfall gauge at Lake Eildon, it was found that:

- Autumn rainfall over the post-1975 historic climate reference period (Jun 1975 to date) is on average 22% lower than over the period from 1902–1975, while winter/spring rainfall is roughly the same and summer rainfall was approximately 5% higher.
- In the post-1997 period, summer rainfall has remained above the 1902–1975 average, but autumn (-31%), winter (-10%) and spring (-13%) all show declines.

This provides a guide to potential seasonal changes in rainfall at this location under recent, higher greenhouse gas concentrations. Changes in cool and warm season rainfall, rainfall intensity, potential evapotranspiration and temperature could be explored in a similar way. However, drawing conclusions about historical seasonal changes from streamflow and groundwater level data can be confounded by historical water and land use changes. The use of the Bureau of Meteorology's Hydrologic Reference Stations (Bureau of Meteorology, 2016) minimises the potential for these other factors to influence historical trends driven by climate. Drawing conclusions about historical seasonal changes can also be limited by the availability of pre-1975 or pre-1997 data at any given location.

Where the potential impacts of seasonal changes in rainfall are required beyond the next decade, historically observed changes in seasonal rainfall behaviour are likely to become less relevant, and the sensitivity analysis method presented in Appendix B.6.2 is likely to be more appropriate to adopt for this purpose.

5.9.3 Changes to drought duration

Changes to drought duration can occur through the application of the average annual rainfall (and runoff) projections presented in previous sections of this chapter. Under projections drier than historical conditions, the application of these scaling factors can slightly increase the duration of rainfall and runoff below nominated thresholds. The downscaling approach adopted in the guidelines does not however change the number of rain days or their sequencing from that observed under historical conditions. As noted previously in Section 4.8, with respect to the Millennium Drought, the GCMs "do not capture spells of this duration; nor do they indicate any likely change in frequency of these prolonged no 'very wet' month spells over the coming century" (Hope et al., 2015b). As such, the GCMs do not offer further insights into changes in extreme drought duration for Victoria at the current time.

For optional testing of the sensitivity of water supplies to changes in <u>multi-year</u> drought duration, in addition to those generated by applying the annual climate change projections, it is recommended that alternative historical sampling or stochastic data generation be adopted, as per the procedures outlined previously in Section 5.3.6 and 5.4.3. For optional testing of the sensitivity of water supplies to changes in <u>within-year</u> drought duration, in addition to those changes generated by applying the annual climate change projections, it is recommended that either stochastic data generation be undertaken, or sensitivity testing directly on drought duration as per the advice in Appendix B.6.1.

5.9.4 Changes to peak rainfall

This section discusses methods to adjust peak rainfall for projected climate change, for consideration where individual supply sources **are sensitive to changes in infrequent but high intensity rainfall events**.

When assessing peak rainfall and peak flow (see Section 5.10.4), short timescales (i.e. sub-daily, hourly, or sub-hourly) are often relevant. For example, short duration storm events may lead to the highest rates of runoff in steep, small or urban waterways, and so are a consideration for Integrated Water Management (IWM) type applications. For this reason, both daily and sub-daily timesteps are considered.

Scope

Australian Rainfall and Runoff (ARR; Ball et al., 2019) is the industry guideline for the estimation of peak rainfall for design flood estimation. These guidelines do not seek to replace the guidance in ARR. Instead, this section provides information to support the assessment of water availability in Victoria, to encourage a consistent assessment approach across water supply types, and to highlight areas of active research that may supplement existing guidance, including research from the Victorian Water and Climate Initiative.

As at September 2020, the *Guidelines for Assessing the Impact of Climate Change on Sewerage Systems* were under development by DELWP. Consistency of the advice in these guidelines, and the sewerage guidelines, will be assessed as the sewerage guidelines are developed.

For peak daily rainfall

The potential physical water holding capacity of air, which is dictated by the laws of thermodynamics, changes by ~6.5% per degree of air temperature change (Guerreiro et al., 2018). This is referred to as the Clausius-Clapeyron rate.

Where individual supply sources are sensitive to changes in infrequent but high intensity rainfall events, and where modelling on a sub-daily time-step is not required, rainfall time series representing projected increases in rainfall intensity can be prepared using guidance outlined in Australian Rainfall and Runoff (Book 1, Chapter 6, Bates et al., 2019). ARR recommends a 5% increase in daily rainfall intensity per degree of local warming for rainfall within the range of probability of one exceedance per year and an annual exceedance probability of 50% to 1%.

$$I_p = I_{ARR} \times 1.05^{T_m}$$

Equation 5

Where: I_{ARR} is the design rainfall intensity (or depth) for current climate conditions (Book 2), 1.05 is the assumed temperature scaling based on the approximately exponential relationship between temperature and humidity and T_m is the temperature at the midpoint (or median) of the selected class interval (Book 1, Chapter 6, Bates et al., 2019).

The steps to prepare time series data are as follows:

1. Generate daily rainfalls for a 24 to 168-hour duration events for any location in Victoria using the Bureau of Meteorology's Intensity-Frequency-Duration Data System (http://www.bom.gov.au/water/designRainfalls/ifd/).
2. Take the rainfall record over the period of the post-1975 historic climate reference period. (Adjustments to peak rainfall in the post-1997 historic climate reference period are not recommended, except for sensitivity testing, should there be a need.)
3. For daily (i.e. 24-hour) rainfall totals that are greater than or equal to the rainfall exceeded once per year, but less than the rainfall exceeded once every 100 years, increase the rainfall by 5% per degree of local warming by use of the equation above. (Note: It is assumed that small urban catchments are most likely to be of interest for IWM type applications, and the critical duration for these catchments is likely to be short. Hence multi-day storms are not considered.)
4. All other daily rainfall should be reduced to counter the increase to peak rainfall and to account for the projected reductions in average annual rainfall. That is, the total change in annual rainfall should be equal to the projections outlined in Table 5.
5. Rainfall is projected to increase for the low climate change projection scenario in 2020–2040 for some basins. In this instance it would be necessary to increase peak rainfall and average annual rainfall. This could be simulated by first increasing the peak rainfall, and then increasing all other rainfalls so that the desired total increase is achieved.

The range of plausible scenarios that could result for 2040 is illustrated by Figure 22, overleaf.

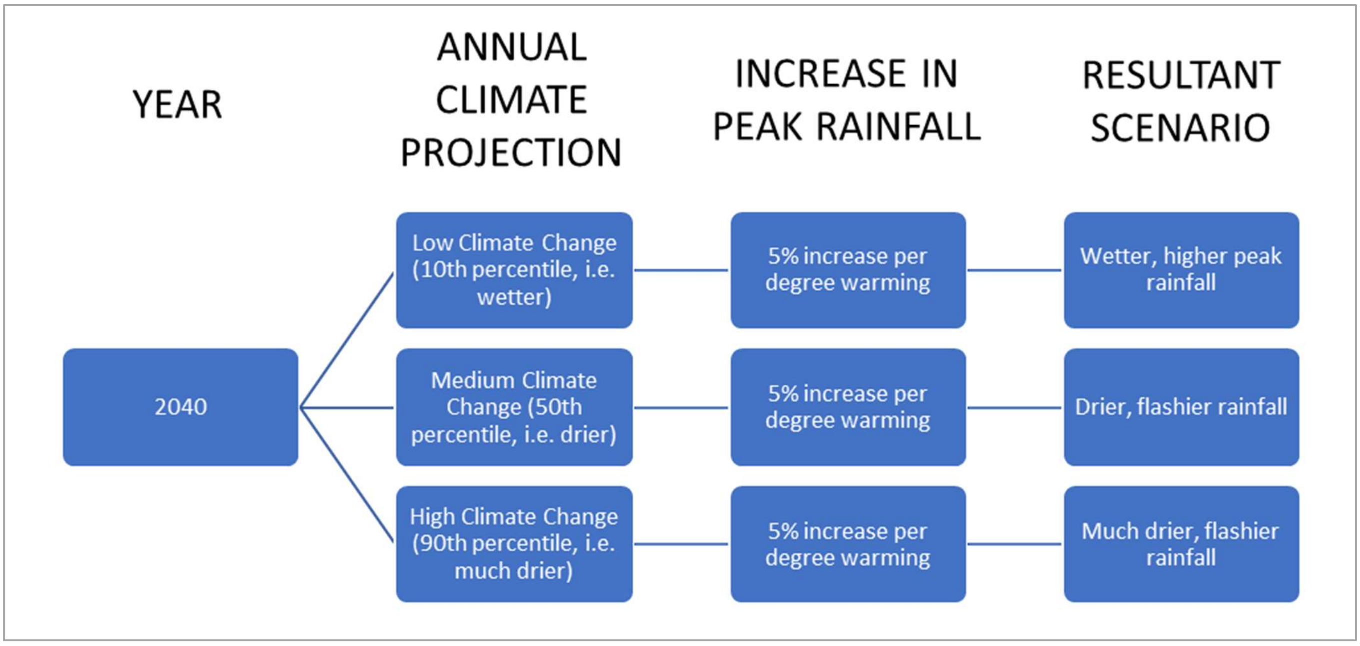

Figure 22 Plausible scenarios of 2040 water availability, coupled with increases in peak daily rainfall.

Alternative approaches

VCP19 datasets could be used as supplementary scenarios to further assess the sensitivity of planning outcomes to the assumptions in the guidelines. Estimates for the change in extreme (1-in-20-year) daily rainfall have been derived for VCP19 datasets on an annual and seasonal temporal scale for ten Victorian regions and can be accessed by use of the projected change summary Excel spreadsheets, available for download on the Climate Change In Australia website. NARCliM (Appendix B.2.2) project datasets could also be used to explore projected rainfall extremes.

For peak sub-daily rainfall (e.g. peak 30-minute rainfall)

Rainfall increases in excess of 5% per degree of warming have been widely observed for sub-daily storms (e.g. Guerreiro et al. 2018); however, the precise rate of increase differs across the research literature on this topic. This is because observed scaling rates depend on the event duration, storm type, study location, and methods of analysis. The processes causing high scaling rates are not well understood and is an active area of research. Although large uncertainties exist, a synthesis of the existing literature by Bureau of Meteorology (2019) suggests that rainfall intensities could increase by as much as 14% per degree warming.

If the scaling of sub-daily rainfall is required for the purpose of exploring water availability under projected climate change, Appendix B.7 sets out some non-prescriptive advice for consideration. This could include, for example, applications where time series pluviograph data is used for Integrated Water Management applications. Appendix B.7 draws on a known example where sub-daily rainfall has been scaled to model Melbourne's sewer network under projected climate change (HARC, 2019).

5.10 Applying climate change projections to runoff (streamflow)

5.10.1 Average annual runoff changes

The projected changes in average annual runoff for each river basin are presented in Table 6. These should only be applied to the post-1975 historic climate reference period (not the post-1997 historic climate reference period).

In the East Gippsland Basin for example, under the RCP8.5 emissions scenario, average annual runoff is projected to increase by up to 23.3% or decrease by up to 25.6% by 2040 relative to 1995, with a median projection of a 5.1% decrease.

In this table, the year 2020 projection has been linearly interpolated between the mid-point of the reference period climate reference period used in the global climate modelling (1995) and the year 2040 projection. The year 2040 and 2065 projections have been extracted from the GCMs by CSIRO.

Table 6 Projected change in average annual runoff

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
East Gippsland (221)	Low	12.9%	9.7%	23.3%	17.5%	21.4%	17.7%
	Medium	-2.8%	0.0%	-5.1%	0.0%	-8.1%	-2.0%
	High	-14.2%	-14.7%	-25.6%	-26.5%	-39.3%	-31.4%
Snowy (222)	Low	12.5%	7.7%	22.5%	13.8%	21.0%	17.3%
	Medium	-3.9%	-1.8%	-7.1%	-3.3%	-17.9%	-9.3%
	High	-14.0%	-16.6%	-25.3%	-29.9%	-36.1%	-31.8%
Tambo (223)	Low	12.9%	9.1%	23.3%	16.4%	20.6%	15.8%
	Medium	-3.3%	-0.7%	-6.0%	-1.2%	-13.1%	-7.1%
	High	-15.2%	-15.1%	-27.4%	-27.2%	-40.0%	-35.0%
Mitchell (224)	Low	5.8%	7.6%	10.4%	13.6%	1.5%	9.4%
	Medium	-6.1%	-2.5%	-11.0%	-4.5%	-15.6%	-11.3%
	High	-14.6%	-16.9%	-26.3%	-30.4%	-44.7%	-34.8%
Thomson (225)	Low	5.7%	6.0%	10.3%	10.8%	2.0%	9.3%
	Medium	-5.1%	-1.2%	-9.1%	-2.2%	-13.9%	-10.6%
	High	-15.3%	-14.8%	-27.6%	-26.6%	-41.9%	-32.0%
Latrobe (226)	Low	4.8%	6.0%	8.7%	10.8%	0.1%	9.2%
	Medium	-6.0%	-0.6%	-10.7%	-1.0%	-16.3%	-12.2%
	High	-17.4%	-17.5%	-31.3%	-31.5%	-41.5%	-35.8%
South Gippsland (227)	Low	4.9%	6.5%	8.8%	11.7%	1.6%	11.0%
	Medium	-6.6%	-0.9%	-11.9%	-1.6%	-16.9%	-15.3%
	High	-18.7%	-20.7%	-33.7%	-37.2%	-44.8%	-33.3%
Bunyip (228)	Low	5.9%	5.8%	10.6%	10.5%	1.5%	11.4%
	Medium	-7.6%	-0.7%	-13.7%	-1.2%	-19.1%	-12.4%
	High	-18.3%	-19.7%	-33.0%	-35.5%	-47.0%	-33.6%
Yarra (229)	Low	5.6%	5.9%	10.0%	10.6%	0.8%	8.7%
	Medium	-6.1%	-1.7%	-11.0%	-3.1%	-16.4%	-11.4%
	High	-16.2%	-16.7%	-29.2%	-30.0%	-44.3%	-34.0%
Maribyrnong (230)	Low	8.3%	11.8%	15.0%	21.3%	5.1%	12.8%
	Medium	-7.3%	-0.7%	-13.2%	-1.2%	-20.0%	-9.7%
	High	-18.4%	-23.8%	-33.1%	-42.9%	-55.4%	-40.0%
Werribee (231)	Low	6.5%	9.2%	11.8%	16.5%	7.5%	10.7%
	Medium	-4.3%	-2.1%	-7.7%	-3.8%	-18.1%	-7.6%
	High	-16.1%	-19.4%	-28.9%	-35.0%	-45.5%	-36.5%
Moorabool (232)	Low	7.5%	11.1%	13.5%	20.0%	5.5%	10.5%
	Medium	-4.5%	-0.6%	-8.0%	-1.1%	-17.3%	-7.1%
	High	-16.9%	-20.4%	-30.4%	-36.7%	-45.6%	-38.7%
Barwon (233)	Low	9.0%	12.2%	16.1%	21.9%	-0.8%	9.8%
	Medium	-3.4%	-0.4%	-6.1%	-0.7%	-21.6%	-15.6%
	High	-18.4%	-20.9%	-33.1%	-37.7%	-47.6%	-37.7%
Lake Corangamite (234)	Low	9.9%	13.6%	17.9%	24.4%	-2.5%	11.3%
	Medium	-5.7%	-2.0%	-10.2%	-3.6%	-26.1%	-18.8%
	High	-20.3%	-24.4%	-36.5%	-44.0%	-53.0%	-40.9%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Otway Coast (235)	Low	3.6%	6.8%	6.6%	12.2%	-4.7%	5.2%
	Medium	-4.0%	-2.3%	-7.2%	-4.2%	-15.8%	-14.4%
	High	-14.1%	-15.3%	-25.3%	-27.6%	-41.9%	-30.0%
Hopkins (236)	Low	8.3%	12.7%	14.9%	22.8%	-5.2%	10.5%
	Medium	-7.2%	-3.5%	-13.0%	-6.3%	-28.5%	-20.0%
	High	-19.8%	-25.6%	-35.7%	-46.0%	-59.8%	-42.2%
Portland Coast (237)	Low	8.6%	11.6%	15.5%	20.9%	-2.7%	10.0%
	Medium	-6.0%	-5.3%	-10.8%	-9.5%	-30.4%	-22.1%
	High	-20.0%	-23.1%	-36.0%	-41.6%	-54.8%	-42.7%
Glenelg (238)	Low	4.2%	7.2%	7.6%	13.0%	-3.4%	5.6%
	Medium	-7.6%	-5.8%	-13.6%	-10.4%	-31.4%	-22.5%
	High	-20.7%	-22.6%	-37.3%	-40.7%	-60.8%	-41.5%
Millicent (239)	Low	7.2%	6.0%	13.0%	10.8%	-0.5%	5.5%
	Medium	-5.5%	-4.2%	-10.0%	-7.5%	-27.5%	-19.2%
	High	-19.6%	-20.2%	-35.2%	-36.3%	-57.3%	-40.3%
Upper Murray (401)	Low	9.5%	8.1%	17.2%	14.5%	13.5%	16.3%
	Medium	-4.7%	-2.9%	-8.4%	-5.2%	-16.6%	-5.6%
	High	-12.9%	-14.7%	-23.3%	-26.4%	-39.4%	-37.4%
Kiewa (402)	Low	6.2%	6.8%	11.2%	12.2%	1.5%	9.4%
	Medium	-5.0%	-2.7%	-9.1%	-4.8%	-12.1%	-13.5%
	High	-12.5%	-17.1%	-22.4%	-30.7%	-39.4%	-34.2%
Ovens (403)	Low	6.5%	7.1%	11.7%	12.8%	1.2%	9.6%
	Medium	-6.0%	-3.3%	-10.8%	-6.0%	-15.7%	-15.9%
	High	-12.9%	-17.2%	-23.3%	-31.0%	-43.9%	-34.4%
Broken (404)	Low	10.3%	10.2%	18.6%	18.4%	8.1%	12.0%
	Medium	-5.4%	-3.7%	-9.7%	-6.7%	-16.8%	-12.6%
	High	-19.9%	-20.2%	-35.9%	-36.3%	-50.0%	-38.4%
Goulburn (405)	Low	5.5%	6.8%	9.9%	12.2%	1.3%	8.1%
	Medium	-5.3%	-2.1%	-9.5%	-3.8%	-13.7%	-11.7%
	High	-16.1%	-15.9%	-29.1%	-28.7%	-41.9%	-33.1%
Campaspe (406)	Low	5.8%	11.6%	10.5%	20.8%	1.0%	9.1%
	Medium	-6.8%	-3.6%	-12.3%	-6.4%	-20.7%	-12.3%
	High	-20.6%	-24.4%	-37.1%	-43.9%	-57.0%	-43.6%
Loddon (407)	Low	6.9%	17.5%	12.4%	31.5%	6.9%	13.6%
	Medium	-4.1%	-4.7%	-7.4%	-8.5%	-17.6%	-14.1%
	High	-20.3%	-21.1%	-36.6%	-38.0%	-57.6%	-43.0%
Avoca (408)	Low	12.7%	19.1%	22.8%	34.3%	25.5%	21.9%
	Medium	-0.2%	-1.3%	-0.4%	-2.4%	-8.8%	-1.3%
	High	-16.2%	-16.3%	-29.1%	-29.4%	-44.4%	-40.8%
Lower Murray (409)	Low	18.2%	12.0%	32.8%	21.6%	27.1%	29.3%
	Medium	-2.5%	0.7%	-4.6%	1.2%	-11.4%	-5.4%
	High	-20.8%	-15.3%	-37.5%	-27.6%	-47.0%	-39.3%

River basin (and basin number)	Projection	Change relative to 1995 (%)					
		Year 2020		Year 2040		Year 2065	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Mallee (414)	Low	22.4%	18.1%	40.3%	32.5%	42.1%	31.0%
	Medium	2.5%	0.8%	4.6%	1.4%	-5.8%	1.4%
	High	-13.9%	-17.4%	-25.0%	-31.3%	-49.0%	-41.8%
Wimmera (415)	Low	6.7%	11.7%	12.1%	21.0%	12.3%	11.5%
	Medium	-3.6%	-2.4%	-6.5%	-4.4%	-14.4%	-12.0%
	High	-18.0%	-18.8%	-32.3%	-33.8%	-53.1%	-38.6%
Victoria*	Low	4.8%	7.8%	8.7%	14.0%	1.5%	9.4%
	Medium	-4.7%	-0.9%	-8.5%	-1.6%	-15.9%	-11.1%
	High	-13.7%	-16.2%	-24.7%	-29.1%	-43.8%	-33.3%

* The statewide change is not an average of the changes for each river basin. This is because the river basins vary in size and some basins include areas that fall within New South Wales.

5.10.2 Average seasonal runoff changes

Projected average seasonal runoff changes under climate change can be qualitatively inferred from the average seasonal rainfall changes discussed in Section 5.9.2; noting, however, that changes in runoff may lag rainfall, and that runoff can change significantly above or below minimum rainfall or soil moisture thresholds for runoff generation. A rainfall-runoff model or the examination of historical relationships between rainfall and runoff may help to inform likely changes in average seasonal runoff for a given change in average seasonal rainfall.

5.10.3 Changes to rainfall-runoff behaviour

Research, including by the University of Melbourne through the Victorian Water and Climate Initiative, has identified that during the Millennium Drought many catchments generated less streamflow than would be expected under previously observed rainfall-runoff relationships. The largest reductions were generally observed in the west of the state. Of the 156 catchments that had suitable data to undertake the analysis, Figure 23 shows catchments where a statistically significant shift has occurred (red, orange and green), catchments that have recovered following the drought (green), and catchments that have not experienced a statistically significant shift (blue). The research indicates that under a future drier climate scenario, downward shifts in rainfall-runoff relationships can be expected in these catchments, and additional catchments may plausibly also shift into a lower runoff state under future drier conditions.

Research has also found that where a shift in the rainfall-runoff relationship occurred, rainfall-runoff models can over-estimate runoff during long-run droughts (e.g. Saft et al., 2016; Fowler et al., 2020). The streamflow projections provided in this document have been developed using rainfall-runoff models, but because these models have been calibrated to a period of observed record that includes the Millennium Drought they may largely, or only partly, incorporate the shift in rainfall-runoff response. The extent to which the streamflow projections provided in these guidelines potentially under-estimate runoff declines under drier climate change projections due to the shift in runoff response is the subject of further research. DELWP will advise users of the guidelines when further information is available for individual catchments across Victoria.

More information about this research is outlined in Appendix B.9 and in *Victoria's Water in a Changing Climate* (DELWP et al., 2020).

Downward shifts in rainfall-runoff relationships in some catchments in and after extended drought may not be fully represented in climate change runoff projections. Further information on this research is outlined in *Victoria's Water in a Changing Climate* (DELWP et al., 2020). DELWP will advise users of the guidelines when further information is available to address this issue for individual catchments across Victoria.

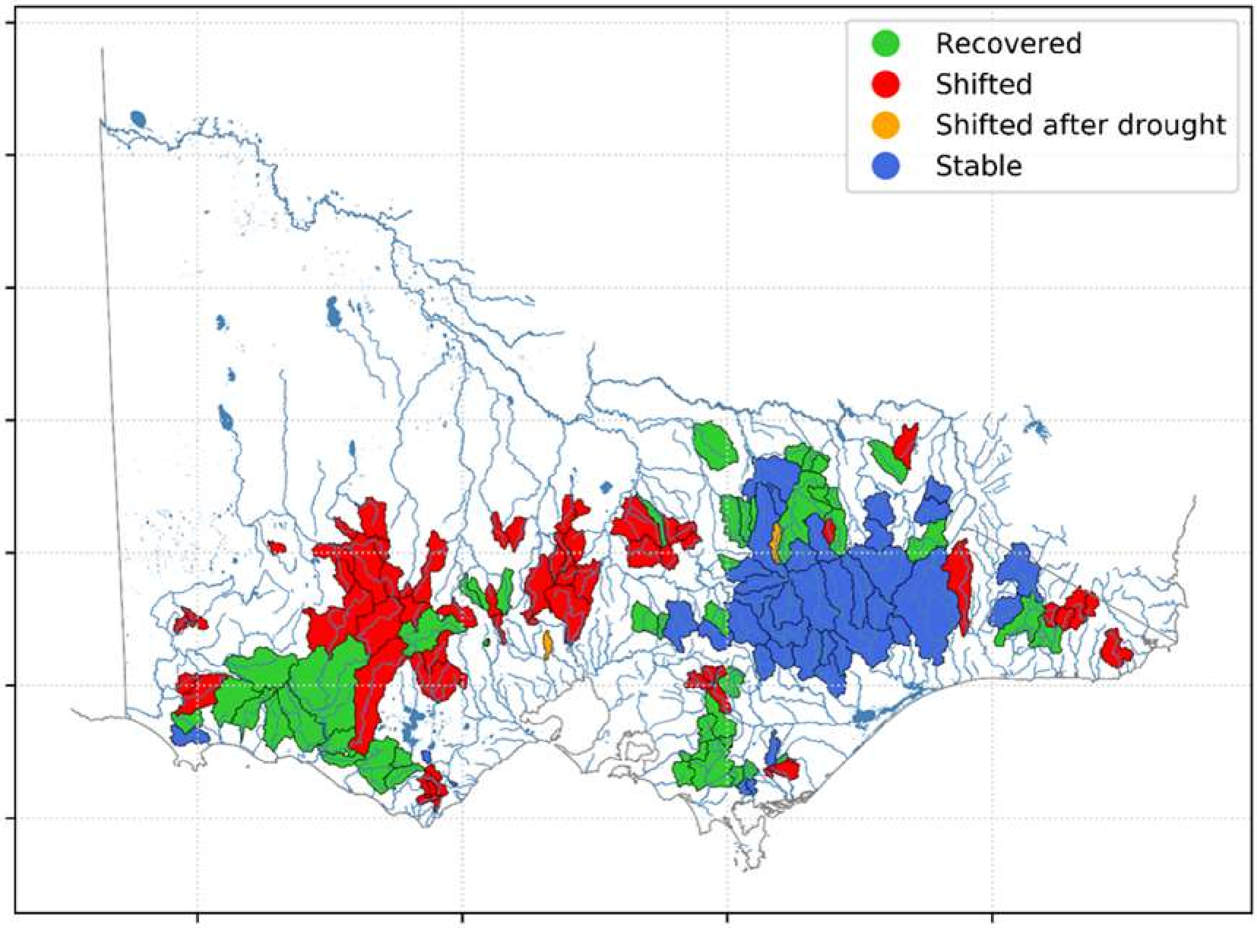

Figure 23 Shift in catchments hydrological response and recovery across Victorian catchments during and after the Millennium Drought. [Source: The University of Melbourne]

5.10.4 Changes to peak flows

Australian Rainfall and Runoff (ARR; Ball et al., 2019) is the industry guideline for design flood estimation.

For water supply systems **that are sensitive to changes in peak rainfall**, the guidance in Section 5.9.4 can be used to adjust historic rainfall time series data to account for projected climate change. This is done by increasing peak rainfall in combination with projected changes to average annual rainfall. These rainfall time series can then be input to rainfall-runoff models to model the impact on water supply systems.

For most water supply systems, adjusting the rainfall inputs for increases in peak rainfall will have little impact on total water availability. This is because rainfall intensities are only increased on days where the rainfall depth is greater than or equal to the rainfall exceeded once per year, and because this increase is balanced by changes to average annual rainfall.

Previous applications (e.g. Jacobs 2020) have found that when increased rainfall intensities for rare events are modelled in conjunction with reductions in average annual rainfall, the magnitude of frequently occurring floods will decline, while the magnitude of rarer floods will increase. This is consistent with recent observations — which indicate that drier antecedent conditions are modulating the impact of increasing rainfall intensities in the historic record — for frequently occurring rural floods (Wasko and Nathan, 2019).

5.11 Applying climate change projections to groundwater

5.11.1 Introduction

Recharge comes from rainfall (diffuse recharge), flooding (flood recharge) and/or from irrigation accessions in irrigated areas. Some groundwater systems are also recharged from streams where they are highly connected or receive increased recharge from preferential pathways such as in basalt (via fractures) and limestone (karstic systems). These systems are generally more responsive to climate.

Climate change may affect rates of recharge and the future availability of groundwater. To assess groundwater resource availability a conceptual model of the system is required, as well as an understanding of how the system is recharged. Some of the key concepts related to this conceptualisation are discussed in Appendix B.10.

Climate change may increase the frequency of high intensity rain events that provide significant recharge events for systems. It may also alter irrigation practices if summer rains increase and alter flood events and stream recharge events to groundwater systems. The variability and complexity of each system means that it is essential that the recharge mechanism to any groundwater system is known prior to any assessment of the resource.

These guidelines provide advice only on how the recharge rates should be estimated to consider climate change projections. They do not provide advice on how to assess the resource, or to undertake groundwater modelling. Industry standards should be referred to for further information, including the *Australian Groundwater Modelling Guidelines* (Barnett et al., 2012).

In Victoria, resource managers (not the licensed user) are responsible for licensing groundwater take up to prescribed limits (set by the Permissible Consumptive Volume; PCV).

5.11.2 Groundwater resources that require assessment of climate change impacts

Some aquifers are more sensitive to changes in climate than others. The most vulnerable systems are those with shallow watertables and highly responsive systems. **The approach below is primarily for sedimentary aquifers that are unconfined with depths to watertable less than 20 metres**. For any other systems, local conditions should be considered and factored into any assessment of the resource. For highly responsive systems the percentage change in runoff can be used instead of the percentage change in rainfall for that catchment to provide a more conservative estimate.

The dependency of an urban Water Corporation, or other user of groundwater, on a given groundwater resource dictates the level of investment recommended to model the groundwater system. Water Corporations should consider the reliability of the supply, and the dependency on groundwater (e.g. whether it is the sole supply source, or a drought supply only). Additionally, as for any groundwater assessment, the availability of data and information to undertake the study should be considered.

5.11.3 Historic recharge rates for analytical modelling of groundwater systems in Victoria

Prior investigations into recharge in Victoria provide indicative recharge rates for the different aquifer systems defined by the Victorian Aquifer Framework (https://discover.data.vic.gov.au/dataset/victorian-aquifer-framework-vaf-3d-surfaces). These prior investigations provide bulk recharge rates that include all forms of recharge to the system. The investigations were undertaken between 1970 and 2018 and are representative of the post-1975 historic climate reference period. The results represent the 25th percentile, the 50th percentile (or median) and the 75th percentile of the estimated annual recharge rates for an aquifer (Table 7). Due to the uncertainty in the recharge rates it is recommended that all three are used, in conjunction with rainfall or runoff climate change projections to determine the sensitivity of the resource to changes in recharge. If there are studies into recharge in the area and/or more recent investigations that provide alternative recharge rates, these may be used as the reference period recharge rate for this assessment.

Table 7 Reference period outcropping recharge estimates (1st to 3rd quartiles and median, mm/yr) for major aquifer systems, statistics and tabulated values

Victorian Aquifer Framework (VAF) Names	VAF Reference	1st Quartile (25th %ile)	Median (50th %ile)	3rd Quartile (75th %ile)
Basement	BSE	14	23	34
Lower Tertiary Basalt (LTBA)	LTBA	37	54	74
Lower Tertiary Basalt (LTBB)	LTBB	26	40	87
Lower Tertiary Aquifer	LTA	13	17	48
Lower Mid-Tertiary Aquifer	LMTD	16	26	34
Upper Mid-Tertiary Aquifer	UMTA	21	34	60
Upper Tertairy Aquifer Fluvial	UTAF	15	20	27
Upper Tertiary Aquifer Marine	UTAM	9	17	40
Upper Tertiary Basalt	UTB	22	30	39
Upper Tertiary Quaternary	UTQA	14	22	35
Quaternary	QA	12	24	43

When applying the values in Table 7, note that:

- Recharge rates are determined from prior assessments including field studies and investigations and, in some instances, groundwater models.
- These recharge rates include irrigation accessions and flood recharge in some cases and so should be used with caution for areas that are recharged solely by diffuse (rainfall driven) recharge.
- Local conditions need to be considered when using these rates:
    - Fractured rocks (limestone, basalts) may have different recharge rates (higher) rates.
    - Unconfined aquifers with greater depths to watertable may have much lower recharge rates.
    - Aquifers that are highly connected to waterways may have much higher rates of recharge.

5.11.4 Approach for including climate change in recharge assessments

Two levels of investigation are proposed here: a simple analytical approach and a more complex groundwater modelling approach. The method to determine the recharge rates for both modelling approaches is provided below. The best available data and information should be used to inform the assessment. Where recent studies have been undertaken into recharge or there is new advice on climate change impacts, these should be considered in the approach taken. Note recharge is only one aspect of assessing groundwater availability, and consideration also needs to be given to changes in flux (aquifer discharge), leakage between aquifers, and changes in aquifer storage, none of which are part of these guidelines.

Step 1: Identify the approach required and whether an assessment is needed.

Is the aquifer sensitive to climate change?

- Is the aquifer sedimentary and unconfined with a depth to watertable less than 20m?
- Is the aquifer highly responsive to rainfall and/or changes in streamflows?

What reliability and dependency does the water authority have on this source?

- Water corporation should determine what level of risk they can accept for the source to determine the level of investigation required. Things to consider are dependency and level of reliability required from the borefield.

What data and information is available on the groundwater resource to inform this assessment?

- For investigations into areas with limited information it is recommended that an analytical approach is used to assess the potential impact of climate change on recharge.
- For investigations into areas with more data and information and a highly developed conceptual model, authorities may like to undertake more detailed groundwater modelling. If the risk to the resource is low then an analytical approach is also appropriate to use.

Step 2: Methodology for each approach (numerical modelling or analytical modelling)

Analytical modelling approach

- Determine what aquifer under the Victorian Aquifer Framework (VAF) that the resource is from and select appropriate recharge rates (25, 50 and 75th percentiles) from Table 7.
- Determine where the recharge area is and what surface water catchment it sits in to determine the % change in rates of rainfall from Table 5.
- If local conditions show that the system is highly responsive and a more conservative approach is needed, apply the change in runoff figures for that catchment (Table 6) instead of the % change in rainfall (Table 5).
- Use the techniques in Section 5.6 to develop climate change runoff projections.
- Use recharge estimates from the analytical models to determine volumetric change in resource availability (ie supply) due to climate change.

Groundwater modelling

- determine where the recharge area is and what surface water catchment it sits in to determine the % change in rates of rainfall from Table 5.
- Identify an appropriate rainfall gauge to construct the climate baseline for the relevant recharge area.
- Use the techniques in Section 5.6 to develop climate change runoff projections.
- Use rainfall estimates to determine recharge for the model (e.g. unsaturated zone modelling, other) and determine change in resource availability (ie supply) due to climate change.
- Determine change in resource availability (i.e. supply) due to climate change.

In addition to direct impacts on recharge urban authorities should consider other possible impacts on supply.

Step 3: Indirect impacts and issues for consideration in determining supply and demand for groundwater sourced urban water supplies.

Is the borefield within a groundwater management area? And if so, does it have any restrictions that may be brought in during periods of drought?

- Check applicable management plans for restrictions on allocations. If there are restrictions, include these in the assessment of supply from the borefield.

Review previous periods of drought / water scarcity to determine any potential impacts on borefield operations.

- If water levels have previously declined in the region due to either reduced inflows or increased demands near the borefield, use these historic levels to determine whether under these conditions there would be an impact on bore yields and supply in the future.

5.12 Applying climate change projections to water demands

Hotter and drier conditions increase the demand for water, notably for private garden watering and the irrigation of municipal parks, gardens, sporting fields, stock and domestic use, and commercial irrigation. Under a hotter and drier climate future in Victoria, demands would be expected to increase, placing an additional strain on water resources over and above the reductions in water availability previously outlined.

Water Corporations have existing climate dependent demand models for either total water use or the residential component of most urban water supply systems, and for irrigation demands in the state's irrigation districts. In this case, these demand models can simply be applied using input climate variables that have been adjusted for climate change using the projected changes previously outlined in these guidelines. An overview of this process is presented in Figure 24, with more detail for each demand type in the sub-sections below. When selecting suitable climate variables, step-wise regression is recommended. This involves testing different climate variables and assessing their influence on the goodness of fit for the modelled demands.

Where a demand model does not currently exist, consideration can be given to testing the sensitivity of the supply system to changes in demand similar to those estimated for nearby towns or irrigation areas which have a demand model. Where the sensitivity is low, changes in demand under climate change can be dismissed. Where sensitivity is high, consideration should be given to fitting a climate dependent demand model, or using the responses from climate dependent demand models in nearby towns or irrigation areas to inform whether changes to demand projections under climate change are warranted.

Other long-term shifts in demand in response to climate change can also occur, such as changes in the way water is used and for what purpose. These responses are often difficult to predict. Workshop scenario planning, for example, could be useful for generating narratives around water use under alternative climate futures.

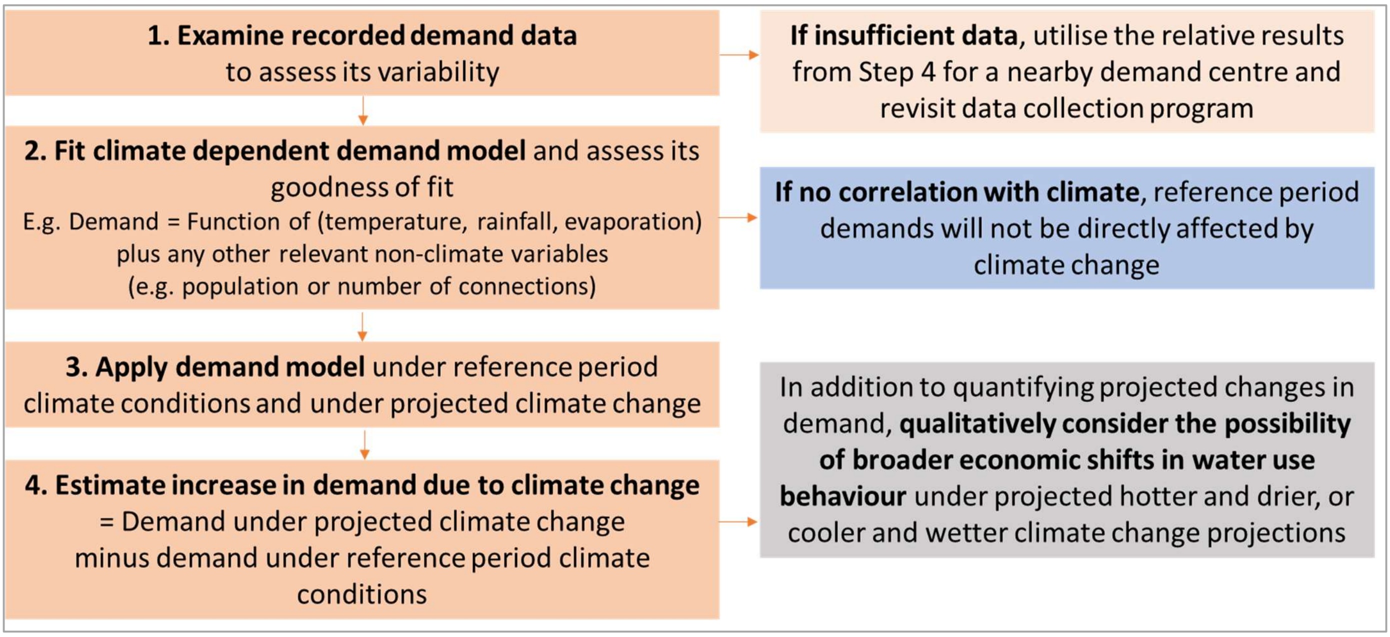

Figure 24 Overview of process for adjusting demands for projected climate change

5.12.1 Urban water demands

Residential and municipal demands will typically vary with climate, primarily due to increasing demand for outdoor parks and garden watering under hotter and drier conditions, and decreasing demand under cooler and wetter conditions. This variability can occur on an hourly, daily, seasonal and annual time step. Industrial and commercial water use may or may not be correlated with climate, depending on the nature of individual businesses. Water Corporations are best placed to liaise with major industrial customers to assess the sensitivity and vulnerability of their demands to climate change, and to utilise metered consumption data to assess the climate sensitivity of demands for non-residential customer groups. Non-revenue water attributable to losses is generally correlated with water use and hence will also vary with climate.

There may also be secondary influences from climate variability and climate change on urban water use that are more difficult to quantify, particularly when they are driven by extreme events. For example, increases in days of extreme heat during peak holiday periods could drive tourist numbers at certain times towards some regions (e.g. coastal towns) and away from other regions (e.g. inland towns in bushfire prone areas), with a corresponding impact on demand for water in tourist accommodation. Water use behaviour in historical extreme climate events may provide an insight into these sensitivities.

Changes in peak daily demands can also occur under climate change, which are associated with increases in temperature on very hot days. For changes in peak day demands, the projected changes in peak day temperature in Section 5.7.2 can be drawn upon.

For urban demand models that rely upon correlations with temperature and/or evaporation, the medium temperature and potential evapotranspiration projections provided in Table 3 and Table 4 will be sufficient for most applications. Where a Water Corporation considers that GCM uncertainty in temperature or potential evapotranspiration projections is likely to significantly impact the supply-demand balance, the uncertainty characterised by the low and high temperature and potential evapotranspiration projections in Table 3 and Table 4 can be explored for that purpose if desired. For most urban water supply systems, projected changes in rainfall and runoff will dominate the nature of that supply-demand balance. In contrast, the uncertainty in the projections for potential evapotranspiration and temperature will contribute a much lower degree of uncertainty to the supply-demand balance.

> For urban demand models that utilise temperature and/or evaporation, only the medium climate change projection for these variables need be applied.

Demands in major cities could be more severely affected by rising temperatures than smaller towns due to urban heat island effects in major cities. Urban heat islands are defined and characterised in the VCP19 technical report (Clarke et al., 2019a). An urban heat island refers to the increased daily minimum near-surface (2 m) air temperature in urban areas due to the storage of heat in buildings and roads. Most major Australian cities have an urban heat island of 1°C to 2°C, depending on the nature of the local built environment. The size of the urban heat island is usually estimated by comparing measurements of daily minimum temperature from the fringe of the city with that at the city centre, inferring the enhanced warming in daily minimum temperature due to the presence of the city. For example, in Melbourne, there is a 2°C urban heat island effect between the city centre and Laverton or Cranbourne. The regional climate model used in the VCP19 projections was demonstrated to much more accurately represent current urban heat island effects in urban areas compared to GCMs. The specific change in the magnitude of the urban heat island effect was not presented in the VCP19 projections (Clarke et al., 2019a). If the projected change in the urban heat island effect on demands were considered to be of significance, the VCP19 projections for minimum temperature in the city centre and reference surrounding areas would need to be extracted and compared between reference period and future conditions.

5.12.2 Rural water demands

Irrigation demands can be estimated using a variety of techniques. The most common approach currently in Victoria is the use of the Program for Regional Irrigation Demand Estimation (PRIDE) irrigation demand model (DSE, 2007). This model estimates daily crop water requirement using an input time series of rainfall and evaporation. The climate change projections for average annual rainfall and evaporation, previously presented in Sections 5.8 and 5.9, can be applied to these input time series to estimate the changes in crop water requirement under projected climate change.

Stock and domestic demands are typically small in volume in comparison to irrigation demands, and the drivers of the variability in demand for stock and domestic water use will depend upon the proportion of in-house use (which is typically invariable with climate) and the type and number of stock being supplied. Unless evidence is provided to the contrary for any given application, it is recommended that climate change projections need not be applied to stock and domestic water use for direct diversions from rivers in rural areas.

Industrial and commercial water use may or may not be correlated with climate, depending on the nature of individual businesses. Water Corporations are best placed to liaise with major industrial customers to assess the sensitivity and vulnerability of their demands to climate change, and to utilise metered consumption data to assess the climate sensitivity of demands for these customer groups.

Changes to water usage resulting from structural changes to the economy arising from climate change (such as a transition to a low-carbon economy) are outside the scope of these guidelines. Such changes will be informed by ongoing monitoring of trends in water consumption by Water Corporations and individual water users.

5.12.3 Farm dams

Farm dam demands are typically estimated in Victoria using the Spatial Tool for Estimating Dam Impacts (STEDI) model (SKM, 2011) or variants thereof (e.g. the ADAM model in Morden, 2017). The STEDI model performs a water balance on farm dams using a time series of input runoff and net evaporation, and assuming that demand is a fixed percentage of the dam capacity. The climate change projections for average annual runoff, rainfall and evaporation, previously presented in Sections 5.8 to 5.10, can be applied to these input time series to estimate the changes in farm dam behaviour under projected climate change. By default, STEDI does not allow changes in consumptive demand for water to be directly altered due to projected changes in rainfall and evaporation. For this purpose, a crop water requirement model (see Section 5.12.2) could be utilised, if desired. However, given the uncertainties in this assumption under reference period climate conditions, this additional level of analysis would be unwarranted in most applications.

5.12.4 Environmental water demands

Minimum environmental water demands have been established in rivers across Victoria using the FLOWS method (DEPI, 2013). These demands have been set with reference to the historical climate conditions under which ecosystems have developed. Precisely understanding current environmental water demands is difficult, but a broad understanding can be obtained through a combination of observations and expert opinion. Understanding how ecosystem water requirements might or might not change under higher greenhouse gas concentrations in the atmosphere, and under projected climate change, involves even greater complexity and uncertainty. In many cases the response (if any) will be unique to the plant and animal species that dwell in any given location. For the purposes of modelling river or water supply systems, it is recommended that existing minimum environmental water demands should be assumed to be retained under projected climate change, unless specific ecological advice has otherwise been provided for your river or water supply system.

5.13 Applying climate change projections to performance metrics

For long-term water planning, the climate change projections can be applied to assess different streamflow characteristics or supply system performance under projected climate change. This section provides guidance on applying climate change projections to performance metrics, including supply system yield, supply system reliability and environmental flow compliance.

There are a range of different performance metrics that can be used to assess water availability, supply system performance or the achievement of environmental flow objectives. These guidelines do not provide advice on which metric should be used for a particular purpose, but other guidance may — for example the *Guidelines for the Development of Urban Water Strategies and the Melbourne Water System Strategy* (DELWP, 2020a).

Measures of water availability and supply system performance can include:

- Volume available within licence or entitlement limits — the volume that can be harvested from the source without considering water demands or level of service criteria.
- Supply system yield — the volume that can be harvested to supply a demand at a given level of reliability.
- Reliability of supply — the frequency of restrictions or shortfalls in supplying demands, the duration of restrictions or shortfalls in supplying demands, the percentage of time below a given threshold volume in storage, etc.
- Other measures directly relevant to the supply system.

Measures of reliability can also relate to other river system objectives such as their ecological performance including:

- Environmental flow compliance — criteria may include the frequency of freshes, and the frequency and duration of cease to flow events.

An example supply-demand projection for a water supply system is illustrated in Figure 25. The vertical axis in this figure can be expressed as a volume (e.g. for comparing supply system yield directly against demand) or as some other performance measure, such as the annual reliability of supply. For illustrative purposes only, demand and yield in Figure 25 are shown as being linear over time, but this may not necessarily be the case. The range of projections at the current point in time (~2020) may compress to two or one points if yield is identical under the three climate change projections from 1995 to now. Equally, as discussed below, the performance metrics and/or the projected demand may respond non-linearly to projected changes in climate and runoff.

The uncertainty in the climate change projections can result in a range of possible dates for when levels of service for reliability of supply (i.e. when demand exceeds yield) will no longer be met. In Figure 25, this uncertainty translates into a 15-year range for when action might be required to address this supply-demand imbalance. If projected demand is also considered highly uncertain due to the influence of climate, then high and low climate change projections for demand can also be presented, but in most cases this additional uncertainty is minor relative to the supply uncertainty, and is not likely to influence planning outcomes.

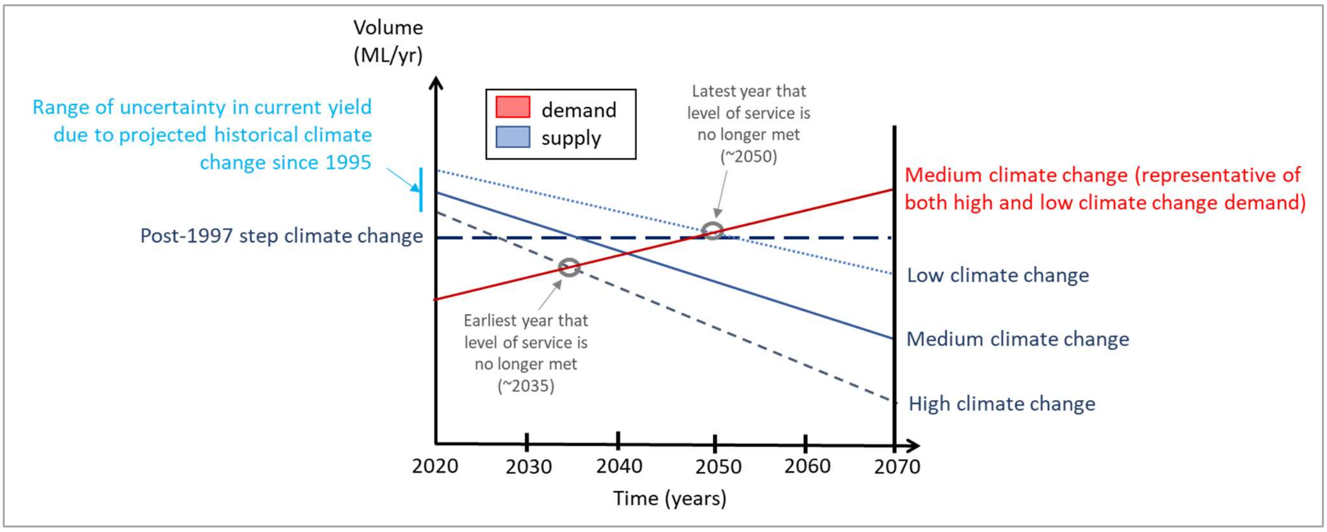

Figure 25 Supply-demand projection under climate change

The recommended approach in the guidelines for estimating streamflow characteristics or supply system performance, when using a river or supply system model for this purpose, is to firstly generate the GCM projected rainfall, evapotranspiration, temperature and runoff for the current (~2020) year. Then these climate change scenarios can be run through a river or supply system model to generate the performance metric of interest under current conditions. The advantage of this order of tasks is that it accounts for any potential non-linear response between climate/runoff inputs and the output performance metrics. It is known, for example, that supply system reliability of supply can change non-linearly, as can ecologically relevant metrics such as the interval between freshes. The extent to which changes in rainfall and runoff will affect supply system reliability depend on a range of factors that can respond non-linearly. These include changes in streamflow volumes relative to cease to divert thresholds, and changes in storage drawdown relative to demand restriction or contingency supply triggers. By explicitly modelling supply system performance under the projected climate change scenarios at the current (~2020) year, it allows for the possibility that this performance metric could be the same as that under the historic climate reference period, the same as that under the year 2040 climate change projection, or a value in-between these two bookends. The same argument would equally apply to assessing performance metrics after the year 2040.

In some circumstances, it may be more efficient to estimate the performance metric under the historic climate reference period and the year 2040 climate change projection, and then linearly interpolate between these two output values for any given projection. The advantage of this approach is that it reduces the amount of data preparation and water resource modelling that needs to be undertaken. This is because it removes the need to separately model performance in the current (~2020) year under the high, medium and low climate change projections. The disadvantage of this approach is that it assumes a linear response between changes in climate/runoff and the performance metric, which will often not be the case. When estimating performance metrics under current conditions, this quicker approach will be most applicable where practitioners are only interested in a single performance metric (e.g. supply system yield) and that performance metric is demonstrated to be the same value (or different but this difference is of negligible consequence to planning decisions) under the historic climate reference period and the year 2040 climate change projection.

Linear interpolation of water resource model inputs (e.g. rainfall, evaporation, runoff) is recommended over linear interpolation of water resource model outputs (e.g. yield, reliability) when estimating current streamflow characteristics or supply system performance. This approach is preferred unless performance is demonstrated to respond linearly with changes in climate, or any non-linearity is demonstrated to be of negligible consequence to planning outcomes. After the year 2040, the linear interpolation of model outputs is considered appropriate, unless more precise measures of performance in years other than 2040 and 2065 are required by stakeholders.

Between the years 2040 and 2065, and after 2065, as mentioned above, the interpolation of model inputs is preferable to the interpolation of model outputs for the same reasons, unless (also mentioned above) that non-linearity is demonstrated to not be evident or of negligible consequence to planning outcomes. It is acknowledged that climate change projection uncertainties after the year 2040 are likely to outweigh any uncertainties associated with the non-linearity of performance metrics. The dependence of current water planning decisions on precise modelling outcomes beyond 2040 is also likely to be lower than that prior to 2040. A linear interpolation of model outputs between the year 2040 and 2065, and linear extrapolation of model outputs after 2065 is therefore considered a reasonable approximation. That is unless stakeholders require more precise measures of performance (particularly if interested in multiple, different performance measures from the model) at a date other than 2040 or 2065.

5.14 Alpine catchments

5.14.1 Alpine catchment orientation

The VCP19 regional climate model projections estimated projected enhanced drying on the western windward slopes of mountain ranges above ~1000 metres elevation, and comparatively little change on eastern slopes. Clarke et al. (2019a) describe this finding as being “physically plausible”. For water supply systems in alpine areas with available choices about whether to site water harvesting infrastructure on the east-facing or west-facing slopes of mountain ranges, these VCP19 findings should be qualitatively considered in decision making. For two or more given catchments of interest, this effect can be quantified (if needed for decision making) by extracting rainfall projections from the six available VCP19 projections.

5.14.2 Changes in snow cover

Precipitation falling as snow that melts shortly after reaching the ground will generate runoff in a similar manner to rainfall. In this case, the runoff projections presented in Section 5.10 will remain applicable. However, if that snow accumulates on the ground as a snowpack, runoff will be delayed until such time as the snowpack melts. This shifts the seasonality of runoff from winter months (when air temperatures in alpine regions are often below zero degrees Celsius) to spring (when air temperatures are sufficiently above zero to melt the snowpack).

The VicCI rainfall projections for Victoria that are presented in the guidelines are based on GCMs that do not represent snow. This is because the model grid sizes are much larger than Victoria’s snow fields, which results in the average elevation of each model grid cell being lower than that required to generate snow. The rainfall-runoff model used to generate runoff projections also does not explicitly model Victoria’s snowpack. Snowmelt is implicitly embedded in the streamflow records to which the rainfall-runoff model is calibrated; however, shifts in the volume of the snowpack under projected climate change, and associated shifts in runoff seasonality, will not be reflected in the runoff projections in the guidelines. This could potentially affect projected reliability of supply for supply systems that are at risk from changes in seasonal streamflow behaviour.

The regional climate model utilised in VCP19 operates at a finer scale and therefore did model changes in snow cover in Victoria. However, these changes were not analysed. Only a descriptive overview from a preliminary analysis of changes in snow cover were presented in the VCP19 technical report (Clarke et al., 2019a), which concluded that modelled changes were similar to those previously assessed in greater detail, such as in Bhend et al. (2012).

The spatial extent of snow in Victoria varies seasonally and from year to year, based on prevailing weather conditions. Snow formation requires both precipitation and sub-zero air temperatures. While snow can occasionally occur at very low altitudes, a snowpack lasting several weeks or more only occurs in alpine regions of north-east Victoria. All of Victoria's ski resorts have ski fields at elevations above ~1300 metres above sea level (based on Harris et al., 2016). This can be regarded as an indicative elevation below which snow is unlikely to aggregate into a snowpack for several weeks or more. The following advice is therefore only applicable to water supply catchments above ~1300 metres above sea level.

A range of studies have estimated both historical and projected changes in snowfall, snowpack and snowmelt in Australia's alpine regions. Some of these studies have utilised either a purpose-built model that assigns precipitation to either snow or rainfall based on local temperature information, or regional climate models that operate on a fine grid scale. As noted in the technical report for the VCP19 (Clarke et al., 2019a), the findings from these studies have been generally consistent. In Victoria's alpine regions, under increased global warming:

- Victoria's climate is drying and is projected to continue to become drier under most GCM projections (Hope et al., 2017).
- Maximum snow depths have declined over recent decades and the snow season is on average finishing earlier (Bhend et al., 2012).
- There is a very high confidence that there will be a decrease in snowfall, an increase in the rate of snowmelt, and thus reduced snow cover in future decades (CSIRO and Bureau of Meteorology, 2015).
- These future trends will be large compared to natural variability and most evident at low elevations (CSIRO and Bureau of Meteorology, 2015).
- Snowmaking activities at alpine resorts may partially offset these climate trends; however, opportunities for snowmaking are expected to reduce significantly due to warmer air temperatures (Harris et al., 2016).

The following guidance is based on considering the potential risk posed to water supplies from changes to seasonal streamflow behaviour associated with changes in accumulated snow depth. This approach draws upon the approach adopted by Gippsland Water in its *2017 Urban Water Strategy* (Gippsland Water, 2017).

The proposed decision process is shown in Figure 26. Given that most water managers will not have high proportions of their water supply sourced from catchments above ~1300 metres in elevation, it is not expected that specific additional adjustments to the runoff projections will be required in most cases. For this reason, the detailed guidance around the application of Figure 26 is presented in the supplementary information on this topic in Appendix B.8.

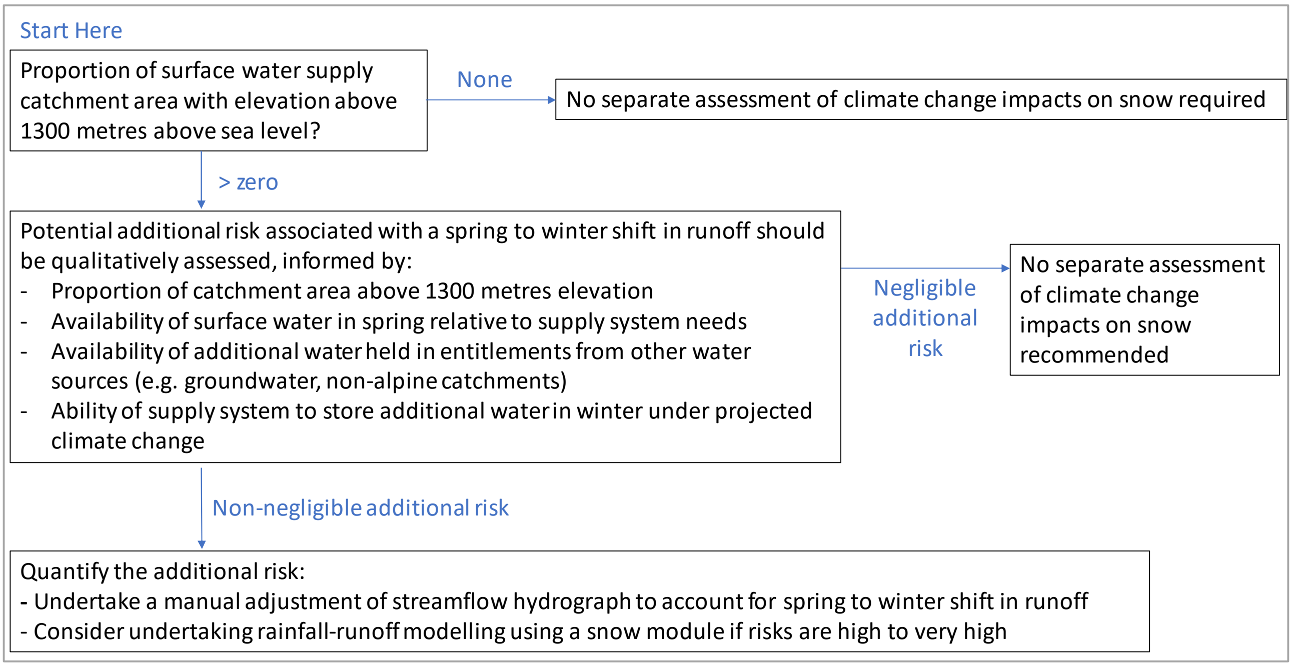

Figure 26 Decision process for assessing the potential risk associated with projected changes in snow cover

5.15 Bushfires

Changes in vegetation cover from bushfires can impact upon runoff and recharge over time. After initial increases in runoff from bushfire affected areas — typically in the first few years following a bushfire — runoff decreases as the forest re-grows over the following years and decades. The precise nature of the interaction between bushfires and runoff/recharge is difficult to predict and can depend on the spatial extent and severity of the fire, the species and the age of the vegetation burnt as well as changes in species composition following the fire.

The incidence of major bushfires in Victoria has increased over recent decades. Dowdy (2018) examined historical changes in the Macarthur Forest Fire Danger Index (FFDI), which is a measure of bushfire risk based on a combination of dryness, temperature, wind speed and humidity. Dowdy (2018) found that from 1950 to 2016, there was:

> *"…a clear trend toward more dangerous conditions during spring and summer in southern Australia, including increased frequency and magnitude of extremes, as well as indicating an earlier start to the fire season".*

While large-scale drivers such as El Niño are often associated with a higher likelihood of bushfires, once these associations are accounted for, there is still a residual increase in the frequency of high fire danger days. Harris and Lucas (2019) attributed this to the changing global climate, suggesting that the observed upward trends will continue. Dowdy and Pepler (2018) also showed that the number of high pyro-convection risk days in summer in Victoria, which are associated with severe bushfires, had increased (up to around a doubling of the number of days) when comparing the period 1979–1997 relative to 1998–2016. A time series of changes to bushfire risk in spring over recent decades in Victoria is shown in Figure 27.

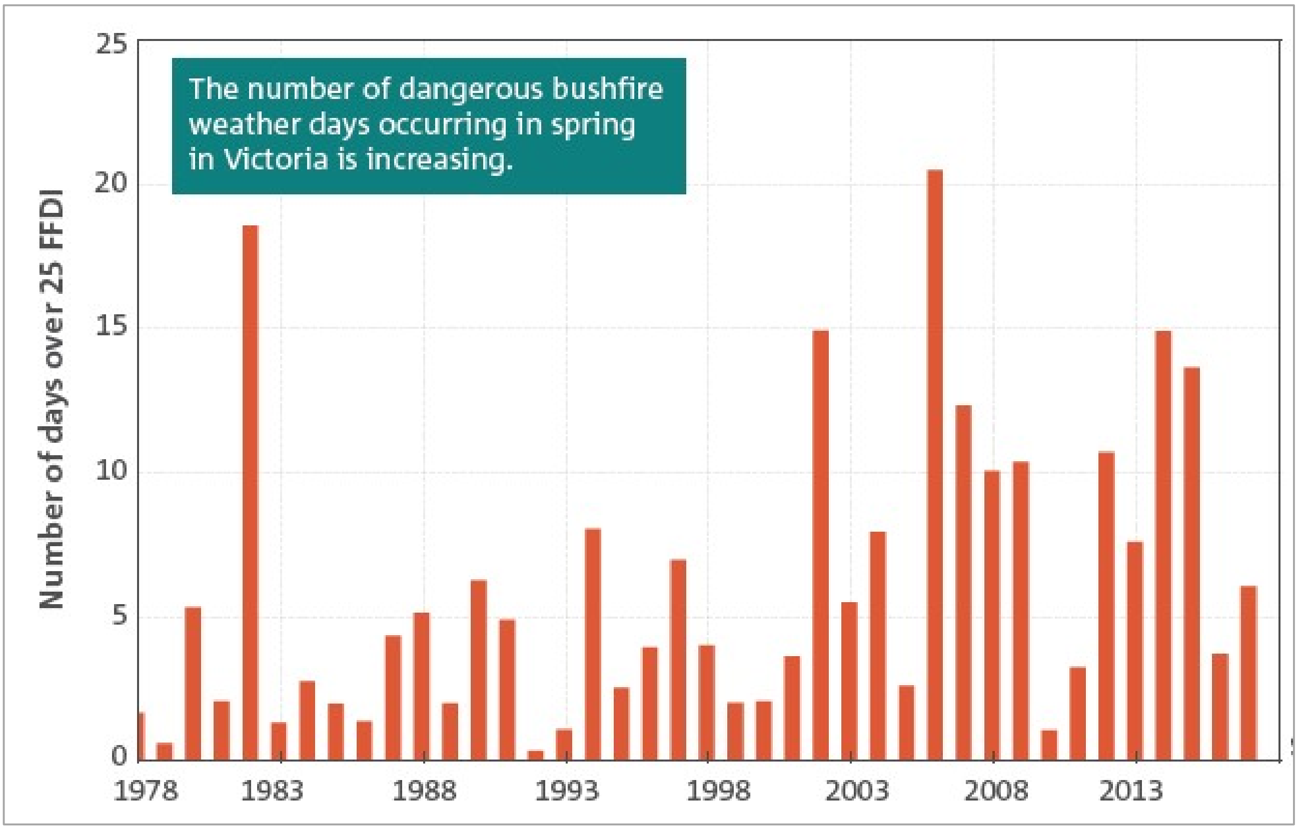

Figure 27 Number of dangerous bushfire days (forest fire danger index > 25) in spring in Victoria from 1978 to 2017 (Bureau of Meteorology and CSIRO, 2018)

General fire weather risk (as indicated by FFDI in Grose et al., 2015a and Timbal et al., 2015) is projected to increase under increased greenhouse gas concentrations. The VCP19 projections explored this further for Victoria using a subset of GCMs run through a regional climate model. It was found that there was typically an increase of 10 to 20 dangerous fire days per year for Victoria by the late 21st century relative to the start of the 21st century under the RCP8.5 emissions scenario (Clarke et al., 2019a). Dangerous fire days were defined as those above the 95th percentile historical FFDI value.

The regional climate model projections highlighted that this rate of change was roughly double in alpine regions relative to non-alpine regions. It is also noted that one of the six regional climate model projections in Clarke et al. (2019a) showed a decrease in bushfire risk by the late 21st century. Changes to bushfire risk are described in the regional summaries available for VCP19, but are not provided in the application-ready datasets available online. Some uncertainties in future bushfire risk are not covered in the GCM projections, such as the interaction between anthropogenic climate change and bushfire ignition by lightning, and between anthropogenic climate change and changes to bushfire fuel loads (NESP ESCCH, 2018).

The risk of bushfires in Victoria is estimated to increase for most climate change projections. However, translating this into projected impacts on water supplies is extremely difficult.

Reliably quantifying projected changes in runoff and recharge due to projected changes in future bushfire risk is extremely difficult. This is not only due to the complex relationship between bushfire and hydrologic response, but also the unknown timing, spatial extent and intensity of future bushfires. Post-fire mortality in forests with mixed *Eucalyptus* species, which cover a large proportion of Victorian catchments, are likely to be lower than mortality in wet *Eucalyptus* forests. This results in relatively modest and short-term changes in post-fire runoff as vegetation recover rather than regenerate in mixed species forests. Shorter intervals between bushfires may inhibit regeneration of some *Eucalyptus* species (such as *E. regnans* and

E.delegatensis) and potentially shift vegetation composition to species with lower water use (such as *Acacia* species).

Projected rainfall reduction under climate change is likely to limit vegetation water use, while projected increase in temperature can increase drought-stress. Following the 2009 bushfires, changes in streamflow yield in Melbourne’s water catchments under average rainfall conditions have been predicted to be much smaller than reductions in streamflow during the Millennium Drought (Feikema et al., 2013). The impact of projected climate change on runoff may be greater than runoff changes associated with post-fire forest regrowth. For any given application, the extent to which the impacts of future changes in bushfire risk on water availability can be quantitatively estimated will depend on the ability to model the impact of fire on vegetation mortality as well as the interaction between climate change and post-fire ecosystem responses.

6. Near-Term Decision Risks

6.1 Introduction

Near-term decision risks occur where a water supply planning decision must be made now about actions to occur over the next ten years, and the planning decisions are vulnerable to the climate change impact assessment assumptions and could be regretted if those assumptions were subsequently found to be incorrect.

There are numerous uncertainties around the climate change projections and related assumptions adopted in these guidelines. Some uncertainties are addressed explicitly in the previous sections of the guidelines. Firstly, the uncertainty in GCM selection is dealt with by offering a high, medium and low climate change projection, representing GCM uncertainty. Secondly, the uncertainty associated with GCM projections is mitigated by also utilising a post-1997 step climate change projection, including for near-term applications such as drought planning. Uncertainty in climate variability from a relatively short reference climate period is addressed through reference period extension procedures. However, the possibility remains that these and other underlying assumptions in the guidelines could be incorrect.

This section outlines additional methods and information available to assess the vulnerability of water resource planning decisions to the guideline assumptions, and any associated regret.

6.2 What if the assumptions in the guidelines are incorrect?

The range of assumptions made in the guidelines could serve to either over-estimate or under-estimate the impacts of climate change on water supplies, depending on the extent to which those assumptions turn out to be correct. A list of assumptions and their implications for assessing climate change impacts on water supplies is provided in Table 8.

Table 8 Potential impact of incorrect assumptions in the guidelines

Guideline assumption	Reason why the assumption could be incorrect	DELWP response
RCP8.5 emissions trajectory.	RCP8.5 could overstate the actual emissions trajectory due to greenhouse gas reduction measures by the world's governments, thereby over-estimating projected climate change impacts after 2030.	Option available to test water supply behaviour under a lower emissions scenario RCP4.5.
RCP4.5 emissions trajectory.	RCP4.5 could understate the actual emissions trajectory, due to a lack of greenhouse gas reduction measures by the world's governments or climate change feedback loops (e.g. bushfires) that are not accounted for in GCMs.	The global temperature response under RCP6.0 is similar to that for RCP4.5 up to ~2065.
	RCP4.5 could overstate the actual emissions trajectory after 2040 if the Paris Agreement targets are fully achieved.	Based on current pledged commitments and key non-signatories to the Paris Agreement, this is unlikely at the current time. This assumption will be revisited in future updates to the guidelines.
10^{th}, 50^{th} and 90^{th} percentile model outcomes adopted for low, medium and high projections.	10% of models project climate change to be wetter than shown by this range, and 10% of models project climate change to be drier than shown by this range.	The approach adopted allows planning for a wide range of projections, without being unduly influenced by outlying GCMs.

Guideline assumption	Reason why the assumption could be incorrect	DELWP response
Apply annual climate change projections.	Changes in seasonal rainfall behaviour could be different to annual changes, as observed in Victoria over the last two decades. This could result in an over-estimation of runoff available for winter/spring harvesting and an under-estimation of runoff available for summer harvesting.	Utilise historical seasonal shifts for near-term applications, and apply sensitivity testing for long-term applications if planning outcomes are considered vulnerable to this assumption.
Historical rainfall-runoff response.	Climate change projections for runoff may overstate runoff under drying climate change projections, particularly for catchments with observed reductions in annual runoff for a given annual rainfall during and after extended drought.	Catchments where a change in response has been observed in extended droughts to date have been identified in the guidelines. DELWP will advise further as research in this area is completed.
Medium temperature and evaporation climate change projection for demand estimation.	This could over-estimate or under-estimate demand under projected climate change if the low or high projection were to eventuate.	High and low temperature and potential evapotranspiration projections have been provided to enable sensitivity testing, but testing to date by DELWP suggests this assumption will generally only be of minor to negligible consequence for planning outcomes for water.
Linear extrapolation after 2065.	Climate change projections under RCP4.5 will be slightly over-estimated, and climate change projections under RCP8.5 will be slightly under-estimated from 2065 to 2075.	The extent of linear extrapolation recommended is limited to ten years beyond the last available projection in 2065. Projections beyond 2065 are expected to be updated in future updates to the guidelines.
Compounding effects from all of the above.	It is possible that more than one, or all, of these guideline assumptions could be incorrect.	Utilise alternative impact assessment datasets and approaches (see Section 6.4).

6.3 Defining vulnerability to climate change assumptions

Vulnerability indicates the potential for unsatisfactory outcomes, if the assumptions in the guidelines are incorrect. Regret indicates the ability of those unsatisfactory outcomes to be reversed or altered, if they were to eventuate. Vulnerability will be lower for supply systems that draw from supply sources that are more climate resilient. Regret considers the availability of alternative, timely corrective actions, and if available, the cost of implementing them. Regret should also consider the possibility of wetter projections or lower emissions trajectories eventuating, and the consequences associated with that, such as lower cost recovery from assets. Where actions arising from application of the guidelines are not required until after ten years into the future, it is expected that there will be the opportunity to re-visit decisions in the next update of the guidelines, with the benefit of additional climate change information and updated climate change projections.

It is proposed that streamflow characteristics or supply system performance should be considered potentially at risk to the assumptions in these guidelines if:

a) For supply systems:

   (i) Projected supply system performance is expected to drop below target levels over the next decade (and/or)

   (ii) Action could be required prior to the next update of the guidelines.

   (iii) The regret associated with inaccurate climate change assumptions in the guidelines would be high.

b) For water dependent assets or values:

   (i) Those assets or values are considered at risk over the next decade.

(ii) The regret associated with inaccurate climate change assumptions would be high.

The above assessment assumes that the assessment process outlined in the guidelines is suitable for the purposes of assessing risks in your supply system or river system. There may be some circumstances where the potential climate change risk that you are facing is not suitably captured by this process. An example of this could be where annual scaling of runoff is applied to a run-of-river supply system and the assessment outcomes are that the supply system will remain above target performance levels over the next decade. However, if small additional increases in within-year drought duration could compromise supply system performance, then this should be considered further and assessed if needed.

6.4 What to do if your planning decisions are considered at risk from the guideline assumptions

Where a near-term risk to the assumptions in the guidelines is identified, the following actions are suggested:

- Reassess projected business as usual streamflow characteristics or supply system performance under climate change using additional techniques and projections; and
- If the proposed action to be implemented over the next decade is not climate resilient, reassess streamflow characteristics or supply system performance with the proposed action using additional techniques and projections.

The decision process is illustrated in Figure 28. It is recognised that alternative datasets and assessment techniques are continuing to be developed, so the advice in this section is not prescriptive. If a user of the guideline wishes to adopt alternative techniques or projections not listed in these guidelines, please discuss this with the Department so that any collective learnings from innovations in climate change impact assessment can potentially be shared with other users of the guidelines.

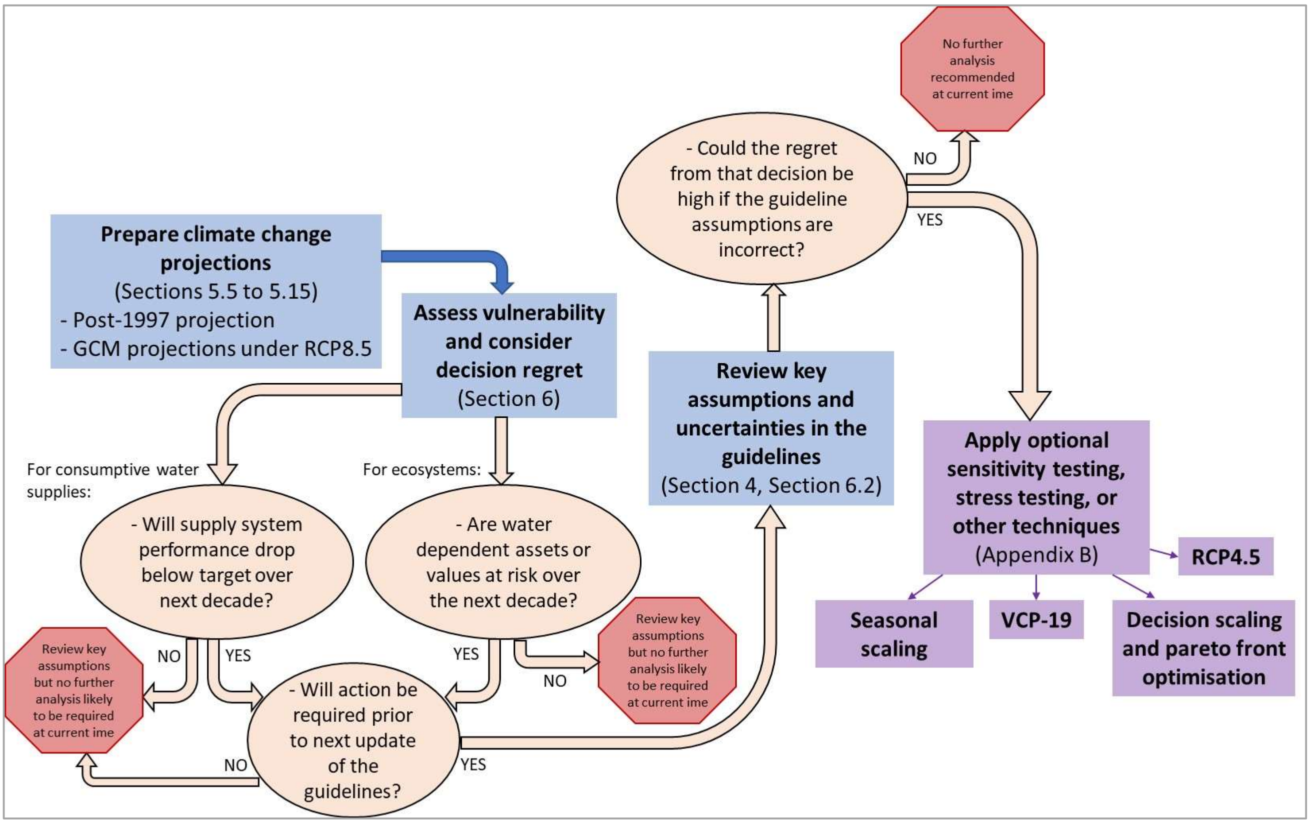

Figure 28 Suggested climate change impact assessment response for near-term decision risks

6.4.1 Additional climate change projections

A range of additional climate change projections are available in addition to the VicCI projections adopted in these guidelines. If alternative climate change projections are being sought, in the first instance DELWP recommends the use of the VCP19 projections. A statement of whether these projections are wetter, drier or about the same as the VicCI projections for any given river basin (for the year 2065, RCP8.5 scenario) is provided in Appendix B.2.1. For river basins where the VCP19 projections lie within the range of the VicCI projections, they could be interpreted as providing greater confidence in the VicCI projections. Where the VCP19 projections lie outside of the range of the VicCI projections, they can be utilised to test a river or supply system to a wetter or drier climate change projection than those available from the VicCI projections.

Other available climate change projections include the NARCliM projections, the Climate Change in Australia NRM region projections, and the National Hydrologic Projections. These are less preferred for use in water supply impact assessment in Victoria than VCP19, but can be drawn upon as required to apply the alternative impact assessment techniques described below. Each of these additional projections are briefly discussed in Appendix B.2.

6.4.2 Additional climate change impact assessment techniques

The guidelines assume that climate change impact assessment will be primarily undertaken using a scenario planning approach combined with adaptive management. This approach has clear advantages in that it is time-based over a planning horizon, is informative for decision making, and is comparatively simple to apply and communicate. A range of other potential climate change impact assessment techniques are also available, which could offer different or complementary insights to scenario planning. The three techniques considered most relevant to climate change impact assessment in Victoria include sensitivity testing / stress testing, decision scaling, and multi-objective pareto front optimisation. These additional techniques are presented in more detail in Appendix B.6.

7. Future Updates to Climate Change Projections

These guidelines incorporate the latest information on climate change projections at the time of writing in 2020. Climate change science, hydrology, hydrogeology and water supply planning are active areas of research and our knowledge of climate change and its impacts will continue to evolve over time. The global politics of greenhouse gas emissions and mitigation is also expected to evolve over time.

The next (sixth) Assessment Report from the IPCC has been delayed by the COVID-19 disruption but is expected to be published progressively from mid-2021 to mid-2022. This will include the release of the CMIP6 suite of global climate modelling results, which are expected to include more GCMs and a greater number of intermediate emissions scenarios.

DELWP will commence reviewing the outputs from the Sixth Assessment Report as they become available and will advise users of any updates to the guidelines using the mechanisms outlined below. Post-processing GCM outputs to make them application-ready for local application by river basin in Victoria, including the generation of projected changes in runoff, is typically around a 12-month process.

7.1 Where to get updated guidance from DELWP as it emerges

DELWP's Hydrology and Climate Science team sits within the Water Resource Strategy Division of the Water and Catchments Group in DELWP. The Hydrology and Climate Science team can be contacted at:

HCS.Team@delwp.vic.gov.au.

You can also use this email address to subscribe to the team newsletter, which periodically provides the latest information on research, publications, webinars and science days from the VicWaCI research program.

Information can also be accessed via the DELWP website:

https://www.water.vic.gov.au/climate-change

Future updates of these guidelines will be made available via the DELWP website and will be tracked by use of a version log (Appendix C).

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Glossary

Adaptation	Changes made to natural or human systems to prepare for actual or expected changes in the climate in order to minimise harm, act on opportunities or cope with the consequences.
Anthropogenic climate change	Climate change attributable to anthropogenic forcing.
Anthropogenic forcing	Increases in energy in the world's atmosphere associated human activity.
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of human actions such as burning fossil fuels or land use changes. It is the main human-generated greenhouse gas that affects the Earth's atmosphere.
Climate	The weather experienced at a site or region over an extended period of at least 20 years (as utilised for GCM time slices of climate conditions).
Climate change	Changes in the state of the climate, including an increase in the occurrence of extreme weather events, long-term changes in weather patterns and sea level rise attributed directly or indirectly to human activity. Distinct from climate variability as the changes persist for an extended period, typically decades or longer.
Climate projection	The modelled response of the climate system to a scenario of future concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are based on a specific emissions scenario, for example Representative Concentration Pathways (RCPs).
Climate variability	See Climate change.
Coupled Model Intercomparison Project (CMIP)	A multiple-phase project that coordinates and archives climate model simulations, based on shared model inputs, by modelling groups from around the world. Models from Phase 5 (CMIP5) informed the Intergovernmental Panel on Climate Change's Fifth Assessment Report, while models from Phase 6 (CMIP6) will feed into the Sixth Assessment Report.
Cool Season	For Victoria, the cool season is assumed to run from April to October.
DELWP	Victorian Department of Environment, Land, Water and Planning.
Downscaling	A method that produces local to regional-scale climate information from larger-scale models or data analyses. Different methods include dynamical, statistical and empirical downscaling.
Emissions scenario	Used within this document to broadly describe Representative Concentration Pathways (RCPs) — see definition below.
ENSO - El Niño Southern Oscillation	A fluctuation in global scale tropical and subtropical surface pressure, wind, sea surface temperature, and rainfall, and an exchange of air between the south-east Pacific subtropical high and the Indonesian equatorial low. Often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. There are three phases: neutral, El Niño and La Niña. During an El Niño event the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the eastern tropical surface temperatures warm, further weakening the trade winds. The opposite occurs during a La Niña event.
External forcing	External forcing refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations,

	anthropogenic changes in the composition of the atmosphere and land-use change are external forcings.
Extreme weather	A weather event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally occur less than 10% of the time.
Global climate model (GCM)	A numerical representation of the climate system across the whole globe that is based on the physical, chemical and biological properties of its components, their interactions and feedback processes. Grid squares in global climate models are usually between 100 km and 200 km in size.
Global warming	Global warming refers to the increase, observed or projected, in global surface temperature.
Greenhouse gas	Gaseous components of the atmosphere, both natural and human-generated, that absorb and emit solar radiation at specific wavelengths. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.
Hadley Cell	A large-scale atmospheric circulation pattern in which air rises at the Equator and sinks at about 30^o latitude north or south. The Hadley Cell controls the position of the band of high pressure systems (called the sub-tropical ridge).
Indian Ocean Dipole (IOD)	A measure of sea surface temperature anomalies across the Indian Ocean at and near the equator. When the dipole is in a positive phase, sea surface temperatures around Indonesia are cooler than average while those in the western Indian Ocean are warmer than average. There is an increase in the easterly winds across the Indian Ocean in association with this sea surface temperature pattern, while convection in areas near Australia reduces. This results in suppressed rainfall over the Australian region. Conversely, during a negative phase, there are warmer than average sea surface temperatures near Indonesia and cooler than average sea surface temperatures in the western Indian Ocean, resulting in more westerly winds across the Indian Ocean, greater convection near Australia, and enhanced rainfall in the Australian region.
Inter-decadal Pacific Oscillation (IPO)	A fluctuation in the sea surface temperature (SST) and mean sea level pressure (MSLP) of both the north and south Pacific Ocean with a cycle of 15 to 30 years. Unlike ENSO, the IPO may not be a single physical 'mode' of variability, but be the result of a few processes with different origins. The IPO interacts with the ENSO to affect the climate variability over Australia
Intergovernmental Panel on Climate Change (IPCC)	The Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change. The IPCC was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).
Mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs).
Natural variability	Variations in the climate (both its average state and the occurrence of extremes) that vary on scales from day to day, up to decade to decade, due to natural processes in weather systems. For example, consecutive summers will not all be the same, with some cooler and some warmer than the long-term average.
Overshoot	Emissions, concentration or temperature pathways in which the metric of interest temporarily exceeds, or overshoots the long-term goal
Paleoclimate	Indirect measurements of climate are referred to as palaeoclimate archives or proxies, which consist of geologic (e.g. sediment cores) and biologic (e.g. tree rings) materials that preserve evidence of past changes in climate.

Palaeoclimate research provides the opportunity to look at changes in climate beyond the relatively short timeline of instrumental records.

Percentile	A value on a scale of one hundred that indicates the percentage of the data set values that is equal to, or below it. For example, the 90th (or 10th) percentile may be used to refer to the threshold for the upper (or lower) extremes.
Potential evapotranspiration (PET)	The rate of evapotranspiration from a limitless source of water. It is typically higher than actual evapotranspiration, which will be limited by water availability. Evapotranspiration includes transpiration from vegetation and evaporation from water bodies.
Pre-industrial	Prior to the industrial revolution (i.e. pre-1750), when human activities such as the burning of fossil fuels increased the concentration of greenhouse gases in the atmosphere. Consistent with the IPCC, this report uses 1850–1900 as the pre-industrial baseline, as it is the earliest period with near-global temperature observations.
Regional Climate Model (RCM)	A climate model used to generate higher-resolution results from a GCM. Like a GCM, an RCM runs a numerical representation of the climate system that is based on the physical, chemical and biological properties of its components, their interactions and feedback processes to produce results at a regional or local scale.
Representative Concentration Pathway (RCP)	Scenarios of emissions and concentrations of the full suite of greenhouse gases and aerosols, and land use/land cover, over time. These are used as inputs to climate models.
Shared Socio-Economic Pathway (SSP)	In the IPCC's Sixth Assessment Report, due for release from mid-2021 to mid-2022, Shared Socio-Economic Pathways are a framework under which emissions pathways can be developed. Multiple concentration pathways (RCPs) have been developed under each of the five SSPs.
Southern Annular Mode (SAM)	The north/south movement of the strong westerly winds that dominate the middle to higher latitudes of the Southern Hemisphere. The belt of strong westerly winds in the Southern Hemisphere is also associated with the storm systems and cold fronts that move from west to east.
Stationarity	The absence of trends in a dataset. In the context of hydro-climate data, stationarity refers to the absence of trends in those datasets. In the context of rainfall-runoff modelling, hydrologic stationarity refers to the absence of trends in the relationship between rainfall and runoff.
Sub-tropical ridge	A belt of high pressure that encircles the globe in the middle latitudes. It is part of the global circulation of the atmosphere. The position of the sub-tropical ridge plays an important part in the way the weather across Australia varies from season to season.
Uncertainty	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).
Victorian Aquifer Framework (VAF)	Victoria's aquifers are defined within the Victorian Aquifer Framework. The framework provides a consistent approach to defining aquifers across the state. There are 15 aquifers represented in the aquifer framework, which occur at various depths and locations.
Victorian Climate Initiative (VicCI)	A three-year research program (ending in 2017) funded by the Victorian State Government to improve our understanding of past, current and future climate influences on Victoria.

Victorian Water and Climate Initiative (VicWaCI)	A four-year program of research that began in 2017 funded by the Victorian State Government to improve our understanding of past, current and future climate influences on water resources in Victoria.
Warm season	For Victoria, the warm season is assumed to run from November to March.

Appendix A Case Studies and Explanatory Notes

A.1 Introduction

This appendix to the guidelines lists some complementary references for additional information on climate change science, climate change projections, and broader climate change impact assessment guidance. It also includes some illustrative examples of historical data scaling.

A.2 Complementary references

A full list of references for the guidelines is provided in Section 8. Some of the most relevant complementary references are provided in Table 9. This list is by no means exhaustive, and may be updated by DELWP at regular intervals.

Table 9 Complementary references

Reference	Potential complementary uses
Water planning guidance and other climate change guidance	
DELWP (in development) *Guidelines for Assessing the Impact of Climate Change on Sewerage Systems.*	Complementary climate change impact assessment guidance specific to sewerage planning
DELWP (2020a) *Guidelines for the Development of Urban Water Strategies and the Melbourne Water System Strategy*	Guidelines for how to incorporate climate change impact assessment into long-term and short-term water supply planning
DELWP (2018a) *Pilot Water Sector Climate Change Adaptation Action Plan*. ISBN 978-1-76077-274-1 (pdf/online/MS word)	The climate change adaptation strategy for the water sector, which included a commitment to update these guidelines on water supply impact assessment
DELWP (2019a) *Managing Climate Change Risk. Guidance for Board Members and Executives of Water Corporations and Catchment Management Authorities*. June 2019. ISBN 978-1-76077-694-7 (pdf/online/MS word)	Guidance on how to integrate climate change impact assessments on water supplies into decision making
Water Services Association of Australia (WSAA) (2016) *Climate Change Adaptation Guidelines*. February 2016. WSA 303 – 2016-v1.2	Illustrates how climate change impact assessment on water supplies fits in with broader climate change adaptation and mitigation measures by Water Corporations
Climate science	
DELWP (2019d) *Victoria's Climate Science Report 2019*. ISBN 978-1-76077-853-8 (pdf)	An overview of the latest findings from scientific research into climate change in Victoria
DELWP et al. (2020) *Victoria's Water in a Changing Climate*.	An overview of the scientific findings from the VicWaCI research program from 2017–2020
Clarke JM, Grose M, Thatcher M, Hernaman V, Heady C, Round V, Rafter T, Trenham C & Wilson L (2019a) *Victorian Climate Projections 2019 Technical Report*. CSIRO, Melbourne Australia	VCP19 projections using six GCMs in combination with a regional climate model. Available from https://www.climatechange.vic.gov.au/adapting-to-climate-change-impacts/victorian-climate-projections-2019
Climate Change in Australia website https://www.climatechangeinaustralia.gov.au/en/	A repository of national climate change information and tools, including the datasets for VCP19.

Reference	Potential complementary uses
Design Flood Estimation	
Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2019, *Australian Rainfall and Runoff: A Guide to Flood Estimation*, Commonwealth of Australia	This is the national guideline for design flood estimation

A.3 Historical data scaling examples

As outlined in Section 5.4.2 of these guidelines, historical data scaling is a method used to adjust historical data so that it has similar exceedance properties to a shorter reference period, for example the post-1975 and post-1997 reference periods used in these guidelines.

HARC (2020) undertook an analysis of the potential for the scaling of historical data to introduce data anomalies in 150 datasets across Victoria. From this analysis it was concluded that:

- Inconsistent scaling factors across adjacent deciles occurred in less than 5% of datasets.
- It was not uncommon for high, low or the majority of historical streamflows to increase after scaling (e.g. low flows increased in 26% of datasets). The frequency with which this occurred was much lower when using a post-1997 historic climate reference period, relative to a post-1975 historic climate reference period.
- Understanding the quality of the reference period data is important for interpreting the validity of the historical data scaling.

HARC (2020) also investigated some of the potential causes of anomalies introduced by historical data scaling. These included examining differences in a sample of wet and dry catchments, differences when analysing the dataset on different time steps, differences when utilising a shorter period of record in the historical (pre-reference) period, differences when applying annual or seasonal scaling, differences due to changes in the method of streamflow derivation and differences in the observed flows over time (e.g. due to changes in gauging practices). This analysis did not identify any conclusive patterns for the drivers of potential data anomalies introduced by historical data scaling, with anomalies likely to be unique to individual datasets associated with local quality control or water management issues. Where potential anomalies were identified, an examination of the stationary of gauged water levels was shown to help identify whether the poor quality of raw data was a cause of the anomaly.

When comparing seasonal versus annual scaling factors, HARC (2020) noted with an example dataset that scaling factors over the cool season typically resulted in flow reductions in the historical period, while in the warm season, flow increases were applied.

Some examples of historical data scaling are shown in Figure 29 to Figure 31. In these figures, the flow exceedance curve is plotted as ten points, with one point for the average flow within each decile. The scaling conversion factor is the factor that would be applied to the historical data for that particular decile. Figure 29 illustrates the historical data scaling that would typically be expected in a drying climate, namely that the reference period flows are below the historical flows for all deciles, and the scaling factors are therefore all less than 100%. Figure 30 shows an example of potentially anomalous scaling factors, with an unusually high scaling factor of 220% in the third decile. In this example, after investigating the data, it might be more appropriate to adopt say the scaling factor for the fourth decile for application in the third decile. It is likely that the third decile is unduly influenced by a small number of data points within the decile, due to the presence of zero flows within this decile. Figure 31 shows an example of flow increases in the reference period in both the low flow (first to third deciles) and high flow (top decile) range. It is not unusual for the top decile flows to be higher in the reference period than in the historical (pre-reference) period, because flows in this decile will be influenced by relatively rare high flow events. This observation is also consistent (in principle) with the increases in rainfall intensity that are expected under global warming. However, increases in streamflow in the lowest three deciles is unexpected, and would be a trigger to investigate this dataset further, to understand whether it is influenced by flow regulation, drainage, or wastewater treatment plant discharges, all of which could account for this behaviour.

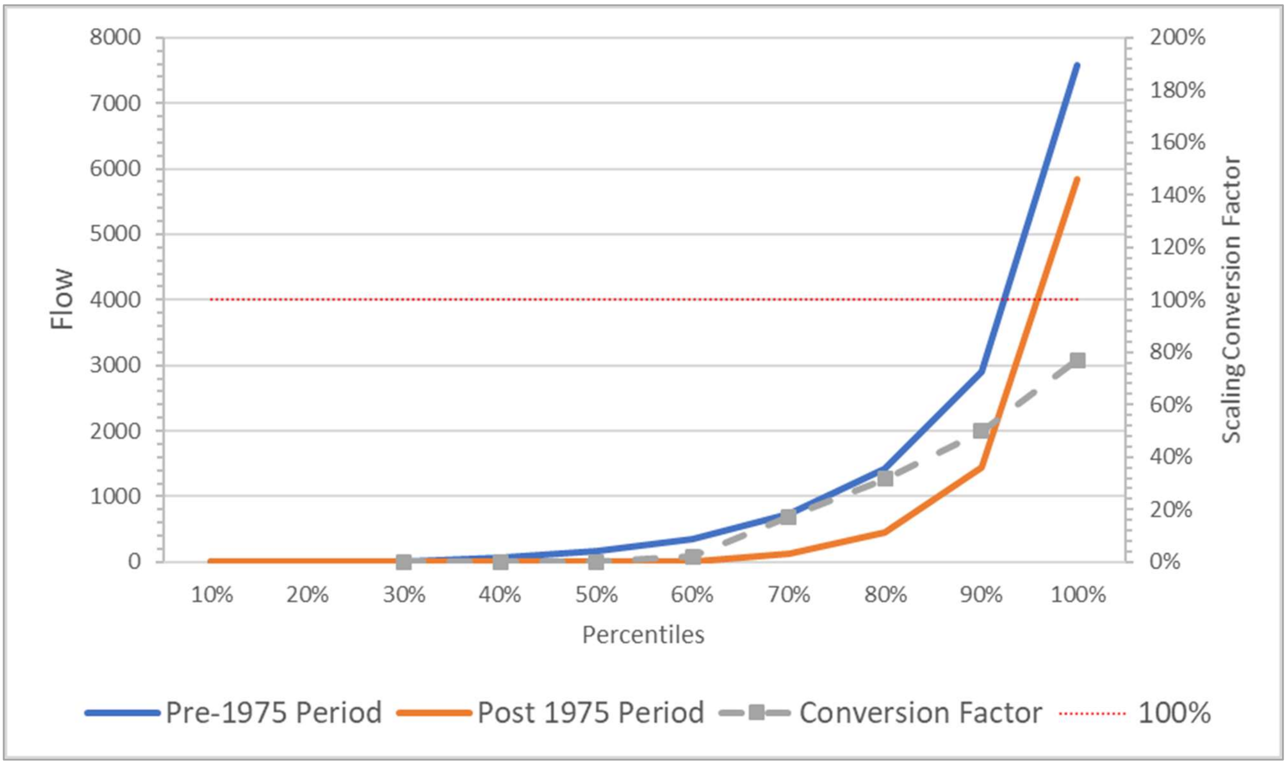


Figure 29 Example of expected historical data scaling, with post-1975 flows lower than pre-1975 flows in all deciles (HARC, 2020a)

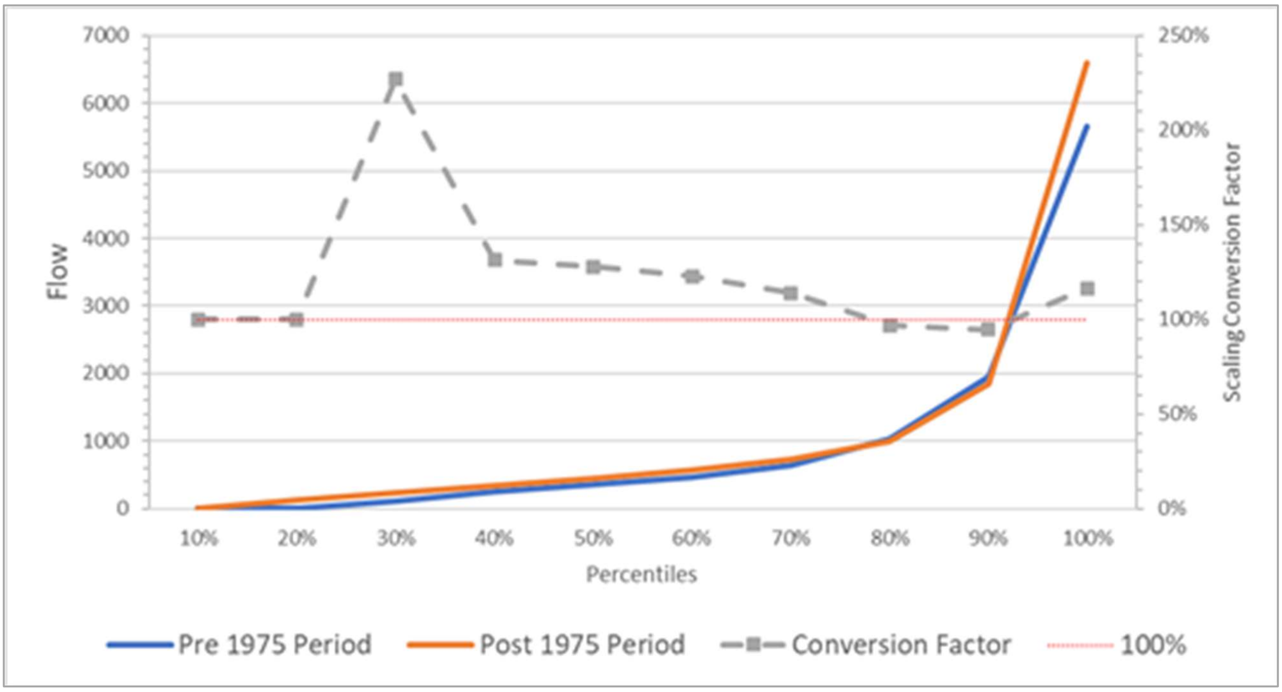


Figure 30 Example of anomalies historical data scaling (HARC, 2020a)

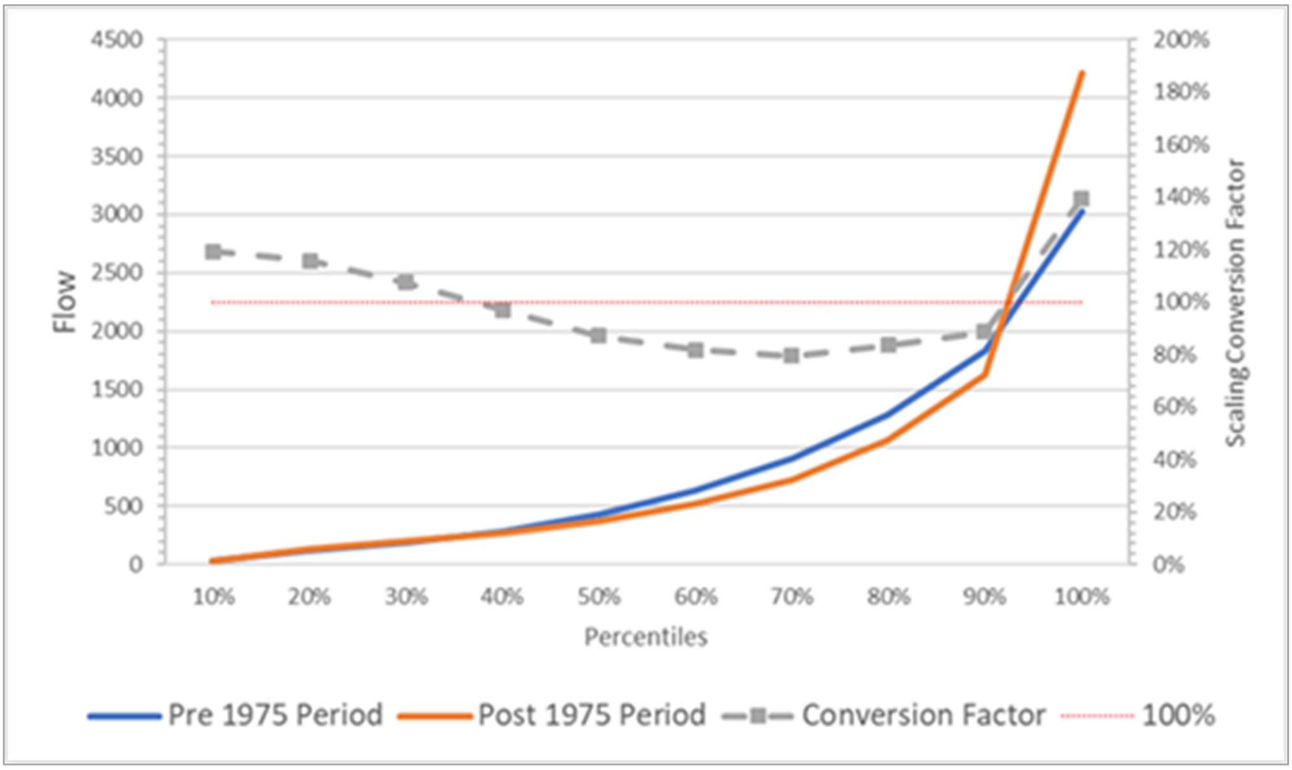


Figure 31 Example of low flow and high flow increases under historical data scaling (HARC, 2020a)

Appendix B Supplementary Information

B.1 Introduction

This appendix to the guidelines includes supplementary information to support potential additional analyses, particularly for water supply planning decisions with near-term risks. This information includes other downscaled climate change projections including a comparison between VCP19 and the VicCI projections (Appendix B.2), advice on obtaining finer spatial scale projections (Appendix B.3), climate analogues (Appendix B.4), paleoclimate proxy records (Appendix B.5), and other climate change impact assessment techniques that can be used in addition to the approaches recommended in the guidelines (Appendix B.6). Furthermore, this appendix provides supplementary information on sub-hourly rainfall (Appendix B.7), streamflow hydrograph adjustments for climate change impacts on snow cover (Appendix B.8), observed shifts in rainfall (Appendix B.9) and groundwater recharge processes (Appendix B.10). Tables for sensitivity testing for seasonal rainfall changes under climate change are presented by river basin in Appendix B.6.2.

B.2 Other downscaled climate change projections

B.2.1 VCP19

The VCP19 climate change projections draw from six host GCMs to run a regional climate model with finer detail over Victoria. This process generates six climate change projections (from the 42 available GCMs) that potentially offer greater insights at a local scale than their host GCMs. At the time of writing the guidelines, these projections were not available for runoff; however, these are expected to be prepared by late 2020, to allow different runoff projections derived using different modelling approaches to be compared. The information below focusses on comparisons of the rainfall projections only.

CSIRO (S.Charles and F.Chiew, pers.comm. 2/9/20) compared the VicCI and VCP19 projections for Victoria by river basin for rainfall only, for the RCP8.5 scenario at 2065. This involved the identification of the GCMs used in both sets of projections, and a comparison of the projected change in rainfall in the GCMs, the raw regional climate models (RCMs) and the bias-corrected RCMs. The bias-corrected results presented in this appendix were derived by CSIRO as part of VicWaCI research, and may differ slightly from the bias-corrected results presented in the application-ready datasets derived as part of Clarke et al. (2019a). The VicWaCI bias corrected rainfall changes were calculated for each 5 km x 5 km grid cell within each basin, using VCP19 rainfall that has been bias corrected on a seasonal basis using the method outlined in Potter et al. (2020). They were than averaged to produce basin average rainfall changes as shown on the following pages.

These results, when averaged across Victoria, indicated that at 2065:

- The six host GCMs in VCP19 provide a range of rainfall projections that can either lie within the 10^{th} to 90^{th} percentile VicCI projections or outside of those projections, depending on the individual river basin being considered.
- The RCM typically produces drier projections than the VicCI downscaled projections for the host GCM.

These differences are illustrated for three example river basins (Werribee, Goulburn and Mitchell) in different parts of Victoria, in Figure 32, Figure 33 and Figure 34. In these figures, the VCP19 projections are denoted by the CCAM regional climate model, before (raw) and after (BC) bias correction. In these figures, the six GCMs selected for use in VCP19 are shown by the dark blue dots. After running these GCM inputs through the CCAM regional climate model, the resulting raw projected changes in rainfall are shown by the orange dots. After bias correction of the CCAM results, the final projected changes in rainfall are shown by the grey dots. The change in the direction and magnitude of the projected rainfall change at each step of the process is unique to each river basin.

These results suggest VCP19 cannot be used to stress test supply systems to wetter future conditions at 2065 in the Werribee, Goulburn and Mitchell basins, as the VCP19 projections are all drier than the VicCI low climate change projections. However, VCP19 could be used to stress test supply systems to drier futures. The potential to use VCP19 for supply system stress testing should be assessed on a case by case basis, as other trends could be apparent if extracting VCP19 results at a finer (supply catchment) scale or for other time slices (as individual models will exhibit inter-decal variability so outcomes could vary).

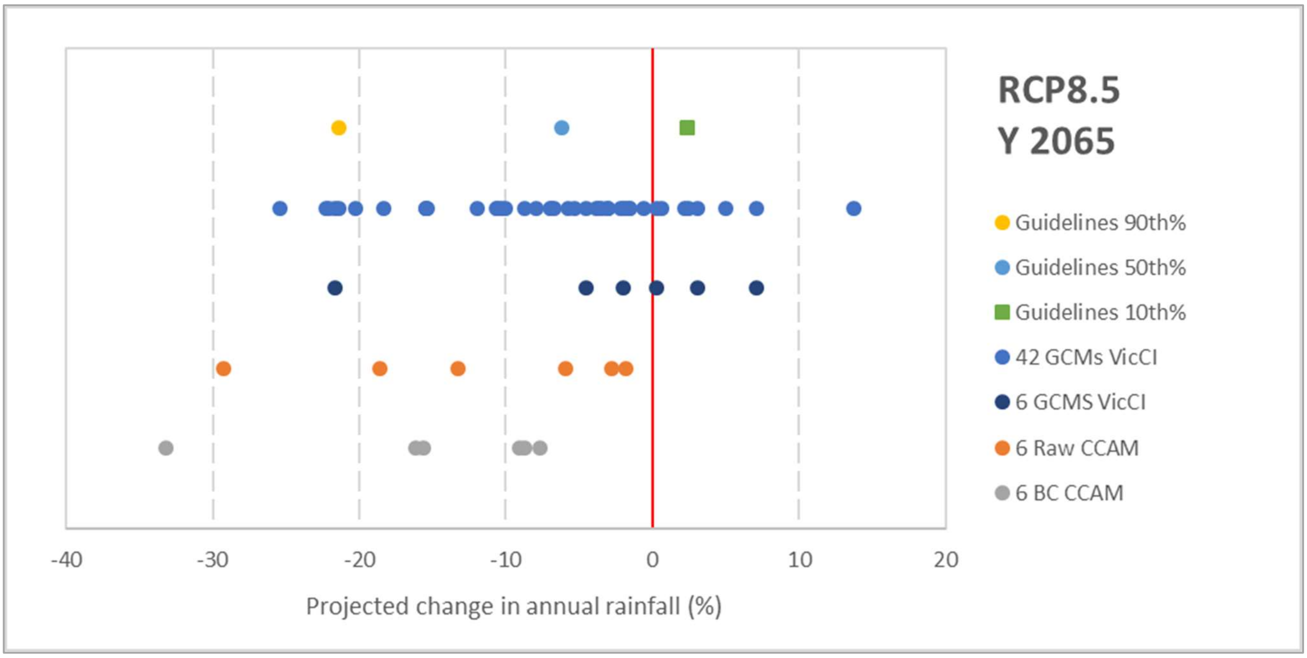


Figure 32 Werribee Basin comparison of VicCI and VCP19 (CCAM) rainfall projections 2065

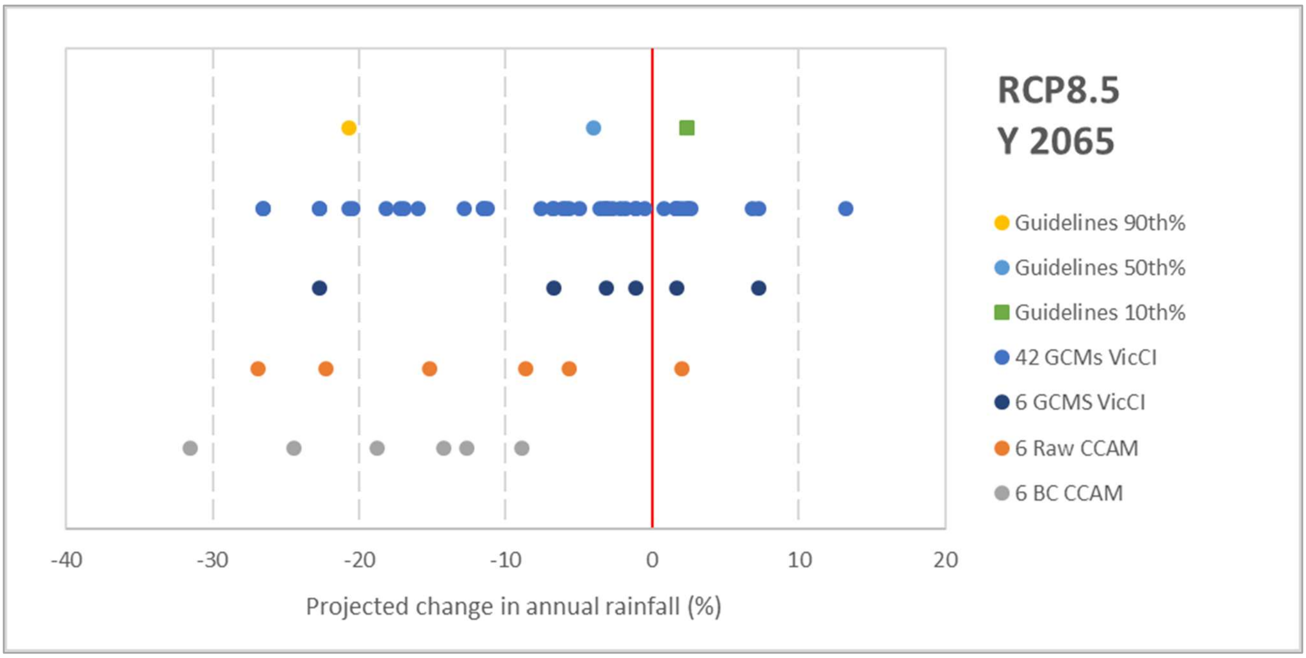


Figure 33 Goulburn Basin comparison of VicCI and VCP19 (CCAM) rainfall projections in 2065

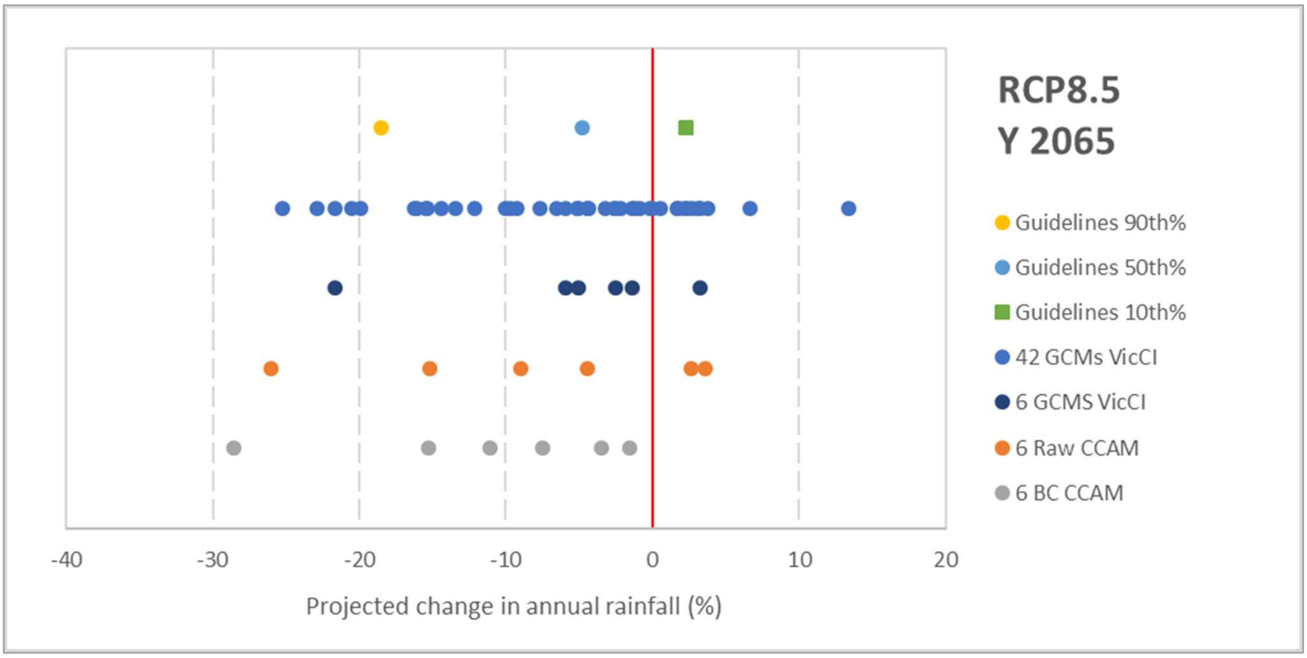


Figure 34 Mitchell Basin comparison of VicCI and VCP19 (CCAM) rainfall projections 2065

The above information is summarised for all river basins in Victoria in Table 10. This information can be used to identify whether the VCP19 projections are likely to be useful for stress testing supply systems with projections that are outside of the range of the VicCI projections.

By way of example, for the East Gippsland Basin, for the RCP8.5 emissions scenario in the year 2065:

- Two of the VCP19 projections lie outside of the range of the VicCI projections, and four lie within that range.
- The VCP19 projections using the GFDL_ESM2M and HadGEM2CC models are drier than the VicCI high climate change projection and could therefore be used for stress testing a river or supply system in this basin to a drier climate change projection than is available from the VicCI projections. One or both of these VCP19 projections could be used for this purpose. These VCP19 projections produce a 15.9% and 30.6% reduction in rainfall for the year 2065, respectively, compared to the VicCI high climate change projection of a 15% decline in rainfall in the body of the guidelines.
- None of the VCP19 projections are wetter than the VicCI low climate change projection, so VCP19 could not be used to assess streamflow characteristics or supply system performance under a wetter climate change projection than what is available in the body of the guidelines.

Table 10 Comparison of VCP19 (VicWaCI bias corrected) versus VicCI climate change projections by river basin for RCP8.5 in 2065.

Basin	Year	Projection	Projected change in annual rainfall (%)					
			Access10	CNRM_CM5	GFDL_ESM2M	HadGEM2CC	MIROC5	NorESM1_M
221 East Gippsland	2065	VCP19 (Bias Corrected)	-6.8	1.8	-15.9	-30.6	-11.3	3.9
		VicCI equivalent	Med-High	Low-Med	Drier than High	Drier than High	Med-High	Low-Med
222 Snowy	2065	VCP19 (Bias Corrected)	-6.8	-1.5	-15.4	-28.3	-15.0	1.9
		VicCI equivalent	Med-High	Low-Med	Drier than High	Drier than High	Drier than High	Low-Med
223 Tambo	2065	VCP19 (Bias Corrected)	-5.2	-1.1	-14.7	-27.8	-14.2	2.4
		VicCI equivalent	Med-High	Low-Med	Med-High	Drier than High	Med-High	Low-Med

224 Mitchell	2065	VCP19 (Bias Corrected)	-7.5	-3.4	-11.1	-28.5	-15.3	-1.5
		VicCI equivalent	Med-High	Low-Med	Med-High	Drier than High	Med-High	Low-Med
225 Thomson	2065	VCP19 (Bias Corrected)	-5.3	-1.0	-8.3	-29.1	-13.0	0.5
		VicCI equivalent	Med-High	Low-Med	Med-High	Drier than High	Med-High	Low-Med
226 Latrobe	2065	VCP19 (Bias Corrected)	-9.7	-7.7	-10.2	-28.5	-17.0	-3.5
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Low-Med
227 South Gippsland	2065	VCP19 (Bias Corrected)	-11.1	-9.4	-11.4	-27.4	-18.4	-4.0
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Low-Med
228 Bunyip	2065	VCP19 (Bias Corrected)	-9.7	-8.6	-13.2	-29.4	-19.1	-5.2
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
229 Yarra	2065	VCP19 (Bias Corrected)	-9.5	-7.1	-12.5	-29.3	-15.2	-6.0
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
230 Maribyrnong	2065	VCP19 (Bias Corrected)	-11.9	-6.2	-16.1	-32.6	-16.1	-10.7
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
231 Werribee	2065	VCP19 (Bias Corrected)	-9.1	-7.7	-16.1	-33.2	-15.6	-8.7
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
232 Moorabool	2065	VCP19 (Bias Corrected)	-6.9	-7.3	-15.2	-34.7	-17.8	-10.1
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
233 Barwon	2065	VCP19 (Bias Corrected)	-8.1	-5.6	-16.2	-34.7	-20.6	-9.5
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
234 Lake Corangamite	2065	VCP19 (Bias Corrected)	-9.1	-6.4	-15.5	-34.0	-21.4	-6.3
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
235 Otway Coast	2065	VCP19 (Bias Corrected)	-12.0	-5.9	-16.7	-31.0	-25.3	-6.8
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
236 Hopkins	2065	VCP19 (Bias Corrected)	-10.6	-8.9	-15.7	-34.0	-22.6	-4.8
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Low-Med
237 Portland Coast	2065	VCP19 (Bias Corrected)	-10.6	-6.9	-12.2	-29.4	-22.9	-2.5
		VicCI equivalent	Med-High	Low-Med	Med-High	Drier than High	Drier than High	Low-Med
238 Glenelg	2065	VCP19 (Bias Corrected)	-8.1	-11.4	-16.3	-32.7	-26.6	-6.2

		VicCI equivalent	Low-Med	Med-High	Med-High	Drier than High	Drier than High	Low-Med
239 Millicent	2065	VCP19 (Bias Corrected)	-9.7	-11.8	-20.1	-33.7	-29.7	-10.2
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
401 Upper Murray	2065	VCP19 (Bias Corrected)	-13.3	-8.5	-20.2	-30.0	-24.2	-6.2
		VicCI equivalent	Med-High	Med-High	Drier than High	Drier than High	Drier than High	Med-High
402 Kiewa	2065	VCP19 (Bias Corrected)	-17.3	-9.3	-22.2	-32.8	-27.0	-8.1
		VicCI equivalent	Drier than High	Med-High	Drier than High	Drier than High	Drier than High	Med-High
403 Ovens	2065	VCP19 (Bias Corrected)	-17.4	-11.2	-21.2	-32.4	-26.0	-8.5
		VicCI equivalent	Med-High	Med-High	Drier than High	Drier than High	Drier than High	Med-High
404 Broken	2065	VCP19 (Bias Corrected)	-15.9	-12.1	-21.5	-32.6	-22.2	-7.0
		VicCI equivalent	Med-High	Med-High	Drier than High	Drier than High	Drier than High	Med-High
405 Goulburn	2065	VCP19 (Bias Corrected)	-14.3	-12.7	-18.8	-31.6	-24.4	-8.9
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High
406 Campaspe	2065	VCP19 (Bias Corrected)	-13.5	-10.7	-19.0	-32.8	-22.5	-10.6
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
407 Loddon	2065	VCP19 (Bias Corrected)	-13.2	-10.5	-18.1	-33.4	-21.9	-11.3
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
408 Avoca	2065	VCP19 (Bias Corrected)	-11.1	-9.9	-17.5	-33.2	-20.2	-10.5
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Med-High	Med-High
414 Mallee	2065	VCP19 (Bias Corrected)	-6.5	-8.9	-19.2	-31.4	-19.2	-8.5
		VicCI equivalent	Median	Med-High	Med-High	Drier than High	Med-High	Med-High
415 Wimmera	2065	VCP19 (Bias Corrected)	-10.9	-11.6	-20.6	-33.0	-23.1	-10.5
		VicCI equivalent	Med-High	Med-High	Med-High	Drier than High	Drier than High	Med-High

B.2.2 NARCliM

NARCliM is the NSW and ACT Regional Climate Modelling Project (NSW DPIE, 2019). However, the high resolution modelling undertaken for this project extends to cover all of Victoria. The project ran the results from four GCMs through three representations of a regional climate model (the Weather and Regional Forecasting model), to generate 12 alternative downscaled climate projections. The three representations included different assumptions around the climate physics in the model. The NARCliM model outputs were used in both the VCP19 (Clarke et al., 2019a) and *A Synthesis of Findings from the Victorian Climate Initiative* (Hope et al., 2017) for comparison purposes. The VicCI synthesis report comparison indicated that NARCliM generated wetter rainfall changes in northern Victoria, particularly in autumn, and wetter projections in southern Victoria in winter, relative to the VicCI projections. However, the regional climate model adopted for NARCliM targeted better performance in storm events (e.g. to perform better when estimating changes in rainfall intensity), with performance against long-term average rainfall behaviour a secondary consideration.

At the time of writing the guidelines, the NARCliM modelling is in the process of being updated, with new results not due to be released until late 2020. DELWP will consider the suitability and value of the updated NARCliM modelling results for Victoria when they are made available.

B.2.3 Climate Change in Australia NRM Region Projections

The Climate Change in Australia (CCIA) projections for Australia's NRM regions produced a range of datasets of projected climate change, including changes in air temperature, rainfall and potential evapotranspiration (CSIRO and BoM, 2015). Summary information is available from the CCIA website, with time series datasets available for users who register their details with CSIRO.

Relative to the projections used in the DELWP guidelines, the CCIA projections have these advantages:

- Projections are available Australia-wide, so can be used in studies for shared water resources that span well beyond the Victorian border
- Lower emissions scenarios are available in addition to the emissions scenario adopted in the guidelines
- The projections include an additional, earlier time slice (at 2030, 2050, 2070 and 2090)

The disadvantages of the CCIA projections are:

- The runoff estimates for NRM regions (covering many river basins) were regarded as an "interim product" only in CCIA reporting (CSIRO and BoM, 2015)

Results are available for NRM regions that span many river basins. Finer grid information was produced but could be misinterpreted as it does not contain additional information than what is available at the larger GCM grid scale. This is due to the method used to generate the grids, which is a simple interpolation method that is not informed by local climate conditions.

The CCIA projections are best suited for (i) studies at a national scale or where the study area of interest extends well into other states and territories (e.g. for whole of Murray-Darling Basin studies) and (ii) if a particular parameter of interest is not available from the guidelines or the VCP19 projections.

The CCIA website (https://www.climatechangeinaustralia.gov.au) does, however, include a wide range of useful contextual information and tools. These include the Climate Futures Tool (which provides a matrix of GCM agreement for a particular region) and the Climate Analogues Tool (which allows the projected change in climate of one location to be mapped to the historical climate of other locations).

Note that the VCP19 datasets are stored on the CCIA website, but for the purposes of these guidelines are considered a separate product to the CCIA national projections of climate change.

B.2.3 National Hydrologic Projections

The Bureau of Meteorology is currently developing a national hydrological projections service for Australia, which would complement the existing CCIA projections of climate variables. As of May 2020, the project team had run the outputs from four GCMs and CCAM downscaling model at 50 km resolution through three different bias correction methods and then a water balance model, AWRA-L, that has been calibrated nationally (L. Wilson, BoM, pers. comm. 28/05//11/2020). Model results are currently being assessed. Further activities planned for 2020 include the development of case studies and ongoing user engagement activities. These have a planned beta delivery date of late 2020 and full delivery in early 2021, with plans for extension to include more datasets as resources allow. These national projections are likely to be suitable for continental-scale applications but are not expected to replace the existing VicCI runoff projections. DELWP will consider the potential role of these projections in applications for Victoria when they are produced.

B.3 Obtaining finer spatial resolution for projected changes

Projected changes in climate and runoff/recharge are provided for each Victorian river basin and are considered appropriate for future water supply planning purposes in most Victorian systems. Obtaining projected changes at a finer or different spatial resolution likely involves considerable effort and collaboration with the climate change researchers who have derived the projections of interest.

In the case that the use of the projected changes for a different spatial extent (and potentially at a different spatial scale) is warranted, climate change projections can be generated in a manner consistent with the VicCI projections in the guidelines. They are as follows:

(iv) Obtain the 5 km grids of hydroclimate projections generated by CSIRO (Potter et al., 2016), as illustrated in Figure 35 and Figure 36. The available gridded information provides the projections from each of the 42 GCMs for rainfall, potential evapotranspiration and runoff under current climate and for 2040 and 2065. This data can be obtained from DELWP.

(v) For each GCM aggregate the total runoff over the entire region of interest for both the current climate and future scenario (either 2040 or 2065) and calculate the percentage change (or absolute change for temperature).

(vi) Select GCMs to represent each of the three scenarios as follows:

> Low — select the GCM that is associated with the 10th percentile change in runoff.

> Medium — select the GCM that is associated with the median change in runoff.

> High — select the GCM that is associated with the 90th percentile change in runoff.

(vii) The projected changes calculated using this approach may not be exactly consistent with the basin-wide factors if the GCMs selected are different than those selected for the entire river basin.

(viii) For each scenario (low, medium and high), adopt the projected changes for each variable (rainfall, potential evapotranspiration and runoff) from the GCM selected in step iii.

Alternatively, the VCP19 downscaled projections can be utilised. This would involve the following steps:

(ix) Obtain the 5 km grids of hydroclimate projections generated for VCP19 (Clarke et al., 2019a). The available gridded information provides the projections from six GCMs for temperature, rainfall and potential evapotranspiration in 1995, 2030, 2050 and 2090. This data can be obtained from DELWP. Runoff projections for VCP19 were not yet available at the time of publishing these guidelines, but are expected to be prepared by late 2020 to allow different runoff projections derived using different modelling approaches to be compared.

(x) Identify the GCMs of interest from the six available, by referring to the comparison of VCP19 and VicCI rainfall projections by river basin, presented in Appendix B2.1. More detailed GCM comparisons (e.g. Hope et al., 2016 or Grose et al., 2017) can be used at this step, if desired, to check the ability of that particular host GCM to replicate climate characteristics considered of most relevance to the region of interest.

(xi) For each GCM aggregate or average each variable over the region of interest and calculate the percentage change (or absolute change for temperature) from 1995 to the time period of interest.

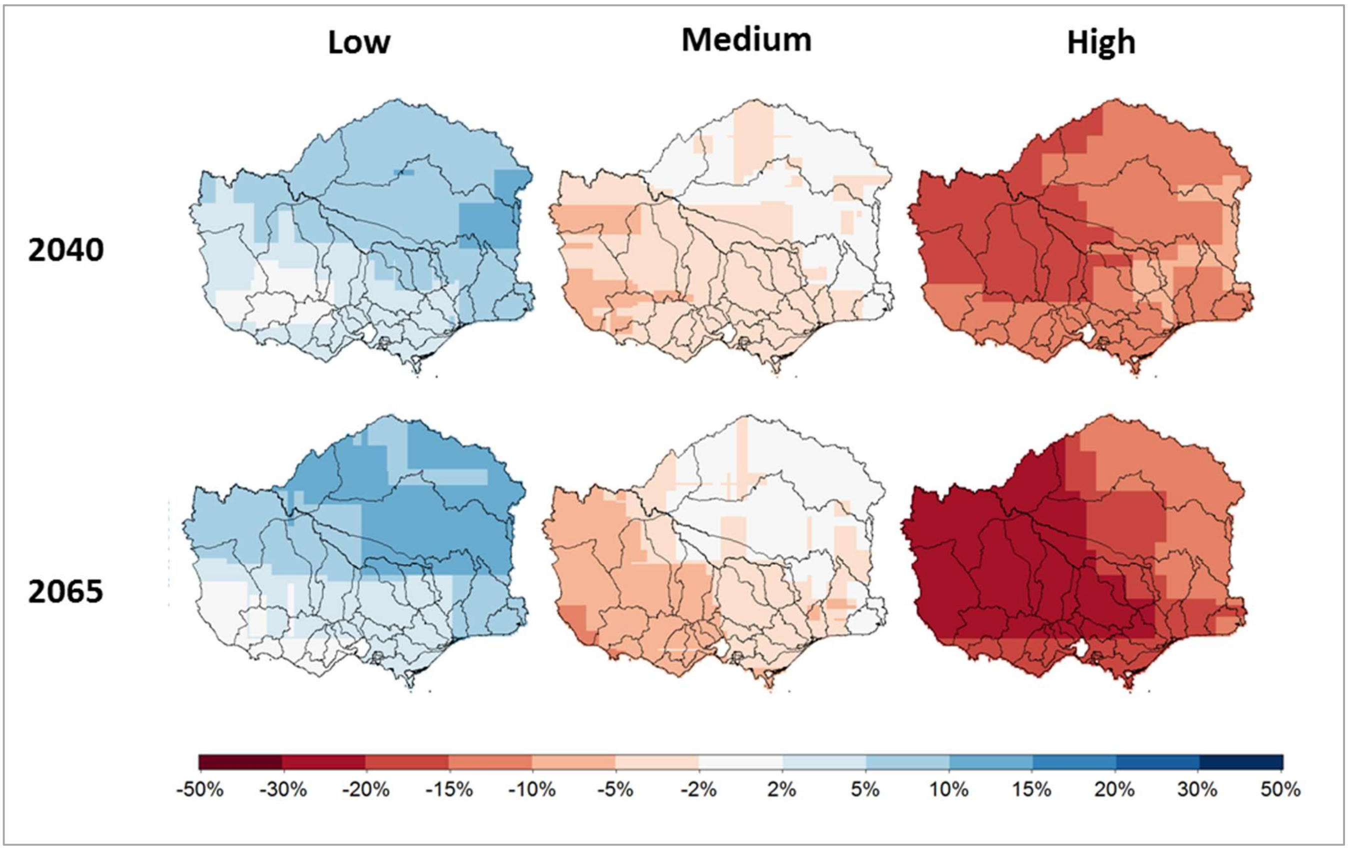


Figure 35 Projected changes in annual rainfall under emissions scenario RCP8.5 relative to current climate at a finer spatial scale (Source: Potter et al., 2016)

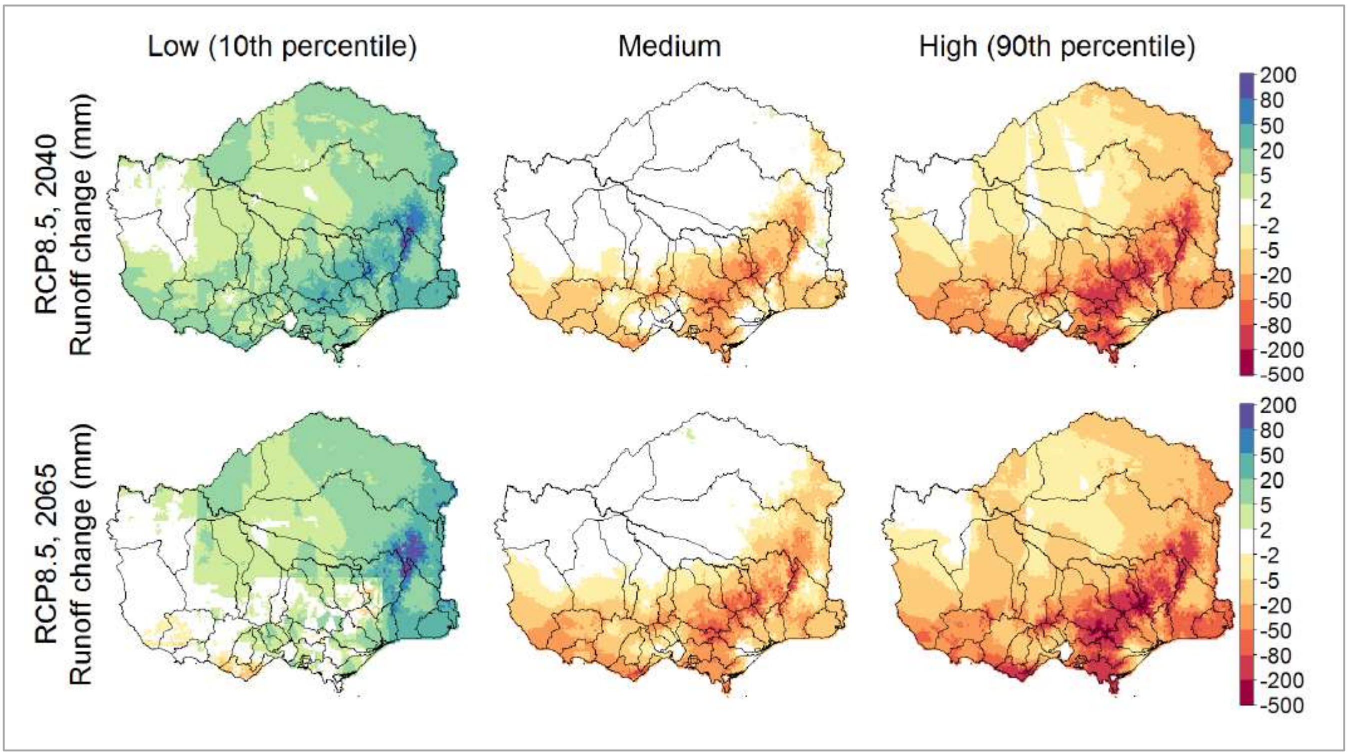


Figure 36 Projected changes in annual runoff under emissions scenario RCP8.5 relative to current climate at a finer spatial scale (Source: Potter et al., 2016)

B.4 Climate analogues

Climate analogues involve selecting historical climate data from another climate station in Australia to represent the anticipated climate behaviour at the location of interest under a future climate change condition. For example, if a location is expected to become drier, then a rainfall station in a drier climate could be selected to illustrate what that location's future climate might be like.

Climate analogues are presented on the Climate Change in Australia using the Climate Analogues Explorer (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/analogues-explorer/), with case studies for Victoria presented in Grose et al. (2015a) and Timbal et al. (2015).

The method used by the Climate Analogues Explorer matches the site of interest to other locations using the average annual rainfall and the maximum temperature (within set tolerances) (CSIRO and Bureau of Meteorology, 2015). The online tool can also be used to refine the search using measures of rainfall seasonality (the proportion of rainfall that falls in summer) and temperature seasonality (expressed as the difference between summer and winter temperatures), as well as average seasonal rainfall and temperature for individual seasons. As noted by CSIRO and the Bureau of Meteorology (2015) the tool ignores other potentially important factors. For this reason, it "should not be used directly in adaptation planning without considering more detailed information" (Grose et al., 2015a). Implicit in this method is the assumption that future climate with higher global greenhouse gas concentrations can be represented by a historical climate with lower global greenhouse gas concentrations, although it is acknowledged that this assumption is not limited to the analogue approach.

Climate analogues have been used to estimate projected changes in climate behaviour but are usually used alongside other techniques as part of sensitivity testing alternative projections. Arnbjerg-Nielson (2012), for example, uses climate analogues to assess climate change impacts on extreme rainfall alongside two other analysis techniques.

Due to the tolerance when selecting analogue sites, multiple sites can potentially be used to represent future climate for a single location for any given combination of future warming and drying. For example, for a one-degree increase in temperature and a 10% reduction in annual rainfall in Melbourne, the tool selects 14 potential climate analogues from regional Victoria, New South Wales, South Australia and Western Australia, as shown in Figure 37. The default tolerances in the tool are ± 1 degree Celsius and ± 20% of mean annual rainfall. By selecting the advanced tools button («) in the top right-hand corner, these tolerances can be narrowed.

Figure 37 Climate Analogues for Melbourne for a 1 degree warming and 10% reduction in annual rainfall

The advanced tools also allow seasonal changes to be considered in selecting the analogue sites. In the above example, the search could be refined to match a one-degree change in annual temperature and a 10% reduction in rainfall (as above), but with an additional constraint that a 10% reduction in rainfall must occur in winter and spring. This yields two climate analogues (Sale and Bathurst) from the original 14 sites. These two sites can then be examined for projected changes in autumn rainfall (in this example, assumed to be 142 mm in Melbourne), indicating that average annual rainfall in Bathurst (133 mm) better reflects an anticipated decline in autumn rainfall than Sale (150 mm). On this basis, Bathurst could be regarded as a suitable climate analogue for Melbourne for this hypothetical future climate scenario.

It is unlikely that a single climate analogue will be representative of anticipated changes in climate at a given site, particularly given that the GCMs produce a wide range of climate responses (low to medium to high). Therefore, multiple analogues are likely to be required to gain an appreciation of the range of potential daily climate behaviour under future climate change. There is also no guarantee that the analogue associated with the high climate change scenario will produce longer duration droughts than the median or high climate change analogues.

Climate analogues could be used in a few different ways:

- As a communication tool to a non-technical audience however, there may be limitations to this if the audience has no understanding of the historic climate at the location of the analogues. In the above example, if a person in Melbourne has never been to Bathurst, they may not be able to grasp how the climate in Melbourne may change, unless it is described to them using other information (e.g. statistical differences in the weather of the two locations, types of water dependent industries that exist in the two locations, etc.). These statistical differences could include daily time step information that the GCMs are unable to accurately provide.
- To provide an indication of drought duration, severity and frequency for run-of-river supply systems, integrated water management options, managed aquifer recharge and single year storage systems, alongside other existing analysis techniques. It was acknowledged in Section 4.8 that GCMs and their downscaled data provide this type of information with only a low level of confidence. Water Corporations could potentially take the selected analogues and run them through a rainfall-runoff model or groundwater model at the local site of interest to get an appreciation of how periods of low flow may change, and the implications for management of the water supply system. Similar to GCMs, any inferences about within-year climate change drawn from climate analogues are likely to be made only with low confidence. However, climate analogues have the advantage of at least presenting the possibility of changes to within-year drought duration that GCMs currently do not.

B.5 Paleoclimate rainfall and streamflow reconstructions

Instrumental records for rainfall are typically only available from the late 19th century onwards in Victoria, with almost all streamflow records in Victoria not starting until the 20th century. Paleoclimate proxy records are indicators of past climate that can provide information about natural climate variability prior to the start of available instrumental records. Paleoclimate proxy records can date back hundreds to thousands of years. Paleoclimate proxy records are derived from a range of sources including from corals, tree rings, ice cores, cave speleothems, lake and marine sediments. Paleoclimate proxy records have been utilised in other states of Australia for water supply impact assessment, including for extending a representative current climate baseline prior to undertaking climate change impact assessment (e.g. Verdon-Kidd et al., 2019).

Victorian Drought Risk Inference Project (VicDRIP) researchers from the University of Melbourne generated paleoclimate reconstruction records of cool season and warm season rainfall dating back 400–800 years across different regions of Australia. The predictive skill of the reconstruction is influenced by the availability of local natural archives, and the connections between those archives, climate influences and rainfall. At the DELWP Climate and Water Science Day, Ballis (2019) indicated that there were no natural archives available in Victoria, as shown in Figure 38. Rainfall reconstructions for Victoria therefore rely upon natural archives in other parts of the country or elsewhere, and their relationship to the regional climate influences that affect Victoria’s climate.

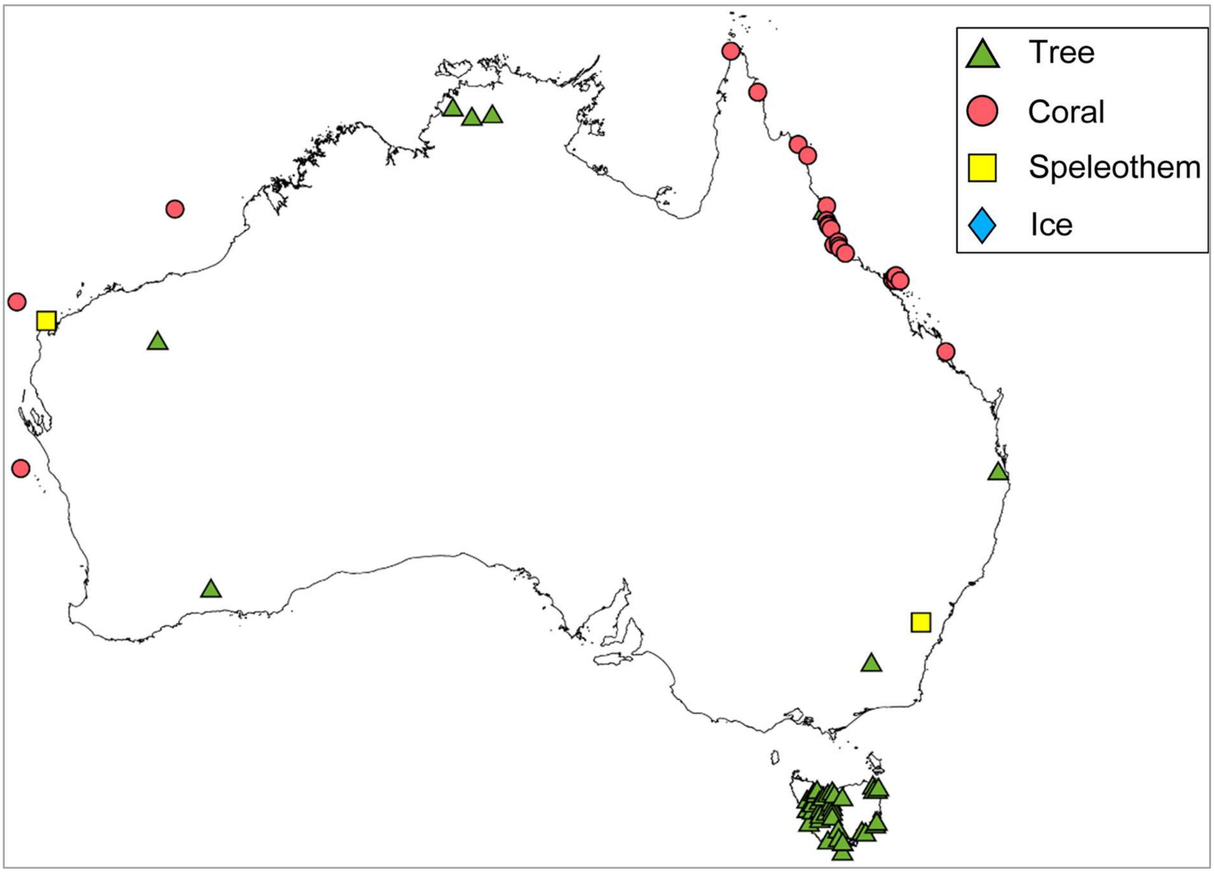


Figure 38 Availability of natural archives for use in paleoclimate reconstructions (Source: presentation by Ballis, 2019)

The predictive skill of paleoclimate reconstructions (i.e. the ability to estimate rainfall, streamflow or drought duration over a gauged reference period) is highest in coastal Queensland, where high quality coral proxy records are available. However, as a result of the lack of local natural archives in Victoria, the skill of Victorian rainfall reconstructions developed from remote proxy archives are low. According to Ballis (2019), the Nash–Sutcliffe efficiency (NSE) of paleoclimate reconstruction records of rainfall and streamflow for south east Australia ranged from less than zero (i.e. worse than assuming mean rainfall or streamflow conditions) up to 0.4, with most reconstructions exhibiting NSE values of zero to 0.25. This is illustrated in Figure 39. The skill of reconstructions reported in Freund et al. (2017), a key VicDRIP funded research paper, was of a similar order of magnitude using a range of different calibration and verification statistics.

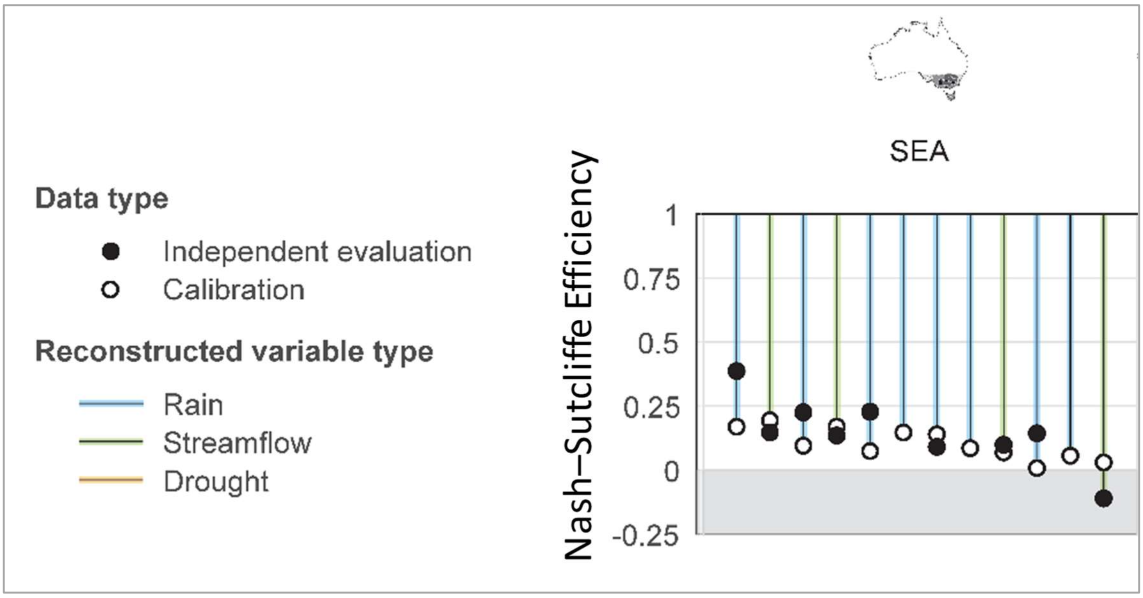


Figure 39 Quality of paleoclimate rainfall and streamflow reconstructions for south-east Australia (Source: Ballis, 2019)

Freund et al. (2017) also compared these most recent rainfall reconstructions with previous rainfall reconstructions. In Victoria the correlations with other studies appear to reinforce the uncertainties associated with paleoclimate proxy records. Freund et al. (2017) did however identify strong correlations with documentary records of past cool season climate events in the Murray-Darling Basin.

Notwithstanding the apparent inability of paleoclimate reconstruction records of two-season rainfall to capture recorded historical variability well in Victoria, Freund et al. (2017) concluded that:

- "The most recent decline in rainfall in the Southern Slopes [covering southern Victoria and Tasmania] is within the range of variability given by the reconstruction".
- "The most recent trends [in rainfall in the Murray-Darling Basin] starting after the 1950s and 1970s are not unprecedented but are below the 25th percentile, pointing towards a drying tendency". Freund et al. (2017) inferred that recent observed reductions in cool season rainfall "are not particularly unusual in terms of natural variability resolved by the reconstruction", despite this observation being "often associated with the intensification of the sub-tropical ridge […], changes in large-scale atmospheric circulation […], and the observed upward trend in SAM".
- "The Millennium Drought stands out as an unprecedented drought in the Southern Slopes region [covering southern Victoria and Tasmania]. The World War 2 Drought seems not to be as exceptional" at a national scale, with only central and eastern regions of Australia most affected. "The Federation Drought […] is confirmed as one of the worst periods of suppressed rainfall in the Murray Basin", while other earlier droughts "appeared to be much more regionally constrained".

If these findings are correct for Victoria, then it would imply that there is little value to be gained from the use of paleoclimate reconstructions based on remote proxies in Victoria for assessing long-term reliability of supply, because the instrumental record captures the most severe droughts of the last 400-800 years.

This research highlights that, unlike for some other parts of Australia, significant uncertainties exist in paleoclimate reconstruction records of annual warm and cool season rainfall for Victoria. If the available reconstruction records are correct, this would suggest that the observed droughts in Victoria from the instrumental record are the worst over the past several centuries. For these reasons, the use of paleoclimate reconstruction records, based on remote proxies, is not recommended as a direct input to water resource modelling assessments in Victoria at the current time.

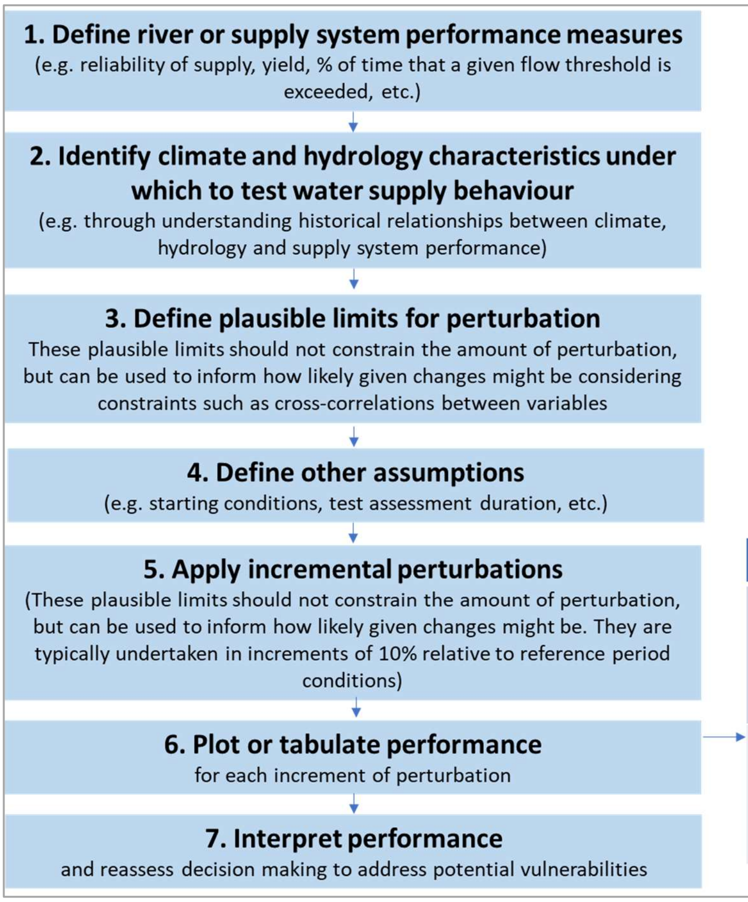
B.6 Additional climate change impact assessment techniques

B 6.1 Sensitivity (stress) testing

Climate sensitivity testing, also known as climate stress testing, involves testing river behaviour or supply system performance under incremental changes in climate, recharge or runoff. This could involve, for example, testing the behaviour of a river system under say a 10% reduction in rainfall, or testing the performance of a supply system under a 10% reduction in streamflows, and examining changes in streamflow characteristics or supply system performance metrics. An overview of the process is shown in Figure 40, with an example output.

Sensitivity testing and stress testing are subtly different and potentially offer different insights. Sensitivity testing typically includes both negative and positive perturbations (e.g. both incremental increases and decreases in rainfall), whereas stress testing typically only considers perturbations that could cause a decrease in performance (e.g. an incremental decrease in rainfall). Stress testing can also be directly related to a specific scenario, with the degree of perturbation related to an output from another process. Stress testing under changes in runoff informed by bushfire impact modelling could be an example of this kind of stress testing.

If perturbing more than one climate or hydrological characteristic, it is important to consider their cross-correlation. For highly correlated variables, only one of those variables should be perturbed. The relationship between correlated variables should be defined using some form of functional equation. For example, it would typically not make sense to increase air temperature and decrease evaporation at the same time, because this is unlikely to be physically plausible. Rather they would be paired so that if air temperature is increased by 10% then evaporation would be assumed to also increase by some related percentage. See Section 5.6.2 for further discussion on GCM uncertainty and consistency between projections.



Hypothetical example only

Variable	Incremental change	Performance
Average rainfall	Reference period	Annual reliability 95%
	-10%	Annual reliability 95%
	-20%	Annual reliability 89%
Drought duration	Reference period	Minimum storage 200 ML
	Extended by 2 weeks	Minimum storage 180 ML
	Extended by 4 weeks	Minimum storage 130 ML

Figure 40 Process and example output from sensitivity testing

One potential advantage of sensitivity testing is that it is not constrained by real-world climate observations or the limitations of GCMs. For example, for run-of-river systems that are perceived as being sensitive to changes in within-year drought duration, a hypothetical rainfall or streamflow sequence can be created that reflects this potential change. The supply system can then be tested to understand what drought duration would start to cause supply system performance to drop below level of service objectives. If the duration at which supply system performance drops below expectations is only marginally longer than historical observations, then the supply system is potentially at risk from the occurrence of a drought only slightly worse than the worst on record, and action to improve supply system resilience could be warranted. On the other hand, if the duration of drought needs to double before supply system performance is compromised, then this indicates both that the supply system is resilient to drought duration, and also provides an indication of the time that might be available to make corrective actions if such a drought were to actually eventuate.

The decision risk associated with sensitivity testing and stress testing is that if the perturbations are not plausible, they can skew decision making to try and plan for an event of extremely low likelihood. For this reason, the perturbations should be related to observed or modelled behaviour wherever possible, including indicating where the perturbations extend beyond those observations or model results.

B 6.2 Sensitivity testing for seasonal rainfall projections

Step three (define plausible limits for perturbation) of the above process in Figure 40 has been developed for sensitivity testing of projected seasonal changes in rainfall. Figure 41 illustrates, for an example river basin, how cool and warm season rainfall varies for a given annual projection from the range of 42 GCMs, for a given emissions scenario. For Victoria, the cool season is assumed to run from April to October and the warm season is assumed to run from November to March. The deviation of the projected cool and warm season behaviour from the annual projection is shown in Figure 42. From this figure the maximum **deviation** for both the cool season and the warm season have been identified, over the range of annual projections adopted in the guidelines (i.e. from the 10th to 90th percentile annual projections). The cool and warm season deviations are paired for each GCM. That is, the GCM that generates the maximum cool season rainfall increase will have a corresponding maximum warm season decrease, and the GCM that generates the maximum warm season increase will have a corresponding maximum cool season decrease.

In the example shown in Figure 42, the GCM with the greatest warm season increase (relative to the given annual projection) generates an 18% increase in warm season rainfall, with a corresponding 11% decrease in cool season rainfall. Similarly, the GCM with the greatest cool season increase (relative to the given annual projection) generates a 13% increase in cool season rainfall, with a corresponding warm season rainfall decrease of 21%.

These are the two paired ranges that can therefore be used for sensitivity testing:

- The first paired sensitivity represents the combination associated with the greatest increase in cool season rainfall relative to the annual projection (and the greatest decrease in warm season rainfall relative to the annual projection).
- The second represents the combination associated with the greatest increase in warm season rainfall relative to the annual projection (and the greatest decrease in cool season rainfall relative to the annual projection).

Both pairs must be utilised to fully understand the potential impact of seasonal projection uncertainty on river or supply system behaviour.

Sensitivity ranges for the seasonal projections were derived for each river basin, as listed in Table 11 (for the low climate change projection), Table 12 (for the medium climate change projection) and Table 13 (for the high climate change projection).

To illustrate how to apply Table 11 to Table 13, the East Gippsland Basin has been adopted. In Table 13, the high climate change projection (from chapter five of the guidelines) for this basin for the year 2040 under the RCP8.5 emissions scenario is for a 10.8% reduction in annual rainfall. From Table 13, the projected range of possible seasonal changes under these conditions would be:

(i) A 3.2% decrease in cool season rainfall coupled with a 22.3% decrease in warm season rainfall.

(ii) A 22.4% decrease in cool season rainfall coupled with a 6.8% increase in warm season rainfall.

Both pairs of cool and warm season changes are equally plausible, and both need to be applied to adequately test the sensitivity of streamflow characteristics or supply system performance to seasonal climate changes for any given annual projection. When applied, the sum of seasonal impacts will not add precisely to the low, medium or high annual projection. This is potentially acceptable; we don't know how climate change will play out seasonally, and if it will manifest in a non-uniform way across the seasons (or in a manner different to the single GCM that was used to derive the annual projected change). But, if desired, a further step can be undertaken, to uniformly scale up or down the seasonally adjusted rainfall to match the annual projection. This step would make it easier to compare scenarios.

To test seasonal sensitivities to the high, medium and low projections (i.e. three projections) for the years 2040 and 2065 (two time slices), up to 12 sensitivity tests could be required. Due to the laborious nature of applying these tables, it is recommended that testing the sensitivity of streamflow characteristics or supply system performance to uncertainty in seasonal rainfall projections for the given projected annual rainfall change should only be undertaken for representative scenarios, with results inferred more broadly from those sensitivities.

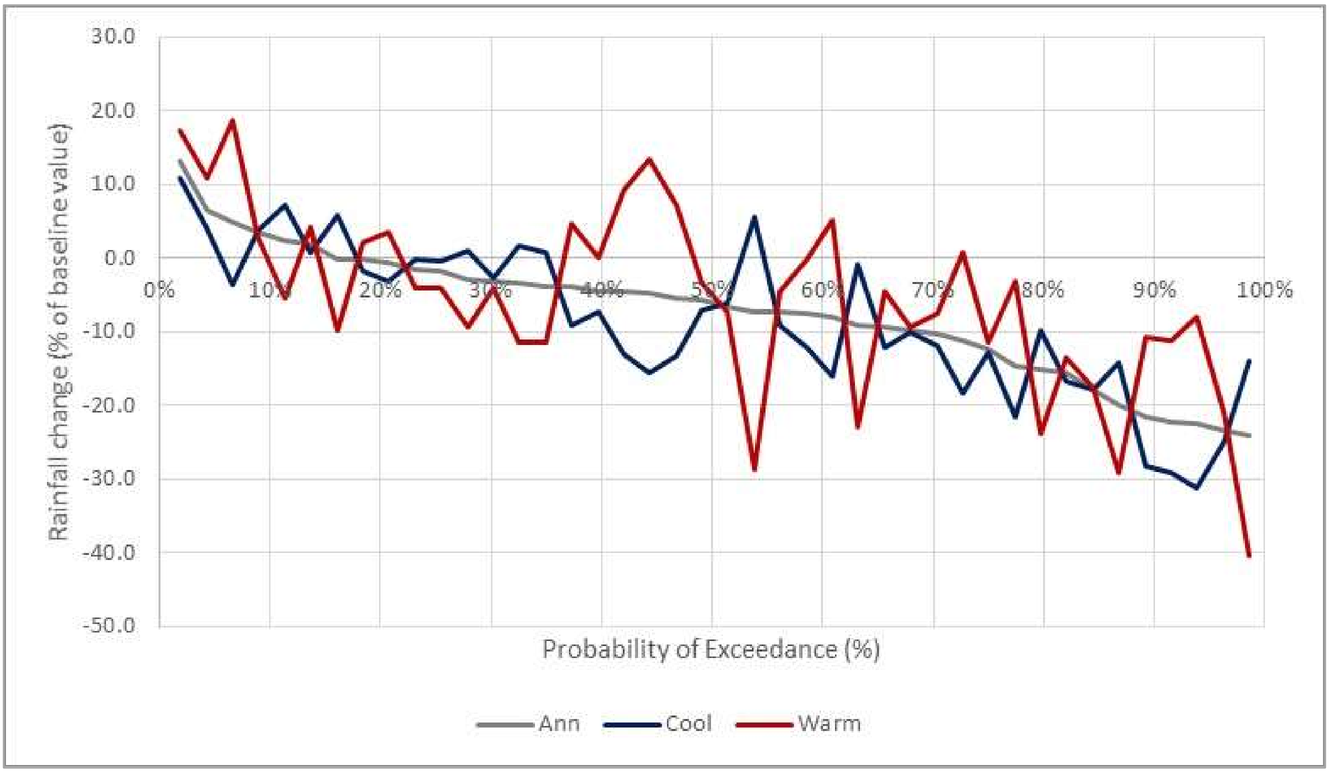


Figure 41 Cool and warm season projection variability by annual projected change for an example river basin, RCP and time slice

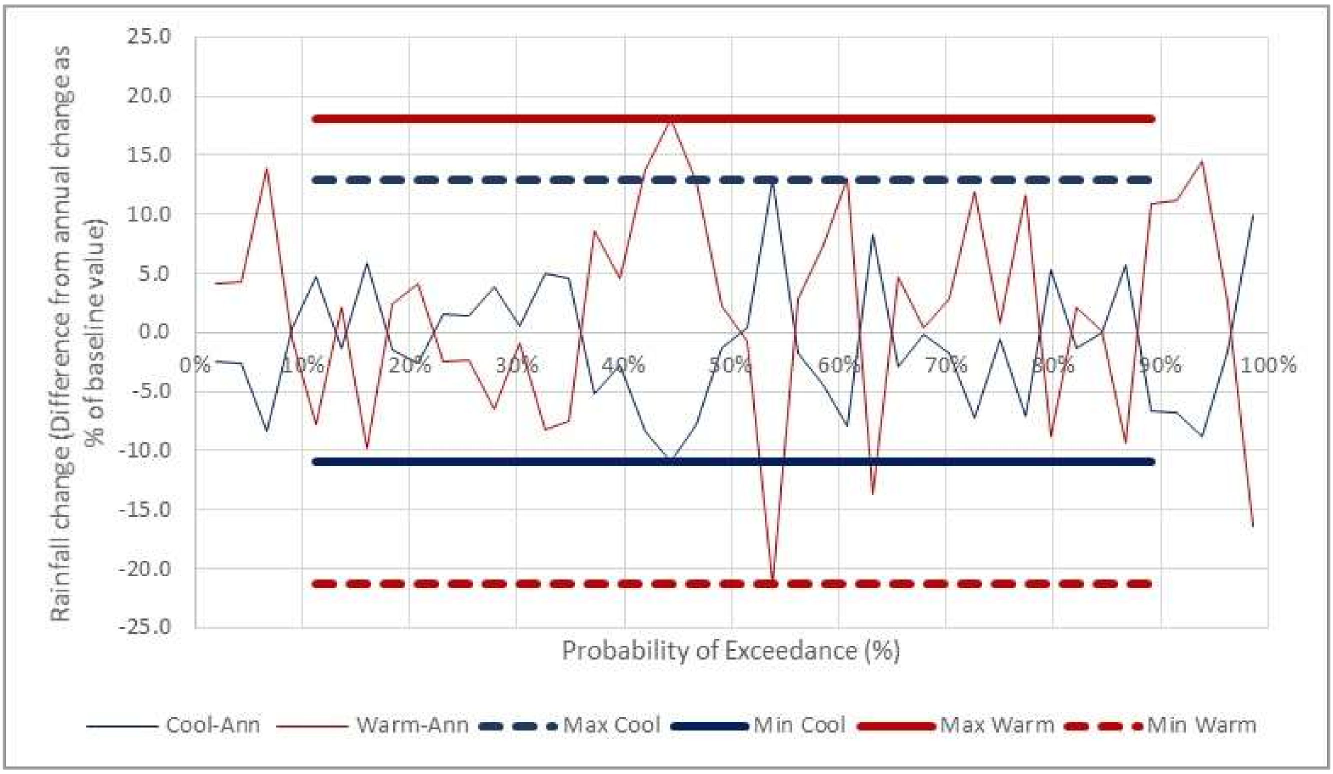


Figure 42 Maximum range of paired cool/warm season rainfall projections for the 10th to 90th percentile annual projections

Table 11 Range of projected seasonal changes in rainfall for maximum cool season rainfall increase (Sensitivity Test 1) and maximum warm season rainfall increase (Sensitivity Test 2) for the LOW climate change projection

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		Low	Cool	Warm	Cool	Warm
East Gippsland (221)	Year 2040 RCP8.5	6.8%	14.4%	-4.7%	-4.8%	24.4%
	Year 2065 RCP8.5	7.9%	19.9%	-10.3%	-2.1%	23.0%
	Year 2040 RCP4.5	5.6%	10.0%	-1.1%	-9.9%	29.1%
	Year 2065 RCP4.5	6.6%	16.7%	-8.7%	-3.0%	21.2%
Snowy (222)	Year 2040 RCP8.5	7.6%	12.0%	1.6%	-3.0%	22.0%
	Year 2065 RCP8.5	8.5%	18.1%	-4.6%	-4.1%	25.7%
	Year 2040 RCP4.5	4.9%	9.4%	-1.2%	-13.3%	29.7%
	Year 2065 RCP4.5	6.7%	15.3%	-5.1%	-3.2%	20.2%
Tambo (223)	Year 2040 RCP8.5	5.9%	11.5%	-1.9%	-5.6%	21.9%
	Year 2065 RCP8.5	7.1%	19.8%	-10.5%	-3.9%	22.4%
	Year 2040 RCP4.5	5.4%	8.7%	0.8%	-11.1%	28.4%
	Year 2065 RCP4.5	5.3%	14.4%	-7.3%	-4.5%	18.9%
Mitchell (224)	Year 2040 RCP8.5	4.3%	9.1%	-3.8%	-5.8%	21.4%
	Year 2065 RCP8.5	2.3%	11.3%	-12.9%	-7.7%	19.2%
	Year 2040 RCP4.5	4.1%	8.0%	-2.5%	-12.7%	32.5%
	Year 2065 RCP4.5	4.0%	12.0%	-9.6%	-4.9%	19.1%
Thomson (225)	Year 2040 RCP8.5	4.1%	9.2%	-4.6%	-5.5%	20.2%
	Year 2065 RCP8.5	2.3%	12.4%	-14.8%	-7.6%	18.9%
	Year 2040 RCP4.5	4.5%	10.0%	-4.8%	-12.5%	33.2%
	Year 2065 RCP4.5	4.0%	12.2%	-9.9%	-4.4%	18.2%
Latrobe (226)	Year 2040 RCP8.5	3.3%	8.4%	-5.9%	-5.7%	19.5%
	Year 2065 RCP8.5	2.2%	13.4%	-18.1%	-6.6%	18.0%
	Year 2040 RCP4.5	4.4%	10.1%	-5.8%	-8.2%	27.1%
	Year 2065 RCP4.5	3.9%	12.0%	-10.7%	-4.2%	18.6%
South Gippsland (227)	Year 2040 RCP8.5	2.6%	8.2%	-8.4%	-6.3%	20.2%
	Year 2065 RCP8.5	2.2%	13.3%	-19.5%	-6.1%	18.4%
	Year 2040 RCP4.5	4.4%	9.7%	-6.0%	-2.3%	17.4%
	Year 2065 RCP4.5	4.0%	11.8%	-11.2%	-3.1%	18.0%
Bunyip (228)	Year 2040 RCP8.5	2.9%	7.8%	-6.4%	-6.2%	20.0%
	Year 2065 RCP8.5	2.1%	14.5%	-21.2%	-6.9%	19.0%
	Year 2040 RCP4.5	4.3%	11.3%	-9.0%	-7.1%	25.9%
	Year 2065 RCP4.5	3.7%	11.6%	-11.3%	-3.6%	17.4%
Yarra (229)	Year 2040 RCP8.5	3.7%	8.5%	-5.3%	-5.6%	21.2%
	Year 2065 RCP8.5	2.4%	14.5%	-20.3%	-6.6%	19.3%
	Year 2040 RCP4.5	4.7%	11.1%	-7.3%	-11.0%	34.3%
	Year 2065 RCP4.5	4.0%	11.3%	-9.7%	-4.0%	19.1%

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		Low	Cool	Warm	Cool	Warm
Maribyrnong (230)	Year 2040 RCP8.5	2.7%	7.5%	-5.8%	-6.2%	18.3%
	Year 2065 RCP8.5	2.6%	14.6%	-18.5%	-7.4%	20.2%
	Year 2040 RCP4.5	5.2%	11.0%	-5.0%	-6.3%	25.4%
	Year 2065 RCP4.5	3.8%	11.5%	-9.7%	-5.8%	20.6%
Werribee (231)	Year 2040 RCP8.5	2.2%	7.2%	-6.1%	-7.2%	17.7%
	Year 2065 RCP8.5	2.4%	15.3%	-18.8%	-8.5%	20.4%
	Year 2040 RCP4.5	5.2%	11.1%	-4.5%	-1.8%	16.7%
	Year 2065 RCP4.5	3.1%	11.8%	-11.2%	-5.2%	16.7%
Moorabool (232)	Year 2040 RCP8.5	2.0%	7.7%	-7.4%	-7.3%	17.5%
	Year 2065 RCP8.5	1.5%	13.6%	-18.7%	-9.9%	20.5%
	Year 2040 RCP4.5	5.0%	10.8%	-4.6%	-2.7%	17.7%
	Year 2065 RCP4.5	2.3%	11.1%	-12.3%	-5.3%	15.0%
Barwon (233)	Year 2040 RCP8.5	2.0%	6.3%	-6.4%	-4.4%	14.5%
	Year 2065 RCP8.5	1.2%	11.3%	-18.6%	-5.6%	14.7%
	Year 2040 RCP4.5	3.7%	8.8%	-6.3%	-2.9%	16.6%
	Year 2065 RCP4.5	1.5%	8.4%	-12.1%	-4.2%	12.7%
Lake Corangamite (234)	Year 2040 RCP8.5	2.0%	6.1%	-6.5%	-4.1%	14.5%
	Year 2065 RCP8.5	-0.2%	8.0%	-17.1%	-6.9%	13.6%
	Year 2040 RCP4.5	3.7%	8.7%	-6.5%	-3.0%	17.4%
	Year 2065 RCP4.5	1.7%	8.4%	-12.0%	-4.2%	13.7%
Otway Coast (235)	Year 2040 RCP8.5	2.1%	6.5%	-8.6%	-3.0%	14.4%
	Year 2065 RCP8.5	0.5%	7.9%	-17.4%	-5.1%	14.1%
	Year 2040 RCP4.5	4.1%	8.2%	-5.8%	-1.9%	18.5%
	Year 2065 RCP4.5	1.9%	7.0%	-10.5%	-2.7%	13.0%
Hopkins (236)	Year 2040 RCP8.5	2.1%	6.8%	-8.1%	-5.1%	17.8%
	Year 2065 RCP8.5	1.0%	8.0%	-14.1%	-7.6%	19.7%
	Year 2040 RCP4.5	3.6%	8.9%	-7.8%	-3.6%	19.2%
	Year 2065 RCP4.5	1.5%	8.7%	-14.2%	-5.6%	16.9%
Portland Coast (237)	Year 2040 RCP8.5	2.6%	5.8%	-5.9%	-2.4%	16.1%
	Year 2065 RCP8.5	-0.2%	6.2%	-17.6%	-7.0%	18.3%
	Year 2040 RCP4.5	3.5%	8.9%	-11.0%	-2.5%	19.8%
	Year 2065 RCP4.5	2.5%	7.4%	-10.7%	-2.4%	15.8%
Glenelg (238)	Year 2040 RCP8.5	1.2%	5.8%	-11.3%	-5.7%	20.0%
	Year 2065 RCP8.5	1.4%	6.0%	-11.1%	-7.8%	26.4%
	Year 2040 RCP4.5	1.9%	6.1%	-9.4%	-4.9%	20.4%
	Year 2065 RCP4.5	2.2%	7.2%	-11.3%	-4.1%	19.2%
Millicent (239)	Year 2040 RCP8.5	1.2%	4.9%	-10.3%	-6.1%	24.1%
	Year 2065 RCP8.5	1.1%	5.8%	-13.6%	-7.7%	28.6%
	Year 2040 RCP4.5	2.3%	6.0%	-9.3%	-4.6%	24.1%
	Year 2065 RCP4.5	2.3%	6.5%	-11.0%	-4.4%	23.3%

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		Low	Cool	Warm	Cool	Warm
Upper Murray (401)	Year 2040 RCP8.5	7.5%	11.1%	0.6%	-1.9%	25.7%
	Year 2065 RCP8.5	8.2%	14.9%	-4.8%	-10.9%	45.0%
	Year 2040 RCP4.5	5.5%	10.4%	-3.9%	-12.7%	40.6%
	Year 2065 RCP4.5	6.6%	13.0%	-5.7%	-2.8%	24.8%
Kiewa (402)	Year 2040 RCP8.5	5.5%	9.8%	-3.9%	-2.2%	22.1%
	Year 2065 RCP8.5	4.0%	10.7%	-10.5%	-11.4%	37.5%
	Year 2040 RCP4.5	4.9%	9.2%	-4.5%	-11.0%	39.5%
	Year 2065 RCP4.5	4.5%	10.9%	-9.5%	-3.4%	21.6%
Ovens (403)	Year 2040 RCP8.5	5.3%	9.6%	-3.9%	-1.5%	19.6%
	Year 2065 RCP8.5	3.8%	11.8%	-13.1%	-11.8%	36.8%
	Year 2040 RCP4.5	4.8%	10.3%	-6.9%	-11.1%	38.4%
	Year 2065 RCP4.5	4.4%	11.0%	-9.5%	-3.5%	21.2%
Broken (404)	Year 2040 RCP8.5	6.0%	10.4%	-2.3%	-4.0%	25.0%
	Year 2065 RCP8.5	6.8%	16.8%	-12.1%	-5.8%	30.6%
	Year 2040 RCP4.5	5.2%	12.9%	-9.4%	-12.7%	39.1%
	Year 2065 RCP4.5	4.9%	11.5%	-7.6%	-3.9%	21.5%
Goulburn (405)	Year 2040 RCP8.5	3.9%	8.1%	-4.8%	-4.1%	20.5%
	Year 2065 RCP8.5	2.4%	12.2%	-17.8%	-6.5%	20.7%
	Year 2040 RCP4.5	4.7%	10.7%	-7.6%	-10.7%	36.4%
	Year 2065 RCP4.5	4.4%	11.4%	-10.1%	-3.9%	21.5%
Campaspe (406)	Year 2040 RCP8.5	2.4%	6.3%	-5.6%	-4.9%	17.5%
	Year 2065 RCP8.5	2.6%	11.9%	-16.4%	-8.3%	25.0%
	Year 2040 RCP4.5	5.1%	10.1%	-5.2%	-5.8%	27.5%
	Year 2065 RCP4.5	3.8%	11.2%	-11.4%	-4.9%	21.6%
Loddon (407)	Year 2040 RCP8.5	2.5%	7.1%	-6.5%	-8.6%	23.9%
	Year 2065 RCP8.5	3.2%	11.0%	-11.8%	-11.6%	31.7%
	Year 2040 RCP4.5	5.5%	10.4%	-4.0%	-9.6%	34.6%
	Year 2065 RCP4.5	4.3%	13.7%	-13.7%	-4.3%	20.9%
Avoca (408)	Year 2040 RCP8.5	4.8%	9.1%	-3.1%	-12.5%	37.0%
	Year 2065 RCP8.5	6.9%	13.8%	-6.0%	-7.2%	33.1%
	Year 2040 RCP4.5	5.5%	10.6%	-4.0%	-13.6%	41.0%
	Year 2065 RCP4.5	6.0%	17.5%	-15.3%	-3.8%	24.2%
Lower Murray (409)	Year 2040 RCP8.5	7.3%	12.2%	-0.8%	-8.5%	33.2%
	Year 2065 RCP8.5	9.1%	15.9%	-2.1%	-9.0%	38.7%
	Year 2040 RCP4.5	6.2%	14.1%	-6.7%	-15.9%	42.5%
	Year 2065 RCP4.5	7.4%	15.4%	-5.6%	-4.5%	26.8%
Mallee (414)	Year 2040 RCP8.5	4.7%	10.6%	-7.1%	-14.2%	42.4%
	Year 2065 RCP8.5	6.9%	13.0%	-5.2%	-9.4%	39.4%
	Year 2040 RCP4.5	4.5%	10.8%	-8.0%	-17.5%	48.4%
	Year 2065 RCP4.5	7.1%	18.5%	-15.7%	-2.5%	26.2%

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		Low	Cool	Warm	Cool	Warm
Wimmera (415)	Year 2040 RCP8.5	2.0%	5.6%	-6.0%	-10.0%	28.5%
	Year 2065 RCP8.5	3.9%	10.2%	-10.1%	-8.2%	30.5%
	Year 2040 RCP4.5	4.9%	10.7%	-7.8%	-9.6%	36.8%
	Year 2065 RCP4.5	4.2%	13.2%	-15.6%	-4.3%	23.0%

Table 12 Range of projected seasonal changes in rainfall for maximum cool season rainfall increase (Sensitivity Test 1) and maximum warm season rainfall increase (Sensitivity Test 2) for the MEDIUM climate change projection

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		Medium	Cool	Warm	Cool	Warm
East Gippsland (221)	Year 2040 RCP8.5	-1.0%	6.6%	-12.5%	-12.6%	16.6%
	Year 2065 RCP8.5	1.2%	13.2%	-17.0%	-8.8%	16.3%
	Year 2040 RCP4.5	-0.7%	3.7%	-7.4%	-16.2%	22.8%
	Year 2065 RCP4.5	-1.0%	9.1%	-16.3%	-10.6%	13.6%
Snowy (222)	Year 2040 RCP8.5	-1.4%	3.0%	-7.4%	-12.0%	13.0%
	Year 2065 RCP8.5	-4.5%	5.1%	-17.6%	-17.1%	12.7%
	Year 2040 RCP4.5	-0.2%	4.3%	-6.3%	-18.4%	24.6%
	Year 2065 RCP4.5	-1.9%	6.7%	-13.7%	-11.8%	11.6%
Tambo (223)	Year 2040 RCP8.5	-2.6%	3.0%	-10.4%	-14.1%	13.4%
	Year 2065 RCP8.5	-4.5%	8.2%	-22.1%	-15.5%	10.8%
	Year 2040 RCP4.5	-0.7%	2.6%	-5.3%	-17.2%	22.3%
	Year 2065 RCP4.5	-2.2%	6.9%	-14.8%	-12.0%	11.4%
Mitchell (224)	Year 2040 RCP8.5	-2.3%	2.5%	-10.4%	-12.4%	14.8%
	Year 2065 RCP8.5	-4.8%	4.2%	-20.0%	-14.8%	12.1%
	Year 2040 RCP4.5	-1.7%	2.2%	-8.3%	-18.5%	26.7%
	Year 2065 RCP4.5	-3.6%	4.4%	-17.2%	-12.5%	11.5%
Thomson (225)	Year 2040 RCP8.5	-2.0%	3.1%	-10.7%	-11.6%	14.1%
	Year 2065 RCP8.5	-4.1%	6.0%	-21.2%	-14.0%	12.5%
	Year 2040 RCP4.5	-1.5%	4.0%	-10.8%	-18.5%	27.2%
	Year 2065 RCP4.5	-3.0%	5.2%	-16.9%	-11.4%	11.2%
Latrobe (226)	Year 2040 RCP8.5	-4.0%	1.1%	-13.2%	-13.0%	12.2%
	Year 2065 RCP8.5	-4.5%	6.7%	-24.8%	-13.3%	11.3%
	Year 2040 RCP4.5	-1.3%	4.4%	-11.5%	-13.9%	21.4%
	Year 2065 RCP4.5	-3.9%	4.2%	-18.5%	-12.0%	10.8%
South Gippsland (227)	Year 2040 RCP8.5	-4.5%	1.1%	-15.5%	-13.4%	13.1%
	Year 2065 RCP8.5	-4.4%	6.7%	-26.1%	-12.7%	11.8%
	Year 2040 RCP4.5	-1.3%	4.0%	-11.7%	-8.0%	11.7%
	Year 2065 RCP4.5	-4.7%	3.1%	-19.9%	-11.8%	9.3%

Bunyip (228)	Year 2040 RCP8.5	-3.9%	1.0%	-13.2%	-13.0%	13.2%
	Year 2065 RCP8.5	-5.0%	7.4%	-28.3%	-14.0%	11.9%
	Year 2040 RCP4.5	-1.2%	5.8%	-14.5%	-12.6%	20.4%
	Year 2065 RCP4.5	-4.3%	3.6%	-19.3%	-11.6%	9.4%
Yarra (229)	Year 2040 RCP8.5	-2.7%	2.1%	-11.7%	-12.0%	14.8%
	Year 2065 RCP8.5	-4.3%	7.8%	-27.0%	-13.3%	12.6%
	Year 2040 RCP4.5	-1.5%	4.9%	-13.5%	-17.2%	28.1%
	Year 2065 RCP4.5	-2.2%	5.1%	-15.9%	-10.2%	12.9%
Maribyrnong (230)	Year 2040 RCP8.5	-2.4%	2.4%	-10.9%	-11.3%	13.2%
	Year 2065 RCP8.5	-5.5%	6.5%	-26.6%	-15.5%	12.1%
	Year 2040 RCP4.5	-1.2%	4.6%	-11.4%	-12.7%	19.0%
	Year 2065 RCP4.5	-3.3%	4.4%	-16.8%	-12.9%	13.5%
Werribee (231)	Year 2040 RCP8.5	-2.7%	2.3%	-11.0%	-12.1%	12.8%
	Year 2065 RCP8.5	-6.2%	6.7%	-27.4%	-17.1%	11.8%
	Year 2040 RCP4.5	-1.6%	4.3%	-11.3%	-8.6%	9.9%
	Year 2065 RCP4.5	-3.4%	5.3%	-17.7%	-11.7%	10.2%
Moorabool (232)	Year 2040 RCP8.5	-3.4%	2.3%	-12.8%	-12.7%	12.1%
	Year 2065 RCP8.5	-5.9%	6.2%	-26.1%	-17.3%	13.1%
	Year 2040 RCP4.5	-1.4%	4.4%	-11.0%	-9.1%	11.3%
	Year 2065 RCP4.5	-3.2%	5.6%	-17.8%	-10.8%	9.5%
Barwon (233)	Year 2040 RCP8.5	-3.0%	1.3%	-11.4%	-9.4%	9.5%
	Year 2065 RCP8.5	-5.2%	4.9%	-25.0%	-12.0%	8.3%
	Year 2040 RCP4.5	-0.9%	4.2%	-10.9%	-7.5%	12.0%
	Year 2065 RCP4.5	-3.6%	3.3%	-17.2%	-9.3%	7.6%
Lake Corangamite (234)	Year 2040 RCP8.5	-3.9%	0.2%	-12.4%	-10.0%	8.6%
	Year 2065 RCP8.5	-5.3%	2.9%	-22.2%	-12.0%	8.5%
	Year 2040 RCP4.5	-1.3%	3.7%	-11.5%	-8.0%	12.4%
	Year 2065 RCP4.5	-3.9%	2.8%	-17.6%	-9.8%	8.1%
Otway Coast (235)	Year 2040 RCP8.5	-3.6%	0.8%	-14.3%	-8.7%	8.7%
	Year 2065 RCP8.5	-5.8%	1.6%	-23.7%	-11.4%	7.8%
	Year 2040 RCP4.5	-0.8%	3.3%	-10.7%	-6.8%	13.6%
	Year 2065 RCP4.5	-4.7%	0.4%	-17.1%	-9.3%	6.4%
Hopkins (236)	Year 2040 RCP8.5	-4.4%	0.3%	-14.6%	-11.6%	11.3%
	Year 2065 RCP8.5	-5.7%	1.3%	-20.8%	-14.3%	13.0%
	Year 2040 RCP4.5	-2.1%	3.2%	-13.5%	-9.3%	13.5%
	Year 2065 RCP4.5	-4.9%	2.3%	-20.6%	-12.0%	10.5%
Portland Coast (237)	Year 2040 RCP8.5	-4.6%	-1.4%	-13.1%	-9.6%	8.9%
	Year 2065 RCP8.5	-8.4%	-2.0%	-25.8%	-15.2%	10.1%
	Year 2040 RCP4.5	-2.2%	3.2%	-16.7%	-8.2%	14.1%
	Year 2065 RCP4.5	-5.5%	-0.6%	-18.7%	-10.4%	7.8%
Glenelg (238)	Year 2040 RCP8.5	-5.0%	-0.4%	-17.5%	-11.9%	13.8%
	Year 2065 RCP8.5	-8.4%	-3.8%	-20.9%	-17.6%	16.6%
	Year 2040 RCP4.5	-2.3%	1.9%	-13.6%	-9.1%	16.2%
	Year 2065 RCP4.5	-4.7%	0.3%	-18.2%	-11.0%	12.3%
Millicent (239)	Year 2040 RCP8.5	-5.5%	-1.8%	-17.0%	-12.8%	17.4%
	Year 2065 RCP8.5	-8.5%	-3.8%	-23.2%	-17.3%	19.0%
	Year 2040 RCP4.5	-2.9%	0.8%	-14.5%	-9.8%	18.9%

	Year 2065 RCP4.5	-4.9%	-0.7%	-18.2%	-11.6%	16.1%
Upper Murray (401)	Year 2040 RCP8.5	-0.7%	2.9%	-7.6%	-10.1%	17.5%
	Year 2065 RCP8.5	-2.6%	4.1%	-15.6%	-21.7%	34.2%
	Year 2040 RCP4.5	-0.2%	4.7%	-9.6%	-18.4%	34.9%
	Year 2065 RCP4.5	-0.7%	5.7%	-13.0%	-10.1%	17.5%
Kiewa (402)	Year 2040 RCP8.5	-2.5%	1.8%	-11.9%	-10.2%	14.1%
	Year 2065 RCP8.5	-2.1%	4.6%	-16.6%	-17.5%	31.4%
	Year 2040 RCP4.5	-1.4%	2.9%	-10.8%	-17.3%	33.2%
	Year 2065 RCP4.5	-2.3%	4.1%	-16.3%	-10.2%	14.8%
Ovens (403)	Year 2040 RCP8.5	-3.4%	0.9%	-12.6%	-10.2%	10.9%
	Year 2065 RCP8.5	-3.7%	4.3%	-20.6%	-19.3%	29.3%
	Year 2040 RCP4.5	-1.5%	4.0%	-13.2%	-17.4%	32.1%
	Year 2065 RCP4.5	-2.8%	3.8%	-16.7%	-10.7%	14.0%
Broken (404)	Year 2040 RCP8.5	-3.7%	0.7%	-12.0%	-13.7%	15.3%
	Year 2065 RCP8.5	-3.5%	6.5%	-22.4%	-16.1%	20.3%
	Year 2040 RCP4.5	-1.2%	6.5%	-15.8%	-19.1%	32.7%
	Year 2065 RCP4.5	-2.0%	4.6%	-14.5%	-10.8%	14.6%
Goulburn (405)	Year 2040 RCP8.5	-2.5%	1.7%	-11.2%	-10.5%	14.1%
	Year 2065 RCP8.5	-4.0%	5.8%	-24.2%	-12.9%	14.3%
	Year 2040 RCP4.5	-1.8%	4.2%	-14.1%	-17.2%	29.9%
	Year 2065 RCP4.5	-2.4%	4.6%	-16.9%	-10.7%	14.7%
Campaspe (406)	Year 2040 RCP8.5	-2.2%	1.7%	-10.2%	-9.5%	12.9%
	Year 2065 RCP8.5	-6.1%	3.2%	-25.1%	-17.0%	16.3%
	Year 2040 RCP4.5	-1.6%	3.4%	-11.9%	-12.5%	20.8%
	Year 2065 RCP4.5	-3.3%	4.1%	-18.5%	-12.0%	14.5%
Loddon (407)	Year 2040 RCP8.5	-2.8%	1.8%	-11.8%	-13.9%	18.6%
	Year 2065 RCP8.5	-5.6%	2.2%	-20.6%	-20.4%	22.9%
	Year 2040 RCP4.5	-2.9%	2.0%	-12.4%	-18.0%	26.2%
	Year 2065 RCP4.5	-3.1%	6.3%	-21.1%	-11.7%	13.5%
Avoca (408)	Year 2040 RCP8.5	-3.8%	0.5%	-11.7%	-21.1%	28.4%
	Year 2065 RCP8.5	-3.4%	3.5%	-16.3%	-17.5%	22.8%
	Year 2040 RCP4.5	-2.3%	2.8%	-11.8%	-21.4%	33.2%
	Year 2065 RCP4.5	-1.4%	10.1%	-22.7%	-11.2%	16.8%
Lower Murray (409)	Year 2040 RCP8.5	-3.8%	1.1%	-11.9%	-19.6%	22.1%
	Year 2065 RCP8.5	-2.3%	4.5%	-13.5%	-20.4%	27.3%
	Year 2040 RCP4.5	-1.8%	6.1%	-14.7%	-23.9%	34.5%
	Year 2065 RCP4.5	-0.8%	7.2%	-13.8%	-12.7%	18.6%
Mallee (414)	Year 2040 RCP8.5	-5.3%	0.6%	-17.1%	-24.2%	32.4%
	Year 2065 RCP8.5	-6.5%	-0.4%	-18.6%	-22.8%	26.0%
	Year 2040 RCP4.5	-2.3%	4.0%	-14.8%	-24.3%	41.6%
	Year 2065 RCP4.5	-2.3%	9.1%	-25.1%	-11.9%	16.8%
Wimmera (415)	Year 2040 RCP8.5	-3.7%	-0.1%	-11.7%	-15.7%	22.8%
	Year 2065 RCP8.5	-5.9%	0.4%	-19.9%	-18.0%	20.7%
	Year 2040 RCP4.5	-2.8%	3.0%	-15.5%	-17.3%	29.1%
	Year 2065 RCP4.5	-3.8%	5.2%	-23.6%	-12.3%	15.0%

Table 13 Range of projected seasonal changes in rainfall for maximum cool season rainfall increase (Sensitivity Test 1) and maximum warm season rainfall increase (Sensitivity Test 2) for the HIGH climate change projection

River basin (and basin number)	Projection	Annual projected change (%) from 1995 baseline	Maximum projected positive cool season change (%) from 1995 baseline value		Maximum projected positive warm season change (%) from 1995 baseline value	
		High	Cool	Warm	Cool	Warm
East Gippsland (221)	Year 2040 RCP8.5	-10.8%	-3.2%	-22.3%	-22.4%	6.8%
	Year 2065 RCP8.5	-15.0%	-3.0%	-33.2%	-25.0%	0.1%
	Year 2040 RCP4.5	-9.2%	-4.8%	-15.9%	-24.7%	14.3%
	Year 2065 RCP4.5	-10.9%	-0.8%	-26.2%	-20.5%	3.7%
Snowy (222)	Year 2040 RCP8.5	-10.4%	-6.0%	-16.4%	-21.0%	4.0%
	Year 2065 RCP8.5	-14.9%	-5.3%	-28.0%	-27.5%	2.3%
	Year 2040 RCP4.5	-9.6%	-5.1%	-15.7%	-27.8%	15.2%
	Year 2065 RCP4.5	-12.3%	-3.7%	-24.1%	-22.2%	1.2%
Tambo (223)	Year 2040 RCP8.5	-10.8%	-5.2%	-18.6%	-22.3%	5.2%
	Year 2065 RCP8.5	-16.6%	-3.9%	-34.2%	-27.6%	-1.3%
	Year 2040 RCP4.5	-10.9%	-7.6%	-15.5%	-27.4%	12.1%
	Year 2065 RCP4.5	-13.2%	-4.1%	-25.8%	-23.0%	0.4%
Mitchell (224)	Year 2040 RCP8.5	-9.7%	-4.9%	-17.8%	-19.8%	7.4%
	Year 2065 RCP8.5	-18.5%	-9.5%	-33.7%	-28.5%	-1.6%
	Year 2040 RCP4.5	-12.3%	-8.4%	-18.9%	-29.1%	16.1%
	Year 2065 RCP4.5	-14.8%	-6.8%	-28.4%	-23.7%	0.3%
Thomson (225)	Year 2040 RCP8.5	-10.6%	-5.5%	-19.3%	-20.2%	5.5%
	Year 2065 RCP8.5	-19.9%	-9.8%	-37.0%	-29.8%	-3.3%
	Year 2040 RCP4.5	-11.7%	-6.2%	-21.0%	-28.7%	17.0%
	Year 2065 RCP4.5	-15.1%	-6.9%	-29.0%	-23.5%	-0.9%
Latrobe (226)	Year 2040 RCP8.5	-11.4%	-6.3%	-20.6%	-20.4%	4.8%
	Year 2065 RCP8.5	-16.7%	-5.5%	-37.0%	-25.5%	-0.9%
	Year 2040 RCP4.5	-11.9%	-6.2%	-22.1%	-24.5%	10.8%
	Year 2065 RCP4.5	-14.2%	-6.1%	-28.8%	-22.3%	0.5%
South Gippsland (227)	Year 2040 RCP8.5	-11.7%	-6.1%	-22.7%	-20.6%	5.9%
	Year 2065 RCP8.5	-15.9%	-4.8%	-37.6%	-24.2%	0.3%
	Year 2040 RCP4.5	-13.1%	-7.8%	-23.5%	-19.8%	-0.1%
	Year 2065 RCP4.5	-13.4%	-5.6%	-28.6%	-20.5%	0.6%
Bunyip (228)	Year 2040 RCP8.5	-10.9%	-6.0%	-20.2%	-20.0%	6.2%
	Year 2065 RCP8.5	-16.1%	-3.7%	-39.4%	-25.1%	0.8%
	Year 2040 RCP4.5	-11.9%	-4.9%	-25.2%	-23.3%	9.7%
	Year 2065 RCP4.5	-13.9%	-6.0%	-28.9%	-21.2%	-0.2%
Yarra (229)	Year 2040 RCP8.5	-10.5%	-5.7%	-19.5%	-19.8%	7.0%
	Year 2065 RCP8.5	-20.6%	-8.5%	-43.3%	-29.6%	-3.7%
	Year 2040 RCP4.5	-12.5%	-6.1%	-24.5%	-28.2%	17.1%
	Year 2065 RCP4.5	-14.8%	-7.5%	-28.5%	-22.8%	0.3%
Maribyrnong (230)	Year 2040 RCP8.5	-12.0%	-7.2%	-20.5%	-20.9%	3.6%
	Year 2065 RCP8.5	-21.6%	-9.6%	-42.7%	-31.6%	-4.0%
	Year 2040 RCP4.5	-13.8%	-8.0%	-24.0%	-25.3%	6.4%

	Year 2065 RCP4.5	-15.3%	-7.6%	-28.8%	-24.9%	1.5%
Werribee (231)	Year 2040 RCP8.5	-11.7%	-6.7%	-20.0%	-21.1%	3.8%
	Year 2065 RCP8.5	-21.4%	-8.5%	-42.6%	-32.3%	-3.4%
	Year 2040 RCP4.5	-14.4%	-8.5%	-24.1%	-21.4%	-2.9%
	Year 2065 RCP4.5	-16.1%	-7.4%	-30.4%	-24.4%	-2.5%
Moorabool (232)	Year 2040 RCP8.5	-11.6%	-5.9%	-21.0%	-20.9%	3.9%
	Year 2065 RCP8.5	-21.4%	-9.3%	-41.6%	-32.8%	-2.4%
	Year 2040 RCP4.5	-14.3%	-8.5%	-23.9%	-22.0%	-1.6%
	Year 2065 RCP4.5	-16.1%	-7.3%	-30.7%	-23.7%	-3.4%
Barwon (233)	Year 2040 RCP8.5	-11.5%	-7.2%	-19.9%	-17.9%	1.0%
	Year 2065 RCP8.5	-19.6%	-9.5%	-39.4%	-26.4%	-6.1%
	Year 2040 RCP4.5	-13.5%	-8.4%	-23.5%	-20.1%	-0.6%
	Year 2065 RCP4.5	-13.6%	-6.7%	-27.2%	-19.3%	-2.4%
Lake Corangamite (234)	Year 2040 RCP8.5	-11.6%	-7.5%	-20.1%	-17.7%	0.9%
	Year 2065 RCP8.5	-19.1%	-10.9%	-36.0%	-25.8%	-5.3%
	Year 2040 RCP4.5	-14.4%	-9.4%	-24.6%	-21.1%	-0.7%
	Year 2065 RCP4.5	-14.5%	-7.8%	-28.2%	-20.4%	-2.5%
Otway Coast (235)	Year 2040 RCP8.5	-11.7%	-7.3%	-22.4%	-16.8%	0.6%
	Year 2065 RCP8.5	-19.0%	-11.6%	-36.9%	-24.6%	-5.4%
	Year 2040 RCP4.5	-13.1%	-9.0%	-23.0%	-19.1%	1.3%
	Year 2065 RCP4.5	-13.0%	-7.9%	-25.4%	-17.6%	-1.9%
Hopkins (236)	Year 2040 RCP8.5	-11.6%	-6.9%	-21.8%	-18.8%	4.1%
	Year 2065 RCP8.5	-20.9%	-13.9%	-36.0%	-29.5%	-2.2%
	Year 2040 RCP4.5	-15.0%	-9.7%	-26.4%	-22.2%	0.6%
	Year 2065 RCP4.5	-14.7%	-7.5%	-30.4%	-21.8%	0.7%
Portland Coast (237)	Year 2040 RCP8.5	-10.9%	-7.7%	-19.4%	-15.9%	2.6%
	Year 2065 RCP8.5	-19.0%	-12.6%	-36.4%	-25.8%	-0.5%
	Year 2040 RCP4.5	-13.7%	-8.3%	-28.2%	-19.7%	2.6%
	Year 2065 RCP4.5	-13.6%	-8.7%	-26.8%	-18.5%	-0.3%
Glenelg (238)	Year 2040 RCP8.5	-12.7%	-8.1%	-25.2%	-19.6%	6.1%
	Year 2065 RCP8.5	-21.7%	-17.1%	-34.2%	-30.9%	3.3%
	Year 2040 RCP4.5	-14.1%	-9.9%	-25.4%	-20.9%	4.4%
	Year 2065 RCP4.5	-14.9%	-9.9%	-28.4%	-21.2%	2.1%
Millicent (239)	Year 2040 RCP8.5	-15.0%	-11.3%	-26.5%	-22.3%	7.9%
	Year 2065 RCP8.5	-22.9%	-18.2%	-37.6%	-31.7%	4.6%
	Year 2040 RCP4.5	-14.4%	-10.7%	-26.0%	-21.3%	7.4%
	Year 2065 RCP4.5	-16.7%	-12.5%	-30.0%	-23.4%	4.3%
Upper Murray (401)	Year 2040 RCP8.5	-8.5%	-4.9%	-15.4%	-17.9%	9.7%
	Year 2065 RCP8.5	-14.4%	-7.7%	-27.4%	-33.5%	22.4%
	Year 2040 RCP4.5	-9.4%	-4.5%	-18.8%	-27.6%	25.7%
	Year 2065 RCP4.5	-14.1%	-7.7%	-26.4%	-23.5%	4.1%
Kiewa (402)	Year 2040 RCP8.5	-9.5%	-5.2%	-18.9%	-17.2%	7.1%
	Year 2065 RCP8.5	-16.0%	-9.3%	-30.5%	-31.4%	17.5%
	Year 2040 RCP4.5	-12.8%	-8.5%	-22.2%	-28.7%	21.8%
	Year 2065 RCP4.5	-14.6%	-8.2%	-28.6%	-22.5%	2.5%
Ovens (403)	Year 2040 RCP8.5	-9.5%	-5.2%	-18.7%	-16.3%	4.8%
	Year 2065 RCP8.5	-17.5%	-9.5%	-34.4%	-33.1%	15.5%

	Year 2040 RCP4.5	-12.7%	-7.2%	-24.4%	-28.6%	20.9%
	Year 2065 RCP4.5	-14.7%	-8.1%	-28.6%	-22.6%	2.1%
Broken (404)	Year 2040 RCP8.5	-14.2%	-9.8%	-22.5%	-24.2%	4.8%
	Year 2065 RCP8.5	-18.3%	-8.3%	-37.2%	-30.9%	5.5%
	Year 2040 RCP4.5	-12.9%	-5.2%	-27.5%	-30.8%	21.0%
	Year 2065 RCP4.5	-16.9%	-10.3%	-29.4%	-25.7%	-0.3%
Goulburn (405)	Year 2040 RCP8.5	-13.6%	-9.4%	-22.3%	-21.6%	3.0%
	Year 2065 RCP8.5	-20.7%	-10.9%	-40.9%	-29.6%	-2.4%
	Year 2040 RCP4.5	-13.1%	-7.1%	-25.4%	-28.5%	18.6%
	Year 2065 RCP4.5	-16.3%	-9.3%	-30.8%	-24.6%	0.8%
Campaspe (406)	Year 2040 RCP8.5	-15.2%	-11.3%	-23.2%	-22.5%	-0.1%
	Year 2065 RCP8.5	-23.2%	-13.9%	-42.2%	-34.1%	-0.8%
	Year 2040 RCP4.5	-15.0%	-10.0%	-25.3%	-25.9%	7.4%
	Year 2065 RCP4.5	-17.3%	-9.9%	-32.5%	-26.0%	0.5%
Loddon (407)	Year 2040 RCP8.5	-14.3%	-9.7%	-23.3%	-25.4%	7.1%
	Year 2065 RCP8.5	-22.9%	-15.1%	-37.9%	-37.7%	5.6%
	Year 2040 RCP4.5	-15.0%	-10.1%	-24.5%	-30.1%	14.1%
	Year 2065 RCP4.5	-17.1%	-7.7%	-35.1%	-25.7%	-0.5%
Avoca (408)	Year 2040 RCP8.5	-15.5%	-11.2%	-23.4%	-32.8%	16.7%
	Year 2065 RCP8.5	-20.6%	-13.7%	-33.5%	-34.7%	5.6%
	Year 2040 RCP4.5	-16.2%	-11.1%	-25.7%	-35.3%	19.3%
	Year 2065 RCP4.5	-18.2%	-6.7%	-39.5%	-28.0%	0.0%
Lower Murray (409)	Year 2040 RCP8.5	-15.0%	-10.1%	-23.1%	-30.8%	10.9%
	Year 2065 RCP8.5	-19.1%	-12.3%	-30.3%	-37.2%	10.5%
	Year 2040 RCP4.5	-12.3%	-4.4%	-25.2%	-34.4%	24.0%
	Year 2065 RCP4.5	-16.0%	-8.0%	-29.0%	-27.9%	3.4%
Mallee (414)	Year 2040 RCP8.5	-17.8%	-11.9%	-29.6%	-36.7%	19.9%
	Year 2065 RCP8.5	-23.6%	-17.5%	-35.7%	-39.9%	8.9%
	Year 2040 RCP4.5	-17.5%	-11.2%	-30.0%	-39.5%	26.4%
	Year 2065 RCP4.5	-19.1%	-7.7%	-41.9%	-28.7%	0.0%
Wimmera (415)	Year 2040 RCP8.5	-13.3%	-9.7%	-21.3%	-25.3%	13.2%
	Year 2065 RCP8.5	-22.3%	-16.0%	-36.3%	-34.4%	4.3%
	Year 2040 RCP4.5	-15.3%	-9.5%	-28.0%	-29.8%	16.6%
	Year 2065 RCP4.5	-17.8%	-8.8%	-37.6%	-26.3%	1.0%

B 6.3 Decision scaling

Decision scaling is an extension of sensitivity or stress testing, which involves overlaying a wide range of available GCM projections onto the sensitivity or stress test results. The process of decision scaling, as applied to climate change impact assessment, is well described in Brown (2011). Decision scaling is a scenario-neutral planning approach that initially makes no explicit assumptions about likely future climate scenarios. Rather it involves testing the sensitivity of a supply system under a hypothetical range of climate uncertainty, to better understand the system's resilience and robustness. This sensitivity testing is in the form of hypothetical perturbations to the climate (as above). These could include, for example, a 10% decrease in mean rainfall, or a 5% increase in potential evapotranspiration, or combinations of perturbations such as a 10% decrease in mean rainfall combined with say a 20% increase in high intensity rainfall events. This helps to identify the vulnerability of water supplies to climate change, and the vulnerability of any proposed portfolio of actions associated with a future supply system. Where multiple actions are available to decision makers, the best performing action(s) can be identified in each region of the sensitivity test results.

For example, Action A may perform best under mildly hotter and drier conditions, but Action B may perform best under much hotter and drier conditions, and Action C may perform best under wetter peak but drier average conditions. The process to this point is sometimes also referred to as a scenario-neutral approach, because it occurs independently of any future climate scenarios. The last step of the process is to overlay GCM projections, or any other plausible climate futures, onto the portfolio sensitivity analysis results. The preferred action is the one that performs the best (to a minimum standard of satisfaction) under the widest range of plausible climate futures.

For climate change impact assessment, scenario planning is sometimes referred to as a “top down” approach. This is because it starts by defining climate scenarios at a global scale and then works down to the local scale by downscaling GCM results, to enable the assessment of climate change impacts on local supply system behaviour. Vulnerability assessments that utilise sensitivity testing are sometimes described as a “bottom up” approach. That is, the analysis starts with testing and understanding the local supply system characteristics under different climate conditions, before considering how global climate change might be represented in those sensitivities. According to Brown (2011), decision scaling seeks to bridge the gap between the bottom up and top down approaches, by presenting a method that can draw upon both approaches to aid decision making.

Brown et al. (2019) identifies three steps to decision scaling:

1. Decision framing — identify objectives, identify metrics to be used to assess system performance against those objectives, identify sources of uncertainty that can affect decision making, develop models or functional relationships, and identify adaptation measures being considered.
2. Climate stress test (as above) — a multi-dimensional sensitivity analysis of the system performance to climate (and potentially other) uncertainties. The climate stress test is typically undertaken using a stochastic climate weather generator (see Appendix 5.3.1) that must be able to preserve (or deliberately modify) the relationships between climate variables. This typically generates tens of thousands of climate sequences that can be run through hydrologic and water resource system models to estimate supply system performance under each set of climate conditions. The stress test allows an area of acceptable performance for any two climate variables to be identified.
3. Estimating climate-informed risks — Prepare future climate information, such as downscaled projections from GCMs, regional climate models, paleoclimate data, etc. to assess the level of concern that might be assigned to vulnerabilities identified in the stress test. This can include attempting to estimate the likelihood of the given climate projections occurring (e.g. assuming equally weighted futures). This can be used to generate the likelihood of system failure, for example under the stochastically generated dataset, of one action over another. It can also include overlaying any number of climate projections.

The stress test can also be used to define climate narratives, to streamline climate scenarios from the multitude of possibilities to a smaller subset of plausible scenarios for decision making.

The advantages of decision scaling are:

- It broadens the emphasis onto all potential future climate possibilities, rather than focussing only on a select number of discrete scenarios.
- It allows an assessment of system performance under variable climate conditions independent of the uncertainties associated with GCMs and their bias-corrected outputs. This can be particularly valuable for river or supply systems that are sensitive to aspects of climate change that are not well represented by GCMs (e.g. drought frequency, severity and duration).
- Sensitivity analysis results are produced, which remain valid even if GCMs are subsequently updated;
- The sensitivity analysis can easily be broadened to include non-climate sensitivities, such as uncertainties in population projections;
- It can inform which climate variables are the most locally relevant to system performance; and, therefore, which climate variables it is most important to match during GCM downscaling.
- Decision makers are directed to give greater weight to system resilience and adaptability to future climate uncertainty, rather than its optimal performance under a limited number of scenarios.

The disadvantages of decision scaling are:

- It significantly increases the modelling and reporting effort, because all combinations of future climate sensitivity must be modelled, in discrete increments, rather than only a handful of selected scenarios. For example, for one assumed perturbation of temperature (e.g. a one degree increase above current temperature), this could be coupled with increases or decreases in mean annual rainfall of different magnitude, increases and decreases in PET of different magnitudes, increases and decreases in drought duration of different magnitude, and increases and decreases in peak flows of different magnitude. In past case studies, this has typically resulted in either reducing the number of climate perturbations run through hydrologic and water resource models, or adopting a simplified supply system model to enable computation of the data.
- It introduces its own information uncertainties in the stochastic data generation process, albeit these are significantly less than those associated with GCMs.
- Education of decision makers is required to be able to interpret sensitivity analysis outcomes. Interpreting sensitivity analysis outcomes to delineate between portfolios in a two-dimensional decision space can be difficult when sensitivity to multiple variables is tested (i.e. the best actions may overlap depending on how they interact with third or fourth order climate or other variables). The introduction of the dimension of time, over the planning horizon, further complicates presentation and communication of results relative to scenario planning.
- Information on vulnerability to climate is provided, which is already well known through operating the system and understanding its historical behaviour. For example, the run of river system will be more vulnerable to changes in severe drought duration than change in mean rainfall, and hence the sensitivity analysis may only confirm what is already known from historical experience.
- It may, without careful consideration of the co-variance of climate variables, generate unrealistic scenarios, particularly when adjusting multiple climate variables, which can distract decision making.
- Climate response functions or models may be required when the perturbations are applied to climate variables. Where climate dependent demand models or rainfall-runoff models are not available, they may need to be created. It is noted that decision scaling can also be applied to runoff, as indicated in one of the example applications below.
- Ultimately, it still relies upon climate change scenarios being overlain onto the sensitivity analysis results (i.e. the scenario modelling approach), particularly when considering the potential timing of changes and associated management responses.

The sensitivity analysis in decision scaling occurs independent of any particular planning horizon. This could be regarded as both an advantage (because the sensitivity analysis is not biased by the inherent uncertainty in the projected timing of climate change) and a disadvantage (because the timing of actions is critical when planning for and financing actions).

There are many applications of decision scaling in the literature. A relevant local example was presented in Henley et al. (2019). This analysis applied decision scaling to assess notional supply system risks for the Melbourne system (based on a case study using simplified representation of the Melbourne water supply system) under global warming of 1.5^{o}C and 2^{o}C. This paper provides a deft example of a clear shift in water supply system resilience and risk with and without a major supply system augmentation. One of the key outputs is presented in Figure 43.

Figure 43 can tell a clear story that the risk of the given water supply shortage (as defined in the paper) was very low under pre-industrial conditions, has increased under current global warming, and could further increase under additional global warming. Those risks are estimated to be addressed by the augmentation for 1.5^{o}C warming but are not completely removed for 2^{o}C warming. The figure also illustrates the spread of projections, and highlights the possibility that even without the augmentation, there are plausible climate projections with 2^{o}C warming that do and do not present a risk of supply shortfall.

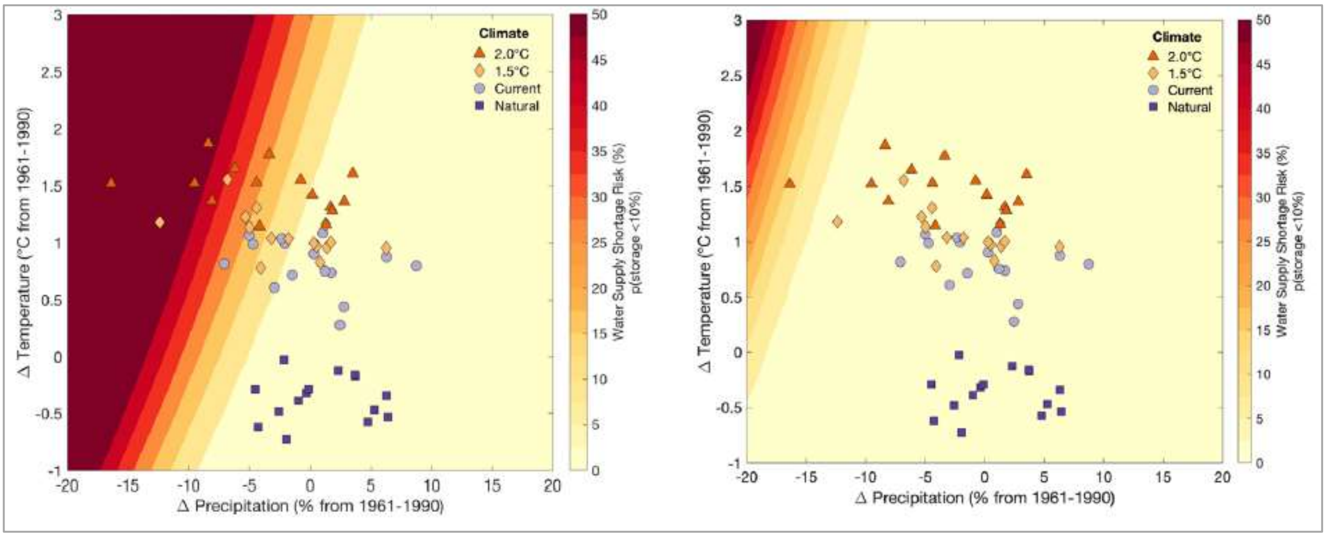


Figure 43 Changes in notional risk of water supply shortage under different levels of global warming without (left) and with (right) the Victorian Desalination Project (Henley et al., 2019)

The value of decision scaling relative to the costs to undertake it will depend upon the nature of the system (its complexity, robustness to climate, availability of contingency measures, availability of functions or models that relate climate to supply and demand system characteristics, etc.), as well as the extent to which scenario planning with adaptive management actions allows robust decisions to be made about the system.

The type of decision scaling that is applied can also vary. For example, application could range from (i) a simple stress test with manually adjusted climate variables, overlain with the four climate change scenarios from the guidelines; up to (ii) a complex stress test using stochastically generated weather perturbations, overlain with the outputs from all available GCMs, various recent historical data, plus paleoclimate proxy records. Decision scaling can also be applied directly to streamflow variables, rather than climate variables. Application to streamflow variables provides a stress test that is more directly relevant to water supply systems than a climate variables stress test.

B.6.4 Stochastic weather generators

Categories of approaches

There are a range of different approaches that have been developed and tested in the literature for generation of stochastic climate or weather data. These can be grouped into two broad categories:

- Short to long time scale methods: generate stochastic data at short time scales (daily or sub-daily), in a manner that aims to replicate the statistics for the short time scale the data is generated at, and typically rely upon scaling relationships to reproduce the statistics at longer time scales (e.g. multi-day, seasonal and annual time scales).
- Long to short time scale methods: first generate stochastic data at long time scales (seasonal, annual or multi-year), normally using a parametric stochastic generator, with generated data then stochastically disaggregated to shorter time scales (monthly, daily or sub-daily), normally using a non-parametric approach.

The short to long time scale methods have typically been applied for systems where outcomes are more strongly driven by events that occur at shorter time scales, such as floods or runoff events into systems with relatively small storage (e.g. household rainwater tanks). Conversely, long to short time scale methods have typically been applied for systems where outcomes are driven by longer-term conditions, such as water resources planning for urban water supply systems, which typically have very large multi-year reservoirs.

Stochastic Climate Library (SCL)

The Stochastic Climate Library (SCL) software was first released in 2005, with only minor updates in 2006 and 2007. SCL was originally produced by the Cooperative Research Centre for Catchment Hydrology and is still available via the eWater toolkit.

SCL (Srikanthan et al., 2007) contains the following options for stochastic models:

- Annual rainfall — first order autoregressive model with parameter uncertainty (Srikanthan et al., 2002a)
- Monthly rainfall — modified method of fragments (with annual data generated using the above annual rainfall model) (Srikanthan et al., 2002b) (long to short time scale generator)
- Daily rainfall — transition probability matrix (with Boughton's correction) (Siriwardena et al., 2002; Srikanthan, 2005) (short to long time scale generator)
- Sub-daily rainfall — DRIP model (Heneker et al., 2001; Frost et al., 2004) (short to long time scale generator)
- Annual climate — first order autoregressive multivariate model (Srikanthan and Zhou, 2003)
- Monthly climate — modified method of fragments (Srikanthan and Zhou, 2003) (long to short time scale generator)
- Daily climate — first order autoregressive multivariate model conditioned on rainfall state and nested in monthly and annual models. (Srikanthan and Zhou, 2003) (long to short time scale generator)
- Multi-site daily rainfall — multi-site two-part model nested in monthly and annual models (Srikanthan, 2006) (long to short time scale generator)

Full descriptions for each of these models are provided in Srikanthan et al. (2007) and the references therein.

The SCL user interface contains tools that allow the user to calibrate a stochastic data generation model and then to generate stochastic replicates. The SCL user interface contains features that allow the key statistics from the underlying (historical) data to be readily compared against the generated replicates, which is a particularly useful feature during model calibration.

The multi-site daily rainfall (long to short time scale) generator from SCL has also been implemented in eWater Source (Satheesh, 2017).

Multi-Site Multi-Season Multi-State Contemporaneous Auto-Regressive Model (MSSSCAR)

The Multi-Site Multi-Season Multi-State Contemporaneous Auto-Regressive Model (MSSSCAR) is a tool that is provided in WATHNET5 (Kuczera, 2020). These are the key features of MSSSCAR:

- Multi-Site: it may be applied across many different sites in a system or catchment — these sites may have precipitation, evaporation/evapotranspiration, temperature and/or streamflow data.
- Multi-Season: it may be applied to first generate annual data, or to first generate data for any number of seasons within a year (although between two and four seasons would be typical).
- Multi-State: the annual / seasonal generation model may (or may not) be conditioned according to one underlying climatic driver variable, such as El-Niño Southern Oscillation (ENSO) or the Inter-decadal Pacific Oscillation (IPO).
- Auto-Regressive: the annual/seasonal generation model preserves the autocorrelation structure of the annual or seasonal totals, i.e. the extent to which a wet or dry season/year is followed by further wet or dry seasons/years.
- Produces outputs at daily, monthly, seasonal or annual time steps, by disaggregating the generated seasonal or annual totals using the method of fragments, with fragments selected using a kernel nearest neighbour approach.

Full details on MSSSCAR are provided in Kuczera (2020).

MSSSCAR has several features that advance it beyond the models that are available in SCL. The multi-season feature in MSSSCAR may be particularly useful for systems where there are clear shifts between wet and dry seasons (compared with SCL's models, which first generate data on an annual time-step only). The multi-state feature in MSSSCAR also allows for conditioning of the stochastic data generation process using an underlying climate driver, which is not available in any of the SCL models. The kernel nearest neighbour approach in MSSSCAR also permits considerably more within-season (or within-year) variability in patterns than the disaggregation approach that is applied in most of the models in SCL.

Although MSSSCAR could probably be used to produce sub-daily data, it is unlikely that it has actually been applied in practice to generate data at time-steps that are shorter than daily. Indeed, most of the applications of WATHNET and MSSSCAR have probably been in water supply systems with large multi-year storages, so the emphasis in testing the stochastic data generation processes has probably been on monthly, seasonal and annual statistics. For generating sub-daily rainfall data, the DRIP model (Heneker et al., 2001; Frost et al., 2004) (contained in SCL) is probably a more appropriate model than MSSSCAR, at least until further testing is carried out on MSSSCAR at sub-daily time steps.

foreSIGHT package in R

The Systems Insights from Generation of Hydroclimatic Timeseries (foreSIGHT) package has been developed in the R statistical analysis system (Bennett et al., 2018, 2019a; Bennett, 2019; Culley et al., 2019). foreSIGHT implements the stochastic data generation approach from (Richardson, 1981), which is a short to long time scale generator, generating daily rainfall occurrence and amount.

foreSIGHT can be configured to undertake the water resources modelling, as well as generating the stochastic climate data for the simulations (Bennett et al., 2018, 2019a, 2019b; Culley et al., 2019). For example, the foreSIGHT documentation contains a package for simulation of a domestic rainwater tank system.

foreSIGHT has been developed to undertake scenario-based planning approaches, sometimes referred to as the “inverse approach”, whereby stochastic replicates are generated to sample the full plausible range of potential future exposure (Guo et al., 2018; Henley et al., 2019). For example, foreSIGHT may be used to test replicates that are generated for each combination of projected changes in mean annual rainfall and mean annual temperature, under projected climate change.

Generators applying Wavelet or Empirical Mode Decomposition

Wavelet Decomposition (WD) (Kwon et al., 2007; Steinschneider and Brown, 2013), Empirical Mode Decomposition (EMD) and Ensemble Empirical Mode Decomposition (EEMD) (Wu and Huang, 2004, 2009) are all long to short time scale stochastic generating approaches, which have been applied to separate out lower frequency (multi-decadal) fluctuations in climate or streamflow data from higher frequency (seasonal to multi-year) fluctuations. The statistical features of these lower and higher frequency variations can be used to drive stochastic data generation processes. Examples of application of EMD and EEMD approaches to stochastic data generation for Australian water resources systems include McMahon et al. (2008) and Peel et al. (2011). WD has been applied to analysis of a water resources system in the United States of America by Kwon et al. (2007) and Steinschneider and Brown (2013).

Using WD, EEMD or EMD to separate out the multi-decadal from the annual to multi-year signals allows the generated stochastic replicates to better capture long-term drivers of climate variability than alternative simpler approaches, such as auto-regressive models. They can be considered as an alternative approach to the multi-state component of MSSSCAR. It may be that WD, EEMD or EMD are better at reproducing the longer-term variability in Victorian climate, which is subject to several different long-term drivers, than a multi-state model that is only tied to one driver (such as IPO or ENSO). Further research would be required to resolve this issue.

To the author’s knowledge, there is no software that can be readily accessed by water resources modellers to implement WD, EMD or EEMD methods. The algorithms for EEMD are set out in several journal publications (Wu and Huang, 2004, 2009; Peel et al., 2015). Similarly, the algorithms for implementation of wavelet decomposition are set out in Kwon et al. (2007) and Steinschneider and Brown (2013).

B.6.5 Multi-objective pareto front optimisation (MOPFO)

MOPFO is a form of robust decision making that can be climate scenario neutral. The concept of MOPFO of major urban water supply systems was first developed and popularised in Australia in Cui and Kuczera (2010), which sought to optimise a combination of operating and infrastructure decisions for Sydney’s water supply system. Since that time, the approach has been further refined and applied to several applications, including but not limited to the optimisation of operating rules and infrastructure decisions for Newcastle (Mortazavi-Naeini et al., 2013; 2015), the optimisation of operating rules for Perth’s reservoirs after integration of multiple desalination plants into the supply system (Kuczera et al., 2015) and the optimisation of operation and planning decisions for the Melbourne supply system (e.g. Kularathna et al., 2015). Various water utilities have also utilised this type of approach in real-time to optimise daily operations for a range of operational uncertainties, including climate variability (e.g. Duncker et al., 2014; van Kalken et al., 2012).

The approach uses a hydro-economic model of a water supply system to find a range of optimal operating rules and infrastructure decisions over a planning horizon. These optimal solutions, of which there may be several, then serve to constrain decision making to a handful of alternative strategies. These alternative strategies can then be debated by decision makers, considering trade-offs between objective functions (e.g. trade-offs between optimality and robustness), as well as non-modelled performance criteria, to define a preferred strategy and/or operating regime.

MOPFO involves several steps:

i. Developing a hydro-economic model of a supply system that incorporates both water resource modelling and economic cost functions. This has been achieved to date by embedding cost functions into existing water resource models, or by developing a separate, simplified financial and water resource model to limit model complexity.

ii. Defining scenarios under which to test the supply system. These typically include any number of current and projected climate scenarios, but as a holistic optimisation process, it usually also includes other types of scenarios such as population projections as well.

iii. Defining the decisions that can be varied within the supply system, such as supply enhancement or demand reduction options, and alternative operating strategies.

iv. Setting of objective functions to define the optimal solution space, and the setting of constraints within which to search that solution space. Objectives to date have typically involved minimising net present cost over the planning horizon, and maximising a measure of robustness. One exception was Purves et al. (2015), which traded-off the likelihood of restrictions against a water restriction and operational cost function under stochastically generated current climate conditions.

v. Running the hydro-economic model through tens of thousands of stochastically generated scenarios of supply and demand.

vi. Production of a pareto-front of optimal solutions.

vii. Identification of common types of strategies within that pareto-front to present to decision makers. This stage may also draw upon other decision-making support tools, such as multi-criteria assessment.

In the context of climate change impact assessment, MOPFO can generate optimal and robust solutions under any number of input climate change scenarios.

An example output from the MOPFO process is illustrated in Figure 44. In this example, a very large number of stochastically generated scenarios, including climate change scenarios, were run through a hydro-economic model to optimise a water supply system's operating rules and augmentation decisions. In this example, robustness is defined by minimising maximum regret on the vertical axis, but alternative measures of robustness are equally valid. This process mostly generates sub-optimal solutions, which can be discarded, plus a pareto front on the edge of the solution space, which consists of solutions that are optimised against the two objective functions. In this case, seven alternative strategies were selected from the pareto front (numbered 1 to 7 in Figure 44), which then allow transparent trade-offs to be made between least cost solutions (e.g. solutions 1 and 2) against the most robust solutions (e.g. solutions 6 and 7) and intermediate solutions 3 to 5. This allows decision makers to consider, for example, whether they are more risk averse to say capital cost uncertainty (e.g. if projected economic uncertainty is high) or climate uncertainty (which is a main component of the range of costs associated with the maximum regret).

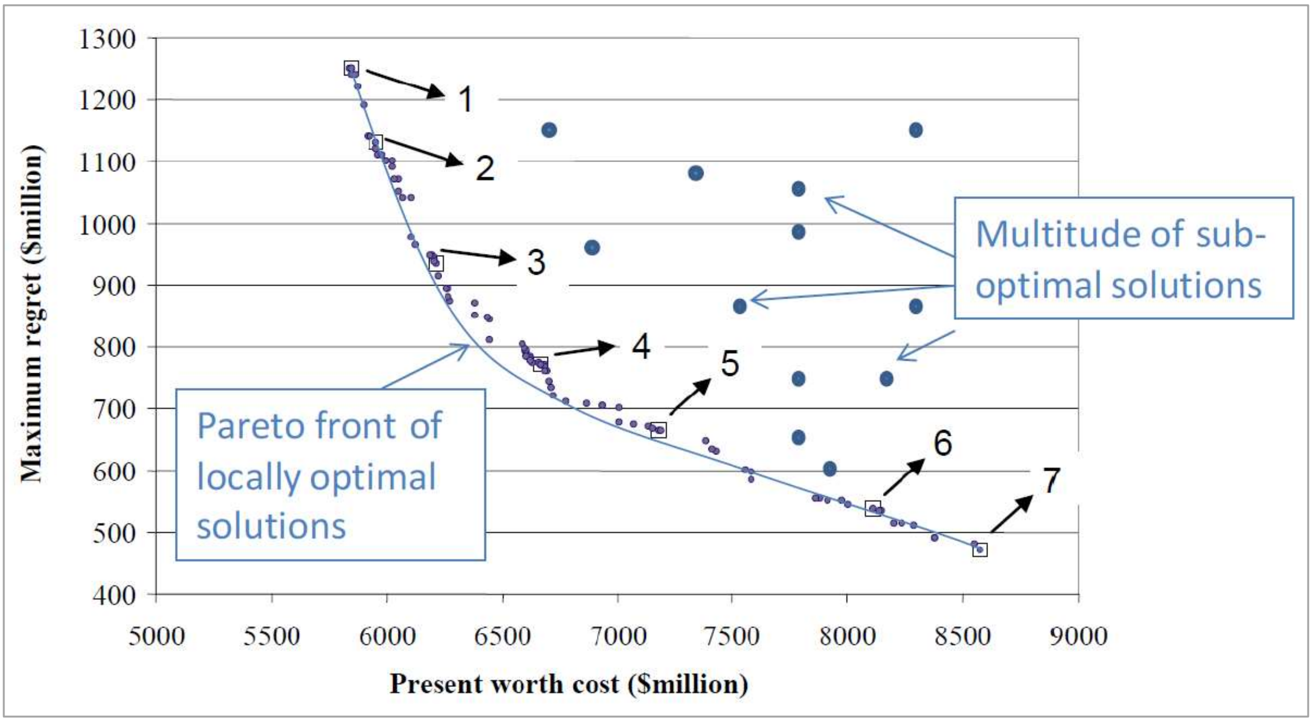


Figure 44 Example two-dimensional Pareto Front (Adapted from Cui and Kuczera, 2010)

While this process is most easily communicated using only two objective functions, pareto fronts can also be prepared for more than two objective functions, particularly if non-financial objectives are also important. An example from optimisation investigations for the Melbourne system, which also considered environmental flow objectives, is illustrated in Figure 45.

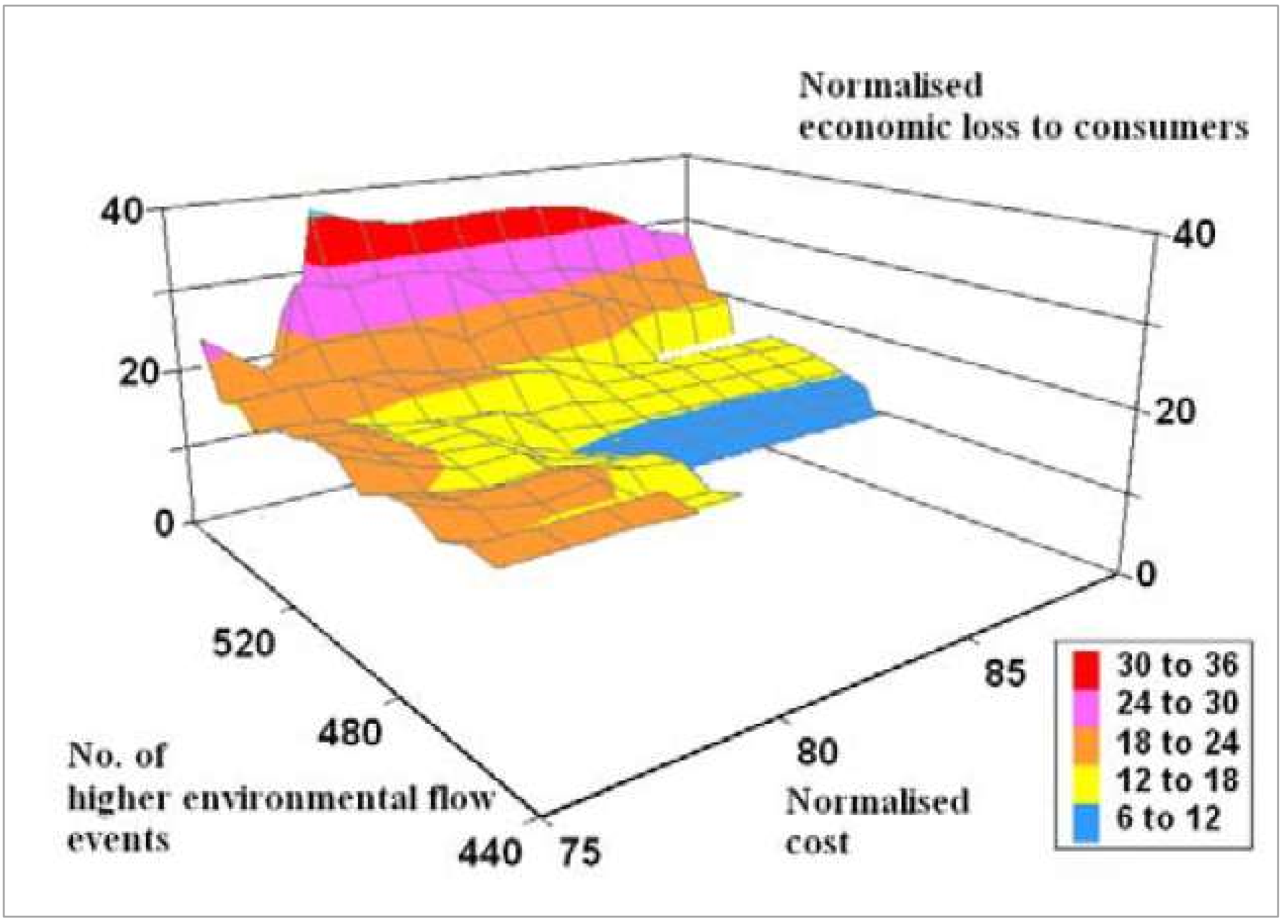


Figure 45 Example three-dimensional Pareto Front (Kularathna et al., 2015)

The advantages of MOPFO are:

- It is climate scenario neutral, in that all climate change scenarios are considered equally likely and are limited in number only by the ability to prepare and process those scenarios.
- As a decision support tool, it effectively helps to limit decisions to fewer, more preferred options from a potentially large range of options.
- It is most effective when the available choices are large, and both the supply system objectives and the incremental differences in choice can be defined mathematically.

The disadvantages of MOPFO are:

- The need for a water resource model that also incorporates cost functions (although it is acknowledged that the technique can also be applied to non-financial objective functions, such as supply system yield).
- Considerable effort in data preparation, modelling and post-processing.
- Results are presented as an abstract curve that are not time-based projections, and therefore need to be coupled with other communication tools around the timing of actions. In this process, the nature of individual climate change projections is no longer transparent (which could also be regarded as an advantage to avoid focussing on any one projection).
- Like other analytical assessment techniques, the pareto front in and of itself does not usually identify the optimal solution, but rather only a range of optimal solutions.
- Outcomes can be more difficult to communicate when there are more than two to three objective functions.
- The value of optimising operating rules over a planning horizon of several decades is questionable where changes are non-stochastic in nature, and actions can be modified over time. In this case, step-wise change of operating rules and/or demand/supply augmentations is typically the optimal solution, rather than a single set of operating rules or supply system configurations over the whole planning horizon. To date, perhaps due to the level of effort involved in applying the technique, MOPFO studies have focussed on optimising operating and infrastructure strategies over a wide range of time scales (i.e. to be valid over the whole 50+ year planning horizon), rather than also assessing shorter windows, which could result in sub-optimal outcomes over some periods within the planning horizon.

In the context of the climate change impact assessment guidelines, MOPFO has typically been used to date for operational optimisation that includes, but is not specifically targeted at, climate change impact assessment.

B 6.6 Other approaches that the guidelines can support

Application of the information presented in the guidelines is not necessarily limited to the additional planning approaches mentioned above, but could potentially also be applied to other approaches (e.g. those in Marchau et al, 2019). The approaches featured in these guidelines were considered to have particular utility for the guidelines, as they had previously been applied to water availability assessments.

B.7 Supplementary guidance on sub-hourly rainfall

The following non-prescriptive guidance is provided for consideration when scaling sub-hourly peak rainfall for water supply systems sensitive to such changes. This information builds on the information presented in Section 5.9.4.

For water supply systems sensitive to increases in peak sub-hourly rainfall, a range of scaling factors, between 5% and 14% per degree warming, could be tested. When this range is combined with climate change projections, there are multiple combinations that result. For example, in the year 2040 as presented in Figure 46, at one end of the range projected average annual rainfall could increase in combination with increased peak rainfall. On the other end of the range, an overall drying of the landscape could combine with increased rainfall intensities, leading to a much flashier system, with short sharp bursts of rainfall and not much rain in between.

For water supply options sensitive to increases in peak sub-hourly rainfall, all six rainfall scenarios presented in Figure 46 should be modelled to understand how water availability could be affected by projected climate change. This is consistent with the philosophy that all scenarios presented in these guidelines are equally plausible.

To prepare time series data, the scaling process can involve a single, simple adjustment of all sub-daily rainfalls above and below a rainfall threshold with a given return interval, as per Example A in Figure 47. This approach resembles the approach described for daily rainfall and is designed to increase peak rainfall while accounting for projected changes to average annual totals. An iterative process may be required to ensure that the change to the peak 24-hour rainfall is within a feasible band (ideally it should increase by about 5% per degree warming).

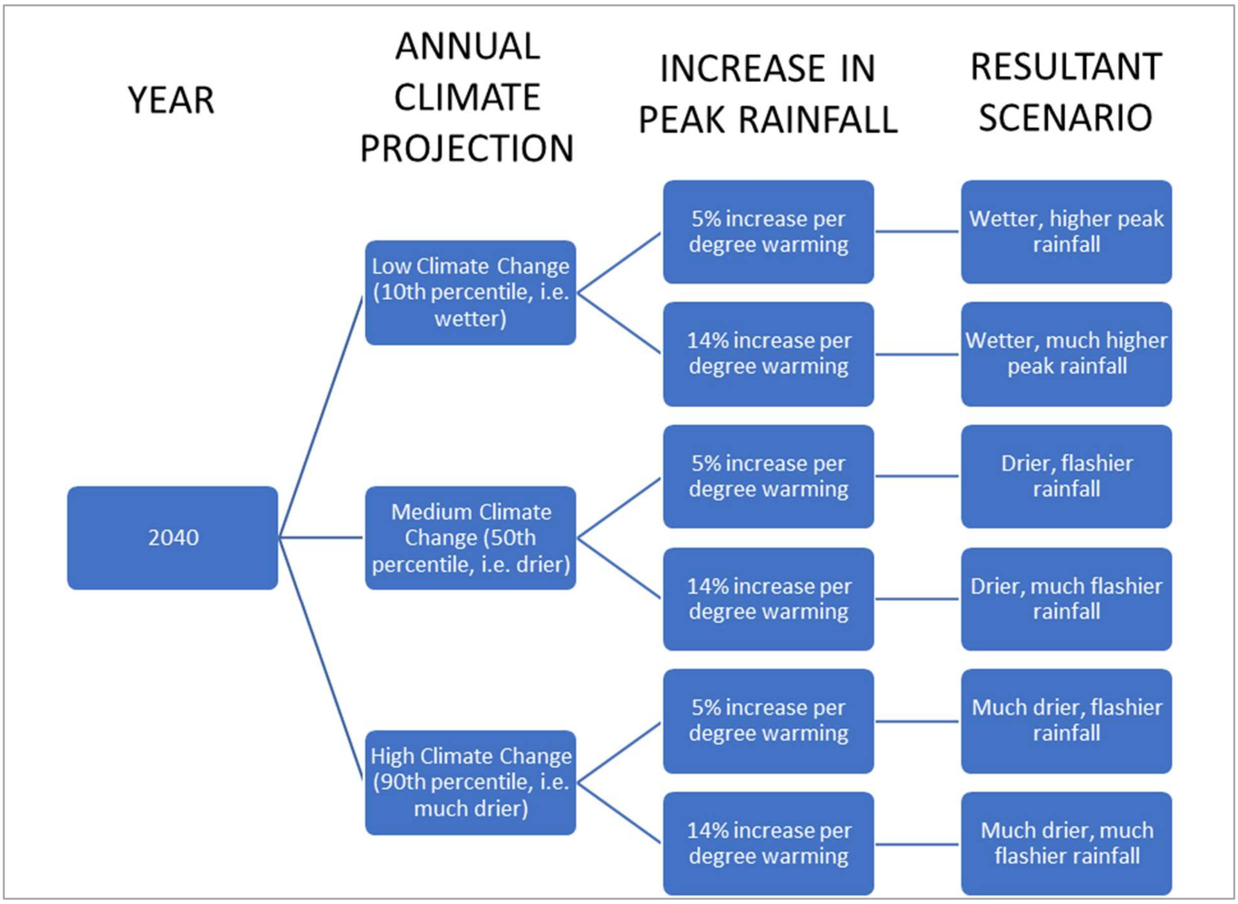


Figure 46 Plausible scenarios of 2040 water availability, coupled with increases in peak sub-daily rainfall

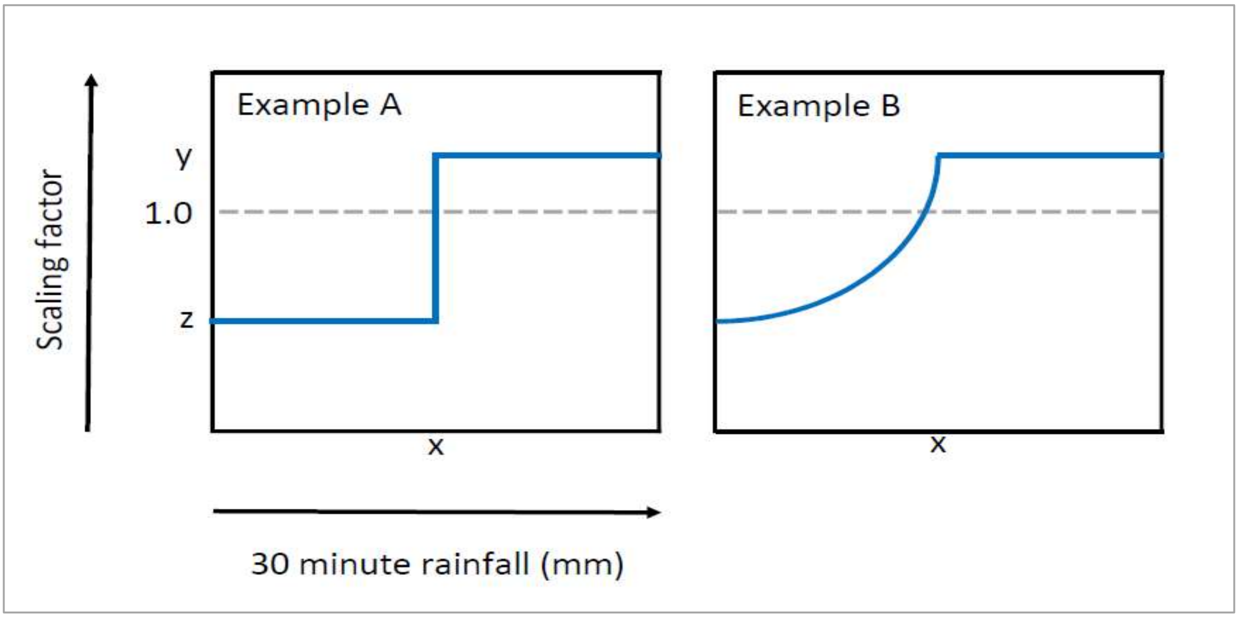


Figure 47 Example methods to scale sub-hourly rainfall (Example B after HARC, 2019).

Note to Figure 47: In some scenarios (e.g. low climate change at 2040) "z" could sit above 1.0.

Alternatively, the scaling process can involve applying a sliding scale that better preserves rainfall intensities, whereby higher short-duration rainfalls below the cut-off point are mostly preserved, and very low rainfalls are all but eliminated. This approach can be justified on the basis that the more intense portions of a storm are expected to intensify under climate change (Wasko and Sharma, 2015).

This more complex approach was applied in HARC (2019) using a non-linear function, as per Example B, for the purposes of representing climate change projections for the modelling of Melbourne's sewer network. The scaling factor y was determined based on the applied scaling per degree warming, and the cut-off point x was assumed to be the 99^{th} percentile of non-zero 30-minute rainfall at several example locations within the study area. HARC (2019) assumed that extreme 30-minute rainfall would increase at 9% per degree warming, consistent with the findings of Wasko et al. (2018). In water supply applications this more complex approach may not be warranted but is provided herein as a proof of concept.

Alternative approaches

VCP19 application-ready datasets do not include datasets on a sub-daily time-step and are therefore not available to directly utilise for sub-daily rainfall climate change projections.

B.8 Supplementary guidance on runoff due to changes in snow cover

Section 5.14.2 provided an overview of the guidance on projected changes in runoff due to changes in snow cover under climate change. This appendix provides additional information on adjustments that can be made to the runoff projections if planning decisions may be at risk to changes in the seasonality of runoff associated with changes in snow cover under projected climate change.

The decision process is shown in Figure 48.

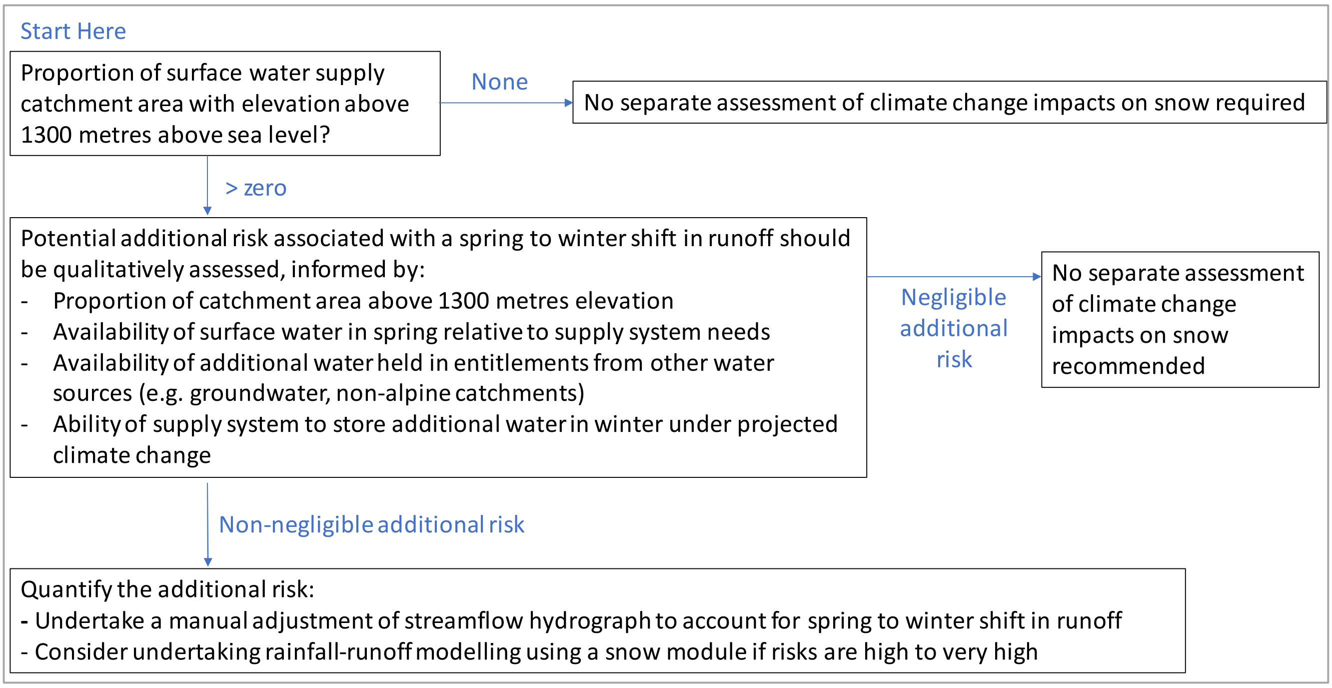


Figure 48 Decision process for assessing the potential risk associated with projected changes in snowfall, snowpack and snowmelt

In this decision process, where a water supply catchment includes areas above ~1300 metres elevation, a qualitative assessment of the additional risk associated with changes in snowpack can be undertaken. This additional risk is due only to the seasonal shift in runoff from spring to winter associated with changes in the snowpack volume. This risk is over and above any supply system risk attributable to projected changes in total precipitation (i.e. rainfall plus snow) under climate change.

In almost all water supply catchments, this additional risk is expected to be negligible because (i) the contributing catchment area covered by snow is small, (ii) projected available surface water in spring under climate change may be well in excess of supply system needs, (iii) under-utilised water entitlements from other sources may be available, (iv) the duration of periods of continuous snowpack accumulation is short, (v) snow depth is already naturally lower and non-existent at lower elevations in drought years, and (vi) more airspace in storages may become available in winter in a drying climate.

By way of example, Gippsland Water (2017) reported no additional risk to its water supply systems on the Tyers and Tanjil Rivers that are partially supplied from Mt Baw Baw, approximately 30 km upstream.

If a non-negligible additional risk is identified for a supply system, a manual adjustment of baseline supply system inflows is recommended to quantify this risk. This adjustment process can be informed by hydrologic advice specific to the location of interest, provided that it is transparently undertaken and reported. As a suggestion, DELWP offers the following process in the absence of specific local and informed hydrologic advice:

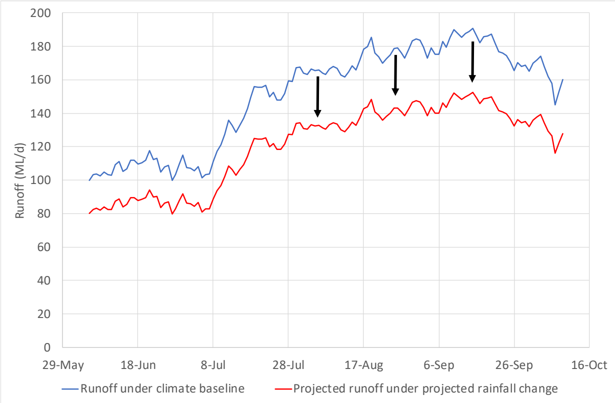
- **Step 1** — Factor supply system inflows for projected changes in runoff (as is done for all surface water systems based on the factors provided in the Guidelines) to assess changes in supply system reliability and yield relative to projected demand under climate change without considering changes in snowpack.
- **Step 2** — Download historical snow depth information from DELWP, by visiting https://discover.data.vic.gov.au/ and searching for "Victorian alpine resorts" in the search window. Then select the resort area that is likely to be representative of changes in snow depth within your water supply catchment, based on its proximity and elevation.
- **Step 3** — Identify historic days of snowpack accumulation and depletion over the available period of record. Snow depth data associated with snowmaking is likely to only cover a small area of the natural snowpack extent and can be ignored for the purposes of water supply impact assessment.
- **Step 4** — Based on Bhend et al. (2012) it is plausible that snowpack could be non-existent at lower elevation snowfields in Victoria, and reduced by 80–95% at higher elevation snowfields by 2050. For this analysis it can therefore be conservatively assumed that no snow accumulates in Victoria in both 2040 and 2065, acknowledging that this is a likely upper bound on projected impacts. In practice, in future decades some snow will continue to fall, and snowmaking will continue for as long as it is commercially viable to do so.
    - On days of historical snowpack accumulation over the historic climate reference period, assume that all accumulated snow on that day runs off immediately. The rate of snow to equivalent rainfall can be assumed to be a notional 8% (due to the uncompressed nature of snow) (e.g. from United States Severe Storm Laboratory, 2020). The rate of runoff (as a proportion of precipitation) can be based on historical runoff rates for the streamflow gauge nearest the snowfield of interest. This additional runoff can then be added to the projected streamflow time series.
    - On days of historical snowpack depletion over the historic climate reference period, assume that runoff generated from that depletion is no longer available to runoff. These runoff volumes (again assuming a rate of runoff based on historical observations) can then be subtracted from the projected streamflow sequence.
- **Step 5** — Reassess reliability of supply with the adjusted streamflow sequence to quantify an upper bound on the likely additional risk associated with changes to snowfall, snowpack and snowmelt due to climate change.
- **Step 6** — Sensitivity testing can be undertaken on the runoff coefficient and rainfall to snow conversion if desired.

It is acknowledged that the period of available snow depth data may not fully cover the historic climate reference period (or its extended climate sequence), in which case the analysis can be conducted using a shorter period of analysis. Even an analysis in a representative year, such as that illustrated in Figure 49 below, can provide insights about the level of additional risk posed by changes in snow cover.

Where supply system risks are estimated to be high to very high, the option exists to estimate changes in runoff using a rainfall-runoff model that contains a dedicated snow module. There are several such models that exist, such as the "Snowmelt Runoff Model" (Martinec et al., 2008), which links temperature to precipitation and runoff behaviour. This approach is likely to be more accurate than the approach described above, but would involve additional effort that would only be warranted in supply systems identified as likely to be at high to very high risk from changes in snow behaviour.

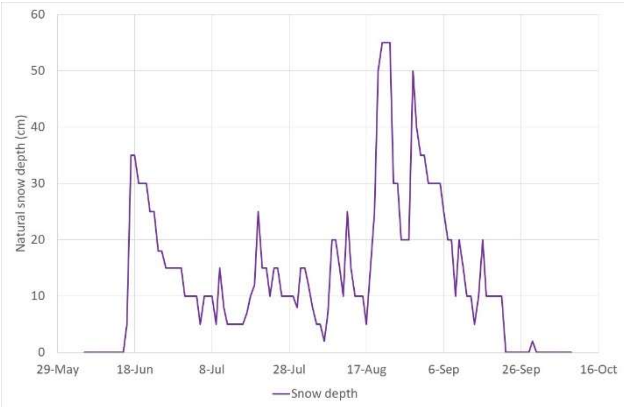
Step 1

Factor supply system inflows for projected changes in runoff



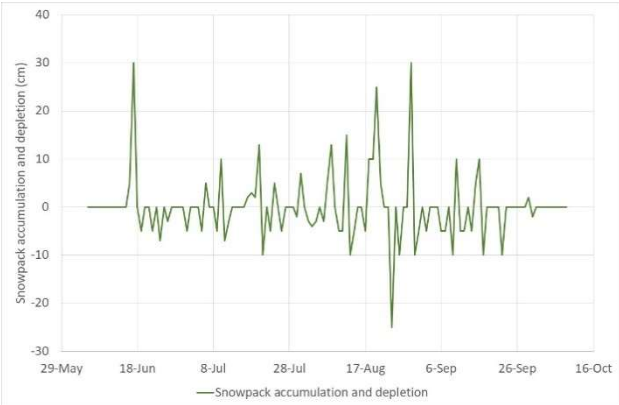
Step 2

Download historical snow depth information



Step 3

Identify historic days of snowpack accumulation and depletion



Step 4

Adjust projected streamflow based on the assumption that snowpack accumulation no longer occurs

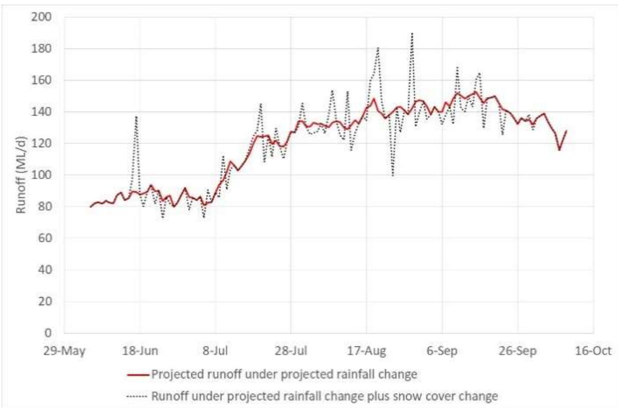


Figure 49 Example adjustment of runoff due to projected climate change in rainfall and snow depth

B.9 Additional information on observed shifts in rainfall-runoff behaviour

In addition to step changes in observed atmospheric climate influences and variables, the University of Melbourne has conducted research into recent changes in the rainfall-runoff relationship in Victorian catchments. This research has examined changes in rainfall-runoff behaviour during and after long-run droughts, with a particular emphasis on changes during and since the Millennium Drought. The findings to date (Saft et al., 2015; Saft et al., 2016; Fowler et al., 2016; Fowler et al., 2020) indicate the following:

- Some catchments in Victoria exhibited a rainfall-runoff response in long-run droughts (> 7 years below the average annual rainfall, such as the Millennium Drought), similar to that seen outside of those long-run droughts (see Figure 50a).
- Some catchments exhibited a shift in the historical rainfall-runoff response in long-run droughts (see Figure 50b), whereby less runoff was generated for a given rainfall on a catchment. Of the 124 catchments examined, 57% displayed this behaviour, with a 30–70% reduction in runoff for a given annual rainfall relative to the response for the same rainfall outside of long-run drought periods.
- Long-term drought is more likely to change the rainfall-runoff relationship in more arid, larger, flatter and less forested catchments. This was independent of any differences in meteorological forcings during these long-run droughts, such as the change in autumn rainfall. This suggests that this change is mostly attributable to catchment characteristics rather than seasonal or annual changes in meteorological forcings, although changes in rainfall from frontal weather systems was implicated in the change in rainfall-runoff relationship (van Rensch, pers. comm. 2020).
- Where a shift in the rainfall-runoff relationship had occurred, rainfall-runoff models consistently over-estimate runoff during long-run droughts (on average by ~80%). All six rainfall-runoff models examined performed poorly, but IHACRES outperformed all of the other models, with Sacramento and GR4J being better than SMARG, AWBM and SIMHYD.
- A multi-objective optimiser was used to identify the model performance Pareto-front over both dry and non-dry conditions for each rainfall-runoff model structure. In around one third of cases, a robust parameter set suitable for both dry and non-dry periods could be found using traditional model calibration techniques. In the other two thirds of cases, traditional model calibration techniques did not find a parameter set that could match both dry and/or non-dry period behaviour well. However, in half of these cases a robust parameter set capable of matching both periods did exist within the model but was not identified using traditional model calibration techniques. This suggests that in two thirds of cases rainfall-runoff models can suitably replicate both dry and/or non-dry period behaviour with a single parameter set, but identifying the appropriate parameter set to achieve this is difficult. Whereas in one third of cases no single parameter set existed within the model structure that could suitably replicate both dry and/or non-dry period behaviour well.
- Many rainfall-runoff models lack the ability to represent long, slow, multi-year trends, like the Millennium Drought, within their modelled water stores. These stores generally fill and empty over the seasonal cycle and do not accumulate extended moisture deficits within the model over several years. This hampers their ability to model under progressively drying conditions.

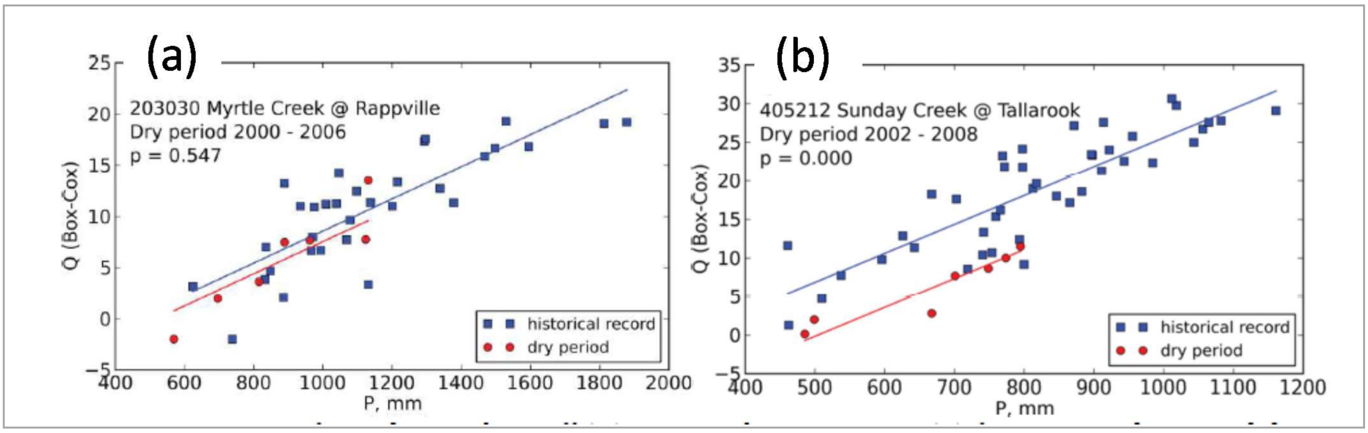


Figure 50 Box-Cox transformed annual runoff (Q) versus annual precipitation (P) for a 7 year dry period during the Millennium Drought relative to the historical record for two catchments (a and b) from Saft et al. (2015)

The implications of this research, which is still ongoing, is that water availability during long-run droughts may be significantly over-estimated where that water availability has been estimated from rainfall-runoff models. Under climate change, where long-run droughts are considered likely to occur more frequently, rainfall-runoff models that do not perform well during historic long-run droughts may also over-estimate future water availability.

The SYMHYD rainfall-runoff models used to develop the projections in these guidelines were calibrated to a period that includes both before and during the Millennium Drought. To what extent they have represented the shift in relationship observed in some catchments is the subject of ongoing study, which is not yet available to summarise here. Any relevant conclusions from this work will be provided, as appropriate, to users of the guidelines as they become available.

More information about this research is outlined in *Victoria's Water in a Changing Climate* (DELWP et al., 2020).

B.10 Additional information on groundwater recharge processes

B.10.1 Influence of climate on groundwater resources

Climate change processes will affect groundwater resources through changes in frequency, duration and quantity of rainfall and evapotranspiration. The combined impact of (i) potential increased storm event intensity, (ii) altered seasonality of rainfall and (iii) reduced annual rainfall volumes affects groundwater resources differently depending on the recharge mechanisms for the aquifer.

For watertable aquifers dependent on diffuse recharge (from infiltration of rain through the unsaturated zone profile to the watertable), the change in frequency, duration and seasonality of the rainfall will potentially reduce recharge rates.

For confined aquifer systems, the recharge areas in outcropping aquifers will similarly be affected. Throughflow to the deep confined parts of the aquifers would obviously take much longer (hundreds to thousands of years) so that changes in contemporary recharge won't as yet be seen in these systems.

In some groundwater systems, such as in western Victoria, it is likely that the systems contain waters recharged millions of years ago, with little contemporary or recent recharge to the system. It is appropriate for systems such as this to assume either no contemporary recharge or very low recharge rates (< 10 mm/yr), where the groundwater response is showing no response to recent (post-1975) climate conditions.

B.10.2 Dominant recharge mechanisms for Victoria's groundwater systems

Recharge can occur through diffuse mechanisms (over large areas in response to rainfall infiltrating the soil) and focused mechanisms (the movement of water from surface water bodies such as lakes or streams to an underlying aquifer) (Figure 51). Diffuse and focused recharge varies temporally and spatially, and systematic trends are often linked to climate, land use and geology.

Many groundwater systems have been assessed to determine the availability of the resource for use. These assessments have independently determined recharge for areas of intensive use. Some of these assessments include both diffuse recharge, and irrigation accessions and/or flood recharge, all of which influence the groundwater system response.

B.10.3 Influence of rainfall quantum, intensity and timing

Groundwater recharge is a 'threshold' process with a minimum amount of rainfall required to generate any recharge. In Victoria, groundwater recharge is most significant during winter and spring. During these seasons, rainfall can maintain a higher moisture content in the soil profile to facilitate recharge to the watertable. During summer and autumn, evaporation rates exceed precipitation and so do not generally facilitate recharge events.

In arid and semi-arid regions, such as in north-western Victoria, it is storm events that provide the driving force for recharge events. Some studies indicate that intense daily rainfall for a period of 100 days is required for recharge to occur (Crosbie et al., 2013), with a minimum daily threshold of 10 mm/day. Other studies indicate that a 100 mm/month is required in arid regions. Most literature agrees that the annual rainfall total does not drive recharge, but the seasonality and intensity of it does.

Empirical evidence in some Victorian catchments indicates that approximately 350 mm/yr of rainfall is required for significant recharge to occur. This aligns with current knowledge about Victorian groundwater systems. There has not been any study into the influence of storm events on recharge to provide guidance on minimum rainfall within hourly or daily time periods to inform these guidelines (Barron et al., 2011).

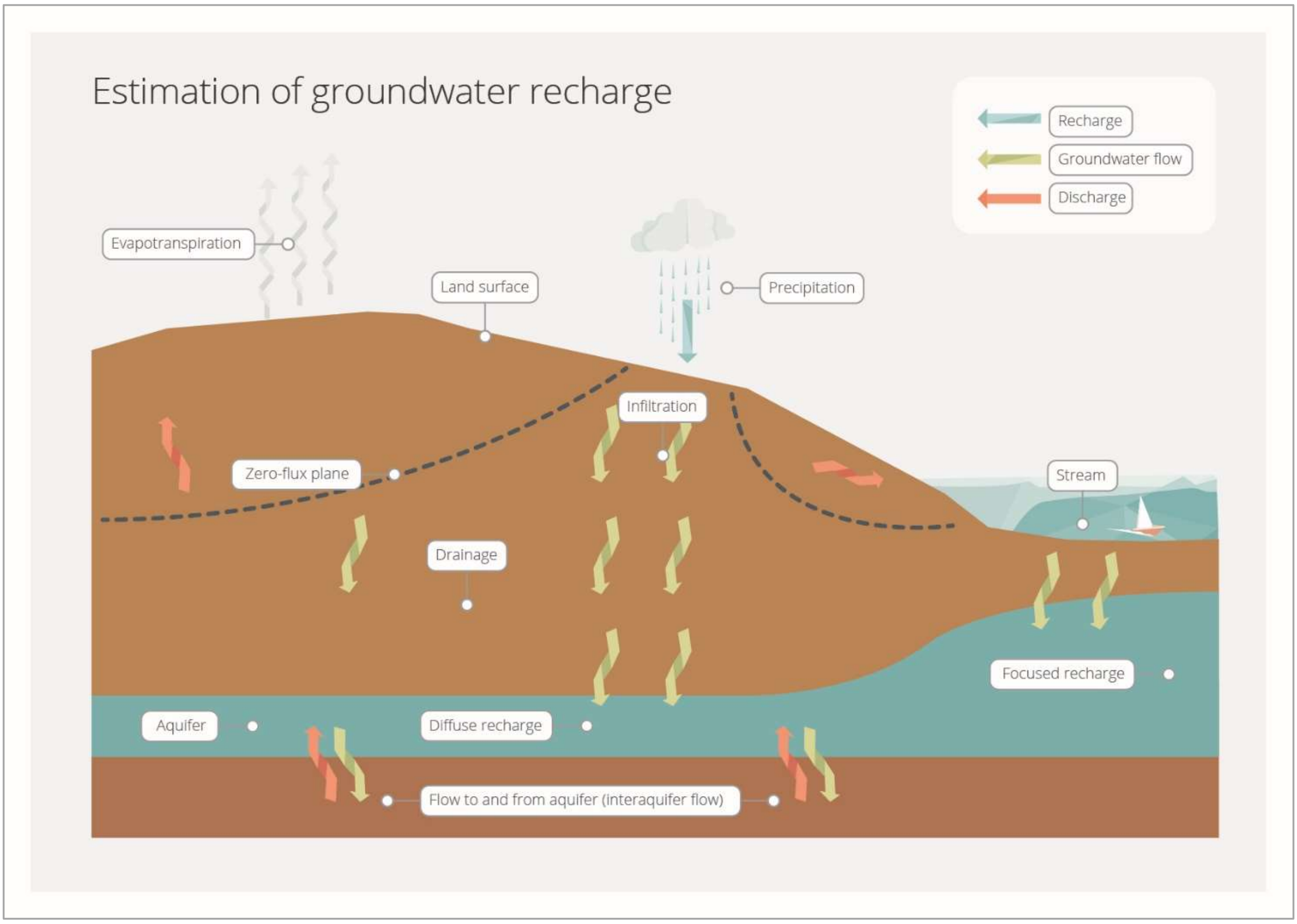


Figure 51 Conceptual diagram showing diffuse and focused recharge processes

B.10.4 Projected changes in recharge due to climate change

Reductions in winter rainfall when diffuse recharge occurs will impact on recharge in the longer term (hundreds of years).

Increased summer rainfall is unlikely to increase recharge but may reduce extraction rates in areas of groundwater use (i.e. in dryland agricultural areas or where farm dams are used) thereby reducing declines in groundwater levels.

Reductions in annual rainfall may affect groundwater recharge occurrence in those catchments with low annual rainfall where it may drop below the 350 mm/yr threshold.

Appendix C Guidelines version log

The following table tracks minor and major updates to the guidelines, commencing from the November 2020 edition.

Table 14 Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria — Version log

Version	Details	Date
Final, 2020 edition	Edition to update and replace the *Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria* (DELWP, 2016).	November 2020