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

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Executive Summary

As most of Victoria's water sources are climate dependent, planning for future climate variability and climate change is important for water resource planners. Although the body of scientific knowledge on climate change continues to evolve, future climate projections remain uncertain. It is therefore important that a range of possible climate futures are considered when planning for the sustainability of Victorian water resources.

The purpose of these guidelines is to update the climate change scenarios and associated projections in light of the increased body of knowledge in climate science, and the observed changes in Victoria's climate. The scenarios provide guidance for long term temperature, potential evapotranspiration, rainfall, runoff and recharge to be used across Victoria to assess the impact of climate change on water supplies. They support water corporations to discharge their responsibilities under Clause 6-A of the Statement of obligations issued by the Minister for Environment, Climate Change and Water in December 2015, that requires water corporations to 'comply with guidelines for forecasting the impacts of climate change on water supplies' as issued by the department of Environment Land Water and Planning.

Victoria's Climate

The influence of numerous climate phenomena makes Victoria's climate naturally highly variable. Over the period of recorded climate data (up to ~150 years), Victoria has experienced numerous floods and several prolonged droughts. Pre-instrumental data suggest that our climate may be more variable than we have observed in the instrumental records.

Victoria's climate is changing

With increased greenhouse gas concentrations and associated changes to the global climate system, changes in the behaviour of the influences in Victoria's climate have occurred. These include the expansion of the tropics and the shifting offshore of rain-bearing low pressure systems. The latest climate research from the Victorian Climate Initiative has identified clear reductions in cool season (April to October) rainfall over recent decades. This trend has continued despite some wetter years since the Millennium Drought. This has significant implications for water corporations as it represents a shift in the reliability of rainfall during the traditional storage filling and aquifer recharge season. Climate change, both globally and in Victoria, has manifested to date as a mix of gradual and step changes.

Climate Change Projections

Global climate models were applied to generate climate change projections for Victoria's river basins for the years 2040 and 2065. Three representative climate change projections have been selected from the range of possible climate futures anticipated by 42 different Global Climate Models (GCMs). The three projections represent a low, medium and high impact on water availability from climate dependent sources. The medium impact scenario represents the median (50th percentile) runoff response from the 42 GCM projections, and the low and high impact scenarios represent the wetter (10th percentile) and drier (90th percentile) runoff responses from the 42 GCM projections.

Based on the premise that greenhouse gas concentrations continue to rise, the majority of climate models project Victoria's climate becomes hotter and drier. Compared to current conditions (1975-2014), by the Year 2065, Victoria is expected to become warmer with a median increase of between 1.9-2.6°C and an increased rate of potential evapotranspiration by a median of 6-8 per cent. The greatest impacts from climate change are projected to occur in western Victoria.

The projections presented in these guidelines have a somewhat wider range than the previous climate change guidance as they include additional global climate models which are consistent with those used by the Intergovernmental Panel on Climate Change in their most recent assessment. Although there is a larger spread in the projections based on the updated suite of global climate models, the majority of models still suggest significant drying for Victoria.

It is acknowledged that there still remains a high degree of uncertainty regarding Victoria's climate future. However, the updated guidance provided in these guidelines gives water corporations some of the necessary information to best manage this uncertainty.

Application of the Guidance by Victoria's Water Corporations

The guidelines outline how the climate change projections can be applied for water resource planning in Victoria.

The guidelines recommended 'current climate' baseline is from 1975 to date. The shortening of the baseline period, compared to historical baselines, is designed to reflect climate behaviour at the current level of greenhouse gas concentrations. It recognises the latest findings from the Victorian Climate Initiative that show current climate conditions and their influences are different to earlier decades of the 20th century, and that rapid global warming has occurred over this period. Techniques are presented to extend this baseline using the full historic climate record so as to incorporate a wider range of natural climate variability.

Four climate change scenarios are presented in a risk based framework that considers the vulnerability of supply systems to climate variability and climate change. The scenarios are low, medium, high and step climate change. The step climate change scenario is important as it captures many of the seasonal changes in rainfall that have occurred over recent years that are not fully reflected in the global climate models and therefore not captured in the low, medium and high scenarios. From these four climate change scenarios, there is no 'most likely' scenario. It is therefore important to explore a range of possible futures. These four scenarios can be augmented with a range of alternative techniques and datasets to provide additional information on the behaviour of water supply systems.

The GCM based projections are provided at a river basin scale and for annual changes in climate variables. These are considered suitable for most water planning applications. The guidelines present a range of different approaches to characterise projected changes at finer scales. However, the degree of confidence diminishes at the finer temporal and spatial scales.

The guidelines are a resource for assessing the impact of climate change on groundwater resources, drought and operational planning, alternative water supply projects and demand projections.

Recommendation 1:
In response to increasing greenhouse gas concentrations and changing climatic conditions, when assessing climate change impacts on water availability it is recommended that water corporations use a 'current climate' baseline period from July 1975 to date. "To date" refers to the most recent available historic climate information at the date of application, not the date of publication of these guidelines. This does not preclude the use of alternative baselines, but in cases where alternative baselines are adopted a comparison of the hydrological differences must be undertaken and reported. Hydrologic differences include measures such as the differences in average annual rainfall, average annual streamflow and supply system yield relative to the July 1975 to date period for a representative supply system.

Recommendation 2:

Water corporations must assess the impact of climate change when developing long-term projections of water availability. When assessing climate change impacts on water availability for long-term planning purposes, climate change scenarios should be selected based on supply system vulnerability to climate change and climate variability.

- For supply systems with very low vulnerability under the current climate baseline (e.g. with climate independent sources of water or resources significantly in excess of requirements during drought): a preliminary assessment of climate change impact should be undertaken, which may not necessarily include water resource modelling

- For all other supply systems: Model supply system vulnerability under the high GCM scenario and the post-1997 step–change scenario. Where these scenarios indicate that the supply system is vulnerable to climate change, the medium and low climate change scenarios should also be modelled to assess the full range of timing for action.

Recommendation 3:
Where planning processes require assessments of impact each year over the fifty year time horizon, linear interpolation between the current, Year 2040 and Year 2065 time slices is suggested as being a reasonable approximation, noting that the projected climate change impact could occur earlier or later than anticipated by this interpolation.

Recommendation 4:
GCM based projections at river basin scale are considered suitable for most water planning applications. Finer spatial scale information can also be used where justified.

Recommendation 5:
Given that GCM projections generally provide within-year (seasonal and daily) climate change information with only a low degree of confidence, for those supply systems that are sensitive to within-year changes in climate, a range of different approaches are suggested depending on the vulnerability of the system. These include characterising recent historical shifts in seasonal climate behaviour and utilising broad-scale changes in seasonal behaviour and rainfall intensity from the GCMs. Other, more complex, analytical procedures are also available.

Recommendation 6:
Confined aquifer systems generally respond very slowly or very little to changes in climate. It is unlikely that any changes would be seen within the current 50 year planning horizon of existing water strategies, and hence are not considered further in the guidelines.

Shallow unconfined aquifers can respond quickly (e.g. within 1-2 years) to changes in climate. For shallow unconfined aquifers in highland areas with a high level of connection to rainfall and surface waters, projected changes to runoff equally apply to recharge. For other shallow unconfined aquifers (e.g. in the sedimentary basins), assessments of changes in availability should be based on the recharge change factors presented in these guidelines.

Recommendation 7:
For drought and operational planning scenarios, recent climate is considered to be a better approximation of likely future conditions than GCM projections. Drought and operational planning scenarios should therefore be drawn from the current climate baseline, consistent with the baseline used for long-term planning scenarios. For most of these short-term planning applications, sampling from this baseline to create droughts more extreme than those observed historically (as is currently the practice by some water corporations) may provide further climate resiliency and is considered preferable to the scaling of historical droughts based on GCM outputs used in long-term planning applications.

Recommendation 8:
The advice contained in these guidelines is considered suitable for assessing the impacts of climate change on water supply options for alternative water supply projects at a range of spatial scales. A range of approaches are described, but these do not preclude the use of alternative techniques.

Recommendation 9:
Where water corporations have climate dependent demand models, the medium potential evapotranspiration and temperature projections provided these guidelines can be applied to model climate change impact on demand. Where sensitivity to climate is low, changes in demand in response to climate change may not be significant and do not need to be considered.

Recommendation 10:
A range of other factors may potentially be significant issues for future water availability in some systems. Other issues that may impact water availability, such as bushfires or increases in catchment interception activities should at least be considered qualitatively. The extent to which these other influences are quantitatively estimated by water corporations will depend on the availability and level of confidence in the modelling tools used to assess each particular issue, relative to the potential impact on supply system water availability and performance.

Contents

1. Introduction

Victoria's climate is changing, and will continue to change into the future. Our water resources are largely climate dependent, so planning for future climate variability and climate change is extremely important for Victoria's water corporations. 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.

The purpose of these guidelines is to set out updated future climate change scenarios for long term temperature, potential evapotranspiration, rainfall, runoff and groundwater recharge to be used across Victoria for assessing the impact of climate change on water supplies.

1.1. The Need for Updated Guidelines

These guidelines are issued by the Department of Environment, Land, Water and Planning (the Department) under Clause 6-A of the Statement of Obligations (General) to Victorian water corporations. The Statement of Obligations was issued by the Minister for Environment, Climate Change and Water in December 2015, and Clause 6-A requires water corporations to comply with these guidelines.

The Department issued guidelines related to assessing the impact of climate change on water supplies in 2006 (Jones and Durack, 2005; Jones, 2006) and again in 2011 (Moran and Sharples, 2011). These 2016 guidelines build upon the previous guidance, and take account of lessons learnt from application of the 2011 guidelines along with updated scientific findings on climate change for Victoria.

The guidelines can be used for a range of purposes, including as an input to the preparation of Urban Water Strategies, Price Submissions, Drought Response Plans, Annual Water Security Outlooks and other operational or corporate plans and strategies.

1.2. Process for Development of the Guidelines

The Department has drawn upon the latest climate research in preparing the guidelines, which water corporations can refer to for more detailed information. These include:

- Findings from the **Victorian Climate Initiative (VicCI)**, a Victorian Government funded research program conducted by the Bureau of Meteorology and CSIRO. The research is specifically focused on the impacts of climate change on Victorian water resources. The latest findings are summarized in these guidelines, and sourced from the 2014/15 VicCI annual report (Hope et al., 2015), Climate Change Science and Victoria (Timbal et al., 2016), and Hydroclimate projections for Victoria at 2040 and 2065 (Potter et al., 2016);
- Outcomes and tools from the federal government's **Climate Change in Australia** initiative, including regional reports on climate change for northern Victoria (Timbal et al., 2015) and southern Victoria (Grose et al., 2015).
- The **Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report** (IPCC, 2014), which summarizes the latest global climate trends and updated global climate model projections; and
- A range of relevant findings from research organizations including Australian universities.

Background material for the guidelines was provided by climate researchers from CSIRO, the Bureau of Meteorology, the University of Newcastle and the University of Melbourne. This included updated climate change projections from the latest suite of global climate models, as prepared for Victoria by CSIRO (Potter et al., 2016).

The Department developed these guidelines in close consultation with Victorian water corporations through a series of workshops hosted in 2016. Water corporations provided valuable input to the guidelines by articulating water corporation needs and exploring the implications of climate change on effective water planning and management. The outcomes of that water corporation involvement are reflected in the guidelines.

1.3. Structure of the Guidelines

These guidelines are structured as follows:

- **Section 2** describes the major influences on Victoria's climate and how these have changed over recent decades;
- **Section 3** presents the future climate and runoff projections for Victoria under increased greenhouse gas concentrations; and
- **Section 4** describes how the future climate, recharge and runoff projections can be applied by water corporations for their water planning, including the preparation of Urban Water Strategies.

Supporting technical information is provided in the appendices and the references referred to throughout the guidelines.

2. The Victorian Climate

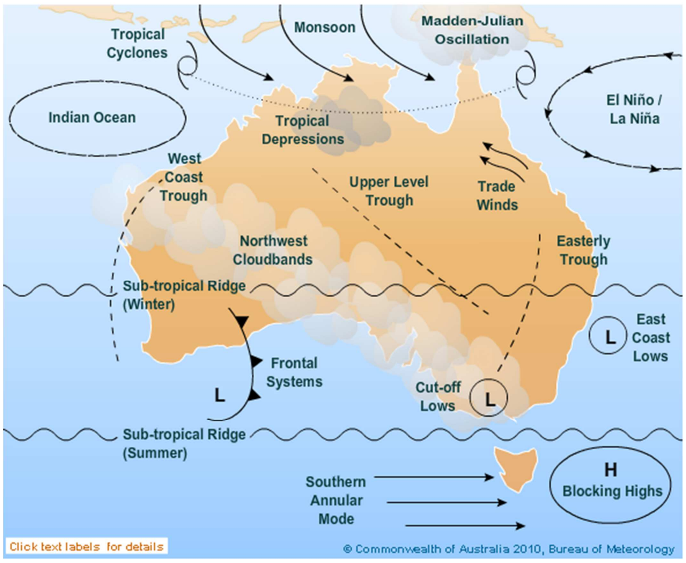
This section of the guidelines provides an overview of the key influences on the Victorian climate (Section 2.1), followed by a description of the extent of the variability that has been observed (Section 2.2). Victoria's climate is changing and the observed trends are described in Section 2.3.

2.1. Climate Influences

The complex inter-play of large scale climate phenomena makes Victoria's climate highly variable. Sources of rainfall include from low pressure systems to the south of Australia, north-west cloud bands, east coast troughs and east coast low pressure systems.

At a continental scale, Australia's climate is influenced by atmospheric circulation patterns that transfer 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 interact to influence the movement of atmospheric moisture to Victoria from low pressure systems to the south of Australia, from the north-west cloud band (originating in the Indian Ocean), from east coast troughs bringing moisture down from northern Australia, and east coast low pressure systems. In particular, they govern the location of the warm, dry band of high pressure across the mid-latitudes of Australia that is known as the sub-tropical ridge, and the associated degree of penetration into Victoria of low pressure systems from south of Australia that are responsible for much of our rainfall in the cooler months of the year. These climate features are illustrated in Figure 1.

Figure 1 Climate influences on Victoria's climate (Bureau of Meteorology)



These circulation patterns are affected by changes in sea surface temperature, wind speeds and pressure in the Indian, Pacific and Southern Oceans. The behaviour of these climate variables in each of these regions give 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) and the Inter-decadal Pacific Oscillation (IPO).

2.2. Climate Variability

Over the period of recorded climate data (up to the last ~150 years), Victoria has experienced numerous floods and several prolonged droughts. The Millennium Drought was the longest drought since records began. Paleoclimate proxy records provide an indication of the climate before instrumental records began, and suggest that the climate may be even more variable than has been observed in the instrumental record.

Rainfall is the most important climate variable to water supply planning, as it governs water availability for our climate dependent water sources. Indicators of the high natural variability of our climate are evident in both the instrumental record (up to the last ~ 150 years) and pre-instrumental proxy records. Rainfall variability is amplified when translated into variability in runoff and recharge.

2.2.1. Historical Variability from the Instrumental Record

Measurement of rainfall began in the 1850s providing us with up to ~150 years of rainfall data at a few locations across Victoria. The long-term average annual rainfall across Victoria is approximately 650 mm/year, but does vary considerably from year to year. This variability is illustrated in Figure 2 for Victorian rainfall, but greater variability is experienced in particular catchments. Victoria has experienced prolonged periods of below-average rainfall, notably in the late-1890s to early-1900s (the Federation Drought), in the late-1930s to early-1940s (the World War II Drought) and between 1997 and 2009 (the Millennium Drought). The climate influences acting in these prolonged droughts were unique to each drought (Verdon-Kidd and Kiem, 2009), resulting in each drought displaying different characteristics. The Millennium Drought was the multi-year drought of longest duration and was also notable for its lack of very wet years and very wet months (CSIRO 2012).

The long-term average annual rainfall varies in different regions of the State (Figure 3). The highest annual rainfalls occur across the Victorian Alps, and the lowest rainfalls occur in the north-west of the State.

Figure 2 Annual rainfall across Victoria – droughts compared to long-term average

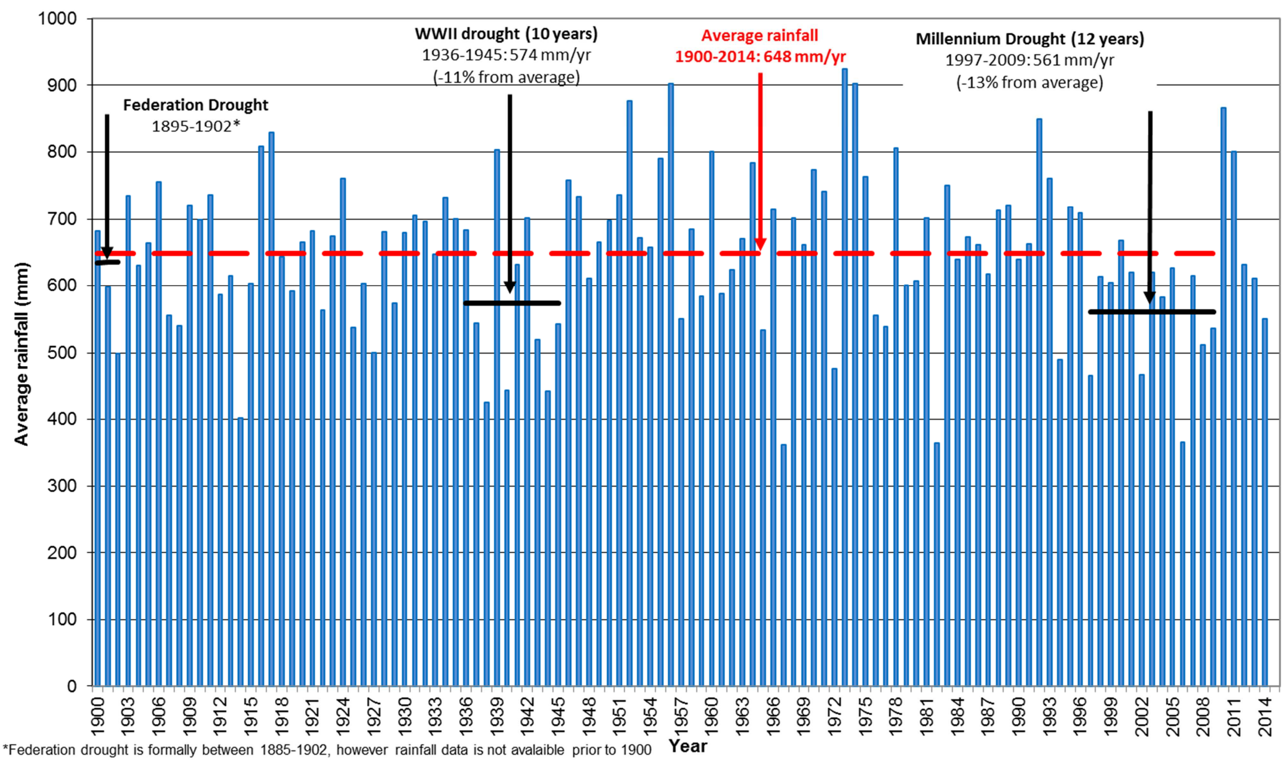
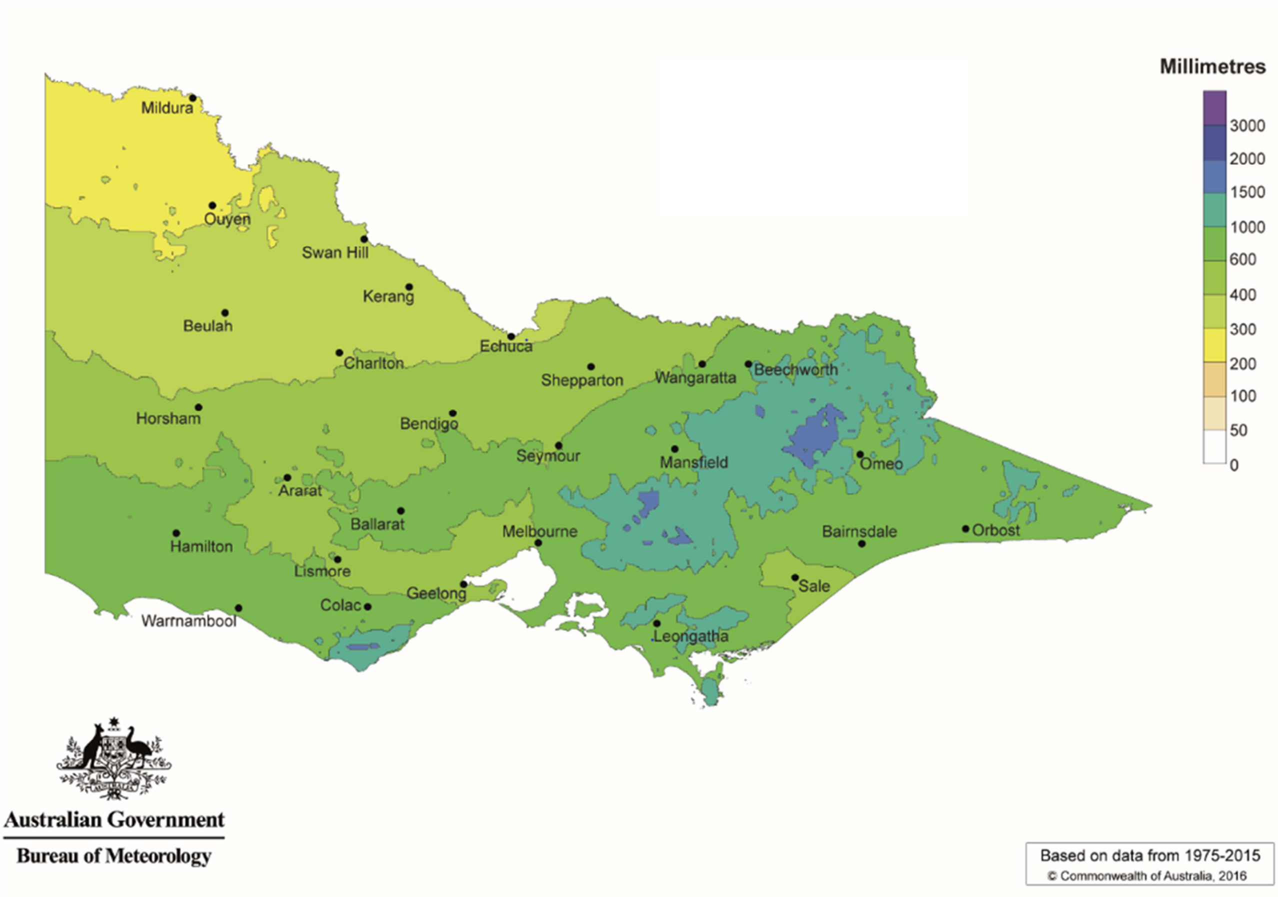


Figure 3 Spatial variation in average annual rainfall (1975-2015)



The Bureau of Meteorology has created "high quality" Australian climate datasets for the purposes of monitoring long-term climate change at http://www.bom.gov.au/climate/change/datasets/datasets.shtml. These include temperature, rainfall, pan evaporation and cloud cover datasets. Hydrologic reference stations have also been identified by the Bureau of Meteorology for identifying long-term trends in streamflow at http://www.bom.gov.au/water/hrs/about.shtml. These climate and streamflow stations are considered to be long, well maintained, of high quality, and with minimal effects of water resource development and land use change. They can be used locally to assess long-term changes in climate and streamflow behaviour.

2.2.2. Historical Rainfall Variability from Paleoclimate Proxy Records

Paleoclimate proxy records are indicators of past climate prior to the start of available instrumental records. These proxy records are derived from a range of sources including from corals, tree rings, ice cores, cave speleothems, lake and marine sediments. They provide an insight into our climate dating back several thousand years.

Paleoclimate reconstructions of south east Australian rainfall (incorporating Victoria and Tasmania) over the last 200 years have provided evidence that the Millennium Drought was likely to be the driest event since European settlement (Gergis et al. 2012). A reconstruction of River Murray streamflow (Gallant and Gergis 2011) found a similar result. The Department intends to participate in a new project that will collate available paleoclimate information for Victoria and investigate the likelihood and impact of severe drought, which will assist water resource planning by providing an improved understanding of drought risk (through an Australian Research Council Linkage Project with the University of Melbourne, Melbourne Water, the Bureau of Meteorology and Monash University (Henley et al. 2015)).

Kiem (2016) presented the published results from a range of pre-instrumental indicators of climate variability in eastern Australia, to reconstruct the sequence of wet and dry periods across different parts of

Australia over the last few thousand years, using data mostly at an annual time step. The information derived independently from these different sources was found to be generally consistent, leading to a reasonable degree of confidence in the conclusions presented below. Although the emphasis in Kiem (2016) was on paleoclimate reconstructions for the central coast of New South Wales, the findings are considered indicative of those that could be expected in Victoria.

Kiem (2016) characterised the last 200 years as being a relatively wet epoch with no long-duration drought events between 1700 and the start of the instrumental record for the east coast of New South Wales, consistent with the findings for Victoria. Prior to the year 1700, key findings from Kiem (2016) after synthesising information from a variety of published sources are:

- Droughts similar to and longer than those over the instrumental climate record have occurred on a regular basis in Australia's past over the last 2700 years; and
- Six mega-droughts that persisted for more than 10 years occurred in the period 1000-1320 AD, including a 39 year drought from AD 1174-1212.

Whilst there are some uncertainties about whether current influences on Australian climate have been stationary over previous millennia, it can be inferred from paleoclimate reconstructions that climate variability from the instrumental record represents only a fraction of the climate variability which has been observed over the last few thousand years. Although a 39 year drought is unlikely, a drought longer than the Millennium Drought seems plausible.

2.3. A Changing Climate

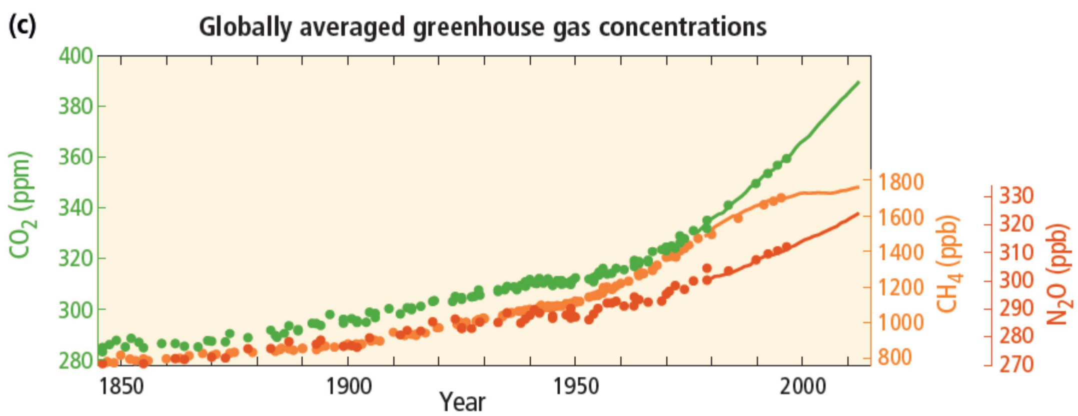
With increased greenhouse gas concentrations and associated changes to the global climate system, changes in the behaviour of Victoria's climate and its influences has occurred. This has resulted in clear reductions in cool season (April to October) rainfall over recent decades. The trend in cool season rainfall reductions was particularly evident during the Millennium Drought, but has continued in many parts of Victoria since the end of the Millennium Drought.

Scientists globally and in Victoria have observed that climate change can occur as both gradual and step changes. In Victoria it appears that there may have been changes in climate that occurred in the mid 1970s and again post 1997.

2.3.1. Historical Changes in Global Greenhouse Gas Concentrations and Temperature

Global greenhouse gas concentrations have been trending upwards since the mid 19th century. Figure 4 illustrates that carbon dioxide concentrations, for example, increased from approximately 280 ppm to just under 400 ppm over this period, with a more rapid increase over the last few decades of the 20th century.

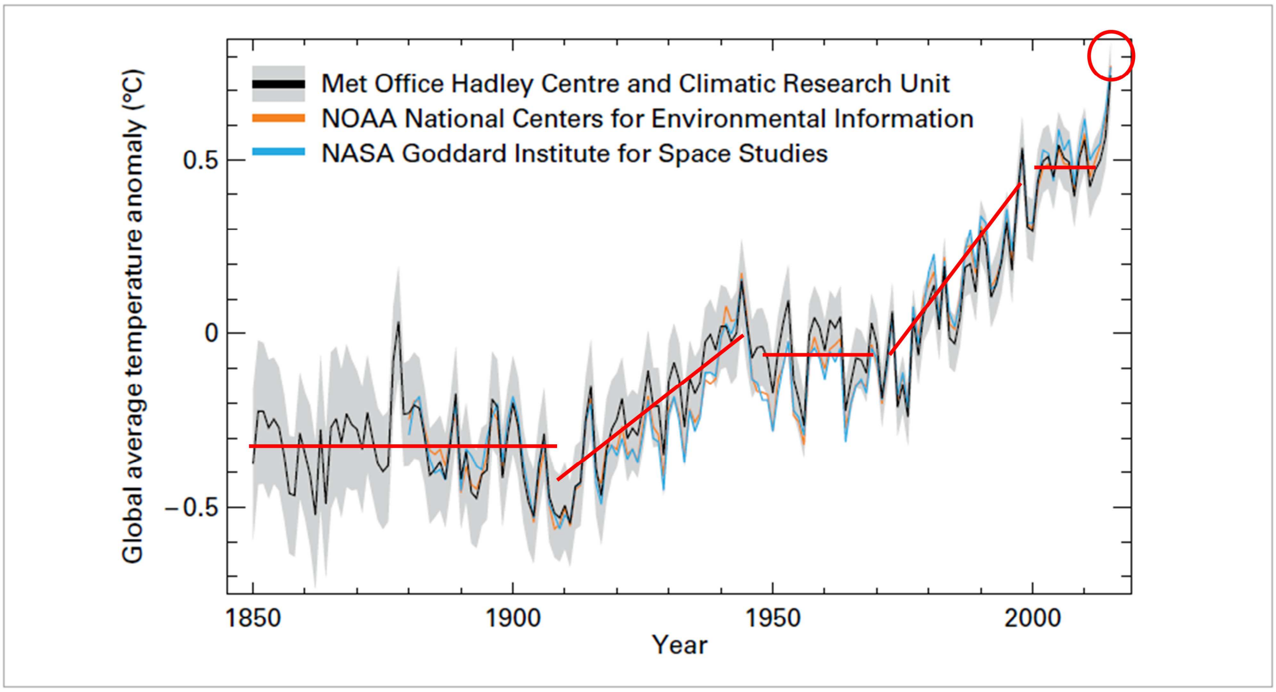
Figure 4 Annually and globally averaged greenhouse gas concentrations for carbon dioxide, methane and nitrous oxide (IPCC, 2014)



The excess energy in the global climate system as a result of increased greenhouse gas concentrations is predominantly stored in the oceans, with only a small fraction resulting in increased air temperatures. The World Meteorological Organisation (2016) states that 93% of this excess energy has been stored in the world's oceans, contributing directly to sea level rise (IPCC, 2014).

Global air temperature has been trending upwards since the start of the 20th century, with 2015 being the hottest year on record (WMO, 2016). The IPCC fifth assessment report (IPCC, 2014) states that the globally averaged combined land and ocean surface temperature data, as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06]°C over the period 1880 to 2012. Local temperature trends in Victoria over a similar period, as presented in Grose et al. (2015) and Timbal et al. (2015), are of a similar magnitude to global trends. Most of this warming has occurred from 1970 onwards, as shown in Figure 5.

Figure 5 Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005 (Note: Colours indicate different data sets) (adapted from WMO 2016, with red trendlines added for these guidelines and a red circle included to show the increase observed in 2015)



Unlike the increases in greenhouse gas concentrations, temperature has exhibited discrete periods of rapid warming (or steps) followed by periods of stable global temperatures (Figure 5). Jones (2012) draws upon the findings by Meehl et al. (2011) which suggests that the likely origin of this step-like behaviour lies in the interactions between the atmosphere and the oceans. Increased deep ocean mixing was observed during periods when global atmospheric temperatures remained static, suggesting increased heat transfer from the atmosphere to the oceans over these periods. Observed step changes in temperature include:

- Statistically significant step changes in south-east Australian temperature of 0.7°C in 1968 for minimum temperature, 0.5°C in 1973 and 0.8°C in 1997 for maximum temperature (Jones, 2012). This latter change was coincident with a statistically significant step change in global maximum temperature of 0.3°C (Jones, 2012);
- Statistically significant step changes in the relationship between annual maximum and minimum temperature for the south-east Australia region (Jones, 2012); and
- Statistically significant step changes in the relationship between annual maximum temperature and annual precipitation from 1968-1973 for the south-east Australia region (Jones, 2012).

According to Jones (2012) this is also evident in the way that global climate models behave, with statistically significant step changes in climate variables from the models being identified over historical periods.

It is currently unclear whether 2015 marks the first year of a renewed acceleration in the rate of warming following the hiatus since the late 1990s (shown using a red circle in Figure 5). The year 2015 was around 0.3°C warmer than average across the first decade of this century.

2.3.2. Historical Changes in Rainfall

Research being undertaken by VicCI has improved our understanding of the behaviour of the large scale circulation patterns that influence Victoria's climate. This research has found that:

- The tropics are expanding southward and the sub-tropical ridge has intensified and shifted southwards, influencing changes in both cool season and warm season rainfall in Victoria. The current rate of expansion is around 65 km per decade in our region of the southern hemisphere (Hope et al., 2015); and
- The southern annular mode (SAM) has trended positively since the 1950s, influencing changes in both cool and warm season rainfall in Victoria.

The changes in these large scale circulation patterns are not necessarily gradual. The expansion of the 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., 2015).

Grose et al. (2015) found for southern Victoria and Tasmania, an annual decrease in rainfall of 5 mm per decade was identified from 1901 to 2012, with seasonal rainfall trends varying by region. There was "a generally negative trend in mean annual rainfall since the mid-1970s" in this cluster. However, as stated in Timbal et al. (2015), none of these rainfall trends are statistically significant for Victoria. Rainfall trends over shorter periods include wetter periods in the 1950s and 1970s, and a drying trend over the Millennium Drought.

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). The large rainfall decline in autumn was a prominent feature of the Millennium Drought and these conditions have persisted following the end of the Millennium Drought. This is shown across Victoria in Figure 6, where it can be seen that cool season rainfall anomalies relative to the long-term average (as indicated by increasingly deeper shades of red) have increased in each of the last two decades and have affected almost all of the State. The observed reduction in cool season rainfall is consistent with the observed intensification of the sub-tropical ridge and the positive trending of the Southern Annular Mode. Since the end of the Millennium Drought, the trend in cool season rainfall reductions has continued for many parts of Victoria.

Figure 6 Cool season rainfall between 1986 and 2015 (Source: Bureau of Meteorology) - Deeper red areas represent rainfall deficits relative to the long-term average

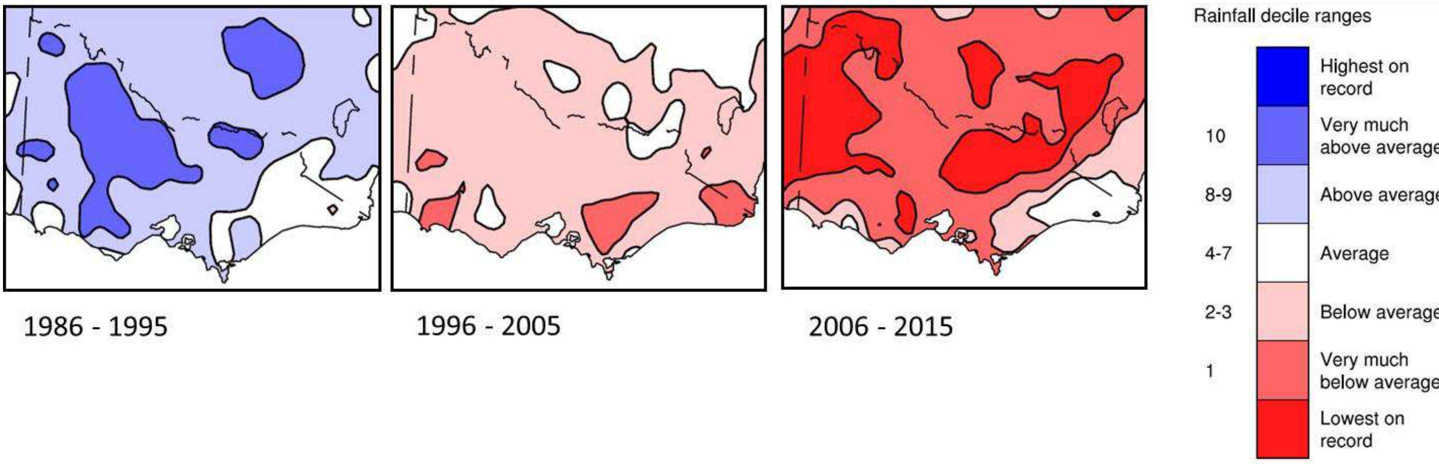
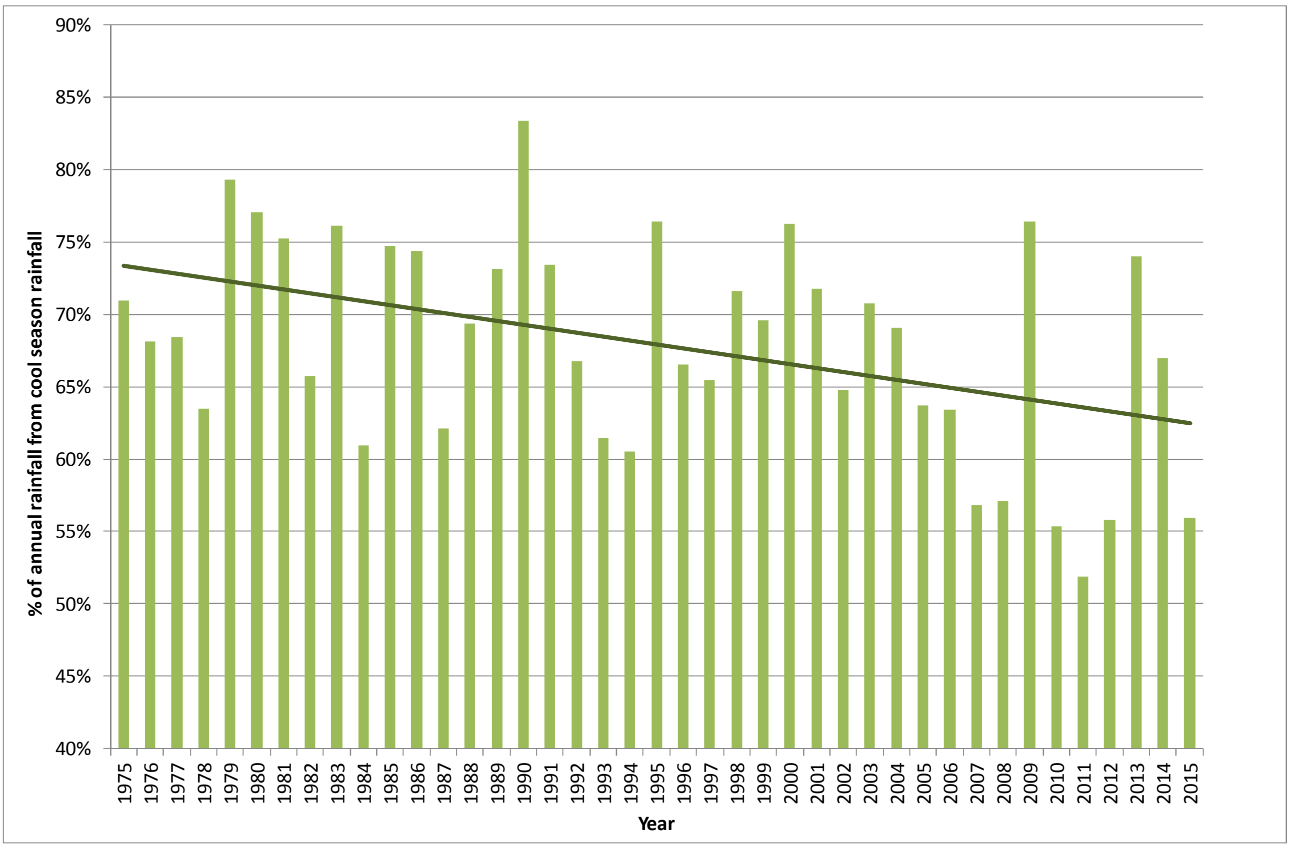


Figure 7 illustrates this behaviour over a longer time scale for an example rainfall station in Victoria (at Lake Eildon), where it can be seen that the contribution of cool season rainfall to annual rainfall totals has been trending downwards. Six of the last nine years, including several years after the end of the Millennium Drought, displayed a cool season rainfall contribution lower than any other year since 1975. In this example, cool season rainfall was trending downwards in absolute terms by around 35 mm per decade. Prior to 1975, no long-term trend was evident in the contribution of cool season rainfall to annual rainfall totals at this site.

Figure 7 Cool season (Apr-Oct) rainfall contribution to annual rainfall at a representative gauge in Victoria (Lake Eildon) with linear trend shown as a darker solid line



The decline in cool season rainfall has been partially offset by increases in warm season rainfall in some parts of the State. For example, at this same rainfall gauge, autumn rainfall from 1975 to date was on average 19% lower than over the period from 1902-1975, whilst winter/spring rainfall was roughly the same and summer rainfall was approximately 6% higher. In the post-1997 period, summer rainfall remained above the 1902-1975 average, but autumn (-29%), winter (-10%) and spring (-11%) all showed declines. Whilst the magnitude of the changes varies across Victoria, the general trends are similar throughout.

2.3.3. Historical Changes in Runoff

Changes in rainfall are amplified when translated into changes in catchment runoff. Historical changes in the runoff in Victorian streams, particularly over the Millennium Drought, have been well documented. They have been presented in each year's Victorian Water Accounts (e.g. DELWP, 2015b), with the statistical significance of a step change in streamflow being identified in several studies, including the CSIRO Murray-Darling Basin Sustainable Yields project (CSIRO, 2008), and by the Bureau of Meteorology at its hydrologic reference stations across Victoria (Bureau of Meteorology, 2016a). The higher than anticipated change in runoff over the Millennium Drought has been attributed to the reduction in cool season rainfall, the absence of any above average rainfall years, and higher potential evapotranspiration (Potter and Chiew, 2011), with changes in the associated hydrological processes that identify the extent of change being an area of ongoing research (e.g. Saft et al. 2015 & 2016).

The magnitude of changes in streamflow over the Millennium Drought for inflows to Melbourne's main harvesting storages and GWMWater headworks storages are illustrated in Figure 8 and Figure 9. Inflows during the Millennium drought were on average around 35% lower than the long-term average for Melbourne and 71% lower for GWMWater, with no single year of inflows above the long-term average. Only twice within the last twenty years has the long-term annual average been exceeded.

Figure 8 Annual inflows to Melbourne's main water supply reservoirs (Source: Melbourne Water 2016)

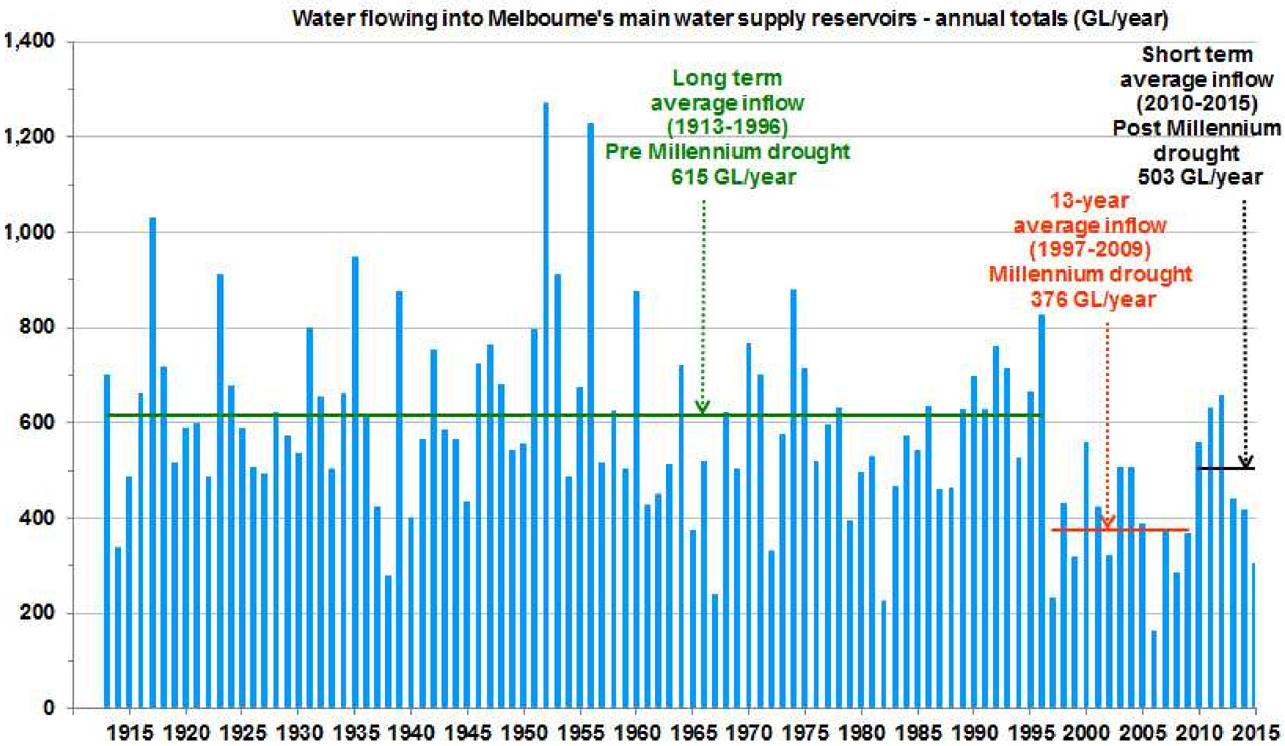
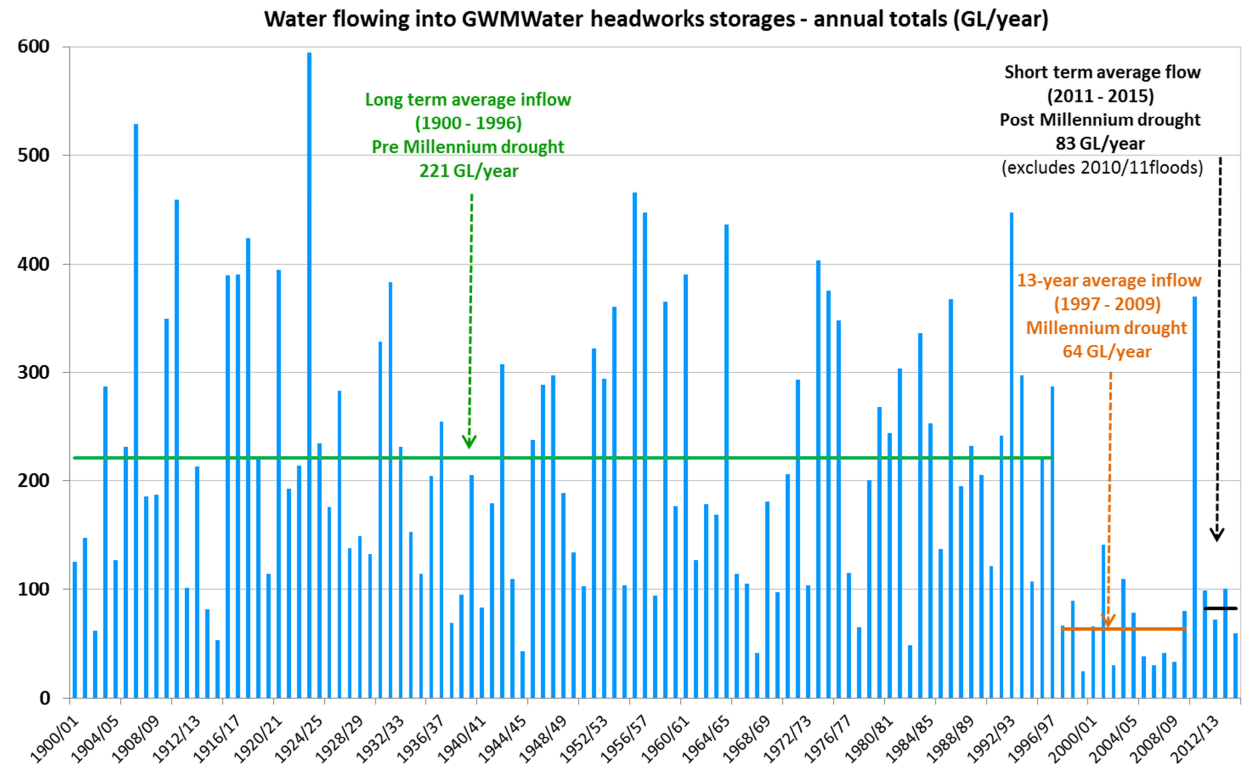


Figure 9 Annual inflows to GWMWater headworks storages



Note: Inflow data excludes Taylors Lake and Toolondo Reservoir.

These historical reductions in cool season rainfall and the corresponding reduction in annual streamflows mimic historical behaviour in south-west Western Australia in the mid-1970s and more recently in Tasmania. Both of these areas are heavily reliant on the rain-bearing low pressure systems that have traditionally provided Victoria with reliable cool season rainfall and runoff.

In addition to potential changes in atmospheric climate inputs, future runoff can also be influenced by changing rainfall-runoff relationships and ecohydrological processes (vegetation water use), and atmospheric and land surface feedbacks in a warmer and higher CO_2 environment. The implications of hydrologic non-stationarity and changing rainfall-runoff relationships on extrapolating hydrological models to predict runoff have been investigated in SEACI and VicCI (CSIRO, 2012; Chiew et al., 2014). Whilst research on this is ongoing in CSIRO and the University of Melbourne (Potter et al., 2013; Chiew et al., 2014; Chiew et al., 2015; Saft et al., 2015; Saft et al., 2016; Fowler et al., 2016; Appendix D), results thus far suggest that current modelling approaches may overestimate water availability during long-run droughts which are likely to occur more frequently under climate change. Further details of some of this research are presented in Appendix D.

2.3.4. Historical Trends in Potential Evaporation

Potential evaporation has been shown to decrease over recent decades (measured as pan evaporation) despite increases in temperature, as summarised in Potter et al. (2015). This has been attributed to a decline in wind speeds offsetting changes in evaporation associated with increases in temperature in data leading up to the end of the Millennium Drought (Roderick et al. 2009a, 2009b). However, more recent data for Victoria since the end of the Millennium Drought (e.g. http://www.bom.gov.au/climate/change/#tracker) has pan evaporation returning to average or above-average conditions, thus resulting in no discernible trend since 1970. Identifying and attributing trends in pan evaporation is an ongoing research field, and it is worth noting that future changes in rainfall would tend to have a much greater effect on water availability than changes in potential evaporation (e.g. Potter et al., 2011; Chiew et al., 2013).

3. Future Climate Projections for Victoria

Projections of runoff and related climate variables have been prepared for Victoria's river basins by CSIRO. This chapter of the guidelines provides a brief overview of the modelling approach (Section 3.2 and 3.3). To ensure appropriate use of these projections, key limitations in their applicability are discussed (Section 3.4). For further technical details please see (Potter et al., 2016).

In addition to the three climate change scenarios (low, medium and high) prepared by CSIRO, a fourth scenario is considered in these guidelines. The fourth scenario represents a step change in the climate and is described in Section 4.2 of the guidelines.

3.1. Overview of Modelling Approach

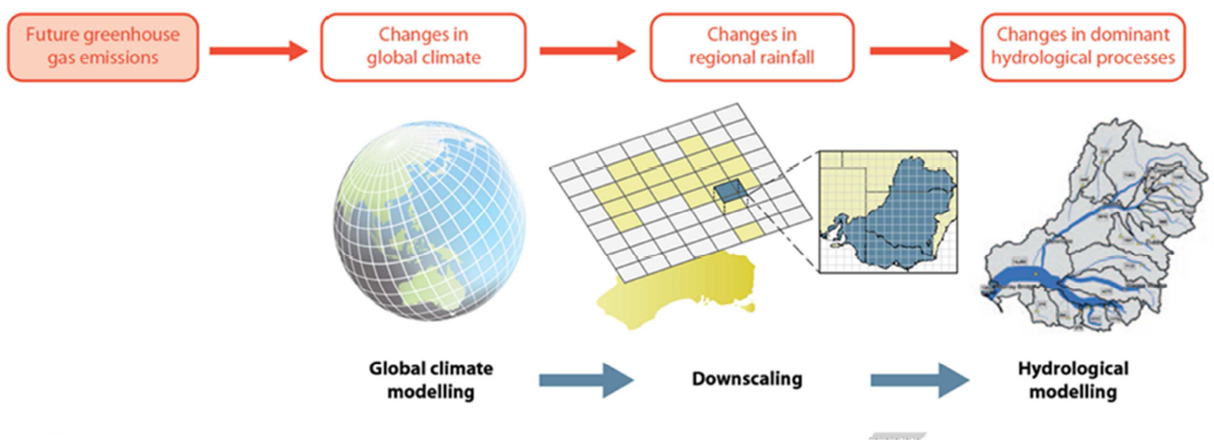
CSIRO has generated climate change projections for Victoria's river basins for the years 2040 and 2065.

Global climate models (GCMs) are used to project anticipated changes in climate based on greenhouse gas emission scenarios. The IPCC Fifth Assessment Report provides four plausible greenhouse gas emissions scenarios. The scenario with the highest concentration of greenhouse gases (known as RCP8.5) has been adopted in line with the recent historical trajectory of greenhouse gas concentrations, as well as because this scenario can be expected to provide both the wettest and driest projections.

Overall, the outputs from 42 GCMs were used, along with hydrological modelling, to derive scenarios representative of a low, medium and high impact of climate change on water availability from climate dependent sources.

There are several steps involved in deriving projections of changes in temperature, rainfall, potential evapotranspiration (PET) and runoff (as shown in Figure 10). This section outlines each of the steps applied in the production of the regional projections presented in this report.

Figure 10 Overview of modelling process to derive climate change projections from global climate models (CSIRO, 2016)

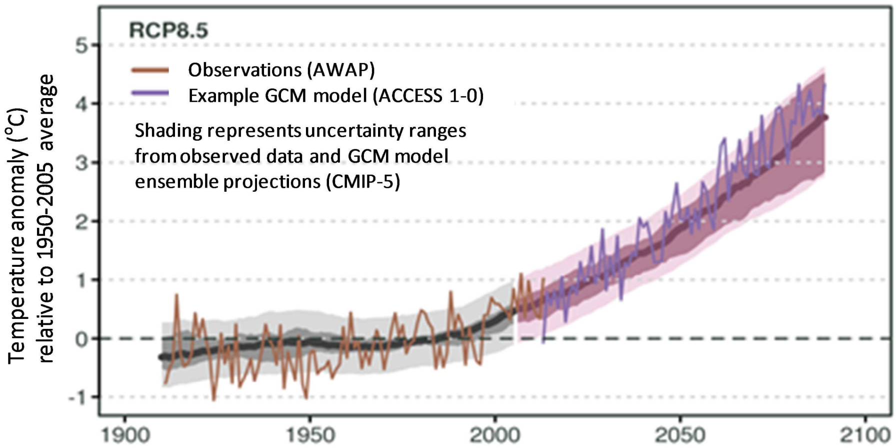


These steps include:

1. **Selection of GCM current climate period and future time slices:** The three time slices selected from the global climate models were 20 year climate windows representing current (1986-2005), Year 2040 (2031-2050) and Year 2065 (2056-2075). These were chosen in line with the IPCC's 5th Assessment Report and recent national climate change projections (CSIRO & BoM, 2015).
2. **Selection of an emissions scenario(s):** Emission scenarios represent plausible changes in greenhouse gas and aerosol concentrations over time in response to changes in emissions and land-use. From the four available emissions scenarios presented in the IPCC's 5th Assessment Report, these guidelines have adopted representative concentration pathway (RCP) 8.5 scenario. This is the highest concentration emissions scenario of the four scenarios available. This scenario

has been selected because recent data (Peters et al., 2013; Friedlingstein et al., 2014) has current and near-future GDP growth based projections (2010-2019) tracking at or near the RCP8.5 emissions scenario, and because this scenario can be expected to provide both the wettest and driest projections (from Potter et al. 2016). Of the four available emissions scenarios, the RCP8.5 scenario generates the both the wettest and driest outcomes for Victoria. The temperature response to the RCP 8.5 emissions scenario is shown in Figure 11.

Figure 11 Historical and projected time series for Victorian annual average surface air temperature anomaly (°C) (adapted from Timbal et al., 2016)



3. **Selection of global climate models (GCMs):** The range of future climate conditions is derived from the 42 global climate models (the model ensemble) used in the IPCC's 5th Assessment Report. These models are provided by research organisations from around the world, including CSIRO. All 42 models were included in the analysis after extensive consideration of alternative approaches to model choice and sampling.
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 here because it is robust, computationally less complex than other methods, 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 was also implemented. These empirical scaling factors were then applied to a 40 year current climate baseline from 1975-2014 to derive the results for presentation in these guidelines.
5. **Hydrological modelling:** SIMHYD rainfall-runoff models were 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 scenarios:** The results from the GCMs with the 10th percentile, median and 90th percentile runoff response to the climate projections are selected in the guidelines to define the low, medium and high climate change scenarios. The median of the model ensemble is the result which is projected to be exceeded by 50% of the 42 global climate models. 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. These scenarios represent a low, medium and high climate change impact on water availability from climate dependent sources.

7. **Projected changes for each river basin in Victoria:** Results are presented as Statewide maps and tables for each river basin in Victoria.

3.2. Climate Model Projections for Victoria

With increased greenhouse gas concentrations, the majority of climate models project Victoria to become hotter and drier. The medium and high climate change scenarios show a decrease in rainfall and runoff across all of Victoria by 2040, with the greatest impacts seen in western Victoria. The low climate change scenario projects a small increase in rainfall and runoff across Victoria in 2040 and 2065.

The outcomes of the modelling indicate that under increased greenhouse gas concentrations, the majority of climate models project Victoria to become hotter and drier. Under the medium climate change scenario the temperature is projected to increase by 1.3°C by 2040 and 2.3°C by 2065. For this medium climate change scenario, the overall decline in rainfall is 3.6% by 2040 and 4.7% by 2065 and potential evapotranspiration (PET) is projected to increase by 4.5% by 2040 and 7.4% by 2065. The combination of less rainfall and increased potential evapotranspiration is expected to lead to reductions in runoff across Victoria.

The projected changes will differ depending on which climate scenario is used. Maps are used within this section of the guidelines to illustrate the differences between the selected climate change scenarios and the variability across Victoria (Figure 12 to Figure 25). Further details about the preparation of data in each of these maps are provided in Appendix A.

The low, medium and high climate change scenarios show the range of projections made by the 42 GCMs. Under the medium and high climate change scenarios a decline in rainfall is projected by 2040 (3.6% and 10.4% respectively), while an increase in rainfall is projected under the low climate change scenario (+2.4%) (Figure 12). In comparison, during the Millennium Drought the average annual rainfall for Victoria was 11% less than the average rainfall over the baseline period , indicating that the high climate change scenario in 2040 is similar to the rainfall experienced during the Millennium Drought. Runoff is also projected to decrease under the medium and high climate change scenarios, however, the percentage decrease is greater than for rainfall (8.5% and 15.9% for the medium and high scenarios respectively) (Figure 14).

The impacts of a changing climate are likely to vary across Victoria. The greatest reductions in annual rainfall (or smallest increases for the low scenario) are expected in the north-west part of Victoria (Figure 12). Greater variability is seen in the projected changes in runoff that reflects differences in the way catchments are predicted to respond to changes in rainfall and potential evapotranspiration. In general, the impacts are greatest in the west and the smallest in far East Gippsland (Figure 14). Less variability is expected in the changes for potential evapotranspiration (Figure 13).

Different changes are expected between seasons for rainfall. The high climate change scenario shows decreases in all seasons and the low climate change scenario has increases in all seasons. The medium climate change scenario projects the greatest reductions in rainfall in winter and spring, with small increases in rainfall projected over northern Victoria in both summer and autumn. Maps illustrating the seasonal changes for rainfall are provided in Appendix G. There is no indication from the modelling that the seasonal changes in temperature or potential evapotranspiration will differ substantially from the projected annual changes.

Figure 12 Projected changes in annual rainfall under emissions scenario RCP8.5 relative to current climate

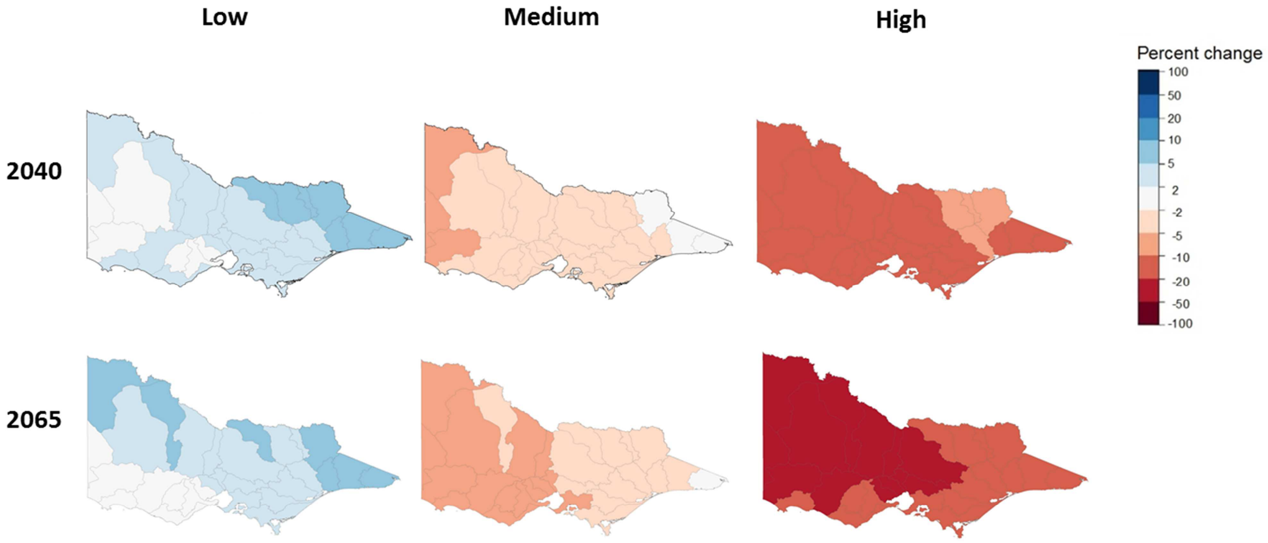


Figure 13 Projected changes in annual potential evapotranspiration under emissions scenario RCP8.5 relative to current climate

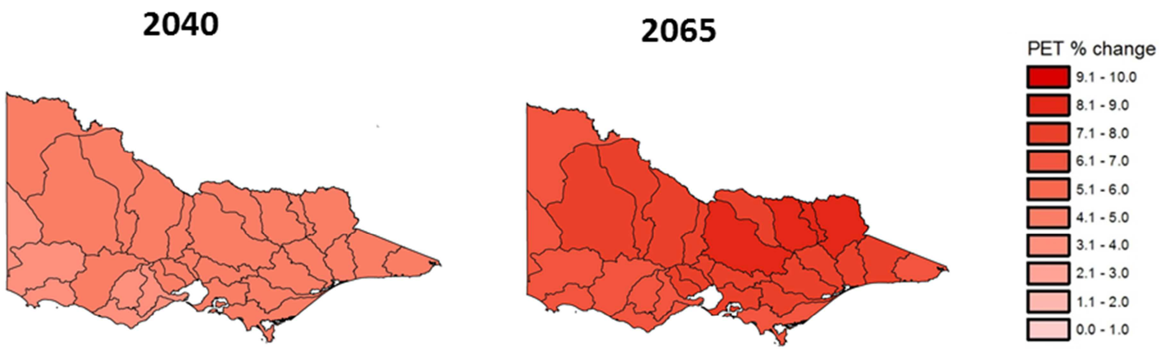
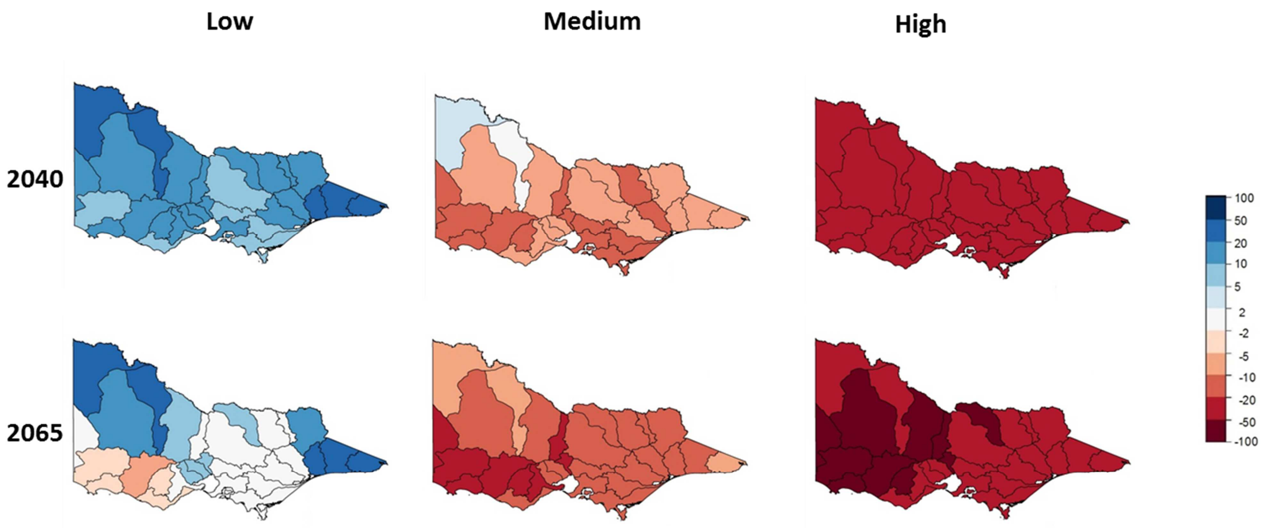


Figure 14 Projected changes in annual runoff under emissions scenario RCP8.5 relative to current climate



3.3. Climate Model Projection Tables for Victoria

The impacts of climate change are projected to vary across Victoria. A range of projected changes for each river basin have been developed for application based on the subsequent guidance in Chapter 4.

An overview of the climate change projections was provided in the previous section and showed that the impacts are projected to vary across Victoria. In order to allow this spatial variability to be reflected in regional water resource assessments, the projections are provided for each of Victoria's River Basins. Further details about the preparation of data in each of these tables are provided in Appendix A.

3.3.1. Temperature and Potential Evapotranspiration Projections

The changes in local temperature and potential evapotranspiration (PET) anticipated by the median of the GCM model ensemble are presented for each river basin in Table 1. In the East Gippsland basin, for example, average daily temperature is projected to increase by 1.3^{o}C by 2040 relative to the current climate baseline. Projected changes in maximum daily temperature are similar in magnitude to changes in average daily temperature in this region (Grose et al., 2015). For the same river basin, potential evapotranspiration is projected to increase by 4.2% by the Year 2040 relative to the current climate baseline.

3.3.2. Rainfall Projections

The projected change in rainfall in each river basin for the Year 2040 and Year 2065 relative to the current climate baseline is shown in Table 2. In this table, the medium climate change scenario projects a decline in average annual rainfall in all river basins at the two future time slices presented. The low climate change scenario is projected to be wetter than the current climate baseline. For the East Gippsland basin, for example, the average annual rainfall is projected to range from a decrease of 10.8% (high scenario) to an increase of 6.8% (low scenario) by the Year 2040, with a 1% decrease in rainfall for the medium climate change scenario.

Note that the projections of temperature, potential evapotranspiration and rainfall presented in Table 1 and Table 2 have been determined based on the distribution from all 42 GCMs for each of the climate variables separately. For the majority of applications by water corporations, the projected changes to temperature, potential evapotranspiration and rainfall in Table 1 and Table 2 should be adopted. Exceptions to this, such as for specific investigations into potential evapotranspiration and temperature uncertainty and for research purposes, are discussed in Appendix A.

3.3.3. Runoff Projections

Runoff projections for Victoria are listed in Table 3, which shows that the medium climate change scenario projects a decline in runoff in all river basins at the two future time slices presented. The low climate change scenario is projected to be wetter than the current climate baseline, consistent with the projected change in rainfall. For the East Gippsland basin, for example, the average annual runoff is projected to range from -25.6% to +23.3% by the Year 2040, with a 5.1% decrease in runoff for the medium climate change scenario.

Table 1 Median change in average daily temperature and potential evapotranspiration (PET) for use in all GCM-based climate change scenarios (based on all GCMs)

River basin	Temperature change relative to current climate baseline (^oC)		PET change relative to current climate baseline (%)	
	Year 2040	Year 2065	Year 2040	Year 2065
East Gippsland	1.3	2.4	4.2%	6.9%
Snowy	1.4	2.5	4.5%	7.5%
Tambo	1.3	2.4	4.5%	7.5%
Mitchell	1.3	2.4	4.7%	7.9%
Thomson	1.3	2.4	4.6%	7.5%
Latrobe	1.2	2.2	4.5%	7.6%
South Gippsland	1.1	2.1	4.2%	7.0%
Bunyip	1.2	2.1	4.3%	7.3%
Yarra	1.3	2.3	4.6%	7.6%
Maribyrnong	1.3	2.3	4.8%	7.7%
Werribee	1.3	2.3	4.7%	7.7%
Moorabool	1.2	2.2	4.5%	7.7%
Barwon	1.1	2.1	4.0%	7.0%
Lake Corangamite	1.1	2.0	3.9%	6.9%
Otway Coast	1.0	1.9	3.7%	6.4%
Hopkins	1.1	2.1	4.1%	6.9%
Portland Coast	1.0	1.9	3.4%	6.1%
Glenelg	1.1	2.0	3.8%	6.7%
Millicent	1.1	2.1	3.8%	6.7%
Upper Murray	1.4	2.6	4.6%	8.1%
Kiewa	1.4	2.5	4.8%	8.1%
Ovens	1.4	2.5	4.8%	8.1%
Broken	1.4	2.5	5.0%	8.0%
Goulburn	1.4	2.4	4.9%	8.2%
Campaspe	1.3	2.4	4.7%	7.8%
Loddon	1.3	2.4	4.6%	7.7%
Avoca	1.4	2.4	4.3%	7.1%
Lower Murray	1.5	2.5	4.5%	7.6%
Mallee	1.3	2.4	4.2%	7.0%
Wimmera	1.3	2.3	4.2%	7.1%
Victoria*	1.3	2.3	4.5%	7.4%

* 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.

Table 2 Change in average annual rainfall relative to the current climate baseline across all seasons (based on all GCMs)

	Average annual rainfall (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
River basin	**Historic**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
East Gippsland	941	6.8%	-1.0%	-10.8%	7.9%	-1.2%	-15.0%
Snowy	813	7.6%	-1.4%	-10.4%	8.5%	-4.5%	-14.9%
Tambo	786	5.9%	-2.6%	-10.8%	7.1%	-4.5%	-16.6%
Mitchell	953	4.3%	-2.3%	-9.7%	2.3%	-4.8%	-18.5%
Thomson	859	4.1%	-2.0%	-10.6%	2.3%	-4.1%	-19.9%
Latrobe	919	3.3%	-4.0%	-11.4%	2.2%	-4.5%	-16.7%
South Gippsland	872	2.6%	-4.5%	-11.7%	2.2%	-4.4%	-15.9%
Bunyip	860	2.9%	-3.9%	-10.9%	2.1%	-5.0%	-16.1%
Yarra	961	3.7%	-2.7%	-10.5%	2.4%	-4.3%	-20.6%
Maribyrnong	676	2.7%	-2.4%	-12.0%	2.6%	-5.5%	-21.6%
Werribee	619	2.2%	-2.7%	-11.7%	2.4%	-6.2%	-21.4%
Moorabool	596	2.0%	-3.4%	-11.6%	1.5%	-5.9%	-21.4%
Barwon	650	2.0%	-3.0%	-11.5%	1.2%	-5.2%	-19.6%
Lake Corangamite	629	2.0%	-3.9%	-11.6%	-0.2%	-5.3%	-19.1%
Otway Coast	950	2.1%	-3.6%	-11.7%	0.5%	-5.8%	-19.0%
Hopkins	634	2.1%	-4.4%	-11.6%	1.0%	-5.7%	-20.9%
Portland Coast	724	2.6%	-4.6%	-10.9%	-0.2%	-8.4%	-19.0%
Glenelg	655	1.2%	-5.0%	-12.7%	1.4%	-8.4%	-21.7%
Millicent	533	1.2%	-5.5%	-15.0%	1.1%	-8.5%	-22.9%
Upper Murray	1053	7.5%	-0.7%	-8.5%	8.2%	-2.6%	-14.4%
Kiewa	1143	5.5%	-2.5%	-9.5%	4.0%	-2.1%	-16.0%
Ovens	962	5.3%	-3.4%	-9.5%	3.8%	-3.7%	-17.5%
Broken	573	6.0%	-3.7%	-14.2%	6.8%	-3.5%	-18.3%
Goulburn	767	3.9%	-2.5%	-13.6%	2.4%	-4.0%	-20.7%
Campaspe	596	2.4%	-2.2%	-15.2%	2.6%	-6.1%	-23.2%
Loddon	459	2.5%	-2.8%	-14.3%	3.2%	-5.6%	-22.9%
Avoca	358	4.8%	-3.8%	-15.5%	6.9%	-3.4%	-20.6%
Lower Murray	394	7.3%	-3.8%	-15.0%	9.1%	-2.3%	-19.1%
Mallee	306	4.7%	-5.3%	-17.8%	6.9%	-6.5%	-23.6%
Wimmera	394	2.0%	-3.7%	-13.3%	3.9%	-5.9%	-22.3%
Victoria*	643	2.4%	-3.6%	-10.4%	2.7%	-4.7%	-19.4%

* 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.

Table 3 Change in average annual runoff relative to the current climate baseline across all seasons

River basin	Average annual runoff (mm) (1975-2014) Historic	Change relative to current climate baseline (%) Year 2040 10th percentile Low	50th percentile Medium	90th percentile High	Year 2065 10th percentile Low	50th percentile Medium	90th percentile High
East Gippsland	166	23.3%	-5.1%	-25.6%	21.4%	-8.1%	-39.3%
Snowy	136	22.5%	-7.1%	-25.3%	21.0%	-17.9%	-36.1%
Tambo	107	23.3%	-6.0%	-27.4%	20.6%	-13.1%	-40.0%
Mitchell	183	10.4%	-11.0%	-26.3%	1.5%	-15.6%	-44.7%
Thomson	186	10.3%	-9.1%	-27.6%	2.0%	-13.9%	-41.9%
Latrobe	186	8.7%	-10.7%	-31.3%	0.1%	-16.3%	-41.5%
South Gippsland	170	8.8%	-11.9%	-33.7%	1.6%	-16.9%	-44.8%
Bunyip	147	10.6%	-13.7%	-33.0%	1.5%	-19.1%	-47.0%
Yarra	227	10.0%	-11.0%	-29.2%	0.8%	-16.4%	-44.3%
Maribyrnong	81	15.0%	-13.2%	-33.1%	5.1%	-20.0%	-55.4%
Werribee	77	11.8%	-7.7%	-28.9%	7.5%	-18.1%	-45.5%
Moorabool	58	13.5%	-8.0%	-30.4%	5.5%	-17.3%	-45.6%
Barwon	47	16.1%	-6.1%	-33.1%	-0.8%	-21.6%	-47.6%
Lake Corangamite	34	17.9%	-10.2%	-36.5%	-2.5%	-26.1%	-53.0%
Otway Coast	241	6.6%	-7.2%	-25.3%	-4.7%	-15.8%	-41.9%
Hopkins	51	14.9%	-13.0%	-35.7%	-5.2%	-28.5%	-59.8%
Portland Coast	85	15.5%	-10.8%	-36.0%	-2.7%	-30.4%	-54.8%
Glenelg	67	7.6%	-13.6%	-37.3%	-3.4%	-31.4%	-60.8%
Millicent	26	13.0%	-10.0%	-35.2%	-0.5%	-27.5%	-57.3%
Upper Murray	219	17.2%	-8.4%	-23.3%	13.5%	-16.6%	-39.4%
Kiewa	280	11.2%	-9.1%	-22.4%	1.5%	-12.1%	-39.4%
Ovens	205	11.7%	-10.8%	-23.3%	1.2%	-15.7%	-43.9%
Broken	51	18.6%	-9.7%	-35.9%	8.1%	-16.8%	-50.0%
Goulburn	182	9.9%	-9.5%	-29.1%	1.3%	-13.7%	-41.9%
Campaspe	64	10.5%	-12.3%	-37.1%	1.0%	-20.7%	-57.0%
Loddon	24	12.4%	-7.4%	-36.6%	6.9%	-17.6%	-57.6%
Avoca	17	22.8%	-0.4%	-29.1%	25.5%	-8.8%	-44.4%
Lower Murray	13	32.8%	-4.6%	-37.5%	27.1%	-11.4%	-47.0%
Mallee	4	40.3%	4.6%	-25.0%	42.1%	-5.8%	-49.0%
Wimmera	21	12.1%	-6.5%	-32.3%	12.3%	-14.4%	-53.1%
Victoria*	93	8.7%	-8.5%	-24.7%	1.5%	-15.9%	-43.8%

* 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.

3.4. Global Climate Model Limitations

Global Climate Models 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 3.1 and in the associated technical report (Potter et al., 2016) there are a number of assumptions made throughout the modelling process which 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 global climate model projections (10th percentile, median and 90th percentile) from the 42 model ensemble.

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 at finer temporal scales are outlined below. A handful of GCMs perform poorly in some aspects of modelling at a regional scale, as listed in Grose et al. (2015) and Timbal et al. (2015, 2016);
- 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; and
- 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. (2015) and Timbal et al. (2015) assessed the level of confidence of a given modelled change in climate conditions from the global climate models. This level of confidence was based on the rating method used in the Intergovernmental Panel on Climate Change (IPCC) 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 4, with an emphasis on the level of confidence associated with projected within-year climate change.

Of particular relevance to water resource planning in Victoria are projected changes to prolonged droughts such as the Millennium Drought, which recently tested our water supply system performance. When looking at modelled future long duration droughts, Hope et al. (2015) note that the Millennium Drought recorded 121 months without any ‘wet’ months, and that global climate models “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.

Table 4 Level of confidence in seasonal and daily time step changes in climate from global climate models

Modelled 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	
Increase in potential evaporation rates in all seasons	High with regard to direction of change, but medium confidence in magnitude of the change	
Decrease in the frequency of frost-risk days	High	
Rainfall decreases in winter and spring	High	Hope et al. (2015) 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. (2015) 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. (2015) states drought durations in the GCM outputs over the 21st century are all shorter than the Millennium Drought

With respect to projected daily and seasonal changes it is concluded from this overview of model limitations that:

1. **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 in uncertainty in the projected changes from the GCMs;
2. **The projected changes do not reflect changes in the number of rain days** that can be important for understanding changes to within-year drought duration; and
3. **The projected changes reasonably reflect changes in winter/spring rainfall and changes in summer rainfall**, but the **magnitude of changes in cool season (Apr-Oct) rainfall may be under-estimated** (based on the fact that 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 global climate model results and utilises them to create locally relevant information in a robust manner that has been peer reviewed. Model limitations are a reflection of the considerable challenges faced by climate scientists and hydrologists in making projections about our future climate and water availability. These limitations on 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 of the information needed by water resource managers in Victoria at a suitable level of confidence.

4. Assessing the Impact of Climate Change on Water Supplies

This section of the guidelines provides advice and recommendations for how the climate change projections (from Section 3) and an additional step climate change scenario can be applied to water resource planning in Victoria, taking into account what we know about recent historical changes in our climate (from Section 2).

4.1. Selecting a Baseline Period

Climate baselines are used to estimate water availability for water supply systems over a defined climate period, and are an important consideration in managing the risks of climate variability and climate change to those systems.

A range of climate information is available from which to choose suitable climate baselines for water resource planning, as shown in Figure 15. For water resource planning, the primary climate variable of interest is rainfall, which is available as recorded data over the instrumental record (up to ~150 years), plus proxy information derived from various paleoclimate sources in the pre-instrumental record dating back a few thousand years (as previously discussed in Section 2.2.2). Within the instrumental record, periods of interest include the IPCC baseline (the period used for GCM downscaling) (1986-2005), the baseline period used to generate projected changes in rainfall, evaporation and runoff (1975-2014), the Millennium Drought (1997-2009) and the period from the start of the Millennium Drought to date (1997 to date). For specific supply systems, there may also be other baselines that have been used in past water resource assessments, such as for the allocation of water under bulk entitlements, that are useful to retain for comparison purposes.

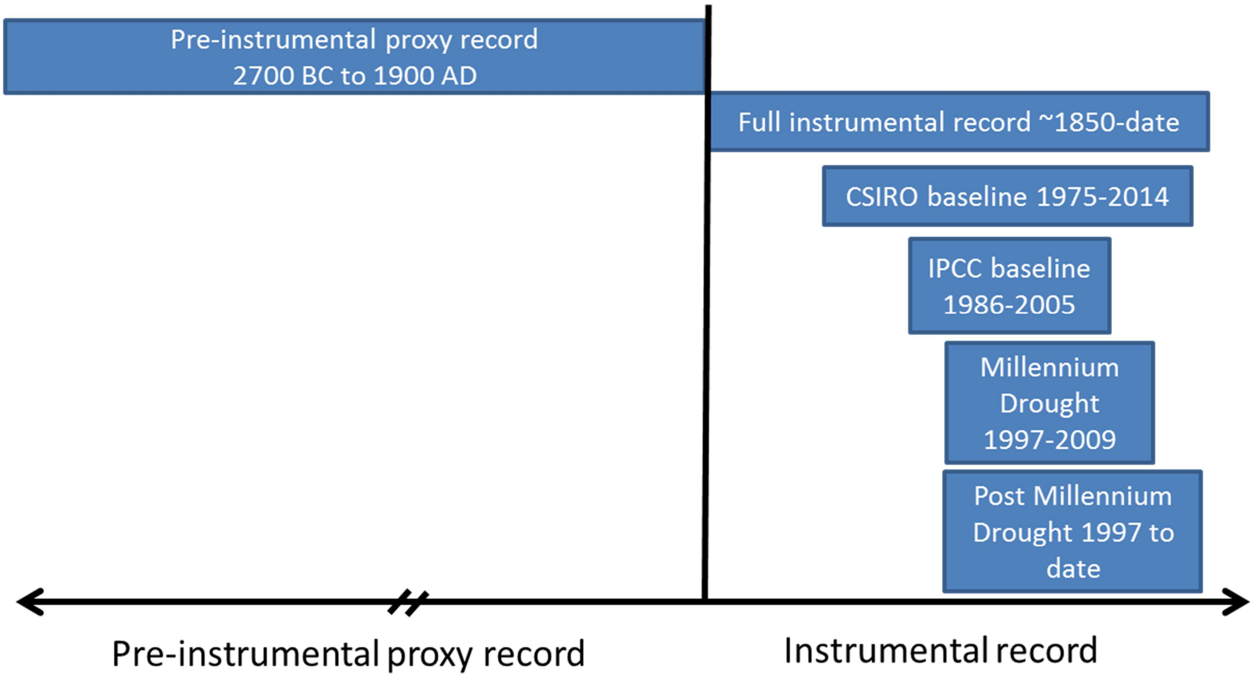
The selection of a suitable climate baseline(s) is usually a trade-off between being long enough to capture natural climate variability (droughts, floods and everything in between), but short enough to avoid the confounding effects of trends over the baseline period, such as those driven by changes in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

- Includes a wide range of natural climate variability;
- Is reasonably stationary with respect to greenhouse gas induced climate change; and
- Is preferably comparable across supply systems and water corporations.

In Victoria a long baseline is needed to capture the wide range of natural climate variability. McMahon and Mein (1986) found that very long streamflow records (100+ years) were required to estimate mean annual flow for highly variable Australian streams with low error. Long baseline periods are also needed for estimating supply system yield, as shorter periods may not capture the influential dry periods, such as the Millennium Drought. Supply system yields estimated using data collected during the Millennium Drought are markedly lower than they were based on historical data prior to the Millennium Drought.

Different estimates of water availability can arise over different baseline periods that are sampled from different phases of natural climate cycles. Verdon et al. (2004) demonstrated how rainfall and streamflow magnitudes vary across eastern Australia under both the shorter term El Niño/La Niña and longer term Inter-decadal Pacific Oscillation (IPO) climate phases. In Victoria it was shown that (i) streamflow was often more than twice as high in La Niña years compared to El Niño years, (ii) streamflow was up to twice as high in the IPO negative phase relative to the IPO positive phase, and (iii) climate variability was higher in the IPO negative phase. Selecting a baseline with a much higher proportion of La Niña years or a much higher proportion of years in the IPO negative phase is therefore expected to result in a higher estimate of supply system yield, and vice versa.

Figure 15 Climate (Rainfall) Information Availability



Another consideration is the quality of information. The quality of available information is highest in recent periods and diminishes in the earlier sections of the instrumental records. This is due to changes in the density of rainfall gauges and the degree of quality control over the data. Information from the pre-instrumental proxy record is an indicator of rainfall behaviour rather than a direct measurement.

For the purposes of undertaking climate change impact assessments, the Department recommends the use of a **current climate baseline from July 1975 to date**. "To date" refers to the most recent available historic climate information at the date of application, not the date of publication of these guidelines, and preferably will include the period up to at least June 2015. The rationale for selecting this baseline period is:

- It incorporates a wide range of natural climate variability, including the Millennium Drought, the 1982/83 drought and several relatively wet years;
- It is representative of climate behaviour at current levels of greenhouse gas concentrations (see Section 2.3.1 for more information);
- It differentiates between historic, current and future levels of global warming. Warming to date since the 1970s is significant relative to projected changes up to the first GCM time slice in the Year 2040. The change in global warming since 1970 (~0.8^{o}C) is much greater than that which occurred in the first half of the 20th century (~0.2^{o}C) and is large relative to the anticipated global warming up to the first time slice from the GCMs (~0.8^{o}C projected to occur from 2015 to 2040 after allowing for the 0.5^{o}C projected change which has already occurred since the GCM baseline period centred around 1995). Furthermore, the World Meteorological Organization (2016) identified that global warming at the year 2015 (1^{o}C above pre-industrial levels) is now half way towards the 2^{o}C target set by the world's governments for the end of the 21st century;
- It aligns (with a minor adjustment from calendar years to years beginning in July) with the baseline period adopted by CSIRO when estimating the projected changes in temperature, rainfall, potential evaporation and runoff from global climate models. CSIRO (Potter et al., 2016) argued that this 40 year period is appropriate because:
    - It is consistent with World Meteorological Organisation conventions of a 30 year baseline, 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 global climate models, 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; and
    - 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; and
- The start date is consistent with observed step changes in climate behaviour, particularly temperature (Jones, 2012).

Additional reasons for the selection of the baseline period area that it allows for a fairer comparison of available water supply across supply systems and between water corporations, as well as acknowledging the limitations of the early instrumental records.

The full (pre-1975) instrumental record remains important for water resource planning purposes for:

- Analysis of water supply system performance over an alternative baseline, both for the purposes of comparison against past water supply availability estimates and for sensitivity testing of supply system performance to baseline assumptions; and
- For deriving long-term representations of shorter reference climate periods, such as the use of flow-duration curve decile scaling or stochastic data generation to derive a long-term representation of the 1975-2015 climate baseline (see Appendix E for details).

A current climate baseline period commencing in July 1997 was also considered, in line with recent step changes in climate and streamflow, but is not recommended because it does not include the full range of single and multi-year climate variability (i.e. combinations of wet, average, dry and very dry years) that could be expected in the long-term. The post-1997 climate period has however been included as a step climate change scenario, discussed further below.

The choice of one current climate baseline in these guidelines will not preclude the use of alternative baselines. There is likely to be value in exploring the sensitivity of supply system behaviour to alternative baselines, particularly for supply systems that are considered vulnerable to climate variability and climate change. However, it is noted that the more that the alternative baseline differs from the designated current climate baseline, it is less likely that the projected climate changes will remain valid.

Where water corporations apply modelling over only the 40 year current climate baseline period (rather than a long term representation of this baseline), output performance measures relating to the frequency of drought may change relative to the output from the same measures previously applied over longer baseline periods. This is because output performance based on the frequency of drought is often driven by infrequent events, of which there are only two (1982/83 and the Millennium Drought) in the post-1975 period. Options to address this may include developing a long-term representation of the current climate baseline, which can be prepared over a period of assessment similar to that previously adopted by water corporations (so that it includes historical drought events prior to 1975), or alternatively adjusting performance measures to focus more on measures of drought duration and severity during droughts in the post-1975 period.

In cases where water corporations use a current climate baseline that differs from the period recommended in these guidelines, a hydrological comparison of the differences should be undertaken and reported. Differences in mean annual rainfall, streamflow and supply system yield for a representative supply system are suitable measures of hydrologic difference. By considering these differences, water corporations can reflect upon the implications to water availability of adopting an alternative baseline to that recommended in these guidelines.

The impact of adopting the recommended current climate baseline relative to previous estimates of supply system yield based on longer reference periods will depend on the characteristics of the supply system. Where supply system yield was previously limited by supply system performance over the Millennium Drought, supply system yield is not expected to change significantly under the new baseline.

Recommendation 1:

In response to increasing greenhouse gas concentrations and changing climatic conditions, when assessing climate change impacts on water availability it is recommended that water corporations use a 'current climate' baseline period from July 1975 to date. "To date" refers to the most recent available historic climate information at the date of application, not the date of publication of these guidelines. This does not preclude the use of alternative baselines, but in cases where alternative baselines are adopted a comparison of the hydrological differences must be undertaken and reported. Hydrologic differences include measures such as the differences in average annual rainfall, average annual streamflow and supply system yield relative to the July 1975 to date period for a representative supply system.

4.2. Selecting Climate Change Scenarios for Long-Term Planning

There is no "most likely" scenario that can be specified for future climate in Victoria. Rather, future planning needs to be built around consideration of a range of plausible climate futures. This section of the guidelines identifies a range of plausible future climate change scenarios (Section 4.2.1) and provides an approach for selecting the scenarios to be considered for long-term planning (Section 4.2.3). Guidance related to the selection of scenarios to use for shorter term planning is provided in Section 4.7.

4.2.1. Climate Change Scenarios

Four plausible future climate scenarios are considered in these guidelines. Three of these scenarios (low, medium and high climate change scenarios) were developed by CSIRO (as presented in Section 3) based on the RCP8.5 emissions scenario. The fourth scenario represents a step-change in the climate.

The low, medium and high climate change scenarios may have vastly different implications for water supply system planning, but they are still all plausible climate projections. They are all based on the same emissions scenario, and the range of results represents uncertainty in the way that complex climate processes are modelled. The modelling approach used by CSIRO utilises the latest global climate model results and utilises them to create locally relevant information in a robust manner that has been peer reviewed. Nevertheless, it may also be possible that none of the GCM-based scenarios are realised as anticipated, due to natural climate variability, significant changes to the anticipated greenhouse gas concentration pathway or unforeseeable abrupt changes in climate (e.g. modification of the ocean's circulation, climate responses to volcanic eruptions, etc.).

The three GCM based scenarios can be applied by multiplying the low, medium and high climate change projections (from Section 3.3) to local climate datasets over the current climate baseline (or long-term representation thereof).

A historical step climate change scenario is also of use for water planning in Victoria. Given (i) the low confidence in GCMs' ability to model long duration droughts (ii) the inability to replicate some of the recent seasonal changes in autumn rainfall (and the magnitude of cool season rainfall decline) (iii) the other GCM limitations previously outlined in Section 3.4 and (iv) the presence of historical step climate changes in Victoria's climate variables and their influences (see Section 2.3), it is prudent to consider other climate change scenarios informed by recent climate variability at current levels of global warming. This will be particularly important for supply systems that are deemed to be vulnerable to climate variability and climate change, or where recent trends in rainfall and streamflow reductions are more severe than GCM projections would suggest. Below average cool season rainfall has continued to be a feature of Victoria's climate, even after the end of the Millennium Drought, indicating the possibility of a more permanent shift in cool season rainfall behaviour despite recent years of above average annual rainfall. Higher summer rainfall is also a climate response anticipated by the GCMs under higher greenhouse gas emissions.

The step-change scenario recommended in these guidelines represents a permanent shift in climate similar to that experienced since July 1997 (or 1997 to date). This represents a reduction of approximately 6% in rainfall averaged across Victoria (based on the data presented in Figure 2). As the period since 1997 includes less than 20 years of data it does not include some of the multi-year variability experienced in Victoria's climate in the long-term. In order to incorporate this variability, the scenario needs to be based on a long-term representation of climate conditions from July 1997 to date. The long-term representation can be derived by adjusting the historical record using various techniques, including the flow-duration curve decile scaling method that was recommended in the 2011 guidelines, or stochastic data generation. Refer to Appendix E for more details on the application of these techniques. In most systems the long-term representation will include periods more extreme than experienced since 1997 because over the long term more extreme years can be expected than have been experienced to date. The timing and intervals between extreme events is highly uncertain.

4.2.2. Comparison of Climate Change Scenarios

The post-1997 step climate change scenario represents a drier climate change scenario that is generally drier than those anticipated by the GCMs at the Year 2040 and Year 2065 time slices.

To illustrate these differences, data from two streamflow gauges were examined from the Bureau of Meteorology's list of Hydrologic Reference Stations, plus inflows to Melbourne's four major harvesting storages. One of the hydrologic reference stations was from a relatively wet catchment in Victoria (Big River at Jamieson in the Goulburn River basin) and another from a relatively dry catchment (Wimmera River at Eversley in the Wimmera River basin). It can be seen from the results in Table 5 that in these examples, the post-1997 step climate change scenario is often (but not always) as dry as or drier than the high climate change scenario projected by the GCMs for the Year 2040, and in some cases is also drier than projected change for the year 2065. Consistent with the previous climate change guidance on step climate change (Moran and Sharples, 2011), the post-1997 climate change scenario is therefore still considered prudent to explore alongside the GCM-based climate change scenarios. This will particularly be the case where it offers the possibility of testing supply system resilience to a shift in climate that could occur earlier or is drier than that anticipated by the GCMs.

The post-1997 climate change scenario differs from the previous (and no longer recommended) "return-to-dry" climate change scenario in that it incorporates the continuation of trends in cool season rainfall after the end of the Millennium Drought, as well as increases in summer rainfall that are consistent with trends in Victoria's climate influences. It also includes streamflow data from the relatively wet years (2010/2011) immediately after 2009. As a result the step climate change scenario is milder than the "return-to-dry" climate change scenario. Further discussion on the former "return-to-dry" scenario is included in Appendix B.

Table 5 Change in Runoff under Step Climate Change Scenario Relative to GCM Projected Changes and the Millennium Drought

Indicator	Big River at Jamieson	Wimmera River at Eversley	Inflow to Melbourne's four major harvesting reservoirs
Average annual flow over current climate baseline, July 1975 to June 2015	324 GL	23.6 GL	506 GL
Average annual flow over post-1997 step climate change baseline, July 1997 to June 2015	231 GL	6.1 GL	423 GL
Average annual flow over Millennium Drought, July 1997 to June 2009	194 GL	3.2 GL	376 GL
% change in average annual flow for post-1997 step climate change (relative to current climate baseline)	-29%	-74%	-16%
% change in average annual flow for Millennium Drought (relative to current climate baseline)	-40%	-87%	-26%
Projected change in runoff from GCMs at Year 2040	-29% to +10%	-32% to +12%	-29% to +10% (Yarra) -28% to +10% (Thomson)
Projected change in runoff from GCMs at Year 2065	-42% to +1%	-53% to +12%	-44% to +1% (Yarra) -42% to +2% (Thomson)

4.2.3. Approach for Selecting Climate Change Scenarios for Long-Term Planning

When assessing climate change impacts on water availability for long-term planning purposes, a vulnerability based approach should be used to select the appropriate climate change scenarios. This approach to climate change scenario selection is based on the degree of sensitivity to climate variability and climate change and the associated vulnerability of the supply system. Using this approach the number of climate change scenarios considered increases for water supply systems with increased climate change vulnerability and is minimised for those of low vulnerability.

The recommended approach to select climate change scenarios is consistent with other climate change guidelines used in Australia. The Water Services Association of Australia (WSAA) Climate Change Adaption Guidelines (WSAA, 2016) adopt a similar risk management approach to managing climate change, as do Engineers Australia in their climate change guidance for design flood estimation in Australian Rainfall and Runoff (Bates et al., 2015).

The process to select climate change scenarios involves several steps to assess water supply availability and associated water supply system vulnerability.

1. **Assess water availability under the current climate baseline** –water availability under the current climate baseline must be assessed for all water supply systems. Guidance on the selection of the baseline is set out in Section 4.1.
2. **Undertake qualitative assessment of vulnerability** – assess if the water supply system is able to cope with the adverse effects of climate change by considering:
   - The relative supply contribution from climate resilient and climate dependent sources;
   - The supply and demand imbalance under the current climate;
   - Supply system performance over the Millennium drought relative to minimum storage, streamflow or aquifer operating levels, and any associated level of service objectives; and,
   - A preliminary assessment of the likely impact of the high climate change scenario, which need not necessarily involve water resource modelling.

Further modelling may not be required if this assessment shows that the water supply system is not considered to be vulnerable to climate change and variability over the 50 year planning horizon.

3. **Undertake quantitative assessment of vulnerability** – for all supply systems qualitatively assessed as potentially vulnerable to climate change and climate variability over the 50 year planning horizon, apply water resource models to quantitatively assess water supply system performance under a range of climate change scenarios.

    a. **Model the step climate change and dry climate change scenario and assess vulnerability** – if this assessment identifies that there is enough supply to meet demand under these drier scenarios over the 50 year planning horizon, then no further climate change scenarios need to be modelled.

    If this assessment identifies that action is required;

    b. **Model the low and medium climate change scenarios to identify the range of timing of actions** – The range of timing of action will be defined by the earliest and latest year at which supply is no longer able to meet projected demands from the four climate change scenarios considered.

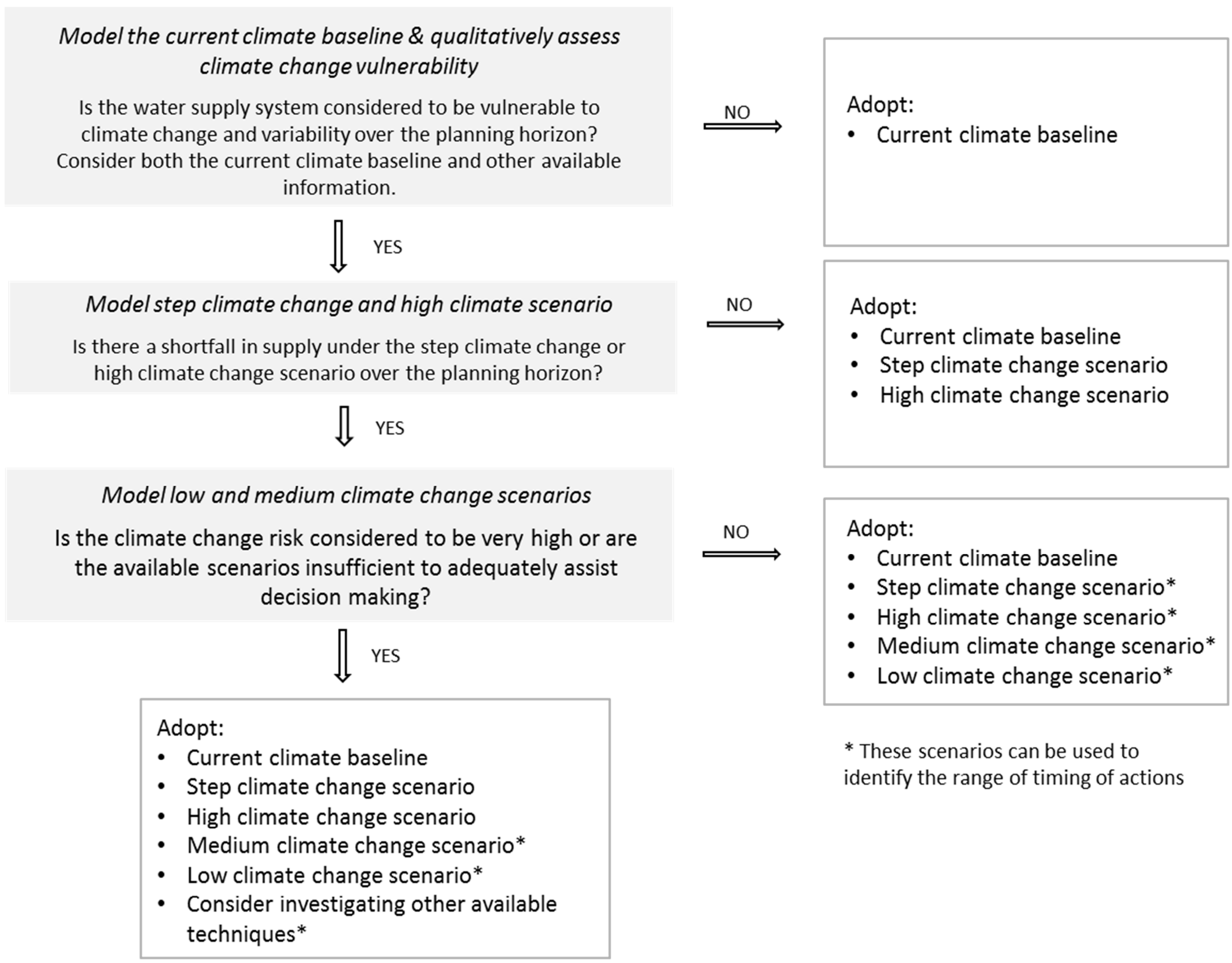
4. **Optional further assessments of vulnerability** – more complex analysis techniques can be applied in addition to the above scenarios if climate change risk is considered very high and/or if the above scenarios do not provide sufficient information to adequately assist decision making. In these instances, climate analogues and/or paleoclimate reconstructions can be used to further assist decision making.

In addition to vulnerability, the subsequent risk to supply systems should also take into account the consequences of poor supply system performance and the availability and cost of short-term contingency supply measures to mitigate that risk. Where vulnerability is high but mitigated consequences are low, then there may be some justification for limiting the extent of climate change analysis. Similarly where vulnerability is low but consequences are high, it may be prudent to consider a broader range of scenarios.

The process of scenario selection and assessment is shown diagrammatically in Figure 16.

Where climate change scenario assessments are not being undertaken for the purpose of balancing supply and demand, the scenarios selected for assessment will need to be determined based on what is considered to be the most appropriate for the particular circumstance. It is expected in most cases a similar sequence of scenario assessment to that described above would be appropriate.

Figure 16 Process to select climate change scenarios



Recommendation 2:

Water corporations must assess the impact of climate change when developing long-term projections of water availability. When assessing climate change impacts on water availability for long-term planning purposes, climate change scenarios should be selected based on supply system vulnerability to climate change and climate variability.

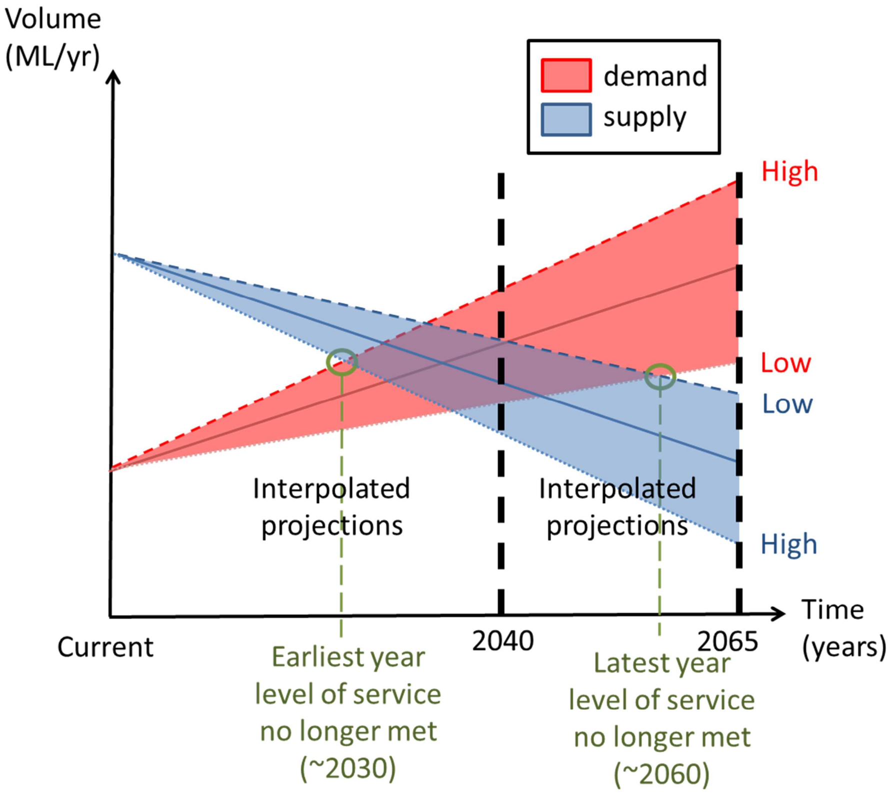
- For supply systems with very low vulnerability under the current climate baseline (e.g. with climate independent sources of water or resources significantly in excess of requirements during drought): a preliminary assessment of climate change impact should be undertaken, which may not necessarily include water resource modelling

- For all other supply systems: Model supply system vulnerability under the high GCM scenario and the post-1997 step–change scenario. Where these scenarios indicate that the supply system is vulnerable to climate change, the medium and low climate change scenarios should also be modelled to assess the full range of timing for action.

4.3. Interpolating Between GCM Time Slices

For the GCM based climate change scenarios, GCM outputs are extracted for three time slices, namely year 1995, which is representative of current conditions, and the future time slices of Year 2040 and Year 2065. The current time slice is considered to be representative of climate over the longer 40 year climate baseline from July 1975 to June 2015, consistent with the recommendations by CSIRO in Potter et al. (2015). For long-term planning, water corporations have traditionally linearly interpolated between each time slice to infer the likely timing of a supply enhancement or demand reduction option to the nearest year, as shown in Figure 17.

Figure 17 Illustrative supply-demand projection as presented in the 2011 WSDSs



Such an approach potentially implies that climate change will occur gradually over time, which as discussed previously in Section 2.3, is not likely to be the case with respect to air surface temperature, rainfall, recharge and runoff.

It is therefore important that the timing of supply enhancement or demand reduction options that are triggered by future climate change are not presented as being overly precise. This is partly expressed in the range of years over which level of service objectives would no longer be met without intervention (shown in Figure 17 as being an approximately 30 year window between 2030 and 2060). However it still needs to be remembered that:

- There are GCMs (10% of models) that anticipate conditions that are drier than the "dry climate change" scenario;
- Climate change can occur as a step change at any time; and
- Natural climate variability can create natural events at any time that are more severe than those anticipated by the GCMs.

Due to these factors, the trajectory of change between GCM time slices will not necessarily be linear. However, in the absence of knowledge about the precise annual timing of climate change, a linear interpolation is still a reasonable approximation of the future climate change trajectory for long-term planning.

Recommendation 3:

Where planning processes require assessments of impact each year over the fifty year time horizon, linear interpolation between the current, Year 2040 and Year 2065 time slices is suggested as being a reasonable approximation, noting that the projected climate change impact could occur earlier or later than anticipated by this interpolation.

4.4. Spatial Resolution of GCM Projections

Projected changes in hydro-climate variables are provided for each Victorian river basin. They are considered to be appropriate for use at this scale for future water supply planning purposes in most Victorian water supply systems. The use of finer scale information may imply false precision in its accuracy, as indicated in the Victorian Climate Initiative Annual Report from 2014/15, which concludes that (Hope et al., 2015):

> *"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."*

In a few water supply systems this spatial resolution of the adjustment factors may be too coarse. For example, during the Millennium Drought, runoff in the Grampians was found to be more resilient than runoff in the nearby Pyrenees. To reflect this variability Grampians Wimmera Mallee Water directed research to estimate projected changes in runoff for local catchments (Sachindra et al., 2014a).

The generation and use of projected changes in hydro-climate variables at a finer spatial scale may be justified if:

a) The projected changes are expected to vary across the region in a manner that is consistent with either observed catchment response (such as during the Millennium Drought) or the expected changes in climate influences in the region (see maps in Appendix C); and,
b) The change relates to key points in the water supply system, such as the location of water harvesting infrastructure.

Further guidance on how climate change adjustment factors can be generated for regions other than river basins is provided in Appendix C.

Recommendation 4:

GCM based projections at river basin scale are considered suitable for most water planning applications.

Finer spatial scale information can also be used where justified.

4.5. Temporal Resolution of GCM Projections

There is a clear need to derive daily and seasonal climate change information for Victoria's water corporations. This was expressed by water corporations during consultation for the development of the guidelines. It is reflected in current water resource modelling applications that use historical daily time step data, and was also put forward as a research priority in the Victorian Climate Initiative (VicCI) Science Plan (VicCI, 2016). Particular applications include the assessment of within-year drought severity and duration, rainwater tank and stormwater harvesting scheme design and assessment, managed aquifer recharge scheme design and assessment, and environmental flow studies, amongst others. All of these applications currently take advantage of daily or seasonal (monthly) time step information, when available, when assessing historical performance.

In deriving the annual projections reported in Section 3, CSIRO estimated daily rainfall empirical scaling factors. These scaling factors may be appropriate for assessing the impact of climate change on a daily time step where changes in daily rainfall intensity are the dominant influence on water planning outcomes. However existing alternative information sources from Engineers Australia (discussed below) are more easily applied in that circumstance. Where within-year drought duration is important, the daily rainfall empirical scaling factors are not considered appropriate to use because the GCMs do not reliably model changes in the number of rain days. Where seasonal changes in rainfall are important, the use of the seasonal rainfall empirical scaling factors will improve the estimation of cool season runoff compared to using annual scaling factors. However it has the potential to provide misleading indications of the nature and magnitude of anticipated changes in rainfall behaviour under climate change in some seasons, as previously discussed in Section 3.4. It should also be noted that adoption of the current climate baseline already contains a changed seasonal signal, which may give a more realistic projection of conditions at least over the next few decades than using the seasonal signals from GCMs. Therefore if used, seasonal rainfall empirical scaling factors would need to be applied with caution and in conjunction with other techniques (discussed subsequently) that provide an alternative estimate of changes in seasonal rainfall conditions under climate change. Seasonal rainfall empirical scaling factors are available in the outputs from Potter et al. 2016.

When within-year climate change information is translated into rainfall-runoff or groundwater models to generate changes in streamflow and recharge, any uncertainties in daily rainfall estimation under climate change are amplified. This is reflected in the wide range of uncertainty associated with the runoff projections in Potter et al. (2016), even after removing the influence of the global climate models that generate the driest 10% and wettest 10% of simulated changes.

Where supply system performance is considered sensitive to within-year (daily and seasonal) climate change, the use of annual projected changes in hydro-climate variables may be insufficient to adequately assess the vulnerability of a supply system to climate change. Vulnerability can be informed in the same manner as previously outlined in Section 4.2, but with a greater emphasis on historical supply system performance in individual seasons and the outcomes presented in the Statewide overview of seasonal climate changes in Section 4.5.2 below. Sensitivity to within-year climate change can result in either an increase or a decrease in vulnerability. For example, increased summer rainfall or increased daily rainfall intensity for very intense rainfall events may be significant in reducing vulnerability for some supply systems (e.g. for stormwater harvesting schemes). A suggested approach to considering within-year climate change for each supply system is as follows:

1. For supply systems which are considered to be of low vulnerability at a sub-annual scale, either:
    a. do not consider daily and seasonal changes in climate behaviour and water resource availability, and focus on annual changes; and/or
    b. utilise the Statewide summary of descriptive changes to within-year climate and water resource availability, combined with recent historical changes in climate at a representative

location within the water corporation's area to make general observations locally, as outlined in Section 4.5.2 below;

2. For supply systems which are considered to be of moderate to high vulnerability at a sub-annual scale, consider whether the supply system is sensitive or vulnerable to within-year changes in climate during very wet conditions only, during very dry conditions only, or across the full range of climate conditions;
    a. For supply systems only sensitive to changes during very wet conditions, utilise Australian Rainfall and Runoff guidance for changes to rainfall intensity above the 50% annual exceedance probability event (1 in 2 year average recurrence interval). A practical example of using the Australian Rainfall and Runoff guidance is presented in Section 4.5.1;
    b. For supply systems only sensitive to changes during very dry conditions or for supply systems sensitive to changes across the full range of climate conditions, adopt one or more techniques to inform potential within-year supply system response. There is likely to be a high degree of uncertainty in climate information generated from this range of techniques. Suitable techniques in order of broad ease of analysis:
        i. flow duration curve decile scaling of historic data (see Appendix E);
        ii. quantitative use of climate analogues (see Appendix F); and
        iii. stochastic modelling based on historic data (see Appendix E).
    c. When preparing a long-term representation of the post-1997 step climate change scenario, apply the flow-duration curve decile scaling method to each season of the year, rather than just to annual data.

4.5.1. Adjustments to GCM Projections for Changes in Rainfall Intensity

Where individual supply sources are sensitive to changes in infrequent but high intensity rainfall events, apply the Australian Rainfall and Runoff Guidance (Book 1, Chapter 6, Bates et al. 2015) of a 5% increase in daily rainfall intensity per degree of local warming for rainfall with an annual exceedance probability of 50% to 1%. This adjustment for intense rainfall events can be accompanied by a comparable reduction in rainfall on all other days when undertaking time series modeling. However in practice, due to the infrequent adjustment made to the more intense rainfall events, this comparable reduction will be close to zero and can be ignored for water planning applications. Daily rainfalls with an annual exceedance probability of 50% to 1% can be generated for a 24-168 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/).

For a representative example in north east Victoria (latitude -37.23 degrees and longitude 145.91 degrees), the intensity of a rainfall event of 24 hours duration is 51.8 mm/d for a 50% annual exceedance probability (AEP) and 124.4 mm/d for a 1% AEP event. For time series analysis, any daily rainfall between 51.8 mm/d and 124.4 mm/d would be increased by 5% per degree of warming. For 1.3^{o}C of warming by Year 2040 for the RCP8.5 emissions scenario, these daily rainfalls would be increased by 6.5%. Increasing these relatively intense daily rainfalls was found to increase the average daily rainfall by 0.2%. Applying adjustments to longer duration events up to 168 hours was found to increase the average daily rainfall by 0.4%, so a corresponding reduction of 0.4% could be applied to all rainfalls outside of the 50%-1% AEP values so as to match the average daily rainfall over the baseline period. Similar very minor changes in rainfall events below the 50% AEP would be equally expected in other parts of the State.

The above guidance allows changes in runoff under more intense rainfall events due to climate change to be estimated using rainfall-runoff models. For catchments where a rainfall-runoff model does not exist, tools or techniques to rapidly scale streamflows with exceedance probabilities from the 50%-1% AEP do not currently exist. The possibility of developing scaling factors that are directly applicable to streamflows within this AEP range has been discussed with CSIRO, and has been identified as an area for potential investigation.

For applications in environmental water planning and delivery, the recommended changes to the 50%-1% AEP rainfall events are unlikely to impact upon water availability for the environment in most catchments. This is because within bank events (e.g. summer freshes, winter freshes and bankfull events) are likely to be generated from rainfalls with an annual exceedance probability of more than 50%, which are not expected to increase under climate change. Lower likelihood rainfall events that generate overbank flows may however increase in magnitude under climate change, however the ability to influence these events through water management activities is generally very limited.

4.5.2. Statewide Overview of Seasonal Climate Changes

Two sources of information are presented below to better understand anticipated seasonal changes in climate under future climate change. These are an overview of the GCM outputs for individual seasons and 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 3.4. Recent historical changes in seasonal climate will be their most relevant for short to medium-term projections, whilst GCM outputs are more relevant for long-term projections.

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, whilst 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 changes in individual seasons for the medium and high climate change scenarios, but less so for the low climate change scenario, where there was also less model agreement on seasonal changes. Relative to the projected annual changes in rainfall in Table 2 for the Year 2040 time slice and relative to the current climate baseline:

- The spread of GCM model 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 current climate baseline in river basins across Victoria) is estimated to be much wetter in summer (8-21% wetter than the current climate baseline) and autumn (8-23% wetter than the current climate baseline). 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 current climate baseline in river basins across Victoria) is estimated to be drier in spring (11% to 3% drier than the current climate baseline), roughly the same in winter, and slightly wetter or drier in summer (-6% to +4% change relative to the current climate baseline) and autumn (-4% to +3% change relative to the current climate baseline);
- The projected high climate change scenario (which on an annual basis ranges from 18% to 8% drier than the current climate baseline 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 current climate baseline); and
- 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.

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 current climate baseline (1975 to date), the post-1997 step climate change baseline (1997 to date), and the instrumental record prior to the start of the current climate baseline (start of record to 1975). Variables which 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:

- Autumn rainfall over the current climate baseline (1975 to date) is on average 19% lower than over the period from 1902-1975, whilst winter/spring rainfall is roughly the same and summer rainfall was approximately 6% higher.
- In the post-1997 period, summer rainfall has remained above the 1902-1975 average, but autumn (-29%), winter (-10%) and spring (-11%) all show declines.

This provides a guide to potential seasonal changes in rainfall at this particular 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. Drawing conclusions about historical seasonal changes from streamflow and groundwater level data can however be confounded by historical water and land use changes. The use of the Bureau of Meteorology's Hydrologic Reference Stations (http://www.bom.gov.au/water/hrs/) minimises the potential for these other factors to influence historical trends driven by climate.

Recommendation 5:

Given that GCM projections generally provide within-year (seasonal and daily) climate change information with only a low degree of confidence, for those supply systems that are sensitive to within-year changes in climate, a range of different approaches are suggested depending on the vulnerability of the system. These include characterising recent historical shifts in seasonal climate behaviour and utilising broad-scale changes in seasonal behaviour and rainfall intensity from the GCMs. Other, more complex, analytical procedures are also available.

4.6. Groundwater

Groundwater is supplied to over 70 towns located throughout Victoria, and is an essential water source for irrigation, commercial and domestic and stock use. Larger users, such as urban water corporations typically extract from the deeper confined aquifers. Irrigation and stock and domestic use is typically extracted from unconfined aquifers which are shallower (less than 25m deep) and generally cheaper to extract from.

To assess the potential impact of climate change on groundwater availability two things need to be considered:

- The response of groundwater resources to climate change, and particularly recharge; and
- Increased use of shared groundwater resources from other users during periods of water scarcity, and the management arrangements of groundwater resources during these times.

4.6.1. How does groundwater respond to changes in climate?

Groundwater recharge is dependent on rainfall, and comes from water draining from the surface or from rivers through the soil profile down to the water table. Recharge is also highly dependent on soil type and land use which can either increase or decrease the rate of recharge to the watertable. In unconfined systems the changes in rainfall can be seen in the watertable response albeit with a time lag.

Barron et al. (2010) noted that “the change in the frequency and seasonality of rainfall may influence changes in recharge” and that it is this sensitivity to rainfall that makes it difficult to predict recharge or its alteration based on altered climates. Recharge is a ‘threshold’ process with minimum amount of rainfall required to generate any recharge. It will also be significantly influenced by changes to the number and seasonality of higher rainfall events which could increase recharge in some instances (Crosbie et al., 2010; Crosbie et al., 2012).

Recharge typically occurs during winter and spring rainfalls when the soil profile is wetter. Changes to the seasonality of the rainfall so that larger events occur in summer may significantly reduce recharge due to the soil profile being dry at that time of year. Larger storm events at other times of the year could potentially increase the recharge if the soil profile is already wet from previous rainfall events.

An empirical relationship between rainfall and recharge has been used previously to estimate changes in recharge based on changes in annual rainfall. This relationship is described in Petheram (2002), and was used as a basis to predict changes in recharge in the 2011 WSDS guidelines (Moran and Sharples, 2011).

In confined systems recharge occurs through leakage between aquifers and from water draining to the aquifer in outcropping areas. Generally, current changes to climate are not seen in the aquifer response in confined aquifers either due to the very long lag times between rainfall and recharge or due to the impacts of altered rainfall on recharge being too small to notice.

4.6.2. Methodology to assess groundwater responses to changes in climate.

Groundwater recharge processes differ for confined and unconfined systems. Hence the recommended method of assessment also differs for these aquifer types.

For Shallow (< 20m deep) Unconfined Aquifers (i.e. aquifers where the depth to water is less than 20m below surface):

- In areas where groundwater has a high level of connection to surface waters (and rainfall) the factors applied to runoff is a good approximation of the factors to be applied to reflect changes to groundwater recharge (see Table 3). This will apply to the highlands and upland valleys where the aquifer thickness is a maximum of 10m above bedrock;
- For regional unconfined aquifers in the sedimentary basins the approach is to factor the groundwater volume required down by a percentage (%) of recharge, as determined by Petheram (2002) for each of the 3 climate scenarios (low, medium, high) (see Table 6).

For Confined Aquifers and Deep (> 20m deep) Unconfined Aquifers: Confined aquifers and deep unconfined aquifers do not respond to changes in climate over the management timeframes that are being considered in these guidelines.

Recommendation 6:

Confined aquifer systems generally respond very slowly or very little to changes in climate. It is unlikely that any changes would be seen within the current 50 year planning horizon of existing water strategies, and hence are not considered further in these guidelines.

Shallow unconfined aquifers can respond quickly (e.g. within 1-2 years) to changes in climate. For shallow unconfined aquifers in highland areas with a high level of connection to rainfall and surface waters, projected changes to runoff equally apply to recharge. For other shallow unconfined aquifers (e.g. in the sedimentary basins), assessments of changes in availability should be based on the recharge change factors presented in these guidelines.

Table 6 Projected change in recharge for regional unconfined aquifers in the sedimentary basins

River basin	Average annual rainfall (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
	Historic	Low	Medium	High	Low	Medium	High
East Gippsland	941	14.8%	-2.4%	-31.6%	16.8%	-3.0%	-48.0%
Snowy	813	16.1%	-3.3%	-30.3%	17.8%	-11.8%	-47.7%
Tambo	786	12.9%	-6.5%	-31.5%	15.2%	-11.7%	-55.1%
Mitchell	953	9.7%	-5.7%	-27.8%	5.4%	-12.7%	-63.8%
Thomson	859	9.2%	-5.0%	-31.1%	5.3%	-10.6%	-70.9%
Latrobe	919	7.5%	-10.3%	-33.9%	5.1%	-11.6%	-55.5%
South Gippsland	872	5.9%	-11.7%	-35.1%	5.1%	-11.6%	-51.9%
Bunyip	860	6.7%	-10.2%	-32.2%	4.9%	-13.1%	-52.8%
Yarra	961	8.3%	-6.9%	-30.8%	5.6%	-11.2%	-74.2%
Maribyrnong	675	6.2%	-6.0%	-36.1%	6.0%	-14.5%	-80.0%
Werribee	619	5.2%	-6.8%	-34.9%	5.6%	-16.8%	-78.8%
Moorabool	596	4.6%	-8.7%	-34.5%	3.5%	-15.7%	-78.8%
Barwon	650	4.6%	-7.7%	-34.2%	2.9%	-13.9%	-68.9%
Lake Corangamite	629	4.7%	-10.1%	-34.4%	-0.4%	-13.9%	-66.8%
Otway Coast	950	4.9%	-9.2%	-34.9%	1.2%	-15.4%	-66.4%
Hopkins	634	4.9%	-11.4%	-34.7%	2.4%	-15.3%	-75.8%
Portland Coast	724	6.1%	-11.9%	-32.0%	-0.5%	-23.6%	-66.0%
Glenelg	655	2.8%	-13.2%	-38.9%	3.4%	-23.5%	-80.5%
Millicent	533	2.9%	-14.6%	-47.9%	2.6%	-23.9%	-87.2%
Upper Murray	1,053	16.0%	-1.6%	-23.8%	17.4%	-6.4%	-45.4%
Kiewa	1,143	12.1%	-6.3%	-27.1%	8.9%	-5.2%	-52.3%
Ovens	962	11.7%	-8.7%	-27.1%	8.6%	-9.4%	-59.2%
Broken	573	13.0%	-9.4%	-44.5%	14.6%	-8.9%	-62.6%
Goulburn	767	8.8%	-6.4%	-42.3%	5.5%	-10.4%	-75.1%
Campaspe	596	5.5%	-5.5%	-48.6%	6.0%	-16.4%	-88.8%
Loddon	459	5.8%	-7.2%	-45.0%	7.2%	-15.0%	-87.4%
Avoca	358	10.7%	-9.8%	-50.1%	14.8%	-8.8%	-74.6%
Lower Murray	394	15.5%	-9.8%	-48.1%	18.9%	-5.8%	-66.8%
Mallee	306	10.5%	-14.1%	-60.5%	14.9%	-17.6%	-91.4%
Wimmera	394	4.6%	-9.5%	-41.0%	8.8%	-15.7%	-84.0%
Victorian river basins	n/a	-60.5 to +16.1%			-91.4 to +18.9%		

4.7. Climate Change for Drought and Operational Planning Scenarios

If recent climate change includes abrupt steps, as suggested by Jones (2012), then a step climate change scenario is potentially relevant to both short and long-term planning. Jones (2010) also argues that a climate change adaptation strategy at a local scale (such as for a water supply system) should be based on monitoring and responding to changes in local behaviour in real-time, rather than relying primarily on periodic updates of GCM scenarios at future time slices. The view expressed by Jones (2010) places a very high emphasis on short-term planning instruments and processes (for example, the water security outlook, drought response plans and major operational planning decisions) for climate change adaptation, rather than just as tools for managing climate variability.

The purpose of these guidelines is not to replace existing guidance on the preparation of Drought Response Plans (DNRE, 1998), but rather to provide general advice on the manner in which climate change can be incorporated into drought and operational planning scenarios.

Drought and operational planning scenarios for water resource planning typically have a planning horizon of several months up to around five years, depending on the nature of the supply system. For reasons of consistency with long-term planning scenarios, climate and streamflow information adopted for drought and operational planning should be selected from the current climate baseline (July 1975 to date) or the long-term representation thereof. This ensures that drought and operational planning scenarios are using information which is representative of current climate conditions under current levels of greenhouse gas concentrations.

One area of uncertainty is whether historical droughts from the historic climate baseline should be factored using the projected changes in runoff from the global climate models, for the purposes of drought and operational planning scenarios. We know from the recent climate behaviour, global climate model behaviour and information from pre-instrumental proxy record that it is possible that:

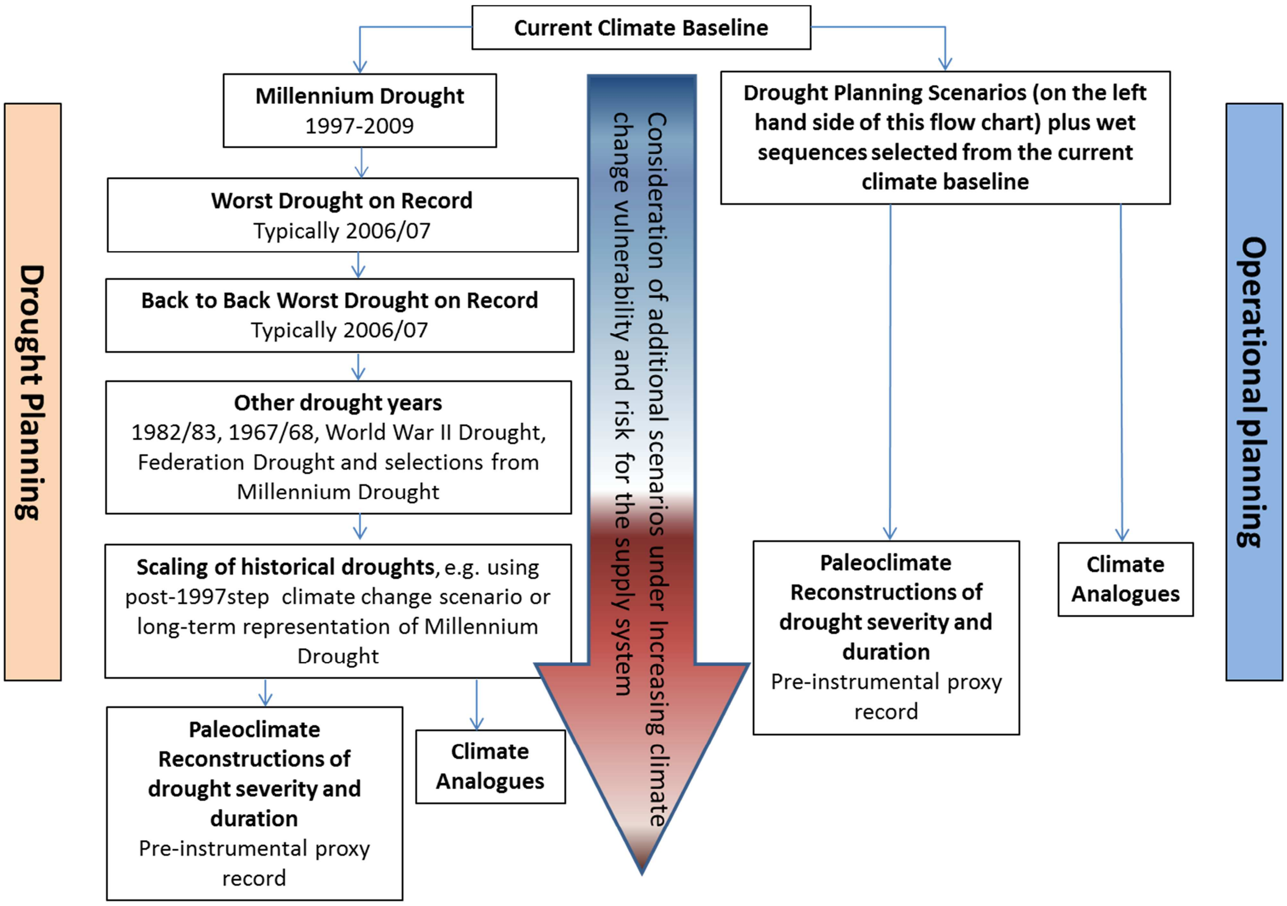
- Projected climate change can occur earlier than the first time slice (the Year 2040 time slice starts in 2031) from the GCMs;
- Projected climate change can occur as an abrupt step change at any time from the current year; and
- Considerably greater climate variability can occur than that witnessed over the instrumental record.

It is therefore prudent to consider the possibility of a drought occurring over the short to medium term which is more severe (in terms of magnitude of the rainfall deficit and/or its duration) than that which has occurred historically, irrespective of whether this is driven by increased greenhouse gas concentrations or natural climate variability.

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 GCMs anticipate a drought duration near to or longer than the Millennium Drought (Hope et al., 2015). If the GCMs do not replicate extreme drought events, then any projected changes derived from the GCMs and applied to historical drought events like the Millennium Drought, would only be applied with a low degree of confidence. For short to medium term planning activities, where the incremental change in greenhouse gas concentrations is relatively small, it is difficult to justify using the GCM outputs to scale historical drought events given low confidence in this aspect of GCM behaviour. This is in contrast to longer term planning out to the Year 2040 time slice and the Year 2065 time slice, where the climate change signal becomes a more dominant factor and the scaling of historical droughts using GCM outputs becomes more justifiable.

When considering climate change for short to medium term planning, including operational planning, a higher degree of confidence can be placed in the alternative technique of adjusting historical droughts based on sampling (with or without replacement) from the historical record, as is currently adopted by the 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. For this reason it is recommended that for drought and operational planning, information from the current climate baseline should be selected and rearranged to create potential drought events of lower likelihood than the Millennium Drought, similar to what water corporations are already doing, rather than scaling past drought events within the current climate baseline using GCM outputs. This does not exclude the use of scaled historical drought events, such as a long-term representation of the Millennium Drought or the non-GCM based, post-1997 step climate change scenario, which is a potential realisation of climate change in the short to medium-term.

Figure 18 Drought and operational planning baselines and scenarios consistent with the climate change guidance



There may be exceptions to this 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 of historical drought events, including the Millennium Drought, is considered appropriate as long as the higher degree of uncertainty in this process is acknowledged.

Recommendation 7:

For drought and operational planning scenarios, recent climate is considered to be a better approximation of likely future conditions than GCM projections. Drought and operational planning scenarios should therefore be drawn from the current climate baseline, consistent with the baseline used for long-term planning scenarios. For most of these short-term planning applications, sampling from this baseline to create droughts more extreme than those observed historically (as is currently the practice by some water corporations)may provide further climate resiliency and is considered preferable to the scaling of historical droughts based on GCM outputs used in long-term planning applications.

4.8. Climate Change Projections for Alternative Water Supply Projects

The approaches presented earlier in the guidelines are equally applicable to alternative water supply projects. Specific advice is provided in this section for alternative water sources, impacts and demands.

Integrated urban water management seeks to manage the whole urban water cycle so as to improve reliability of supply for potable and non-potable uses, but also to achieve a range of other benefits associated with supplying or retaining water within the urban landscape. These include the reduction of downstream water quality impacts from urbanisation, the reduction of downstream flooding impacts from urbanisation, reduced urban heat island effect and more green space. Integrated urban water management recognizes the potential value of all water sources within urban areas, including rainwater, stormwater and recycled wastewater.

Climate change has the potential to impact upon these alternative water supplies to varying degrees. Relative to traditional potable water supply sources, alternative water supply projects can involve much smaller scale supply sources. However, for climate change impact assessment, the scale of the water source is less important than its climate resilience, which is independent of scale.

Climate change also has the potential to alter the relative supply contribution from alternative water sources, depending on the location and nature of existing supply sources. Climate resilient sources, such as desalination and recycled water, potentially have a greater role to play in maintaining potable and non-potable urban water supply under climate change. Stormwater may also have a larger role to play in augmenting supplies and in improving liveability outcomes of healthy urban landscapes.

A summary of the urban water management guidance on climate change for each supply source or impact is listed in Table 7. This guidance is consistent with that presented elsewhere in these guidelines, including the limitations of GCMs in projecting the magnitude of changes to daily rainfall intensity (see Section 3.4 and Section 4.5).

It is recognized that some alternative water supply options will be sensitive to seasonal and daily changes in rainfall under climate change. For example, changes to the number of rain days or changes in the frequency and intensity of summer storms could impact upon the reliability of supply from rainwater tanks or stormwater harvesting schemes, as well as affecting estimates of their downstream flood reduction and water quality treatment benefits. However, as discussed previously in the guidelines, there is currently insufficient confidence in projected seasonal and daily changes to rainfall under climate change to provide more precise guidance on these changes. Attempting to incorporate them at the current time is likely to imply a degree of false precision. For this reason, when utilizing the global climate model scenarios, only the average annual projected changes in rainfall and the advice previously provided in Australian Rainfall and Runoff (Bates et al. 2015) are recommended for use, noting that in some cases alternative supply systems may be relatively insensitive to changes in daily scale rainfall intensity. Use of the statewide guidance on within-year climate change (Section 4.5.2) in a qualitative sense, and seasonal adjustments within a long-term representation of the post-1997 climate change scenario, is nevertheless encouraged.

As is the case for some of the other types of supplies and demands discussed in these guidelines, the impact of climate change on some of alternative supply projects may be small relative to other factors including infrastructure design.

Table 7 Integrated Urban Water Management Guidance on Climate Change

Alternative water supply source, impact or demand	Climate change guidance
Source: Rainwater, Stormwater	Utilise the anticipated changes in annual rainfall and potential evapotranspiration (Section 3.3), and the anticipated changes in intense rainfall events (Section 4.5.1) presented in these guidelines
Source: Groundwater	Utilise the anticipated changes in groundwater availability by aquifer type (Section 4.6.2) presented in these guidelines
Source: Aquifer storage and recovery	Utilise the anticipated changes in annual rainfall (or runoff) and potential evapotranspiration (Section 3.3), and the anticipated changes in intense rainfall events (Section 4.5.1) presented in these guidelines
Source: Recycled wastewater	Climate resilient – no adjustment required unless reduced sewer infiltration rates are anticipated or changes to treatment processes during heatwaves are expected to affect throughput
Source: Greywater	Climate resilient – no adjustment required
Impact: Downstream flooding	Utilise the anticipated changes in intense rainfall events (Section 4.5.1) presented in these guidelines
Impact: Downstream water quality	Utilise the anticipated changes in annual rainfall and runoff (Section 3.3), and (if relevant) the anticipated changes in intense rainfall events (Section 4.5.1) presented in these guidelines as an input to assessing changes in water quality
Impact: Urban heat island effect	Utilise the anticipated changes in annual temperature and potential evapotranspiration (Section 3.3) presented in these guidelines
Demands	Utilise the anticipated changes in annual rainfall, potential evaporation and/or temperature (Section 3.3) presented in these guidelines, for use within climate dependent demand models

4.8.1. Achieving consistency in climate change guidance for different scale water supply options

The advice presented elsewhere in these guidelines for assessing the impacts of climate change on water supply options is considered applicable to both large scale and neighborhood or lot scale water supply options.

For the global climate model scenarios, the projected changes in annual rainfall, recharge, runoff, temperature and potential evaporation can be applied to all supply sources and demands, and for the estimation of climate related costs and benefits. The adoption of the current climate baseline (e.g. July 1975 to date) for all water cycle components at all scales promotes consistency between different supply options. If representative climate years are adopted for analysis of small scale options instead of continuous time series analysis, then those representative years can be selected from the same current climate baseline adopted for time series analysis of larger supply schemes.

For the long-term representation of the post-1997 step climate change scenario, all rainfall, recharge, runoff, temperature and potential evaporation information should be scaled in a consistent manner using the flow-duration curve scaling technique (or stochastic data generation) described in Appendix E, regardless of the supply source size.

This advice does not preclude the use of alternative techniques, such as the use of alternative climate baselines, the use of climate analogues, etc., to further explore climate change impacts for individual water sources deemed more vulnerable to climate change.

Recommendation 8:

The advice contained in these guidelines is considered suitable for assessing the impacts of climate change on water supply options for alternative water supply projects at a range of spatial scales. A range of approaches are described, but these do not preclude the use of alternative techniques.

4.9. Impact of Climate Change on Demand

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. Adapting to the changing climate while seeking to improve liveability outcomes may also impact on water demands.

Water corporations have existing climate dependent demand models for 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.

The median potential evapotranspiration and temperature projections provided in Table 1 can be applied to model climate change impact on demand. In the supply-demand balance, for the large majority of water supply systems, projected changes in rainfall and runoff will dominate the nature of that supply-demand balance and a range of climate change scenarios should be considered. 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 and it is sufficient to consider one climate change scenario.

Where a water corporation considers that GCM uncertainty in temperature or potential evapotranspiration projections is likely to significantly impact the supply-demand balance (or any other water resource modelling process involving two or more climate parameters), the uncertainty in temperature and potential evapotranspiration from the GCMs associated with the low, medium and high runoff scenarios are provided in Appendix A, and can be utilised for that purpose if desired.

The temperature increases provided in Table 1 should be added to the local climate datasets. The temperature projections are for the average daily temperature, but may also be applied to the maximum daily temperature as the projections are consistent between these two variables.

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.

Areas of uncertainty include the estimation of future major industrial and commercial demands, which may or may not be climate dependent. 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 other customer groups.

Changes in peak demands can also occur under climate change, which are associated with increases in temperature on very hot days. 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, however these are often difficult to predict but may be very important to consider when developing future demand projections.

Recommendation 9:

Where water corporations have climate dependent demand models, the median potential evapotranspiration and temperature projections provided in these guidelines can be applied to model climate change impact on demand. Where sensitivity to climate is low, changes in demand in response to climate change may not be significant and do not need to be considered.

4.10. Other Influences on Runoff and Recharge

A range of other landscape, vegetation and other water use changes can potentially interact with the projected changes in rainfall and potential evapotranspiration to further impact upon projected changes in runoff and recharge presented above. These include:

- **Bushfires** – Irrespective of climate change, changes in vegetation cover from bushfires can impact upon runoff and recharge estimates over time. The incidence of major bushfires in Victoria has increased over recent decades, and general fire weather risk (as indicated by the Macarthur Forest Fire Danger Index in Grose et al., 2015 and Timbal et al., 2015) is projected to increase under increased greenhouse gas concentrations. 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, and also changes in species composition following the fire.

- **Small catchment (farm) dams** – Demand for water in small catchment (farm) dams in the landscape is expected to increase under drier climate change scenarios and decrease under wetter climate change scenarios. Farm dams intercept runoff before it reaches downstream rivers, and can therefore affect the amount of runoff reaching bulk urban and rural water supply offtakes. The use of water from commercial farm dams is limited by license conditions, and is therefore not expected to change without a corresponding change in licence conditions. Where small catchment (farm) dams are for stock and domestic purposes, the usage from those dams (by evaporation or for consumptive purposes) would be expected to increase under drier climate change scenarios. Farm dams have a disproportionately greater impact on runoff during dry periods, intercepting a much higher percentage of the total runoff. Farm dam hydrologic impact tools such as TEDI and CHEAT can be applied to assess changes in water use from farm dams under climate change where a water corporation considers changes in this use to be a significant risk to water supply availability.

The potential impact on water availability from these other issues can be assessed qualitatively or by using surrogate indicators of that potential impact (e.g. by quickly dismissing potential impacts from small catchment (farm) dams in catchments without any of these dams). The extent to which these other influences are quantitatively estimated by water corporations will depend on the availability and level of confidence in the modelling tools used to assess each particular issue, relative to the potential impact on supply system water availability and performance.

Recommendation 10:

A range of other factors may potentially be significant issues for future water availability in some systems. Other issues that may impact water availability, such as bushfires or increases in catchment interception activities should at least be considered qualitatively. The extent to which these other influences are quantitatively estimated by water corporations will depend on the availability and level of confidence in the modelling tools used to assess each particular issue, relative to the potential impact on supply system water availability and performance.

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Any questions on these guidelines should be directed to the Hydrologic Risks & Planning team, Water Resource Assessment Branch, Water Resource Division, Water & Catchments Group, Department of Environment, Land, Water and Planning;

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7. Glossary and Acronyms

This glossary and list of acronyms has been prepared with reference to Hope et al. (2015), Bureau of Meteorology (2016b), IPCC (2014), WSAA (2016) and Potter et al.(2015).

Baseline – A reference climate period.

Climate scenario – There are four climate scenarios presented in the guidelines. The low, medium and high climate scenarios represent the range (10th to 90th percentile) of modeled outcomes from global climate models under the RCP 8.5 emissions scenario. The fourth climate scenario is a step climate change scenario derived independently of the GCMs.

CMIP-5 – The suite of global climate models on which the IPCC's 5th Assessment Report is based. CMIP-5 refers to the fifth Coupled Model Intercomparison Project.

Cool season – Defined as months where average monthly temperature for a given month of the year is below the average monthly temperature for all months. For temperature, rainfall and potential evapotranspiration in Victoria it covers the months from April to October inclusive. For runoff it is from May to November.

DELWP – Victorian Department of Environment, Land, Water and Planning.

Downscaling – The process of deriving local climate change impacts from large scale global climate models.

Emissions scenario – The IPCC's 5th Assessment report considers four emissions scenarios, which are referred to as representative concentration pathways (RCPs). The RCP 8.5 emissions scenario has been adopted in these guidelines. See the definition of "RCP" in this glossary for further information.

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.

GCM – Global Climate Model.

IOD – Indian Ocean Dipole – 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 whilst 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.

Instrumental record – Data that is measured directly in the field using instruments such as rainfall gauges, streamflow gauges and evaporation pans.

IPCC – Intergovernmental Panel on Climate Change.

IPO – Inter-decadal Pacific Oscillation –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 15–30 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.

PET – Potential evapotranspiration – 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.

Resilience – The capacity to adapt to stress and adversity.

RCP – Representative Concentration Pathway – the greenhouse gas emissions scenario expressed in terms of the radiative forcing by the year 2100 relative to pre-industrial levels. The RCP8.5 represents a radiative forcing of 8.5 W/m^2 at the year 2100.

SAM – Southern Annular Mode – 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 trend 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 modeling, hydrologic stationarity refers to the absence of trends in the relationship between rainfall and runoff.

Sub-Tropical Ridge – A region of high pressure across the mid-latitudes of the southern hemisphere.

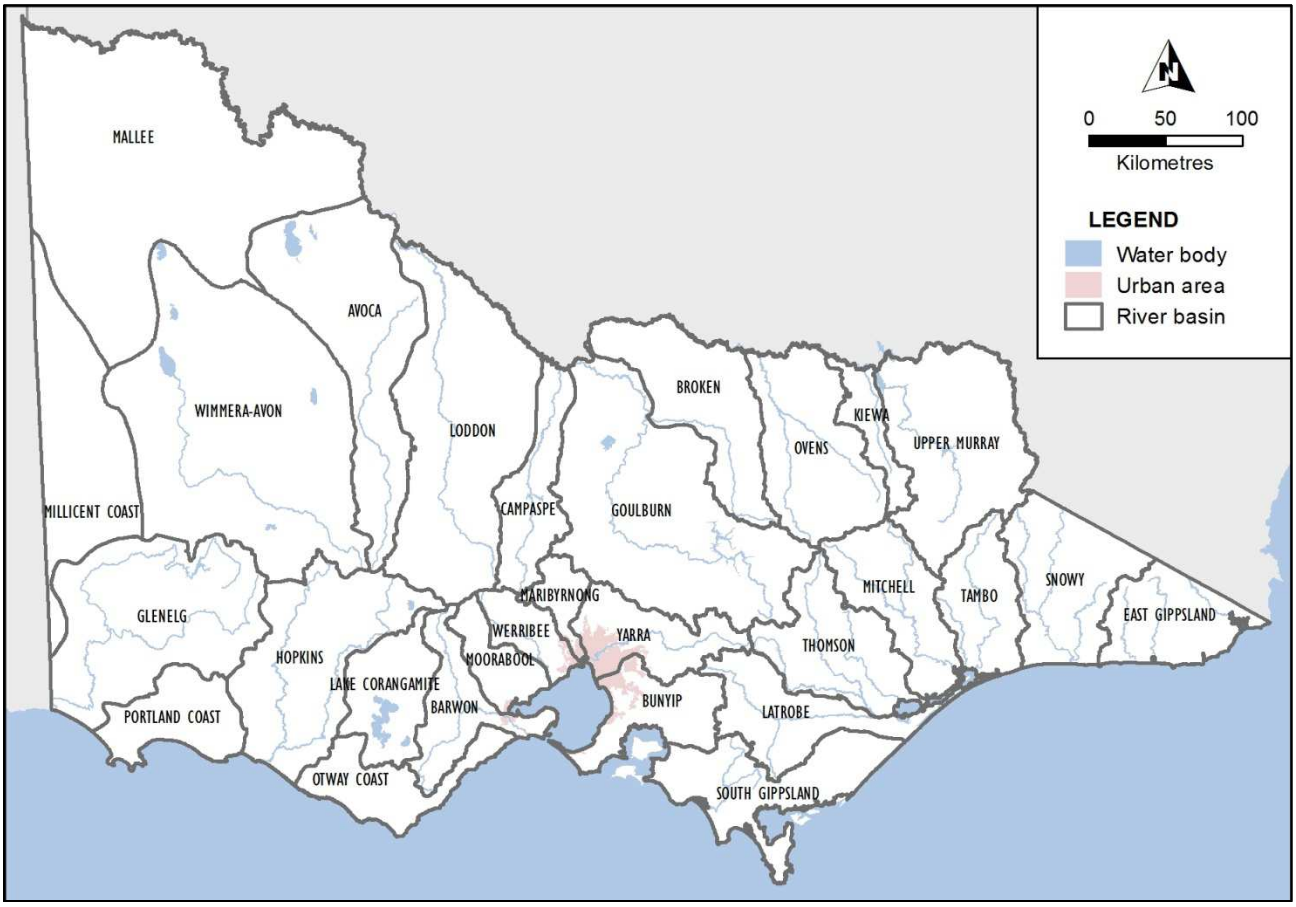
VicCI – Victorian Climate Initiative – A three year research program funded by the Victorian State Government to improve our understanding of past, current and future climate influences on Victoria.

Vulnerability – The propensity or pre-disposition to be adversely affected.

Appendix A Global Climate Model Projections – Supplementary Maps and Tables

The global climate model projections have been developed for each of Victoria's River Basins. A map of these river basins is shown in Figure 19.

Figure 19 Victorian River Basins



The low, medium and high climate change scenarios were selected based on ranking the GCMs by their projected change in runoff. The low climate change scenario is adopted from the GCM with the 10th percentile change in runoff, the high climate change scenario is adopted from the GCM with the 90th percentile change in runoff and the medium climate change scenario is adopted from the GCM with the median change in runoff.

Where results across all climate variables are adopted from a single GCM based on the projected change in runoff, the resulting changes in temperature and potential evapotranspiration from that same GCM are often spatially inconsistent across river basins. They are also at odds with broader observations from the GCM ensemble as a whole that increases in temperature are projected to result in a drier climate future for Victoria, as indicated by the majority of models. Where an exceedance percentile falls midway between two GCMs (e.g. the median of 42 models could be either the 21st or 22nd ranked GCM), the selection of either GCM can result in different associated changes in temperature and potential evapotranspiration, further highlighting the arbitrariness of selecting temperature and potential evapotranspiration changes from GCMs ranked according to runoff alone. CSIRO has addressed this issue in national climate projections through the use of multi-parameter climate futures; however such an approach generates a much higher number of future climate scenarios (typically 6-8) that would contribute to greater complexity in water resource modelling and decision making for water corporations relative to the three projected scenarios currently adopted.

In Appendix A.1 the 10th percentile, median and 90th percentile scenarios (or low, medium and high scenarios) presented are based on ranking the GCMs by their projected changes in the given climate variable (e.g. temperature, potential evapotranspiration or rainfall). These projections may be different to those associated with the GCMs that produce the low, medium and high climate change scenarios based on ranked runoff, particularly for temperature and potential evapotranspiration. However, in the case of rainfall, the consistency in values (percentiles and medians) ranked by rainfall change and ranked by runoff change will be very similar, because the annual runoff change is driven primarily by the annual rainfall change, with potential evapotranspiration change and seasonal rainfall change being secondary drivers.

As outlined in Chapter 3 of the guidelines, for the majority of water corporation applications, uncertainty in temperature and PET projections is expected to have only a minor influence on water planning decisions, and hence the median projected changes in temperature and PET from Chapter 3 can be adopted. This includes applications in demand estimation, rainfall-runoff modelling and estimates of reservoir evaporation in water resource modelling. However, there may be applications where a water corporation wishes to consider the sensitivity of water planning inputs or outcomes to the range of temperature and PET projections. This would include applications for research purposes. In these circumstances, the range of projected changes in temperature and PET from Appendix A1 should be used where temperature or PET uncertainty is considered in isolation from rainfall and runoff uncertainty, and from Appendix A2 where temperature or PET uncertainty is considered in conjunction with rainfall and runoff uncertainty. As noted above, the utilisation of the range of temperature and PET projections in Appendix A2 can result in inconsistent outcomes across river basin boundaries (because the GCM selected as say the median in one river basin will not necessarily be the same GCM selected as the median in an adjacent river basin), but has the advantage within a single river basin that it ensures a physically consistent projection sourced from a single climate model. As noted above, the differences in rainfall projections in Appendix A1, which are the same as those previously presented in Table 2, and Appendix A2 are minor, and hence the values in Appendix A2 should only be used for investigations into rainfall-runoff uncertainty resulting from GCM selection uncertainty, such as for research purposes.

Where a water corporation undertakes modelling that involves two or more climate parameters, the range in temperature and potential evapotranspiration projections from the GCMs associated with the low, medium and high runoff scenarios can be used. This is because the coupling of the 90th percentile change in potential evapotranspiration and the 90th percentile change in rainfall has the potential to over-estimate the projected change. The projected changes in temperature, potential evapotranspiration and rainfall associated with the GCMs that generate the low, medium and high scenarios are given in Appendix A.2. As noted above, this approach can result in inconsistent outcomes across river basin boundaries (because the GCM selected as say the median in one river basin will not necessarily be the same GCM selected as the median in an adjacent river basin), but has the advantage within a single river basin that it ensures a physically consistent projection sourced from a single climate model.

A.1 Changes in temperature, potential evapotranspiration and rainfall derived from all Global Climate Models

Table 8 Change in average daily temperature relative to the current climate baseline across all seasons derived from all GCMs

	Change relative to current climate baseline (°C)					
	Year 2040			Year 2065		
	10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
River basin	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
East Gippsland	1.0	1.3	1.7	1.9	2.4	2.9
Snowy	1.0	1.4	1.6	1.9	2.5	2.9
Tambo	1.0	1.3	1.6	1.9	2.4	2.8
Mitchell	1.0	1.3	1.5	1.9	2.4	2.9
Thomson	1.0	1.3	1.5	1.9	2.4	2.8
Latrobe	0.9	1.2	1.5	1.7	2.2	2.8
South Gippsland	0.8	1.1	1.5	1.6	2.1	2.7
Bunyip	0.9	1.2	1.5	1.7	2.1	2.7
Yarra	1.0	1.3	1.5	1.9	2.3	2.8
Maribyrnong	1.0	1.3	1.5	1.9	2.3	2.8
Werribee	1.0	1.3	1.5	1.8	2.3	2.8
Moorabool	0.9	1.2	1.5	1.7	2.2	2.6
Barwon	0.8	1.1	1.4	1.6	2.1	2.6
Lake Corangamite	0.8	1.1	1.4	1.6	2.0	2.6
Otway Coast	0.8	1.0	1.3	1.4	1.9	2.5
Hopkins	0.9	1.1	1.4	1.6	2.1	2.5
Portland Coast	0.7	1.0	1.3	1.3	1.9	2.4
Glenelg	0.8	1.1	1.4	1.6	2.0	2.6
Millicent	0.8	1.1	1.5	1.7	2.1	2.5
Upper Murray	1.1	1.4	1.7	1.9	2.6	3.0
Kiewa	1.1	1.4	1.6	1.9	2.5	3.0
Ovens	1.0	1.4	1.6	2.0	2.5	3.0
Broken	1.0	1.4	1.6	2.0	2.5	3.0
Goulburn	1.0	1.4	1.6	2.0	2.4	2.9
Campaspe	1.0	1.3	1.6	1.9	2.4	2.9
Loddon	1.0	1.3	1.6	1.9	2.4	2.9
Avoca	1.0	1.4	1.6	1.9	2.4	3.0
Lower Murray	1.1	1.5	1.7	2.0	2.5	3.1
Mallee	1.0	1.3	1.6	1.9	2.4	2.9
Wimmera	1.0	1.3	1.6	1.9	2.3	2.9

Table 9 Change in average annual potential evapotranspiration (PET) relative to the current climate baseline across all derived from all GCMs

River basin	Average annual PET (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
	Historic	Low	Medium	High	Low	Medium	High
East Gippsland	1100	2.9%	4.2%	5.9%	5.0%	6.9%	9.7%
Snowy	1113	3.1%	4.5%	5.8%	5.2%	7.5%	10.4%
Tambo	1104	3.1%	4.5%	5.9%	4.6%	7.5%	11.2%
Mitchell	1111	3.1%	4.7%	5.7%	5.6%	7.9%	11.7%
Thomson	1110	3.1%	4.6%	5.7%	5.6%	7.5%	11.7%
Latrobe	1091	2.5%	4.5%	5.8%	4.8%	7.6%	11.3%
South Gippsland	1100	2.4%	4.2%	5.5%	4.4%	7.0%	10.9%
Bunyip	1117	2.6%	4.3%	5.7%	4.8%	7.3%	10.1%
Yarra	1111	3.1%	4.6%	5.9%	5.6%	7.6%	12.0%
Maribyrnong	1146	3.0%	4.8%	6.1%	5.7%	7.7%	11.1%
Werribee	1128	2.9%	4.7%	5.9%	5.7%	7.7%	11.5%
Moorabool	1127	2.8%	4.5%	5.7%	5.5%	7.7%	10.5%
Barwon	1126	2.3%	4.0%	5.4%	4.8%	7.0%	9.9%
Lake Corangamite	1135	2.1%	3.9%	5.4%	4.8%	6.9%	9.8%
Otway Coast	1090	1.8%	3.7%	5.3%	3.9%	6.4%	9.5%
Hopkins	1144	2.3%	4.1%	5.6%	5.1%	6.9%	10.5%
Portland Coast	1113	2.1%	3.4%	5.1%	4.2%	6.1%	9.0%
Glenelg	1157	2.6%	3.8%	5.7%	5.0%	6.7%	10.1%
Millicent	1243	2.5%	3.8%	5.5%	5.1%	6.7%	9.1%
Upper Murray	1203	3.0%	4.6%	5.7%	5.3%	8.1%	10.7%
Kiewa	1233	3.2%	4.8%	5.7%	5.6%	8.1%	11.4%
Ovens	1247	3.2%	4.8%	5.8%	5.6%	8.1%	11.4%
Broken	1316	3.2%	5.0%	5.6%	5.7%	8.0%	11.0%
Goulburn	1230	3.2%	4.9%	5.8%	5.6%	8.2%	11.4%
Campaspe	1257	3.0%	4.7%	5.9%	5.7%	7.8%	10.3%
Loddon	1305	3.0%	4.6%	5.7%	5.5%	7.7%	9.9%
Avoca	1366	2.9%	4.3%	5.4%	5.5%	7.1%	9.9%
Lower Murray	1378	2.8%	4.5%	5.3%	5.4%	7.6%	10.0%
Mallee	1386	3.0%	4.2%	5.2%	5.4%	7.0%	9.5%
Wimmera	1313	3.0%	4.2%	5.5%	5.4%	7.1%	9.8%

Table 10 Change in average annual rainfall relative to the current climate baseline across all seasons derived from all GCMs

	Average annual rainfall (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
River basin	Historic	Low	Medium	High	Low	Medium	High
East Gippsland	941	6.8%	-1.0%	-10.8%	7.9%	-1.2%	-15.0%
Snowy	813	7.6%	-1.4%	-10.4%	8.5%	-4.5%	-14.9%
Tambo	786	5.9%	-2.6%	-10.8%	7.1%	-4.5%	-16.6%
Mitchell	953	4.3%	-2.3%	-9.7%	2.3%	-4.8%	-18.5%
Thomson	859	4.1%	-2.0%	-10.6%	2.3%	-4.1%	-19.9%
Latrobe	919	3.3%	-4.0%	-11.4%	2.2%	-4.5%	-16.7%
South Gippsland	872	2.6%	-4.5%	-11.7%	2.2%	-4.4%	-15.9%
Bunyip	860	2.9%	-3.9%	-10.9%	2.1%	-5.0%	-16.1%
Yarra	961	3.7%	-2.7%	-10.5%	2.4%	-4.3%	-20.6%
Maribyrnong	676	2.7%	-2.4%	-12.0%	2.6%	-5.5%	-21.6%
Werribee	619	2.2%	-2.7%	-11.7%	2.4%	-6.2%	-21.4%
Moorabool	596	2.0%	-3.4%	-11.6%	1.5%	-5.9%	-21.4%
Barwon	650	2.0%	-3.0%	-11.5%	1.2%	-5.2%	-19.6%
Lake Corangamite	629	2.0%	-3.9%	-11.6%	-0.2%	-5.3%	-19.1%
Otway Coast	950	2.1%	-3.6%	-11.7%	0.5%	-5.8%	-19.0%
Hopkins	634	2.1%	-4.4%	-11.6%	1.0%	-5.7%	-20.9%
Portland Coast	724	2.6%	-4.6%	-10.9%	-0.2%	-8.4%	-19.0%
Glenelg	655	1.2%	-5.0%	-12.7%	1.4%	-8.4%	-21.7%
Millicent	533	1.2%	-5.5%	-15.0%	1.1%	-8.5%	-22.9%
Upper Murray	1053	7.5%	-0.7%	-8.5%	8.2%	-2.6%	-14.4%
Kiewa	1143	5.5%	-2.5%	-9.5%	4.0%	-2.1%	-16.0%
Ovens	962	5.3%	-3.4%	-9.5%	3.8%	-3.7%	-17.5%
Broken	573	6.0%	-3.7%	-14.2%	6.8%	-3.5%	-18.3%
Goulburn	767	3.9%	-2.5%	-13.6%	2.4%	-4.0%	-20.7%
Campaspe	596	2.4%	-2.2%	-15.2%	2.6%	-6.1%	-23.2%
Loddon	459	2.5%	-2.8%	-14.3%	3.2%	-5.6%	-22.9%
Avoca	358	4.8%	-3.8%	-15.5%	6.9%	-3.4%	-20.6%
Lower Murray	394	7.3%	-3.8%	-15.0%	9.1%	-2.3%	-19.1%
Mallee	306	4.7%	-5.3%	-17.8%	6.9%	-6.5%	-23.6%
Wimmera	394	2.0%	-3.7%	-13.3%	3.9%	-5.9%	-22.3%

A.2 Changes derived from the GCMs that produce the low, medium and high climate change scenarios for runoff

Table 11 Change in average daily temperature relative to the current climate baseline across all seasons for the GCMs that produce the low, medium and high scenarios for runoff

	Change relative to current climate baseline (°C)					
	Year 2040			Year 2065		
	For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff	For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff
River basin	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
East Gippsland	1.4	1.5	1.0	1.7	2.6	2.1
Snowy	1.2	1.6	1.2	1.7	2.8	2.2
Tambo	1.3	1.2	1.2	1.7	2.6	1.9
Mitchell	1.1	1.1	1.2	2.1	1.7	2.9
Thomson	1.1	1.1	1.3	2.3	2.0	3.1
Latrobe	0.8	1.1	1.3	2.3	2.6	2.3
South Gippsland	1.0	1.2	1.3	2.3	2.0	2.3
Bunyip	0.8	1.2	1.3	2.4	2.3	2.2
Yarra	1.1	1.1	1.3	2.2	1.9	2.9
Maribyrnong	1.2	1.7	1.5	2.0	2.6	2.8
Werribee	1.5	1.0	1.5	2.2	2.5	2.3
Moorabool	1.5	1.0	1.3	2.3	1.9	2.3
Barwon	1.0	1.1	1.4	2.1	2.0	2.7
Lake Corangamite	0.8	1.1	1.2	2.2	3.2	2.6
Otway Coast	0.8	1.0	1.2	1.8	2.0	2.7
Hopkins	1.2	1.2	1.1	2.8	1.8	2.5
Portland Coast	1.0	1.1	1.0	1.4	2.0	1.6
Glenelg	0.8	1.0	1.0	2.1	1.8	2.7
Millicent	1.0	0.9	1.1	1.6	2.3	2.5
Upper Murray	1.5	1.5	1.3	2.4	1.9	3.0
Kiewa	1.3	1.5	1.6	2.3	2.5	3.0
Ovens	1.1	1.2	1.6	2.3	2.0	3.0
Broken	1.5	1.2	1.4	2.4	2.0	3.0
Goulburn	1.5	1.4	1.5	2.4	2.0	2.9
Campaspe	1.3	1.2	1.5	2.4	2.6	2.6
Loddon	1.5	1.6	1.5	3.5	2.5	2.6
Avoca	1.6	1.2	1.4	2.0	2.9	3.0
Lower Murray	1.5	1.1	1.2	2.3	2.0	2.8
Mallee	1.0	1.4	1.2	2.1	2.0	2.1
Wimmera	1.1	1.3	1.5	2.1	2.0	2.4

Table 12 Change in average annual potential evapotranspiration (PET) relative to the current climate baseline across all seasons for the GCMs that produce the low, medium and high scenarios for runoff

	Average annual PET (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff	For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff
River basin	**Historic**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
East Gippsland	1100	2.9%	5.0%	3.3%	4.4%	9.7%	6.8%
Snowy	1113	4.2%	4.5%	4.0%	4.4%	7.7%	6.4%
Tambo	1104	4.6%	4.5%	4.1%	4.5%	7.8%	6.2%
Mitchell	1111	3.4%	4.5%	4.3%	7.6%	5.6%	12.7%
Thomson	1110	3.4%	3.9%	5.5%	7.3%	4.8%	11.7%
Latrobe	1091	1.6%	3.9%	5.3%	7.3%	11.1%	8.3%
South Gippsland	1100	4.2%	3.5%	5.0%	7.3%	5.0%	8.3%
Bunyip	1117	1.5%	4.6%	5.0%	7.8%	8.9%	8.2%
Yarra	1111	3.4%	3.1%	4.7%	6.0%	5.6%	12.6%
Maribyrnong	1146	3.8%	5.7%	5.4%	5.1%	8.2%	11.5%
Werribee	1128	5.3%	3.4%	5.6%	6.0%	7.9%	8.7%
Moorabool	1127	5.3%	2.8%	5.7%	7.6%	5.5%	8.7%
Barwon	1126	3.7%	4.8%	5.3%	6.9%	7.9%	9.9%
Lake Corangamite	1135	1.9%	3.8%	4.4%	7.4%	9.2%	9.4%
Otway Coast	1090	1.6%	3.8%	5.2%	4.4%	7.9%	9.1%
Hopkins	1144	3.2%	4.9%	4.2%	9.1%	5.9%	11.0%
Portland Coast	1113	3.1%	4.4%	3.7%	5.5%	7.4%	5.1%
Glenelg	1157	2.7%	3.0%	4.1%	5.6%	6.2%	11.8%
Millicent	1243	2.6%	3.0%	3.7%	6.5%	7.0%	8.9%
Upper Murray	1203	5.7%	5.1%	4.5%	7.4%	4.8%	8.7%
Kiewa	1233	4.4%	5.3%	5.5%	7.2%	8.1%	9.0%
Ovens	1247	3.4%	3.2%	5.8%	7.2%	5.6%	12.8%
Broken	1316	6.0%	3.2%	4.7%	7.4%	5.6%	12.5%
Goulburn	1230	7.2%	5.2%	5.6%	7.8%	5.6%	11.0%
Campaspe	1257	4.0%	4.7%	4.8%	7.4%	8.0%	8.3%
Loddon	1305	5.8%	5.9%	5.9%	10.9%	7.8%	8.3%
Avoca	1366	5.5%	3.6%	3.9%	6.2%	9.5%	10.0%
Lower Murray	1378	5.0%	3.1%	3.7%	6.6%	5.0%	9.0%
Mallee	1386	3.0%	4.6%	4.0%	6.8%	5.4%	6.1%
Wimmera	1313	3.2%	4.4%	5.3%	7.1%	5.7%	7.8%

Table 13 Change in average annual rainfall relative to the current climate baseline across all seasons for the GCMs that produce the low, medium and high scenarios for runoff

	Average annual rainfall (mm) (1975-2014)	Change relative to current climate baseline (%)					
		Year 2040			Year 2065		
		For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff	For 10th percentile runoff	For 50th percentile runoff	For 90th percentile runoff
River basin	**Historic**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
East Gippsland	941	7.9%	-0.5%	-10.9%	11.2%	0.9%	-16.6%
Snowy	813	7.6%	-0.3%	-11.2%	12.0%	-10.3%	-15.9%
Tambo	786	5.9%	0.1%	-10.2%	9.9%	-9.6%	-17.6%
Mitchell	953	3.7%	-4.8%	-14.0%	1.6%	-5.2%	-22.6%
Thomson	859	3.7%	-5.0%	-14.4%	2.2%	-3.8%	-20.4%
Latrobe	919	3.5%	-2.0%	-14.2%	2.2%	-3.6%	-22.8%
South Gippsland	872	-0.2%	-4.8%	-14.2%	2.2%	-4.4%	-22.7%
Bunyip	860	3.3%	-6.2%	-14.6%	4.8%	-10.0%	-21.8%
Yarra	961	3.7%	-1.9%	-14.6%	1.3%	-6.0%	-22.3%
Maribyrnong	675	3.4%	-9.7%	-9.1%	-0.2%	-9.3%	-20.4%
Werribee	619	3.4%	-4.1%	-9.0%	3.5%	-0.6%	-22.5%
Moorabool	596	3.3%	-1.9%	-10.7%	3.4%	-5.3%	-22.4%
Barwon	650	-2.0%	-1.4%	-9.4%	-5.3%	-4.6%	-20.5%
Lake Corangamite	629	1.4%	-3.6%	-16.0%	-4.4%	-10.1%	-22.4%
Otway Coast	950	1.2%	-2.5%	-11.8%	0.6%	-4.6%	-20.9%
Hopkins	634	1.5%	-3.7%	-16.7%	-3.9%	-11.1%	-23.4%
Portland Coast	724	2.7%	-3.1%	-16.2%	0.0%	-11.6%	-19.1%
Glenelg	655	-1.3%	-8.1%	-16.0%	1.2%	-11.3%	-25.8%
Millicent	533	1.2%	-5.3%	-18.1%	-2.0%	-8.0%	-22.2%
Upper Murray	1,053	7.6%	-1.6%	-13.4%	8.2%	-5.0%	-14.5%
Kiewa	1,143	6.2%	-2.5%	-15.3%	4.1%	-1.1%	-19.8%
Ovens	962	5.3%	-0.8%	-15.6%	3.9%	-5.6%	-22.8%
Broken	573	6.0%	0.5%	-15.8%	8.8%	-5.6%	-22.6%
Goulburn	767	4.6%	-5.3%	-14.0%	7.2%	-5.9%	-20.8%
Campaspe	596	3.7%	-11.7%	-17.7%	7.9%	-8.3%	-27.5%
Loddon	459	4.7%	-2.4%	-12.8%	3.1%	0.1%	-27.7%
Avoca	358	2.0%	-4.5%	-14.6%	6.9%	-4.2%	-20.7%
Lower Murray	394	3.6%	-0.7%	-15.0%	13.8%	-0.5%	-19.2%
Mallee	306	3.0%	-5.8%	-21.0%	-1.6%	-4.7%	-29.1%
Wimmera	394	0.2%	-0.9%	-13.1%	4.5%	-5.8%	-26.1%

Appendix B Comparison of Projections with Previous Guidelines

Changes to the GCM based projections

A comparison of the projected change in runoff from the GCMs in the current guidelines versus those presented in the previous guidelines (Moran and Sharples, 2011) is illustrated in Figure 18 for each river basin in Victoria and southern NSW. This figure shows change in runoff relative to the current climate baseline for broadly equivalent future climate change conditions. The current guideline values are for the Year 2065 based on the RCP8.5 emissions scenario prepared as part of the Victorian Climate Initiative (VicCI). The 2011 guideline values are for a 2^{o}C increase in global temperature (occurring around the year 2060 for the A2 emissions scenario) prepared as part of the former South East Australia Climate Initiative (SEACI).

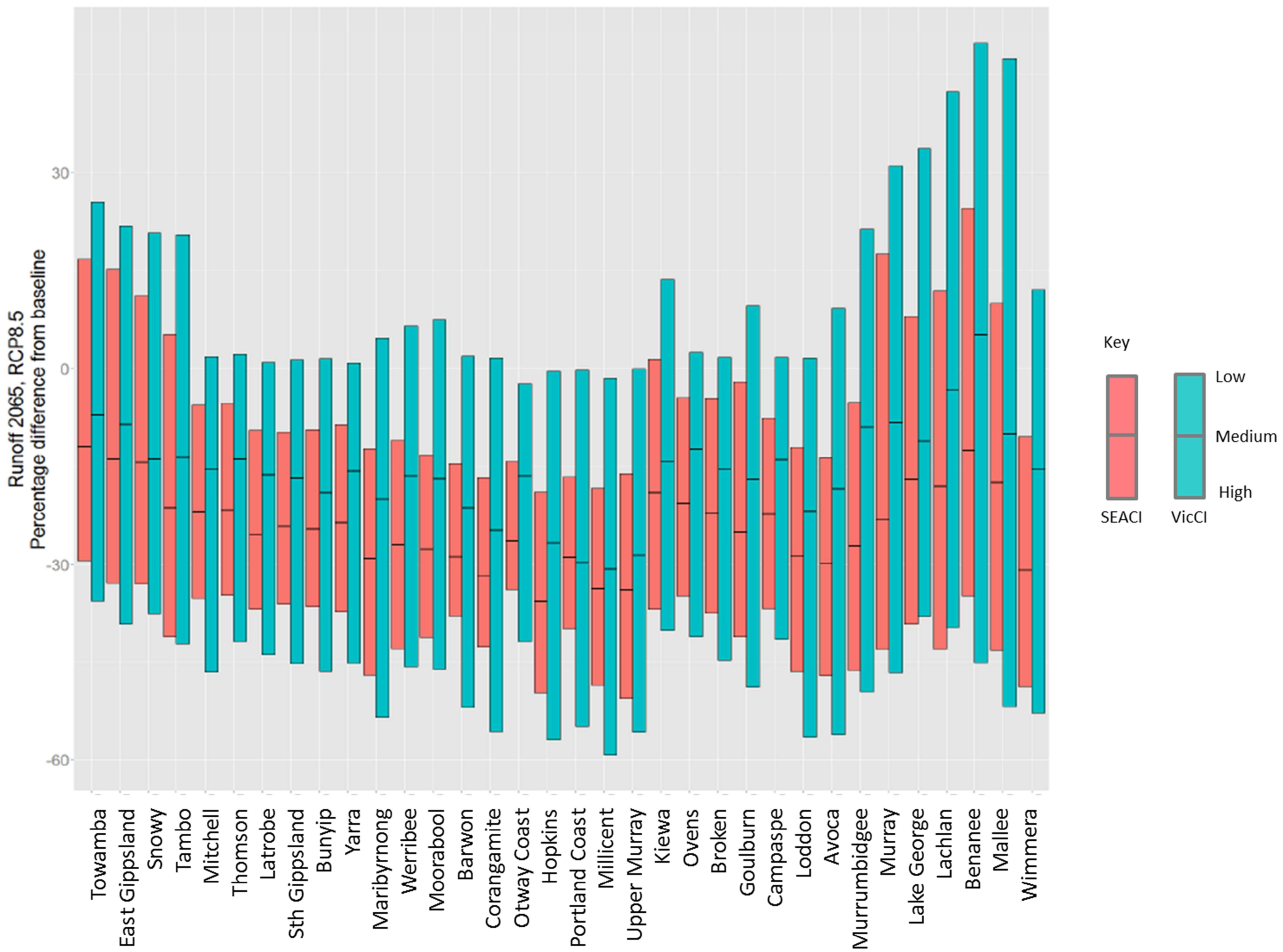
According to Potter et al. (2016), in all river basins:

- The median change in runoff is less dry than previously projected;
- The driest change in runoff (90th percentile value from the model ensemble, i.e. the high climate change scenario) is drier than previously projected; and
- The wettest change in runoff (10th percentile value from the model ensemble, i.e. the low climate change scenario) is wetter than previously projected. For some river basins more runoff is generated under this scenario than under current climate conditions.

By way of example, for the Latrobe River basin, the SEACI medium climate change projection for the year 2030 was for a 25% reduction in runoff. In the current guidelines (using the projected changes previously presented in Section 3.3.3), the Year 2040 medium projection is for an 11% reduction in runoff, which is a smaller reduction at a later time slice. Similarly, the low climate change projection for the year 2030 was for a 10% reduction in runoff, whereas in the current guidelines the low climate change projection for the Year 2040 is for a 9% increase in runoff for the same river basin.

The main reason for these differences is the due to the update of the GCM models (CMIP-5 suite of models versus the earlier CMIP-3 suite of models), which also now includes additional GCMs which were not previously available. It is also partly attributable to the slightly higher amount of projected warming in the assumed emissions scenario, which was selected based on observed historical and anticipated near-future trends, as explained in Section 3.1 of the guidelines. Other minor methodological differences also exist in the way that results are aggregated to a river basin scale that contribute minor differences between the results.

Figure 20 Change in runoff for these guidelines (from VicCI) and the 2011 WSDS guidelines (from SEACI) (adapted from Potter et al., 2016)



Changes to the step climate change scenario

The baseline period adopted for the “return-to-dry” (as it was then called) climate change scenario in the 2011 guidelines (Moran and Sharples, 2011) was from 1997 to 2009. The origin of that return-to-dry climate change scenario was from the experience in south-west Western Australia, where several downward steps in rainfall and runoff were identified from the mid-1970s. The use of this scenario in Victoria commenced during the Millennium Drought, when it was unclear whether Victoria would follow the pattern of ongoing declines in rainfall and runoff observed in south-west Western Australia over previous decades.

A “return-to-dry” climate change scenario could be considered to represent a drought planning scenario used for testing a supply system during dry conditions, or it could be considered a representation of current conditions associated with an abrupt change in climate in response to global warming. The nature and definition (and name) of the “return-to-dry” climate change scenario is each case may be different. For the current (2016) guidelines it has been separated into a post-1997 step climate change scenario for climate change planning, and a Millennium Drought scenario for drought planning.

Appendix C Spatial Resolution of Projected Changes

Projected changes in climate and runoff/recharge are provided for each Victorian river basin and are considered to be appropriate for future water supply planning purposes in most Victorian systems. In the case that the use of the projected changes for a different spatial extent (and potentially at a different spatial scale) is warranted they can be generated as follows:

1. Obtain the 5 km grids of hydroclimate projections generated by CSIRO (Potter et al., 2016), as illustrated in Figure 21 and Figure 22. 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.
2. 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).
3. 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.

    It should be noted that the projected changes calculated using this approach may not be consistent with the basin wide factor if the GCMs selected are different than those selected for the entire river basin.
4. 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 3.

Figure 21 Projected changes in annual rainfall under emissions scenario RCP8.5 relative to current climate at a finer spatial scale (Source: Potter et al 2016)

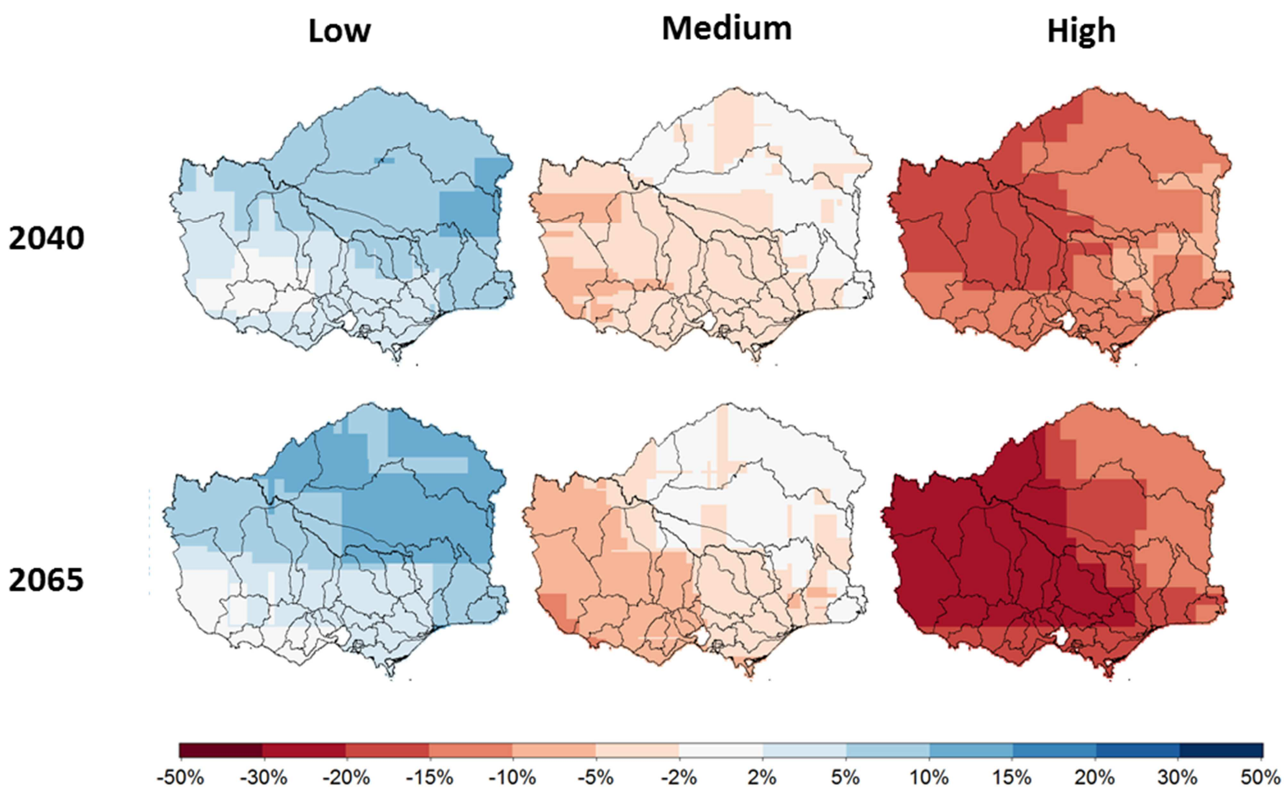
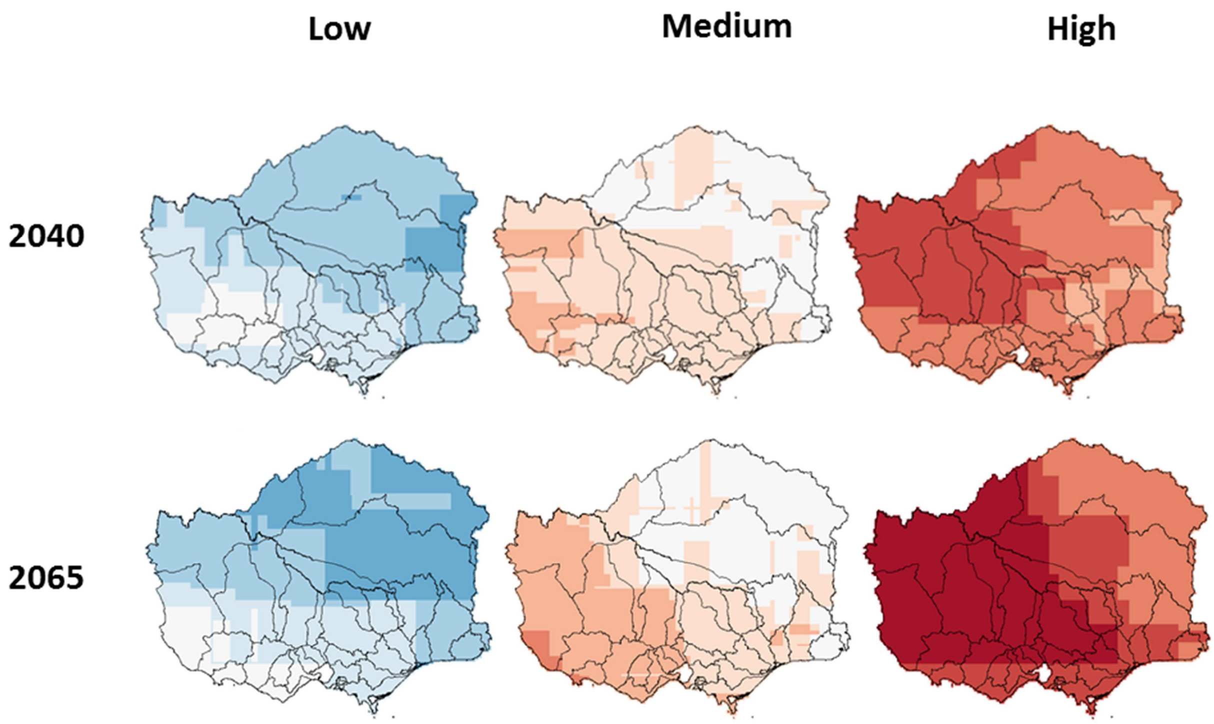


Figure 22 Projected changes in annual runoff under emissions scenario RCP8.5 relative to current climate at a finer spatial scale (Source: Potter et al 2016)

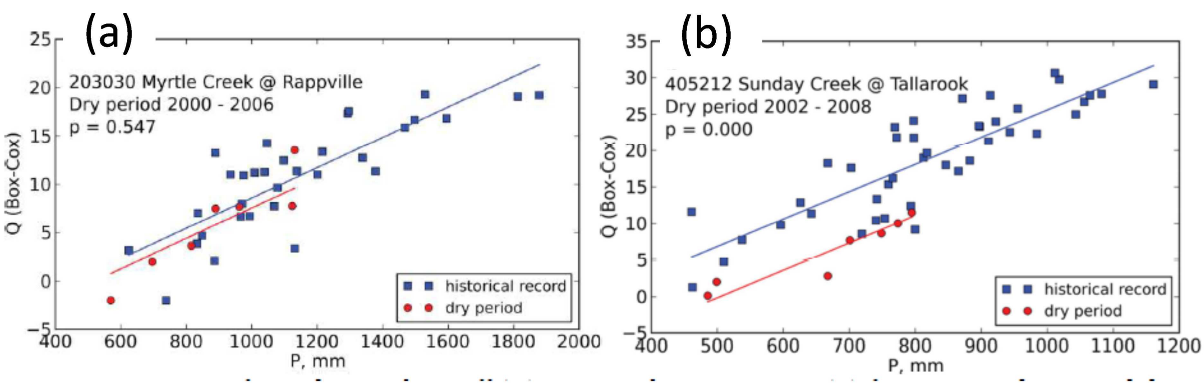


Appendix D Rainfall-Runoff Stationarity

In addition to step changes in observed atmospheric climate influences and variables, the University of Melbourne is currently conducting research into recent changes in the rainfall-runoff relationship in Victoria. 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. Whilst this research is still ongoing, the findings to date have indicated that (Saft et al., 2015; Saft et al., 2016; Fowler et al., 2016):

- 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 23a);
- Some catchments exhibited a shift in the historical rainfall-runoff response in long-run droughts (see Figure 23b), 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, which suggests that this change is attributable to catchment characteristics rather than seasonal or annual changes in meteorological forcings;
- 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 of the 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;
- Rainfall-runoff models were re-calibrated using Pareto-front optimisation, which suggested that in around one third of cases a rainfall-runoff model 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 would 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 was found to 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 that could suitably replicate both dry and/or non-dry period behaviour well.

Figure 23 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 preliminary 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.

Appendix E Incorporating Greater Climate Variability Into Shortened Climate Baselines

The following two techniques can be applied to generate a long-term representation of the current climate baseline (1975 to date) or the post-1997 step climate change scenario so that it incorporates a wider range of natural climate variability.

Flow Duration Curve Scaling

Flow Duration Curve Decile Scaling is a simple to apply technique to adjust historical streamflow data so that it has similar flow exceedance properties to a shorter reference period. It involves deriving average flows for each 10% interval (or decile) of probability exceedance for both the shorter reference period (e.g. post-1997 period) and the earlier historical data (e.g. pre-1997). The historical record prior to the reference period (e.g. pre-1997 flow) is then factored by the ratio of the average flows in each period (e.g. post- and pre-1997) for the decile in which each flow 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 & 2015a). Flow Duration Curve Decile Scaling (and the REALM utility) can be applied to other climate variables in the same manner based on a rainfall, evaporation or temperature exceedance curve.

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 step climate change scenario. The REALM utility tool does not currently allow flow duration 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 take into account potential increases in intense warm season rainfall in the post-1997 step climate change scenario, as well as the cool season rainfall declines that are more pronounced than what is observed at an annual time step.

Any flow duration curve 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, 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.

Stochastic Data Generation

Stochastic data generation involves taking the statistical properties of a known dataset and then using a statistical time series model to generate data over a longer time period so that it has the same statistical properties as the known dataset. Those statistical properties typically include measures such as the mean, median, standard deviation, serial correlation and skewness of the data. Stochastic data can be used in a water resource model to provide insights into the impacts of longer term data uncertainty. Stochastic data generation is most valuable when there is limited baseline climate information from which to assess supply system performance, either because of lack of instrumental data or because of trends in that data.

This approach has been used by the Sydney Catchment Authority in Sydney and Actew in Canberra, and was used in the 2011 WSDSs by Central Highlands Water for two supply systems. A range of stochastic data generation techniques are available, but in their simplest form they consist of estimating each subsequent data point using a factor applied to the previous data point plus a random error term set to operate within certain bounds. Difficulties in applying stochastic data generation include adequately matching all target statistical properties in the generated dataset to a similar degree of accuracy, as well as ensuring temporal consistency across rainfall, evaporation and streamflow datasets if all three are used within water resource models. Once the datasets have been generated, effort is required to set up a modelling framework that can incorporate and post-process the modelled data in a meaningful way. Stakeholders may also need to be educated on how to interpret the additional information on uncertainty that stochastic data presents.

Stochastic data generation can be used in a similar manner to the flow duration curve decile scaling outlined above. That is, the statistical properties of a relatively short but recent historical period (which is considered broadly representative of climate conditions under recent climate change) could be used to generate a longer time series to gain an appreciation of supply system behaviour under a long-term representation of climate variability. Similarly, changes in climate behaviour generated by the GCMs with high confidence could be used to adjust the statistical properties of a historic stochastic model, thereby providing an estimate of potential long-term behaviour under a given climate change condition. Lastly, the approach has been used in the past using climate data sampled from different climate phases over the instrumental climate record so as to better understand long-term climate variability under a particular climate state (e.g. the IPO positive phase).

Potential Implications of Adopting a 40 Year Baseline on Level of Service Objectives

If shorter baselines are adopted for water planning to take into account recent climate change, then changes may also be required to the way that level of service objectives are expressed. Over the shorter 40 year baseline period, defining levels of service by long-term drought frequency starts to make less sense, because the 40 year baseline period has relatively few independent droughts relative to the full instrumental record. This can be overcome using stochastic data generation techniques and flow-duration curve decile scaling (explained above) to create a long-term representation of the current climate record. If it is impractical to do this, an alternative approach may be to define levels of service based on the performance of different supply system configurations over the baseline period in a comparative sense, including comparison with the actual supply system behaviour and performance metrics over the historical baseline period. The level of service objective could then be re-pitched from a “minimum desirable frequency of periods without restriction on average in the long-term”, to say “a frequency, severity and duration of restrictions under a repeat of the Millennium Drought that is similar to (or better than) that experienced over the Millennium Drought” or “a maximum duration of severe restrictions of not more than (say) 12 months under a repeat of the Millennium Drought”. Storage volumes could also be used instead of restriction levels, as per Melbourne Water’s operating zones. Such approaches are considered consistent with the Urban Water Strategy guidance, but is likely to require additional effort for consultation and endorsement within the water corporation.

Appendix F Climate Analogues

Climate analogues involve selecting historical climate data from another climate station in Australia so as 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. (2015) 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., 2015). 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 1 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 24. 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 24 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 refinement to the rainfall selection is informed by the level of confidence in the global climate models, which indicates that annual and winter/spring rainfall changes in Victoria are predicted with a high degree of confidence, but autumn rainfall is not. This censoring yields two climate analogues (Sale and Bathurst) from the original fourteen sites. These two sites can then be examined for changes in autumn rainfall (currently 142 mm in Melbourne), in which it can be seen 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 particular 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 global climate models 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 number of 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 global climate models 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 3.4 that global climate models 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.

Appendix G Paleoclimate Proxy Records

An overview of paleoclimate proxy records relevant to Victoria was presented in Section 2.2.2. Paleoclimate proxy records provide an insight into past climate variability prior to the start of the instrumental rainfall records. Paleoclimate proxy records highlight that the period over which we have instrumental rainfall records has been relatively wet in eastern Australia, and that prolonged dry periods longer than the Millennium Drought have been identified over the past millennium. As indicated throughout the guidelines, for water resource planning this reinforces the need to consider the possibility of conditions that are drier for longer periods than those observed in the historical record, and that climate change can further add to this need.

The development and use of Paleoclimate proxy records suitable for water resource modeling applications have to date largely rested within the academic community, and are likely to remain so in the near future due to the specialist knowledge required in both re-construction and application of this information. They have typically been applied within a stochastic modeling framework, with very few applications beyond rainfall estimation and analysis. An example paleoclimate rainfall analysis of 2,751 years of data for four sites in the Murray-Darling Basin, including one site in the Wimmera River basin and another in the Upper Murray, is presented in Ho et al. (2015a; 2015b).

A pragmatic application of paleoclimate information in water resource modeling is presented in Verdon and Franks (2006). In that paper, Verdon and Franks prepared rainfall reconstructions over the past 500 years in the Lachlan River valley in southern New South Wales. They then tested the robustness of water resource planning assumptions in place at that time, and assessed water supply reliability over this 500 year sequence using the IQQM water resource model. IQQM is the NSW equivalent to Victoria's REALM model. Whilst there are many uncertainties in deriving and applying paleoclimate reconstructions, this example highlighted how it can be used to provide tangible modeling outcomes to enhance decision making.

All paleoclimate reconstructions are reflective of historical (and generally pre-industrial) global greenhouse gas concentrations, which were much lower than concentrations today and into the 21st century. As such, these reconstructions are an indicator of long-term climate variability beyond that which is known in the instrumental record, with climate change impacts being in addition to that pre-instrumental climate variability.

Paleoclimate proxy records are continually improving in their temporal and spatial resolution, the degree of confidence associated with them is improving (due to agreement from multiple independently derived sources) and the duration of available records is extending. At the current time the level of technical complexity and effort involved in deriving and applying locally relevant paleoclimate proxy records means that it is not practical for water corporations to apply in water resource modeling outside of research-based investigations. It is anticipated that the outcomes of the Australian Research Council Linkage Project mentioned in Section 2.2.2, which is being supported by the State Government, will further local knowledge in this area and may facilitate wider applicability of paleoclimate proxy records in Victoria in the future.

Appendix G Seasonal Changes in Rainfall

Figure 25 Projected changes in seasonal rainfall under emissions scenario RCP8.5 by 2040 relative to current climate (Source: Potter et al, 2016)

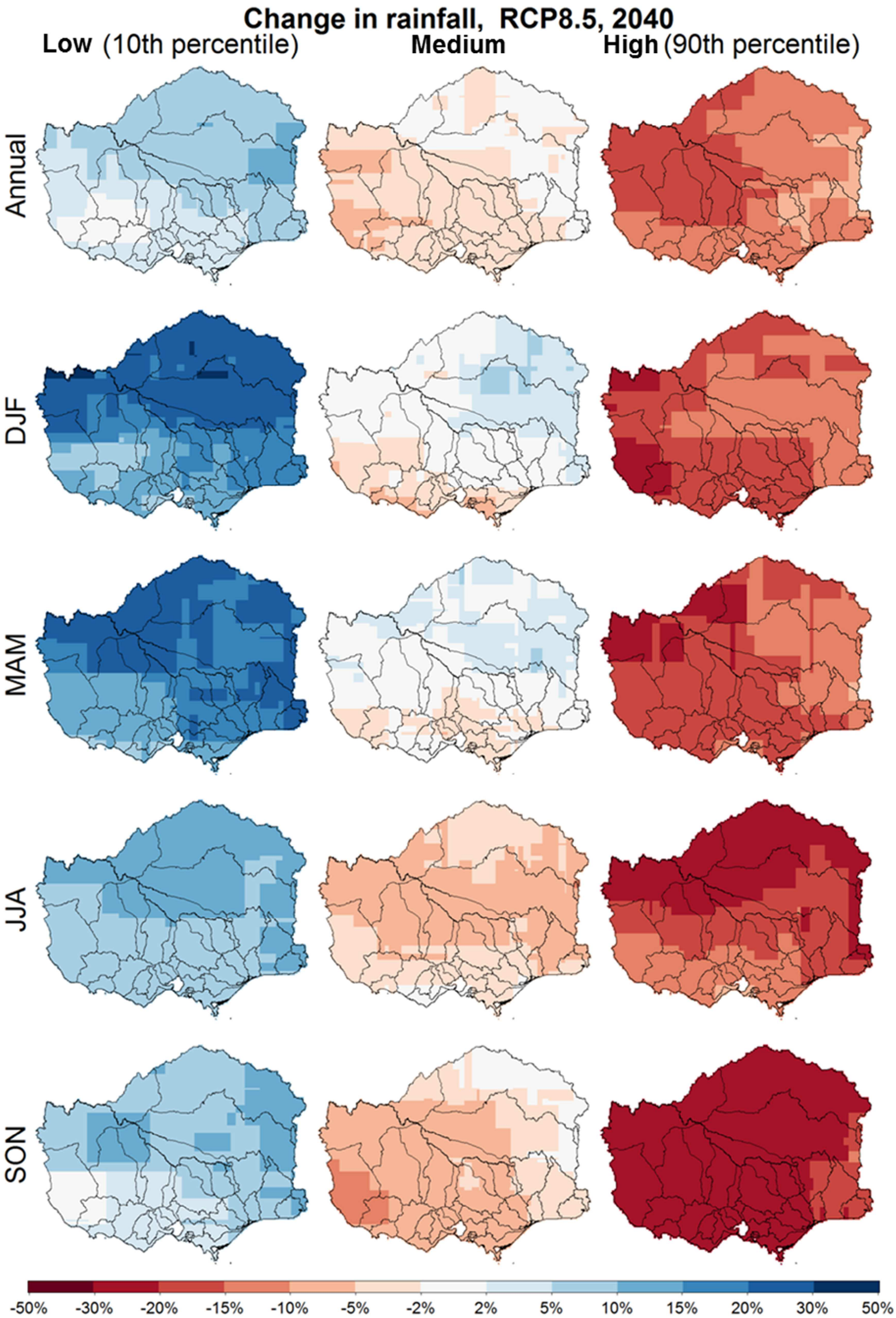


Figure 26 Projected changes in seasonal rainfall under emissions scenario RCP8.5 by 2065 relative to current climate (Source: Potter et al, 2016)