Government of **Western Australia**
Department of **Water and Environmental Regulation**

Guide to future climate projections for water management in Western Australia

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For more information about this report, contact hydroclimatescience@dwer.wa.gov.au.

Disclaimer

Acknowledgement of Country

We acknowledge the Traditional Owners of the land upon which we live and work throughout Western Australia and pay our respects to their Elders past and present.

We recognise the practice of intergenerational care for Country and its relevance to our work as water and environmental managers.

We seek to listen, learn and genuinely engage and build strong partnerships. We aim to provide sustainable opportunities for Aboriginal people within our workforce and through our business.

Working with the community, we move forward with a shared commitment to protect and conserve Country for future generations. We recognise Country is a term used by Aboriginal people to describe the lands, waterways and seas to which they are intrinsically linked, and to which their wellbeing, law, place, custom, language, spiritual belief, cultural practice, material sustenance, family and identity belong.

*The Department of Water and Environmental Regulation's head office, Prime House, is located in Joondalup, on Whadjuk Noongar Boodja. This acknowledgement of Country has been endorsed by our Aboriginal Water and Environmental Advisory Group.

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Summary

This *Guide to future climate projections for water management in Western Australia* provides a practical framework for water planners and decision-makers to use climate change projections in climate impact assessments (Figure 1).

This guide replaces *Selection of future climate projections for Western Australia* (DoW 2015) which has been an important resource for the Western Australian water sector. It provided an accessible set of future climate projections, along with practical advice and guidance. This enabled a consistent and practical application of climate projections to modelling, impact assessment and adaptation planning.

The new framework is underpinned by the 'storylines' concept (Shepherd et al. 2018), which helps decide how to best use future climate projections for an assessment (summarised in Figure 1). We no longer recommend a dry, median and wet projection for scaling a baseline dataset as prescribed in DoW (2015). Instead, we recommend using this climate assessment framework and the latest generation of regional future climate projections from the Australian Water Outlook – the Bureau of Meteorology's National Hydrological Projections (NHP) (BoM 2022) which are up-to-date, application-ready projections available at the time of publication. The framework can be applied to new application-ready climate projections as they are developed.

How to use this guide

We recommend that, depending on your level of familiarity with climate projections, you read the supporting chapters to help you understand the projections in the context of your application (these are summarised in the box below). Detailed descriptions of each step in the climate assessment framework are in Chapter 6.

Chapter 2 – Key differences between this guide and our previous guide (DoW 2015)

Chapter 3 – Summary of climate trends and projected hydroclimate trends in Western Australia

Chapter 4 – Overview of First Nations peoples' climate and water knowledge

Chapter 5 – Summary of climate projections modelling and how the Bureau of Meteorology developed the NHP

Chapter 6 – A framework for using future climate projections for climate impact assessment, planning, and decision-making for water management in Western Australia

Chapter 7 – Summary of the comparison between the CMIP3, CMIP5 and CMIP6 climate projections

Chapter 8 – Where to find more information on future climate projections, water and climate change legislation, advice about flood, sea-level rise, and coastal inundation, and other useful policy documents

Appendix – How to request NHP data from the Bureau of Meteorology

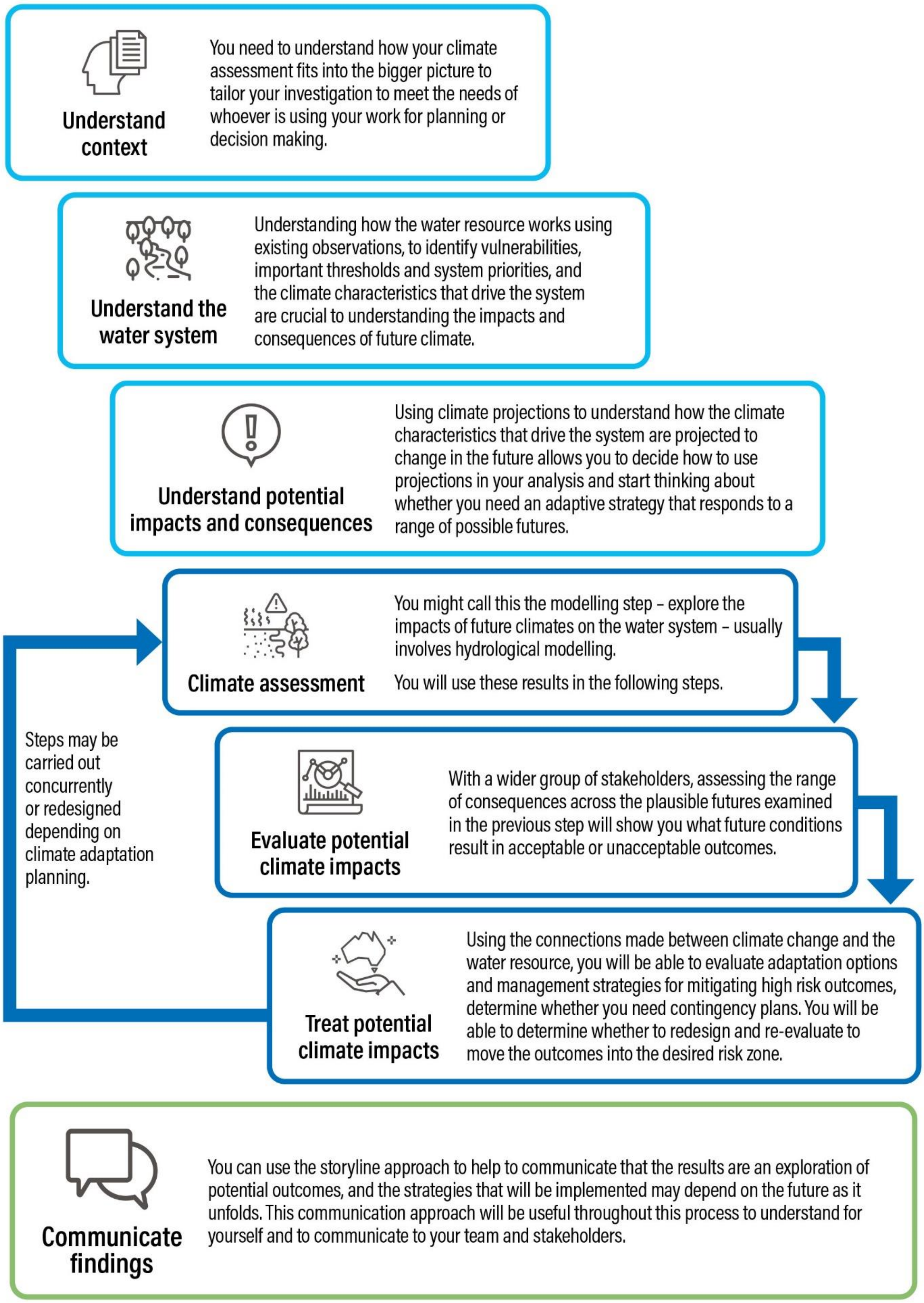


Figure 1 Overview of the climate assessment framework to apply climate projections using the storyline concept in decision making processes for water management (Box 2, Chapter 6)

Target audience

The target audience for this guide is qualified practitioners in the water sector, such as modellers, planners, and consultants, who need to consider future climate in their project-level applications. It is also intended for managers, reviewers and decision-makers, as well as stakeholders more generally, to help:

- indicate how to approach climate change and manage consequences
- manage expectations around what type of information is available and meaningful for a given activity
- assess whether the climate information on which to base a decision is fit for purpose.

Flood risk and hazard management

For flood risk or hazard management we recommend you refer to Australian Rainfall and Runoff (ARR) (Ball et al. 2019) for current climate change practice and to the Australian Rainfall and Runoff website for future updates.

The ARR guidelines provide an approach for adjusting the Intensity Frequency Duration (IFD) rainfall depths for climate change (ARR guidelines Book 1: Chapter 6). This is largely based on the Intergovernmental Panel on Climate Change 5th assessment report.

The Australian Department of Climate Change, Energy, the Environment and Water in partnership with Engineers Australia have commenced a process to update the approach in accordance with the current science and will update the ARR guidelines once complete.

A note on terminology

Several terms describe the outputs produced by downscaling and bias-correcting global climate models to the local scale. These include ensembles, ensemble members, climate projection datasets, futures, scenarios, and projection suites. This guide uses the terms ‘projections’, ‘datasets’ and ‘futures’ interchangeably.

See the Glossary for additional terms.

1 Introduction

Climate change will affect future surface water and groundwater availability and demand, water quality, ecohydrology and integrated water and land use developments. Future climate projections are used in surface water, groundwater and water quality modelling and/or impact assessment studies to assess the effects of climate change. In this guide, the Department of Water and Environmental Regulation (the department) provides a framework to use climate projection information for impact assessment, modelling, and planning. This guide replaces *Selection of future climate projections for Western Australia* (DoW 2015).

The framework described in this guide can be applied to any climate projection dataset. The department recommends using the Bureau of Meteorology's application-ready National Hydrological Projections (Srikanthan et al. 2022a) for local-scale assessment, as at the time of publication they are the up-to-date suite for the water sector.

Our previous guide used the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 3 (CMIP3) datasets that informed the Intergovernmental Panel on Climate Change (IPCC) 4th assessment report (IPCC 2007). The National Hydrological Projections are based on the CMIP5 models that informed the IPCC 5th assessment report (IPCC 2014a and b). Chapter 2 discusses the key differences between this guide and our previous guide.

This guide provides a framework for using future climate projections for modelling and decision-making (Chapter 6). This framework represents a major shift in approach – from using traditional statistics to plan for a 'best estimate' and range of possibilities, to considering climate projections as distinct, equally plausible climate futures with no view on what is most likely. The framework includes the relatively new concept of 'storylines' to help you tailor the application of future climate projections to each assessment, illustrated in the Figure 2.

Climate science is by nature uncertain and applying climate change science to hydrology, hydrogeology and water resource planning and management are ongoing areas of research. Our knowledge of climate change and its impacts evolves over time. Practitioners and managers need to be comfortable working with uncertainty about how climate change will affect water in the future. We will never have a perfect 'crystal ball' view of the future climate, and the specific details of the projections are not as important as understanding the sensitivity of water resources to changes in climate in the context of your decisions or planning and the associated level of risk.

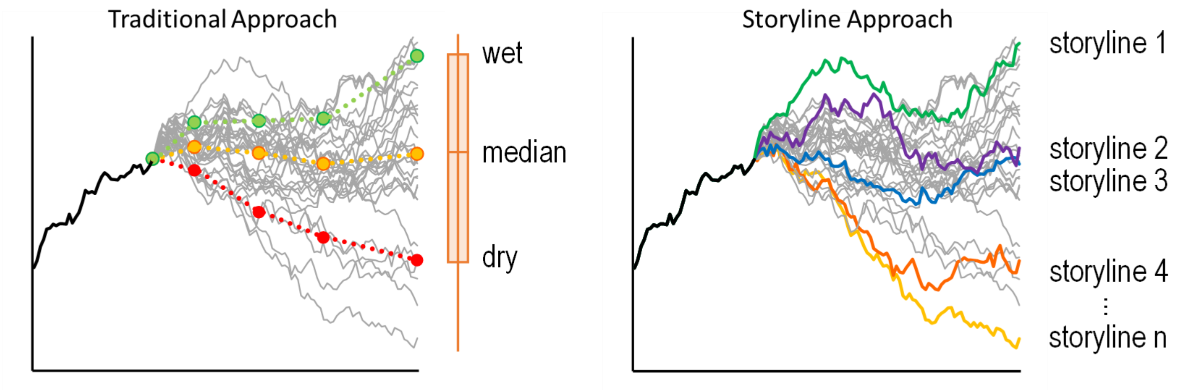


Figure 2 a) Traditional approach (DoW 2015): Representative futures at various time horizons with ranking. Wet, median, and dry scenarios explore the water resource response; b) Storyline approach (recommended in this guide): Identify and describe water resource responses of interest. Use climate projections to explore how important climate drivers change and water resources respond to climate and proposed decisions in the future

There are always new and upcoming sources of climate change projections from the latest generation of global climate models. It takes time for these to be translated into climate projection information and data for water management suitable for local-scale application in Western Australia. Table 1 summarises sources of information and downscaled projection data relevant to Western Australia's water sector.

Although the science is always improving, you do not need to wait for the latest generation of projections to identify, plan for, and manage climate change risks – the specific details may change, but the underlying story remains the same: climate change is already here, and it impacts water in every region of our state. The body of data from global climate modelling gives climate scientists high confidence in the projection for the South West of Western Australia – it will be warmer with more heat extremes (affecting evaporation and water demand), extreme hourly to daily rainfalls will increase, and the South West will keep getting drier.

The CMIP6 dataset has been released and informed the IPCC's 6th assessment report (IPCC 2021). At present, downscaled CMIP6 projections are not available for Western Australia. Different organisations develop application-ready datasets for various purposes and a range of spatial domains (see Section 8.2). The Western Australian Climate Science Initiative (CSI) will provide comprehensive downscaled projections of the state's future climate based on CMIP6.

Table 1 Sources of climate projection information and data for water management in Western Australia

	Previous release	Available now		Future release
Global climate projections	IPCC CMIP3 AR4 (2007)	IPCC CMIP5 AR5 (2014)		IPCC CMIP6 AR6 (2022)
WA-scale climate projections	Selection of future climate projections for Western Australia (DoW 2015)	Climate Change in Australia (CCiA)	Australian Water Outlook – gridded historical and future daily data for Australia from BoM NHP (BoM 2022)	Climate Science Initiative
Climate products	Report, maps, application-ready data	CCiA summary trends, projections and tools	Reports, maps, application-ready data – see next section.	Application-ready data
	Guidance in DoW (2015)	CCiA application-ready data	*Guide to future climate projections for water management in Western Australia* – (this guide)	

The framework and recommendations in this guide should be broadly adaptable to updated projections and new sources of application-ready data. New projections and data are expected to complement the climate projections and advice in this document. This may take the form of reduced uncertainty in climate projections, more precise understanding, quantification of climate-related risks, and/or updates to the details of projections.

As the CSI projections and other application-ready datasets for CMIP6 become available – and as the following generations of future climate projections are developed and downscaled – we will review our advice to the water sector on using future climate projections in water resource management and, if appropriate, update this guide.

2 Key updates in this guide

Choosing climate projections for application

This guide recommends developing ‘storylines’ to consider the potential climate change impacts specific to your water system and to help decide how to choose and apply projections for an assessment. Choosing appropriate future climate data depends on the application and decision you are making. Different applications need information and data at different levels of detail and complexity. We recommend you think about whether it is important to see the full range of plausible outcomes if you are considering choosing a subset of projections. The storyline approach, and the selection of climate projections for application is discussed further in Chapter 6.

The framework set out in this guide has been developed to ensure new projections can be incorporated into planning without the need to overhaul existing assessment processes.

DoW (2015) used dry, median, and wet scenarios based on the 10th, 50th and 90th percentile projections ranked by change in regional mean annual rainfall, or a subset of these projections. However, representative climate projections based on rainfall do not necessarily translate to the equivalent dry, median, and wet results in water system models, particularly when selected from large regions. The combined effects of rainfall with other climate variables can change the ranking of modelled results, which means the potential impacts to the water resource may not be adequately captured. For example, evapotranspiration is often a strong influence on surface water flows or the persistence of dry season pools. Climate projections based on rainfall may differ from the ranking based on surface water flows because of the variation evapotranspiration introduces to the latter.

Using a dry, median and/or wet scenario without additional consideration of how these relate to water outcomes and decision making can have other pitfalls:

- The median projection can be interpreted as the most likely projection. Although the median projection sits in the middle of the range, there is no reason to say any one projection is more plausible than the others. It is possible that the future will resemble the driest projection, the wettest projection, or any projection in between or even outside the current range of plausible projections – particularly as the full range from minimum to maximum was not considered in DoW (2015). We need to be careful as to how we interpret likelihood in relation to future projections. For example, for areas outside of the South West, the median is not a reliable indication of the direction of change given the wide distribution of projected rainfall change (plausibly drier or wetter).
- Selecting only a dry projection for assessment, if observations from recent years appear to follow the same trend, could mean that other possible futures and risks are not adequately assessed. Future climate might sit anywhere within the expected range of plausible projections – not track directly on a chosen projection year by year as if it were a prediction. A well-developed

storyline can help to decide if it is appropriate to use only one projection (see Chapter 6 Box 3).

Scaling methods

The department currently recommends using the Bureau's National Hydrological Projections (BoM 2022), which provide application-ready time-series data – downscaled and bias-corrected climate projections from CMIP5 Global Climate Models (GCMs) (discussed further in Chapter 5).

Recommending the use of climate projection time-series data moves away from the pattern-scaling method in DoW (2015). Pattern scaling maintains the same temporal sequences of, for example, dry and wet days, and dry and wet years in the baseline data. It does not reflect many of the other projected changes in climate characteristics that can influence water systems, such as potential changes in seasonality, inter-event periods, sea-surface-temperature gradient fluctuations, rainfall intensity and drought periods. The pattern-scaling method was the most appropriate method for DoW (2015) given application-ready downscaled projections were not available for the whole state at the time.

Baseline periods

In this guide we recommend using the Bureau's National Hydrological Projections (BoM 2022) future climate time-series data with a baseline period of 1976 to 2005. DoW (2015) recommended scaling historical data from a baseline period of 1961 to 1990. It is apparent since 2015 that this was a wet period for some areas of the South West, and due to continued rainfall reductions across those areas, some of the future climate projections using the pattern-scaling method had higher mean rainfall than the recently observed rainfall (Hughes 2021).

Where to apply this guide

This guide recommends applying the climate projections to all regions of Western Australia. The DoW (2015) guide recommended applying climate projections only in South West WA because historical rainfall in other parts of the State was more variable than the range in pattern scaled future projections.

GCMs outputs show strong signal agreement that the whole state will be hotter, with increased evapotranspiration – an important component of water resource assessments. Uncertainty around the direction of projected rainfall for the state's north has been due to CMIP5 GCMs indicating a range of possibilities in the change to the monsoon, which is important for rainfall in the north of WA. For CMIP5, this range appeared to be linked to the pattern of warming in the western Pacific Ocean (Brown et al. 2016) and was complicated by CMIP5 generally not modelling the monsoon well (Moise et al. 2015).

The new CMIP6 models also show a range of possibilities, linked to factors even broader than the western Pacific (Narsey et al. 2020). The NHP dataset recommended here uses a subset of GCMs that represent well the weather-scale features influencing northern Australia. This includes the El Niño Southern Oscillation (ENSO), which is a key driver of dry season rainfall variability, and a representative of the range of plausible possibilities, so the future changes should be considered reliable given our current knowledge (Srikanthan et al. 2022a). See the tables below for the differences between this guide and DoW (2015). Table 2 summarises changes to our recommended approach and Table 3 explains changes to the climate science.

Table 2 Key changes to our guidance for water resource managers

Change	DoW (2015)	This guide
Projection choice	Dry, median and wet (10th, 50th and 90th percentile projections, ranked by change in regional mean annual rainfall) Specified in the guidance	Risk-based assessment underpinned by ‘storylines’ User to assess
Scenario development	Monthly anomalies applied to a historical baseline period	National Hydrological Projections (BoM 2022) – application-ready continuous time-series from bias-corrected global climate model (GCM) and regional climate model data.
Where to apply	South West WA	All of WA

Table 3 Key changes to the climate science

Change	DoW (2015)	National Hydrological Projections (BoM 2022)
Generation of global climate models	Coupled Model Intercomparison Project, Phase 3 (CMIP3)	Coupled Model Intercomparison Project, Phase 5 (CMIP5)
Scaling method	Pattern scaling	Dynamical downscaling (regional climate model), re-gridding, and bias correction or re-gridding and bias correction
Emissions	SRES (Special Report on Emission Scenarios) (A1F1, A2, A1B, B2; 1.4°C to 5.4°C by 2100)	RCP 4.5 (1.7°C to 3.2°C by 2100) RCP 8.5 (3.2°C to 5.4°C by 2100) (IPCC, 2014 p. 57)
Reference/ baseline period	1961–1990 (monthly anomalies applied to this period to generate projections)	1976–2005 (reference period only – not used in generating projections; used in percent change figures)
Variables	Precipitation Temperature – minimum Temperature – maximum Temperature – mean Radiation Potential evapotranspiration (PET) – FAO56 Evaporation Relative humidity	Precipitation Temperature – minimum Temperature – maximum Solar radiation Wind speed Potential evapotranspiration (PET) – Penman[1,2] Actual evapotranspiration[2] Soil moisture[2] Runoff[2]
Time periods	Thirty years centred on 2030, 2050, 2070, 2100	Continuous data from 2006 – 2099 Percent change figures are calculated with respect to the reference period for 30 years centred on 2030, 2050, 2070 and 2085

[1] There are numerous ways to estimate evaporation and transpiration for different hydrological purposes. If Penman is not suitable for your purpose, you may be able to use this variable scaled by a seasonally varying factor (see Section 5.5).

[2] Potential evapotranspiration, actual evapotranspiration, soil moisture, and runoff were generated using the Australian Water Resources Assessment Landscape hydrological model (AWRA-L) (Frost & Wright 2018).

3 Western Australia's climate

Western Australia's climate is influenced by a range of climate drivers and different regions have different dominant climatic influences (Figure 3). Specifically for Western Australia:

- Rainfall in the tropical and subtropical north is influenced by summer monsoonal and cyclone activity resulting in a pronounced wet and dry season, with differences in the timing between eastern and western parts (Moise et al. 2015).
- The south-west is influenced by winter frontal systems, troughs and cut-off lows associated with westerly winds resulting in high winter rainfall and low summer rainfall (Hope et al. 2015).
- The interior and central west are influenced by multiple weather systems, including the north-west cloud band (DoW 2015). This results in high year-to-year and inter-decadal variability in the climate and hydrological systems: ranging from seasonally reliable monsoonal rainfall in the far north through to very low and variable rainfall patterns in much of the centre and south (Watterson et al. 2015).

The year-to-year variability in the climate in different regions of WA is influenced by various remote drivers, including ENSO but also others such as the Indian Ocean Dipole affecting some regions in winter and spring; the Madden Julian Oscillation affecting the north; the Southern Annular Mode affecting the climate of the southwest corner in autumn and winter and atmospheric blocks affecting parts of the south (Risby et al. 2009).

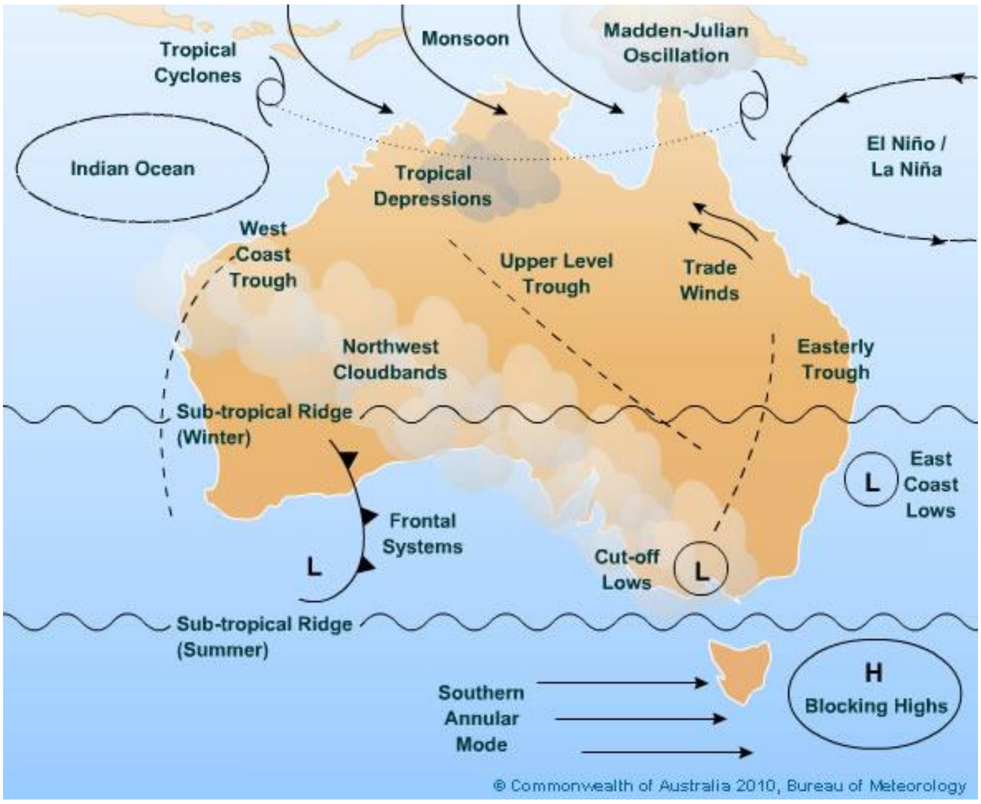


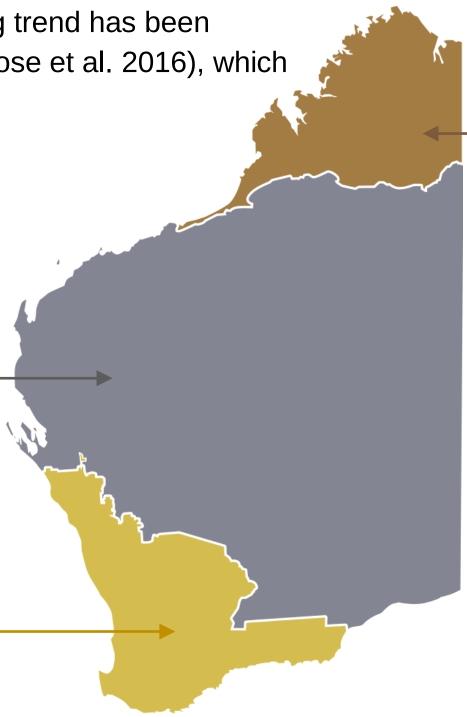
Figure 3 *Schematic of several key climate drivers and weather features of relevance for the Australian continent (BoM 2023)*

3.1 Observed climate change trends

Western Australia is already experiencing the impacts of climate change. It has warmed by about 1.3°C since 1910 (DWER 2021), and likely around 1.5°C since the 1850–1900 period used to approximate the pre-industrial era (Grose et al. 2023).

Kimberley (Monsoonal North) region

The north-west has become hotter and wetter (rainfall and runoff) in recent decades (Srikanthan et al. 2022a). However, low rainfall years still occur, as was the case in the 2018–19 wet season. This variability is a key consideration for any water management decisions in this region (Petheram et al. 2008; Pusey & Kath 2015; Douglas et al. 2019). There have been more hot days but evaporation rates have decreased (BoM 2021). Due to generally wetter conditions in the north-west, the mean warming trend has been supressed compared to other regions of Australia (Grose et al. 2016), which could reverse if the rainfall trend reverses.



Rangelands region

Rainfall trends in the Rangelands area are not spatially consistent across the region. Generally, a shift towards wetter years since the 1970s has occurred – likely due to rain falling in more localised and intense episodes. This has resulted in a corresponding increase in soil moisture and runoff (Oke et al. 2022). Rainfall patterns have shifted, with winter rainfall decreasing and summer rainfall increasing (BoM 2021). Temperature increases and more periods of consecutive hot days have been recorded (BoM 2021).

South West region

South-west Western Australia has become drier and is considered very likely to continue drying in future (IPCC 2021, 2022b). The rainfall decline has been greater than anywhere else in Australia and is highly attributable to human influence (DWER 2021). There are now fewer days of rain and the intensity and frequency of extreme events has decreased (Gallant et al. 2007). Increases in average annual temperature have corresponded with more frequent extreme heat events (Alexander et al. 2007) and longer periods of consecutive hot days for more inland areas (BoM 2021).

The drier and hotter climate is reflected in the lower average annual runoff of the past 50 years. Reduced runoff generation caused by decreasing rainfall since 1975 – and the associated decline in soil moisture, groundwater, and streamflow – has been widely reported (Write 1974; Fu et al. 2007; Bates et al. 2010; Petrone et al. 2010; Silberstein et al. 2012; CSIRO & BoM 2015a; Zhang et al. 2016; Wasko et al. 2021).

3.2 Projected climate change trends

In this section we summarise climate projections for Western Australia by region: the Kimberley, Rangelands and South West. You can use these as a quick reference guide for projected climate trends before getting into the detail of the climate projection data.

For some purposes, this level of information might be all you need – for example you may need a qualitative understanding of climate change impacts at the broad-scale to identify organisational-level risks and assess if more detail work is required. You can use high-level information such as that presented here, or from the *Western Australian climate projections summary* (DWER 2021), or Bureau of Meteorology, CSIRO and IPCC sources. For maps and charts of projection information go to the Australian Water Outlook website (BoM 2022). You can use these to quickly assess the spatial variability of projected changes (maps) and the range of projections (charts). For information on marine and coastal trends, and fire weather, go to the *Western Australian climate projections summary* (DWER 2021).

The observed drying trend in the South West is projected to continue. For the rest of the state, both wetter and drier rainfall futures are plausible projections.

Temperature and potential evapotranspiration are projected to increase throughout Western Australia. These increases will affect crop water demands and evaporation from waterbodies, including riverine pools and shallow groundwater. Increased temperatures may also directly affect vegetation and fire behaviour, which in turn will influence river flows and groundwater recharge.

Future changes can have interconnected and cascading effects. For example, decreasing rainfall, along with increasing temperatures and potential evapotranspiration, leads to deficits in dry-season soil moisture (important for vegetation health). This will influence the abundance and distribution of vegetation, which in turn affects surface water and groundwater, and so on.

Summary of climate trends projected for the Kimberley (Monsoonal North) region of Western Australia

(Srikanthan et al 2022; DWER 2021)

Temperature

Projected climate trend

- Higher temperatures.
- Increased potential evapotranspiration.
- Hotter and more frequent hot days.

Description

- Average, maximum, and minimum temperatures are projected to increase in all seasons.
- The temperature and frequency of very hot days is expected to increase, and heatwaves will get longer and more intense.
- Evapotranspiration (water loss from plants and soil) is projected to increase.

Rainfall

Projected climate trend

- Increases, decreases, or unchanged wet season rainfall.
- Increased intensity of rainfall events.
- Fewer but more intense tropical cyclones.

Description

- The direction of future rainfall change is unclear, and the changes are unevenly distributed across the region.
- While the GCMs cannot represent key climate drivers associated with monsoonal rain, both increases and decreases in wet season rainfall are plausible.
- Little change to dry season rainfall is projected.
- Rainfall events are projected to be more intense.
- Tropical cyclones are projected to decrease in frequency but it is expected that a greater proportion will be higher intensity.
- Multi-year dry periods are projected to increase.
- Natural climate variability remains the main driver of rainfall changes in the next few decades.

Water in the landscape

Projected climate trend

- Reduced soil moisture.

Description

- Increased temperature and evapotranspiration combined with the possibility of reduced or unchanged wet season rainfall has flow-on effects, producing projected decreases in dry-season soil moisture.

Summary of climate trends projected for the Rangelands region of Western Australia

(Oke et al 2022; DWER 2021)

Temperature

Projected climate trend

- Higher temperatures.
- Increased potential evapotranspiration.
- Hotter and more frequent hot days.

Description

- Average, maximum, and minimum temperatures are projected to increase.
- A substantial increase in the temperature reached on the hottest days and the frequency of hot days is projected.
- Evapotranspiration (water loss from plants and soil) is projected to increase.

Rainfall

Projected climate trend

- Increases, decreases, or unchanged wet season rainfall.
- Increased variability of rainfall.
- Increased intensity of rainfall events.
- More drought.

Description

- Projected changes in rainfall are not consistent across the region, in space or in time.
- There is a projected decrease in dry season (winter and spring) rainfall.
- The direction of change in annual and wet season rainfall (summer and autumn) is unclear but tends to project a wetter future.
- Rainfall events are projected to be more intense.
- There is a projected increased variability in the climate and projected increases in length of dry spells/drought.

Water in the landscape

Projected climate trend

- Reduced soil moisture
- Decrease in runoff
- Decrease in groundwater recharge.

Description

- Increased temperature and evapotranspiration combined with the possibility of reduced or unchanged wet season rainfall has flow-on effects, producing projected decreases in dry-season soil moisture.
- Runoff and groundwater recharge are projected to decrease.

Summary of climate trends projected for South West region of Western Australia

(*Turner et al 2022; DWER 2021*)

Temperature

Projected climate trend

- Higher temperatures.
- Increased potential evapotranspiration.
- Hotter and more frequent hot days.
- Each individual season is projected to warm by about the same amount as the annual mean.

Description

- Average, maximum, and minimum temperatures are projected to increase in all seasons.
- The temperature and frequency of very hot days is expected to increase, and heatwaves will get longer and more intense.
- There will be a reduced number of days with frost risk in the long term. Near-term frost risk may not change.
- Evapotranspiration (water loss from plants and soil) is projected to increase.

Rainfall

Projected climate trend

- Declining rainfall.
- Decreases in wet season rainfall.
- Increased intensity of rainfall events.
- More drought.

Description

- The observed drying trend is projected to continue with declines in annual and wet season (winter and spring) rainfall.
- Hourly to one-day rainfall events are projected to be more intense.
- The time spent in extreme dry conditions, including the length and spatial extent of multiyear dry conditions, is projected to increase.

Water in the landscape

Projected climate trend

- Reduced soil moisture.
- Decrease in runoff.
- Decrease in groundwater recharge.

Description

- Drier and hotter conditions will lead to decreases in soil moisture, runoff and recharge that could further exacerbate drought conditions.

4 First Nations peoples' climate and water knowledge

First Nations peoples have a deep understanding of climate and the seasons, developed through millennia of experience and observations. Knowing the relationship between seasons and plants, animals, water, weather and fire was crucial to survival, and helped First Nations peoples adapt to the shifting climate patterns caused by the last ice age of about 20,000 years ago. Expressed through seasonal calendars, traditional knowledge is a way to describe the highly complex climate and seasonal changes and how they relate to Country. These calendars provide an insight into the ecological, meteorological, and hydrological knowledge of Australia's first scientists and demonstrate the profound knowledge of First Nations peoples. This knowledge is highly detailed, localised, and unique to each language group.

Storage of data on Indigenous climate, weather and cultural knowledge is underway – see the Bureau's Indigenous weather knowledge website. The CSIRO has several Indigenous seasonal calendars available for download.

First Nations peoples in urban and regional areas are vulnerable to the impacts of climate change. It affects the availability of bush foods, medicines and fishing and hunting practices. Extreme events cause heat stress, affect drinking water quality, damage infrastructure and homes, cause water-borne viruses and prevent access to culturally important areas. Evacuation orders separate communities from their Country (Hay and Williams 2023).

Indigenous knowledge can provide insight into climate change, its impacts, and adaptation strategies. Stories and practices passed down through generations of First Nations peoples show ways of recognising climate variability and seasons, looking after the land through changing climates and ways to survive extreme weather events (Hay and Williams 2023; King and Cottrell 2007). This traditional knowledge, incorporated into seasonal calendars, provides detailed insight into the interactions between water, ecosystems, fire and seasons. It provides the baseline ecological and seasonal data on which to measure the impact of climate change on the natural environment.

First Nations peoples have told us that the seasons are changing, plants and animals are now behaving differently, and that water places are under threat (DWER 2023a). They see that climate change is occurring now, and this must be recognised and addressed in a collaborative way. Traditional knowledge is part of this process, both for understanding what is happening on Country, and developing solutions to the problems that climate change presents.

Increased knowledge will come if we strengthen our partnerships, collaboration and understanding and listen to First Nations peoples and communities. Current best practice resources for appropriately consulting First Nations peoples is available through the CSIRO Our Knowledge, Our Way website, and the *Our knowledge our way in caring for Country* best practice guidelines (Woodward et al. 2020).

When implementing the framework outlined in this guide, we recommend consulting with First Nations peoples early in the process to find out who wants to be involved and with which steps. It is important to also discuss the acceptable level of risk and how the assessment should be communicated.

5 Understanding climate projections modelling

5.1 Global climate models

Global Climate Models (GCMs) are mathematical representations of the climate system that help us understand what drives climate change, how and why climate changed in the past, and what it may look like in the future. They are used to investigate how the global climate will respond to future greenhouse gas and aerosol concentrations (BoM 2022). Their fundamentals are based on the laws of physics, including conservation of mass, energy and momentum (CSIRO and BoM 2015b). They represent the atmosphere and ocean as three-dimensional grids, with a typical horizontal resolution of around 200 km.

The main inputs into GCMs are the external factors (also known as forcings) that affect the amount of the sun's energy absorbed by the Earth, or how much is trapped in the atmosphere. These include the sun's output, greenhouse gases and aerosols. These individual forcings are run through a model either as a best estimate of past conditions or as part of future emission scenarios (elements of the representative concentration pathways, see Section 5.2). Because the magnitude and timing of global warming depends on future human behaviours that affect greenhouse gas emissions that we cannot predict with certainty, we consider a range of scenarios instead.

While many of the broad-scale mechanisms of climate change are well understood, each GCM may include different ways of simulating particular details of the climate system, including different numerical schemes and different representations of sub-grid processes (BoM 2022). As such, GCM outputs may differ even when starting from identical initial conditions (i.e. the climate variability is different in every simulation). Each GCM produces slightly different projections, especially regarding temperature and rainfall (BoM 2022).

GCM-generated climate projections by their nature are scenarios of equally plausible futures, with ranges of possibilities rather than a single prediction of what will happen. While most models perform reasonably well, there is no single 'best' model or subset of models (CSIRO and BoM 2015b). It is good practice to explore the full range of GCM projections, or else a representative subset of the model results.

GCMs are not expected to reproduce the observed events, and they will inevitably have differences from observations in terms of statistics as well, due to factors such as running models at coarse resolution and our imperfect understanding and representation of some processes (e.g. how clouds form and change). Confidence in the use of models for projections comes from their basis in fundamental physical principles and from their ability to represent important features of the current and past climate (CSIRO and BoM 2015b).

For the National Hydrological Projections, the Bureau selected four GCMs (Srikanthan et. al 2022a and b) which:

- best reflected observed climate conditions and climate processes for Australia
- had data available for the main climate inputs to the Australian Water Resources Assessment Landscape hydrological model (temperature, wind, rainfall and solar radiation) (AWRA-L, version 6.1) (Frost and Wright 2018)
- are representative of the spread of plausible change from the larger set of 8 models (see below) and of the full set of over 40 CMIP5 models in terms of change in temperature, rainfall and wind for different seasons and different regions of Australia. No subset of four can fully cover the range of CMIP5 models, but this subset is representative for many cases.
- could be run through the re-gridding, downscaling and bias correction processes within time and budget constraints.

The four models are a subset of the eight models used in *Climate Change in Australia* (CSIRO and BoM 2015a) and are a useful subset of the full set of GCMs that are part of the World Climate Research Programme's CMIP5. This is because they:

- all represent the climate of Australia to a sufficient standard for projected future changes to be considered plausible
- are relatively independent models (the models are not too similar)
- provide a representative sampling of the range of possible temperature changes and possible wetter and drier rainfall changes from the full set of models, including a very dry projection (GFDL-ESM-2M) through to a model representing the wetter end of possibilities (CNRM-CM5).

For model selection information go to the Bureau's website (BoM 2022) and to *Climate Change in Australia* (CSIRO and BoM 2015a).

GCMs were assessed to be fit-for-purpose in terms of their ability to capture important aspects of climate variability and how they represent important climate processes. Srikanthan et al. (2022b) report on the performance of the models in the three natural resource management areas that cover Western Australia (as well as the rest of Australia).

5.2 Representative concentration pathways

Scenarios of future greenhouse gas and aerosol concentrations, together with land use change, are known as representative concentration pathways. Governments and other institutions use these to explore credible futures for decision-making (BoM 2022). CMIP3 referred to representative concentration pathways as emission scenarios (IPCC 2007). CMIP6 refers to them as shared socio-economic pathways (IPCC 2022a). GCMs simulate future climate using the representative concentration pathway inputs. The modelled climate varies over the longer term of the simulations in response to changing atmospheric levels of greenhouse gases, aerosols, and ozone in the upper atmosphere.

The IPCC's 5th assessment included the following representative concentration pathways:

- very low future concentrations – RCP 2.6, likely to result in less than 2˚C global warming by 2100 relative to preindustrial era (the Paris Agreement limit)
- medium future concentrations – RCP 4.5 and RCP 6.0
- very high future concentrations – RCP 8.5, a return to accelerating emissions, now considered an unlikely worse case pathway.

They are labelled with the possible radiative forcing in watts per square metre in the year 2100. The emissions pathways and concentrations diverge from the time they were defined (2005), but the mean global temperature increases, and many regional climate changes are similar up to 2050 under all the pathways, but deviate from each other beyond this time (CSIRO & BoM 2022) (Figure 4 and Figure 5).

The politics of climate change and technological developments will influence where greenhouse gas emissions head into the future. As the climate-relevant policy and technology evolves, this may mean that a particular representative concentration pathway becomes more relevant or that new emission scenarios become the focus.

Currently the 1.5 degree (above pre-industrial levels) ambitious limit from the Paris Agreement will be reached in around the early 2030s, and the climate will only stabilise somewhere near that under a scenario even more ambitious than RCP2.6 (called SSP1-1.9 in the latest generation of scenarios) (Grose et al. 2021).

To return warming to 1.5°C assumes immediate and drastic global reductions in emissions from 2020, reaching net-zero emissions by 2050, and negative emissions thereafter (an emissions scenario between RCP 2.6 and RCP 4.5) (WMO 2022; IPCC 2022b). At the time CMIP5 was released, without additional efforts to constrain emissions, the future was expected to lead to greenhouse gas emission and concentration pathways ranging between RCP 6.0 and RCP 8.5 (IPCC 2014a and b). In the time since the release of the IPCC's 5th assessment report, the rapid development of renewable energy technologies and emerging climate policy have made it less likely that emissions could end up as high as RCP 8.5, but it cannot be ruled out (IPCC 2022a). RCP 8.5 does not represent a typical 'business-as-usual' projection but is useful as a high-end, high-risk scenario (IPCC 2022b).

All RCPs should be considered possible, and the set of RCPs considered to span a plausible range of change. They diverge in 2005 and our actual emissions have tracked in the upper range of RCPs between then and now. This does not provide a sufficient case to choose some RCPs as most likely and reject others as implausible for the remainder of the century – we don't know how the next 75 years will unfold. However, some RCPs can be given lower weight or focus depending on the application. For a risk management approach to water resource management, the greater changes associated with moderate and higher RCPs represent greater risks to mitigate than a lower RCP. Also, the effect of a low RCP such as RCP2.6 can be considered similar to the others in the medium term (to around 2040 or 2050) and then stabilising near that change for the remaining years to 2100. Therefore, the lower RCP2.6 is put in context but not explicitly modelled or analysed for the Bureau's National Hydrological Projections. The Bureau analyses two higher RCPs as follows:

1. RCP 4.5 represents a future with some mitigation resulting in mid-level greenhouse gas emissions that peak around 2040, the CO_2 concentration reaching 540 ppm by 2100, and a mean global temperature increase between 1.7 and 3.2°C by 2100 relative to the pre-industrial period of 1850–1900 (Met Office 2018).
2. RCP 8.5 represents a future with ongoing high greenhouse gas emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100, and a mean global surface temperature increase between 3.2 and 5.4°C by the end of the century relative to 1850–1900 (Met Office 2018).

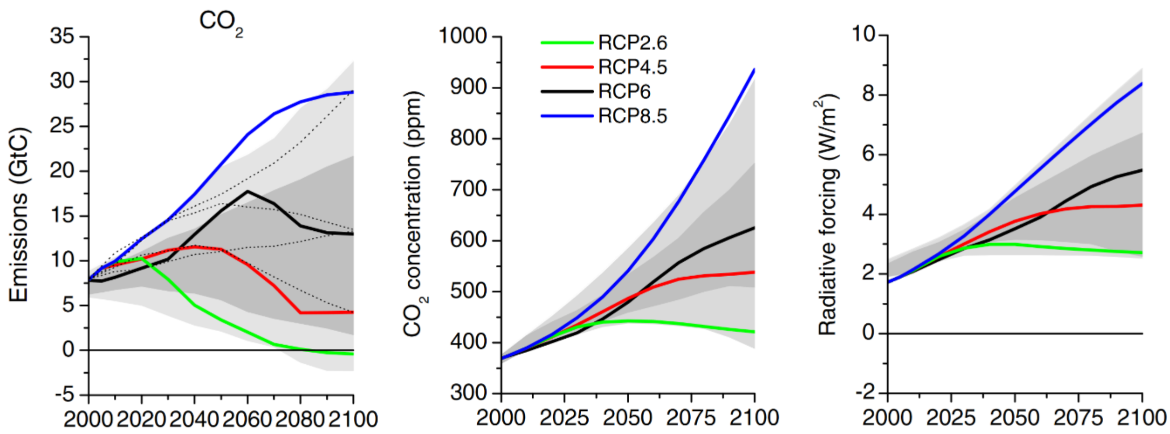


Figure 4 Global scenarios for carbon dioxide emissions in gigatonnes of carbon (left), carbon dioxide concentration in parts per million (centre) and radiative forcing in watts per square metre (right) for the four representative concentration pathways – the final radiative forcing at 2100 gives each scenario its name (8.5, 6, 4.5, and 2.6 W/m²) (van Vuuren et al. 2011)

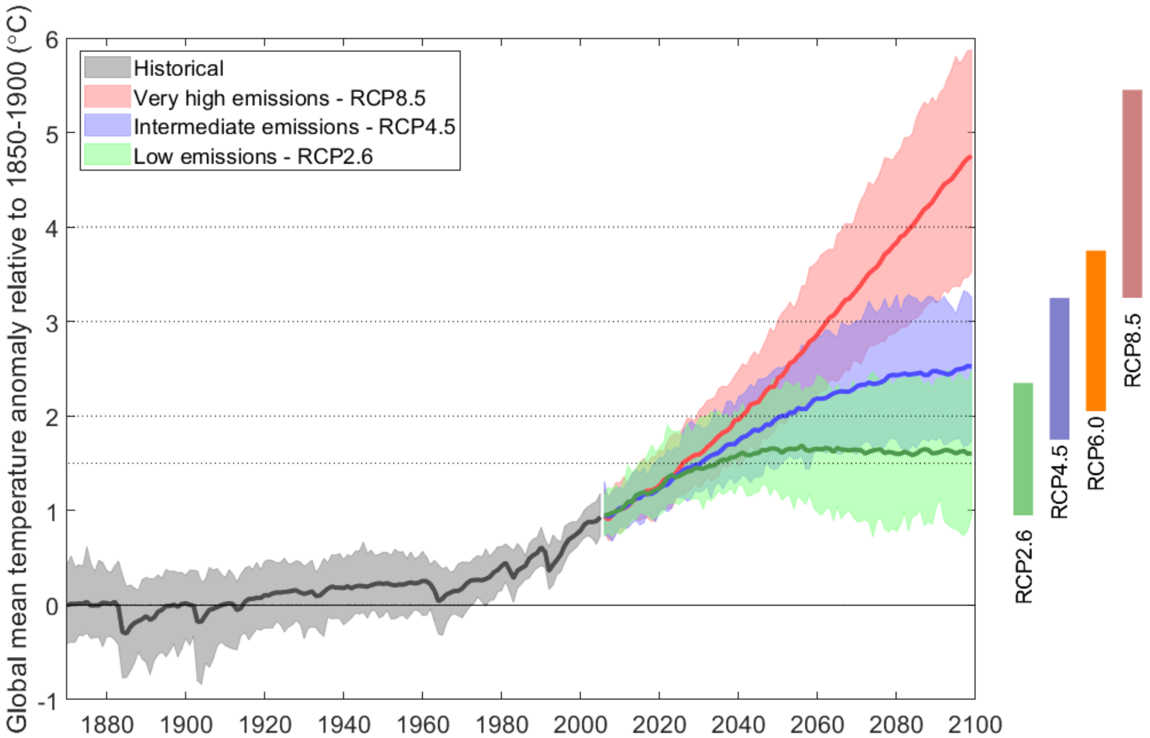


Figure 5 Global temperature change resulting from each representative concentration pathway – global temperature change expected in the next decade is similar under all the representative concentration pathways (Adapted from IPCC 2014a)

5.3 Downscaling methods

GCM output must be refined to a small spatial scale to be useful for local-scale assessment. The outputs from the GCMs and regional climate model have been re-gridded to a 5 km grid across Australia. The Bureau used two approaches for the National Hydrological Projections:

1. re-gridding – the GCM outputs were re-gridded to a 5 km resolution
2. dynamical downscaling and re-gridding – a regional climate model was used to dynamically downscale the GCM projections before re-gridding.

Regional climate models are typically limited-area (not global) models at a higher spatial resolution than GCMs and consider additional Australia-specific climate factors and physical principles such as local topography. The Bureau of Meteorology (2022) used the CSIRO's Conformal Cubic Atmospheric Model (CCAM-r3355) – a high-resolution regional climate model which uses a 50 km grid over Australia (Rafter et al. 2019). It differs from other regional climate models in that it is a global model with the grid point spacing stretched to achieve increased resolution over Australia.

The CCAM projects a notably drier future for Western Australia than the GCMs used as inputs. This provides another plausible projection of change, where this change may be produced by the correction of inputs, the resolutions of finer scale processes producing regional rainfall, or some other factor. Preliminary studies into CCAM show that it adds value: for its ability to represent coastal circulations across most of the state and its improved temperature projections for the greater Perth area (Ulrike Bende-Michl, personal communication, 30 April 2023). Another example from outside WA is the different projections over the Australian Alps, where regional modelling suggests a plausible enhanced drying on the windward slopes (Grose et al. 2019).

5.4 Bias correction methods

Both global and regional climate models have systematic differences from observed datasets (biases) in their output. For example, they often have too many days with persistent low rainfall when there should be none ('drizzle problem') and tend to underestimate rainfall extremes compared to observations from weather stations and other sources. There can be errors in the timing of the monsoon or the amount of seasonal rainfall, or temperatures can be consistently too high or too low. A range of factors can cause errors or biases in climate models: limited spatial resolution (large grid sizes), simplified thermodynamic processes and physics, or incomplete understanding of the global climate system and feedback loops. The use of uncorrected outputs in climate impact assessments and surface water, groundwater, and water quality modelling could, in some cases, give unrealistic results.

Several bias correction methods have been developed to improve the representation of local climate conditions (percentiles) and reduce biases relative to observed data (BoM 2022). Application of bias correction methods help to overcome the larger biases in climate models and produce outputs that are calibrated to an observed dataset, so it is convenient to use. For all methods, the quality of the observational datasets used determines the quality of the bias correction. Good bias correction requires a suitable observation dataset; for example, if correcting extreme rainfall, then a quality long-term observed dataset is needed.

For the National Hydrological Projections, the Bureau used quality observation datasets from the Australian Water Availability Project dataset (AWAP; Jones et al. 2009). It applied three bias correction methods (Table 4) to the data from the four re-gridded GCMs (producing 12 datasets – or 24 if you consider both representative concentration pathways). It then applied one bias correction method (ISIMIP2b) to the four dynamically downscaled (and re-gridded) GCMs (producing four more datasets – or eight if you consider both representative concentration pathways). This modelling framework results in 32 projected climate futures.

The observed dataset used for bias correction shapes the representation of local climate conditions in the projection data, so if you intend to apply the National Hydrological Projections to a hydrological model, the AWAP observed dataset used for bias correction is the most suitable to use in calibrating your model.

Remaining bias between modelled and observed climate conditions – after bias correction – is reported at mean annual, seasonal, monthly, and daily maximum scales for rainfall, temperature, soil moisture, potential evapotranspiration and runoff for each region by Srikanthan et al. (2022a), Oke et al. (2022) and Turner et al.

(2022). Overall, the evaluation shows an ability to replicate observations, however noting that the natural resource management regions cover large areas outside the state, the values presented are not specific to Western Australia. In many areas of the state, rain gauge networks and river gauging stations are sparse and therefore not available for calibration.

Bias correction techniques do not impact on the overall climate change signal as much as the representative concentration pathways and GCMs.

Table 4 Bias correction methods, with description

Bias correction method	Acronym	Description
Quantile Matching Extremes (Dowdy 2020)	QME	Univariate, quantile-based method that adjusts for extremes at seasonal scales (not corrected at daily and monthly scales) (Srikanthan et al. 2022a)
Intersectoral Impact Model Intercomparison (Hempel et al. 2013)	ISIMIP2b	Univariate, quantile-based method that preserves long term trends in the data and adjusts for dry days (Srikanthan et al. 2022a)
Multivariate Recursive Nested Bias Correction (Johnson & Sharma 2012; Mehrotra & Sharma 2017)	MRNBC	Preserves the interdependence between multiple variables across daily, monthly, seasonal and annual time scales to represent low-frequency variability (Srikanthan et al. 2022a)

5.5 National Hydrological Projections summary

The Bureau of Meteorology's National Hydrological Projections are produced from a subset of the CMIP5 representative concentration pathways and GCMs that have previously been assessed to represent the Australian climate (CSIRO & BoM 2015a). The Bureau sampled the uncertainty range by selecting two representative concentration pathways and four GCMs to represent wetter, drier and average future conditions (explained further below). The downscaling and bias correction processes applied to the GCM data improve the representation of local climate conditions and reduce biases relative to observed data (Srikanthan et al. 2022a).

The National Hydrological Projections were developed by:

- selecting two representative concentration pathways and four GCMs from CMIP5
- using outputs from CSIRO's Conformal Cubic Atmospheric Model (CCAM-r3355) regional climate model (Rafter et al. 2019) to produce dynamically downscaled data from the GCMs
- re-gridding the GCM data and the dynamically downscaled (regional climate model) data into a 5 km grid scale

- adjusting the discrepancies between climate input and observation using three bias correction methods – one bias correction method on the dynamically downscaled data and all three on the GCM data
- running the climate data (32 datasets) through the Australian Water Resources Assessment Landscape (AWRA-L) (Frost and Wright 2018) hydrological model to project hydrological change variables and hydrological extremes.

Figure 6 illustrates the Bureau's approach. For a detailed description of the modelling process and a technical assessment of performance, see Srikanthan et al. (2022a).

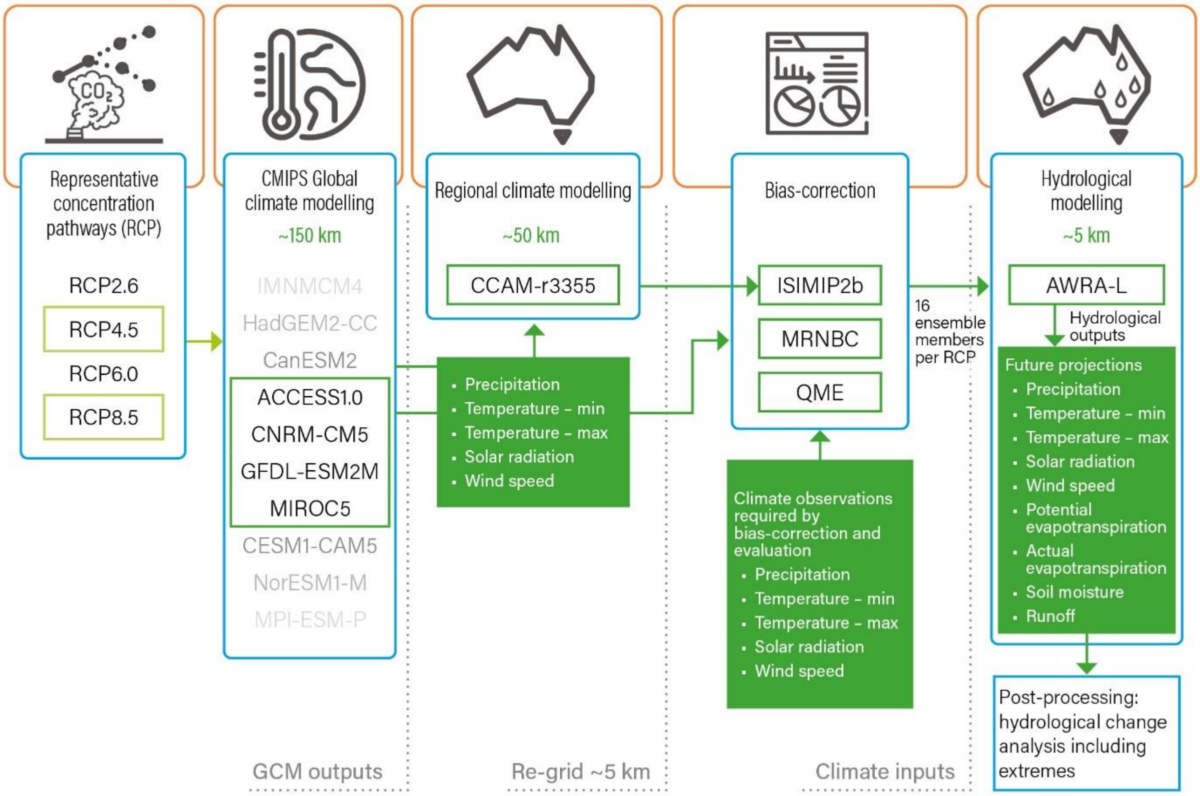


Figure 6 Illustration of climate data processing for the Bureau of Meteorology's National Hydrological Projections (adapted from Chiew et al. 2022 (CC BY); Turner et al. 2022; Oke et al. 2022; Srikanthan et al. 2022a)

Australian Water Resources Assessment Landscape model (AWRA-L)

Climate variables from the downscaled climate models are used as inputs to a landscape hydrological model to produce runoff, soil moisture and potential evapotranspiration across Western Australia.

Co-developed by the Bureau of Meteorology and CSIRO, AWRA-L is a gridded, distributed water balance model. The model estimates runoff, daily soil moisture, and actual and potential evapotranspiration on a 5 km grid for all of Australia. It is calibrated to a wide range of climate conditions with a set of common parameters to simulate hydrology over a large range of climate, geological and vegetation conditions (BoM 2022).

We recommend users assess the suitability of outputs from the AWRA-L version 6.1 model by viewing the validation report (Frost and Wright 2018) and uncertainty report (Azarnivand et al. 2022). You should tailor the assessments to your application – such as how well runoff matches observations at specific streamflow gauging stations, locations, or relevant statistical aspects such as baseflows. The model's estimation of runoff does differ spatially depending on the number of streamflow gauges used in the calibration process. Users should consider the following observations.

- Runoff from AWRA-L should only be used for regional-scale applications. Initial testing shows, for example, that:
    - AWRA-L runoff appears to have the right timing of flow but incorrect magnitude for the Pilbara region. Therefore, we do not recommend using it for event-based or detailed yield analysis.
    - A large difference (up to 25 per cent) exists between observed and modelled runoff for the South West. We recommend local hydrological modelling is undertaken in this region. This is particularly important given the effects of climate change and limited water availability continue to present challenges for water resource management in the region.
    - The precision in the runoff for zero-flow days should be checked using spells analysis or a flow duration curve. Numerical precision has made significant volume differences for large catchments, before any rainfall/runoff events occurring.
- AWRA-L better captures the runoff dynamics in consistently wetter regions with perennial rivers, and longer wet periods. Runoff regimes that consist of long dry periods followed by short periods of extreme rainfall are more difficult to characterise (Srikanthan et al. 2022a; Azarnivand et al. 2022).
- Groundwater–surface water interactions are not well represented in AWRA-L, resulting in a drop in performance in areas where streamflow has a high dependence on the contribution of baseflow (Srikanthan et al. 2022a). AWRA-L has a minimum deep recharge so it cannot model zero-flow days – thus baseflow, low flows and cease-to-flow will be inaccurate.
- Wasko and Nathan (2019) analysed streamflow trends post 1970, looking at streamflow observations and AWRA-L modelled runoff. They found that AWRA-L could not match the trend direction in runoff in the Rangelands. Note that only one site was available for the analysis given the overall streamflow data sparseness in this part of the country (Oke et al. 2022). Other points to note include:
    - Areas in the Rangelands dominated by rock and impermeable surfaces are not modelled as a separate land use type in AWRA-L version 6.1.
    - Most of the calibration and validation catchments located in the Rangelands are for the region's wetter north-west area (Frost and

Wright 2018). Streams in the remaining area are mostly non-perennial with high baseflow dependency – factors not well represented in AWRA-L (Azarnivand et al. 2022).

You could use AWRA-L runoff outputs as a first-pass assessment to find out what projections to run in more detail. This may help with the storyline approach outlined in Chapter 6.

Historical baseline period evaluation and future time horizons

The Bureau uses a reference period from 1976 to 2005 to assess absolute and relative changes. It selected this period for numerous reasons including:

- the 30-year period smooths out variations in model outputs and is a typical length of record used to calculate average climate conditions
- it is after the observed climate shift that started in the mid-1970s (rainfall decline in south-western Australia; temperature shift in the tropics and Southern Hemisphere oceans)
- GCM results are not based on observations after 2005
- it is consistent with the baseline period of the Climate Change in Australia projections (BoM 2022).

The Bureau used the reference period to assess whether the downscaled models could reproduce observed climate statistics (from AWAP) before bias correction, and to assess future changes. Note that the modelled climate data is not intended to reproduce daily observations exactly, but rather its value lies in how it captures statistical aspects of variability as well as important climate processes using climate statistics (e.g. decadal averages, standard deviations).

The Australian Water Outlook reports projected changes compared with the GCM historical baseline data (not observations) over the reference period. The projected changes are based on data aggregated in 30-year periods centred around 2030, 2050, 2070 and 2085. For example, 2050 represents the 2036 to 2065 period. This means that percentage change between an observed baseline dataset (e.g. AWAP, SILO or gauged data) and the future climate projections may be different to those reported on the AWO website.

Projection variables, information and accessing the data

Future projections of the following variables, produced at a daily timestep on a 5 km grid, are available from the Bureau:

- precipitation
- temperature – minimum
- temperature – maximum
- solar radiation
- wind speed

- potential evapotranspiration (Penman; output from AWRA-L model)
- actual evapotranspiration (output from AWRA-L model)
- soil moisture (output from AWRA-L model)
- runoff (output from AWRA-L model).

Go to the Bureau's AWO website for more information on the projections. On the website you can view maps, charts and statistics related to future climate by region, as well as find historical hydroclimate and water resource variables.

Continuous daily time-series modelled data from 1960 to 2099 is available for modelling use. Application-ready datasets are available from the NCI data catalogue or you can obtain the data by emailing water@bom.gov.au. See Appendix A for instructions on how to submit your data.

Practitioners need to consider how best to interpret and present the results (e.g. to avoid them being seen as a prediction or forecast for individual days or years).

The Bureau and the department collaborated to produce several resources to help the Western Australian water sector plan and adapt to climate change. Click on the links to access them:

- **Maps, charts and statistics summarising future climate projections** – these are available nationally or by region on the AWO website. You can also access historical hydroclimate and water resource variables on the website.
- **Hydrological assessment reports** – these provide key climate projection findings for eight natural resource management (NRM) regions in Australia (Figure 7). Three reports cover Western Australia:
    - the Southern and South Western Flatlands (Turner et al. 2022)
    - Rangelands (Oke et al. 2022)
    - Monsoonal North (Srikanthan et al. 2022b).

  Note all three regions cover some land area outside of Western Australia, so assessment findings are not always state-specific. The reports also include technical details about how the climate projections were developed from the CMIP5 generation of climate modelling. See Section 3.2 for summaries of the outcomes for Western Australia.
- **Comparison report** – when available – this compares CMIP5 projections with those produced for Western Australia using CMIP3 datasets (DoW 2015) for rainfall in 2050 across Western Australia. See Chapter 7 for more information.
- **Application-ready datasets** from the National Computational Infrastructure (NCI) data catalogue – these are for technical specialists to understand how particular systems may respond to climate change for impact assessments and modelling. The new datasets include projected rainfall, temperature, solar radiation and wind speed – the main climate drivers relevant to the water sector. Landscape water balance model information is also available for

potential evapotranspiration, actual evapotranspiration, soil moisture and runoff. Users can register for access at NCI Australia or obtain the data by emailing water@bom.gov.au. See Appendix A for instructions on how to submit your data.

- **Demonstration case brochures** – when available – these cover the Myalup groundwater system (DWER 2024) and, in collaboration with the Water Corporation, Harding Dam (Water Corporation 2024). These show you how to apply the National Hydrological Projections for water resource management purposes.
- **National Hydrological Projections – design and methodology** (Srikanthan et al. 2022a).
- **This guide** on how to use climate information in risk-based decision-making for water resources in Western Australia (see Chapter 6).

The next section summarises the scientific information that supports the projections.

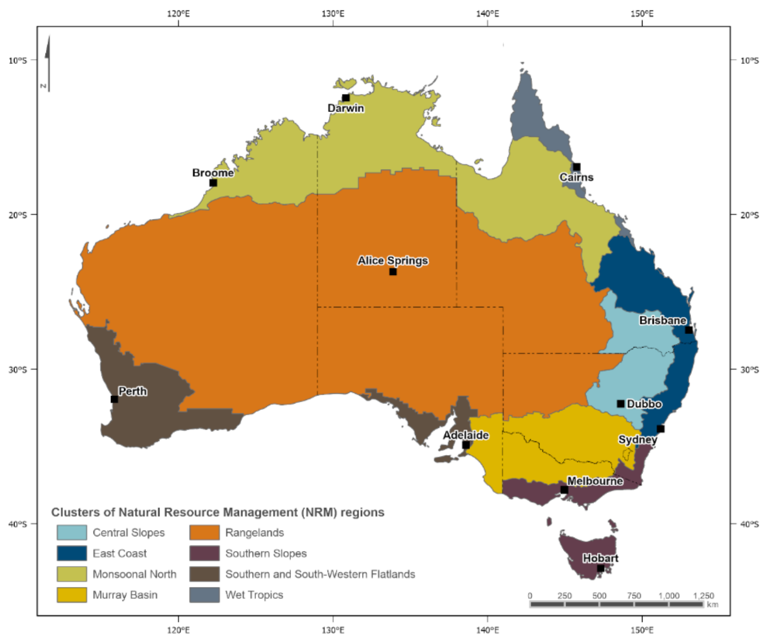


Figure 7 The eight natural resource management regions assessed in the Bureau of Meteorology's National Hydrological Projections (BoM 2022)

A note on data sources

If you intend to use the future projections for potential evapotranspiration, soil moisture or runoff, we recommend you use the Bureau's AWRA-L historical data. This will provide data from a consistent source that uses the same methods for collecting, interpolating and gridding data.

When using a source other than AWAP and AWRA-L for historical data, you need to be aware that different gridding methods (e.g. AWAP and SILO) produce different results, even when based on the same observed data. It would be prudent to obtain the AWAP data and make a comparison. If your historical data is consistently different from the AWAP data – you will need to think about how that affects your interpretation of projections or water model simulations relative to your historical data, or model calibration.

A note on evapotranspiration estimates

Potential evapotranspiration (PET) is the amount of evaporation and transpiration that would occur at a particular location if the water available for this process were unlimited. PET is not measured directly, and there are numerous ways to estimate PET for different hydrological purposes (Table 4; McMahon 2013). The National Hydrological Projections produces PET as an AWRA-L model output, which uses the Penman method (Penman 1948).

Ideally, practitioners should use the same PET estimation method throughout a hydrological model: for calibration and simulations. For new models and models able to be recalibrated, we recommend using historical Penman PET from the Bureau for calibration – for consistency with the PET used in climate projection simulations. This data is not available on the AWO website but you can obtain it from the NCI or email a request to water@bom.gov.au. You should request the data from the same version of AWRA-L for both the historical and projection data (at the time of writing, AWRA-L version 6.1). Also note that the historical PET data is available from 1911, but due to the changing availability of weather observations over time, the data inputs used to calculate PET (wind, solar radiation, and albedo) is only consistent with future projections from 2000.

If you are using a model already calibrated using another type of PET variable (e.g. Penman-Monteith, Morton's shallow lake or synthetic pan), or you are using the National Hydrological Projections but cannot re-calibrate the model, you can adjust the projected Penman PET using monthly or seasonal scaling factors to approximate the PET type you are using. You can develop the scaling factors by examining the correlation between the PET data used for calibration and the historical Penman PET.

The National Hydrological Projections do not include an open water evaporation variable. Where evaporation rates are high and account for a large proportion of the water balance, such as Harding Dam in the Pilbara region, evaporation estimates need to be based on an open water variable. You could use the scaling method mentioned above or, for specific requests, the Bureau may be able to make projections of Morton shallow lake evaporation estimates for major storages at point sources (note this will not be projected for the whole national or state grid).

The Bureau can provide application-specific advice regarding the various sources of evapotranspiration and evaporation data, and the consistency between historical and projected datasets.

Other variables of interest to the water sector

Other variables may be required for future climate assessments that are not available through the AWO. Table 5 describes some of these variables and where you can find them.

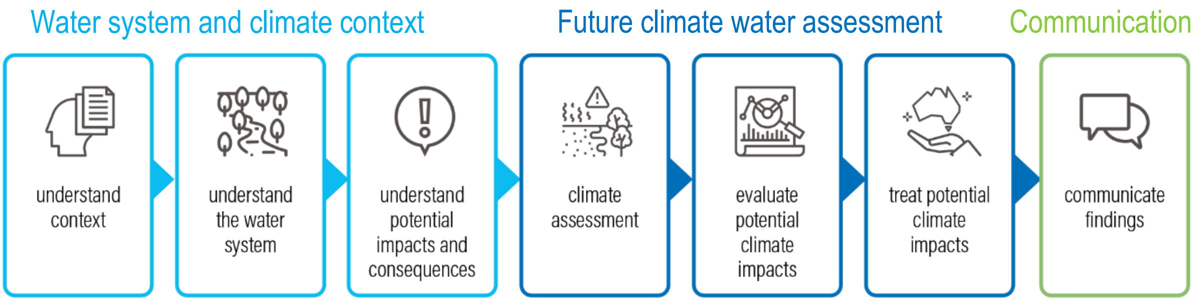
Table 5 Variables not found on the AWO website and where you can find them

Variable	Where to find it
Observed climate data	Climate data online – map search (bom.gov.au)
Sub-daily rainfall	Water information reporting | Western Australian Government Weather station directory (bom.gov.au)
Rainfall intensity-frequency-duration for design peak estimates	Rainfall IFD data system: water information (bom.gov.au)
Relative humidity	www.bom.gov.au/climate/data/
Pan evaporation	Climate Change in Australia www.climatechangeinaustralia.gov.au (CSIRO & BoM 2015a)
Tide	www.transport.wa.gov.au/imarine/tide-data-real-time.asp
Sea level	Australian Baseline Sea Level Monitoring Project (BoM) www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml
Sea surface temperature	Integrated Marine Observing System imos.org.au/

6 Climate assessment framework

Our climate assessment framework for applying climate projection data in water resource planning and decision-making comprises three stages – understanding the water system and climate context, assessing climate change impact to a water system, and communication. The diagram below summarises each step in the framework. While we present the steps in the framework as a linear progression, in practice you may approach the steps iteratively or simultaneously.

We recommend that you work through the framework with your team of subject matter experts, First Nations peoples and other stakeholders, including ultimate decision-makers. As discussed in Section 4, First Nations peoples should be consulted to understand who would like to participate, which steps they wish to participate in, to discuss the acceptable level of risk and how the assessment can be communicated.



The underlying principle of the framework is that climate change should be incorporated into water planning and decision-making by acknowledging the range of plausible future climate projections and assessing the climate risk to the water resource.

The degree and complexity of your future climate analysis should be based on the decision you want to make or your planning objectives. This will vary depending on the type of assessment (e.g. water supply, drainage, salinity management), the objectives, levels of resourcing, the level of acceptable risk, and the ability to adapt. For example, a water supply infrastructure decision is likely to require a low-risk solution, is likely to be well resourced, have limited adaptation options, and therefore require (and be capable of delivering) a high level of climate analysis.

Most climate-dependent water management decisions will have some level of risk; for example, to the environment (e.g. declines in streamflow or groundwater levels risk reducing ecological habitat) or to water users (less water availability impacts livelihoods and the economy). Large uncertainties are inherent in projections of future climate; thus, climate risk management relies on our capacity to be comfortable with the level of uncertainty and manage to a level of risk so that we may respond with effective adaptation strategies. The level of acceptable risk will vary for different parts of the water sector according to the risk appetites and tolerances of decision-makers and stakeholders (Box 1).

Box 1 – Drivers of climate change risks

The drivers of climate change risk are presented in IPCC (2014b) and adapted in the figure below. Risk is defined as "the potential for consequences where something of value is at stake and where the outcome is uncertain …" (IPCC 2014b, p1048). Climate risk is a function of climate hazards (physical climate events or trends), the degree of exposure to the hazards (valued assets in places and settings that could be adversely affected), and the vulnerability (or predisposition) to the negative effects of the hazard (Ministry for Environment 2019). DCCEEW (2023) considers a fourth determinant of 'response', which is imbedded within hazard, exposure and vulnerability. Adaptation actions (socio-economic pathways) and climate change will continue to be the central drivers of hazard, exposure, and vulnerability (Ministry for Environment 2019). However, complex risks arise from interacting, cascading, and compounding risks from multiple risks occurring concurrently, risks interacting, and risks transmitted through interconnected responses (DCCEEW 2023).

Source: Figure adapted from IPCC (2014b)

A risk management approach provides a helpful framework for climate change decision-making, particularly iterative risk management which involves an ongoing process of assessment, action, reassessment, and response that continues over time (NWI 2017). Numerous risk assessment documents have been developed for Australia and Western Australia – see Chapter 8.2. Although these are not specifically for water-related applications, the information in them has contributed to the approach this guide adopts.

Traditional risk assessments aim to understand the nature and level of risk, with risk usually considered to be a combination of the consequence and likelihood of an event. Marchau et al. (2019) distinguishes risk in the context of uncertainty and describes levels of uncertainty which can be quantified using probabilities and losses. In this guide, we place an emphasis on assessing potential consequences and not on quantifying likelihood. This is because climate change causes cascading and gradual-onset impacts to a system, and the risks associated with the impacts are not strictly event-based (Ministry for Environment 2019). Also, there is uncertainty in the climate models, which is further compounded when a subset of models or projections are used. For these reasons, estimating the likelihood of occurrence is less useful (Ministry for Environment 2019), and the emphasis for decision making is on assessing the potential consequences through a storyline approach.

Following from the discussion above, this guide does not provide a traditional risk assessment framework. Instead, we focus on establishing decision parameters that adequately define the climate change attributes of the water system and identify the consequences (Black et al. 2015). The refined outputs from this climate assessment framework are suitable inputs to a formal risk assessment.

We recommend using the concept of ‘storylines’ to decide on the best use of future climate projections for each assessment (see Box 2). Storylines also provide a clear narrative for proponents, stakeholders, and government departments for assessing potential impacts of a change in future climate to water systems, and therefore inform adaptation planning.

Our climate assessment framework takes you through the process of understanding your system and problem, to making a future climate assessment and choosing how to use projections, and finally to communicating your findings. We have designed the framework as a series of questions to help water resource managers and decision-makers understand, assess and report on appropriate climate projections for their application.

Box 2 – Storylines

The conventional approach to interpreting climate models and representing uncertainty in future climate is to use statistics to describe the many, and sometimes conflicting projections underpinned by climate models (even though the forcing scenarios are not probabilistic). The storyline approach to climate change – which is to identify physically consistent, plausible pathways – helps manage future projections without relying on their statistical properties.

In this guide, creating a storyline means to identify and describe the aspects of climate change that drive the water resource responses you are interested in. You can use these storylines to identify projections relevant to an assessment, help understand climate impacts and adaptation strategies, and provide context for communicating findings.

Plots and other visualisations of the projections as storylines can be used to illustrate how those aspects of climate change are represented in the future climate projections (See in Example 1 and Example 2). Plotting measures of climate (climate variables and statistics, metrics, or indices) that drive the water system responses you are interested in – in absolute terms or as the relative change compared with past climate – help to understand how the projections represent different water system responses. If you have a good understanding of the links between climate and your water resource, storylines can help identify which projection is (for example) the 'best-case' future or 'worst-case' in a planning or decision context.

Storylines are system specific. They replace the generalised approach in our previous guideline where we pre-selected a dry, median, and wet projection based on ranking regional mean annual rainfall (DoW 2015). Individually, each projection represents an internally consistent future. Using the storyline approach, you identify and describe the water resource responses you are interested in, then use climate projections to explore how important climate drivers change and the water system responds to climate and proposed decisions in the future.

The application of storylines to global climate science to consider the effect of events or actions on climate change is discussed in Shepherd et al. (2018), Sillman et al. (2020) and NESP (2021).

To understand the applicability of the storylines concept, and applying it to Western Australia, refer to the following sources:

- *Application of the Bureau's National Hydrological Projections dataset to the Myalup groundwater system* (DWER 2024) and *Harding Dam supply reliability* (Water Corporation 2024) – when published
- Pilbara water supply and vegetation – future climate storylines (Narsey et al. 2023)
- chapters 4 and 5 of the Southern and South-Western Flatlands (Turner et al. 2022), Rangelands (Oke et al. 2022) and Monsoonal North (Srikanthan et al. 2022b) hydrological assessment reports.

Water system and climate context

Understand context

- Understand the context of your investigation or decision – what question are you trying to answer?
- Consider future time periods, adaptive management options.

The first step of the framework is to understand and define the context of why an assessment is being carried out and what factors should be considered during the assessment. There are six key questions to consider:

1. What decision are you making and what type of information is needed to make the decision?
2. What is the operational lifespan of the decision?
3. What is the future period you need to consider?
4. Is there a particular time horizon relevant to your decision (e.g. 2030, 2050, 2070 or 2085), or would you require analysis of the full time-series? Table 6 shows typical time horizons associated with decision-making for various water applications.
5. Are there adaptive management (monitoring, evaluation and review) options?
6. Have you considered your stakeholders' perspectives?

For example: To identify new water security/supply options, I want to know if/when and where will there be a demand for additional water supplies and when the consequences to my existing water supply become unacceptable. How might water demand profiles change as conditions become warmer and drier?

The following examples of other applications and decisions will help to contextualise the framework for climate assessments.

Examples of applications and the context for decisions

A **land developer** needs to include future climate in their water management documents to set the fill level for a new suburban development. This is a long-term decision, and the level set cannot be changed in the future.

To **manage water resources sustainably**, I want to determine an appropriate groundwater pumping rate for allocation and regulation that maintains defined water levels in a nearby Ramsar wetland with critically endangered species.

A **mine closure plan** must establish completion criteria. The future climate may create risks to rehabilitation success from changing rainfall patterns or groundwater level recovery following dewatering, from variations in recharge and groundwater flow. How will this affect the final landform and completion timing?

The **cost-benefit** for government investment in a new water supply option is not viable if annual supply falls below a particular threshold volume: I want to know when and how often that might happen over the expected life of the water supply infrastructure.

To **identify new water supply options** or **investigate water security**, I want to know if and where demand exists for additional water supplies and when the risk to my existing water supply becomes unacceptable. How might water demand profiles change as conditions become warmer and drier?

To **optimise available water**, I am modelling a future scenario for a surface water–groundwater interaction or a managed aquifer recharge study and want to know if I should consider all possible future climate scenarios.

I need to know the best time of year to implement interventions to **improve estuary water quality outcomes**. I need to understand how changes in rainfall and flow affect estuary dynamics and then how the seasonality and volume of nutrient loads to an estuary change under a future climate.

To **manage the balance** between water available for agriculture and water available for the environment, I need to understand how runoff rates and the flow regime in a particular river may change in the future.

*Table 6 Example applications and typical time horizons**

Water resource application	10 years 2030	30 years 2050	50 years 2070	80 years 2100
Water supply planning	Dry season response strategy			
	Water supply strategy			
	Water services infrastructure planning			
		Public water supply review		
		Alternative renewable water sources		
Allocation planning	Water availability statement			
	Water allocation plan			
	Allocation limits			
Regulation	Water licensing			
		Mining - dewatering		
			Mining - closure plan	
Integrated land and water management	Catchment management for salinity improvement			
	Water quality improvement plans			
	Drainage management in the land planning process			
Other	Climate adaptation plan			
	Community consultations, presentations or reporting to show drying trends			
Flood risk	The Bureau's NHP can be used for assessing projected frequency of high river flows in future but they are not designed for flood risk. Refer to *Australian Rainfall and Runoff* (Ball et al. 2019) to for the current climate change practice for flood risk assessment and mitigation designs such as levees, diversions, dams and floodways.			

* example applications and time horizons are illustrative – not a prescriptive or exhaustive list

Water system and climate context

Understand the water system

- Look at historical data to understand the resource.
- Identify vulnerabilities, thresholds, and system priorities.
- Identify the climate characteristics that drive the system.

The second step of the framework identifies key climate drivers of a water system, its vulnerabilities and its relationship to regional climate features. Understanding the water resource forms the basis of the storyline approach to assess the impact of future climates on a water resource. In this step we recommend you identify:

1. Observations or historical data available to understand the water system.
2. The water system vulnerabilities and the priorities that should be considered in the assessment, e.g. water levels required for recharge, inundation levels – you may have identified these at step 1.
3. Climate characteristics that drive the water system.
4. Climate metrics that measure the climate characteristics (e.g. number of frost days or average winter rainfall) that are required to sufficiently understand how the water resource will respond to future climate. Table 7 lists some variables, statistics, metrics, or indices you could use to develop plots and other visualisations of the projections as storylines for different types of water resource management questions.
5. Considering the information you have identified in the previous step, determine if climate projections are required to make your decision.
6. If climate projections have been used in previous decisions, which ones? Did the outcomes reflect the impacts of climate change projected in the previous assessment?

The storylines you develop will depend on the specific resource you are assessing, the aspects of climate that drive your system and what metrics are important for your analysis.

Table 7 Water management questions and potential variables to use in developing a storyline

Example of a climate-dependent water resource management question	Potential storyline variables, statistics, metrics or indices
Environmental water – How will the period of no flow change in the future?	Drought duration Low seasonal rainfall High seasonal PET Aridity index (ratio rainfall to PET)
How will runoff, streamflow and/or reservoir reliability of supply change in the future?	Seasonal and annual rainfall changes Seasonal and annual rainfall variability Consecutive dry years Seasonal and annual PET changes Seasonal and annual PET variability Annual aridity index changes
How will recharge, groundwater level or sustainable groundwater yield change in the future?	Cumulative annual rainfall Number of rainfall days above a threshold Consecutive dry years Frequency of very wet years Seasonal and annual rainfall changes

Understand potential impacts and consequences

- Look at the climate projections and summarise measures of climate important to the water resource
- Decide if you need to choose a subset, or use all of the projections in a climate assessment
- Consider possible impacts and consequence for the decision in the context of climate change

After establishing the context of the assessment and building an understanding of water resource drivers and vulnerabilities, climate projections can be examined to consider what projections, i.e. the whole set or a subset, are required for analysis to assess the possible impacts and consequences of future climates. Following on from the second step of the framework, you will:

1. Examine how the measures of climate or climate change important to the water system are represented in the climate projections (see Example 1).
2. Decide whether you will choose a few projections, based on your examination above, to assess a subset of projections that represent particular outcomes (best/worst case, high/low level of change). Alternatively, do you use the full set of projections to help you make an assessment based on the water resource outcomes from modelling or analysis (see Box 3).
3. Consider possible impacts and consequences (low, medium and high), for the decision in the context of climate change. Consider:
    a. How do you think future climate will affect the water resource?
    b. What are the potential consequences of climate change combined with the decision?
    c. Conceptualise a climate impact analysis for the decision, including for each model projection or storyline. Consider the consequence if you plan specifically for one projection, but another climate projection eventuates – what are the robust adaptations? What would be maladaptation?
4. Consider the implications (environmental, social, economic and political) of taking either a precautionary approach or planning for a high level of risk.

You may also need to consider if previous decisions change based on the new climate projection information – see Box 4. This step and the next step in the framework (Climate Assessment) may be done concurrently depending on your analysis approach.

It is important to note that users cannot look at individual years of a projection time-series. It is recommended that at least 20-year time-slice is utilised in assessments to ensure full climate cycles are investigated (DCCEEW 2023).

Example 1 – Surface water supply volumes in the South West

A water supply manager wants a preliminary estimate of the potential range in future average yield from a surface water reservoir over the next 30 years. This example illustrates using the storyline approach to approach this analysis.

An average annual aridity index and a count of the occurrence of two consecutive dry years are two metrics that strongly influence the reservoir water supply (note, this example is illustrative – you should use assessments of observed data and expert knowledge to decide which metrics are important for your analysis and what will sufficiently describe characteristics that drive the water system).

Graphically summarising the average annual aridity index and the occurrence of dry years for the full set of projections from the NHP produces a range of results (below). Our knowledge of the system combined with the projection plot gives us a storyline that says high annual aridity combined with more consecutive dry years, which will result in lower average supply can be explored using the projections:

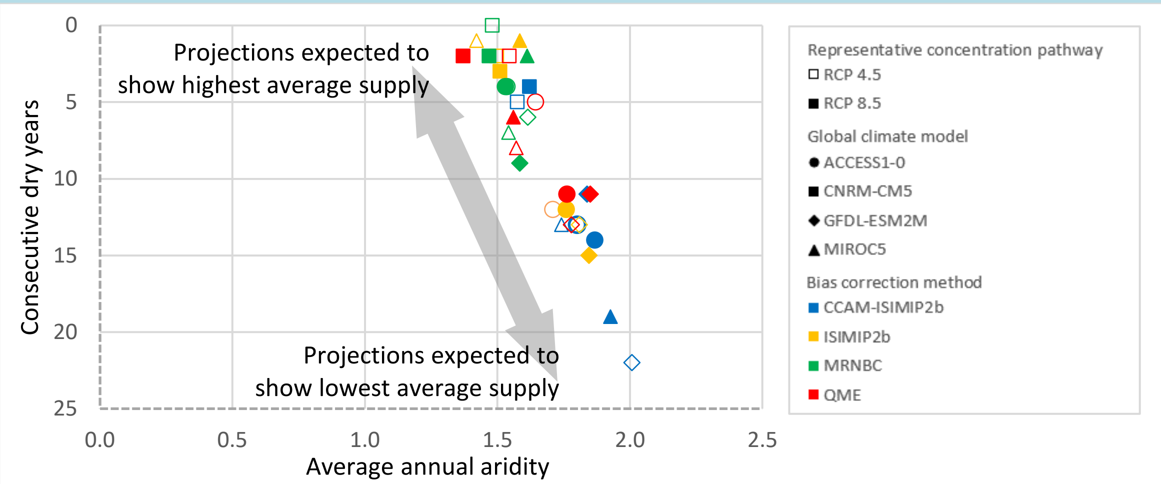
- ◇ RCP4.5-GFDL-ESM2M-CCAM-ISIMIP2b
- ▲ RCP8.5-MIROC5-CCAM-ISIMIP2b

Similarly, low annual aridity combined with fewer consecutive dry years, which will result in higher average supply can be explored using the projections:

- ■ RCP8.5-CNRM-CM5-QME
- □ RCP4.5-CNRM-CM5-MRNBC
- △ RCP4.5-MIROC5-ISIMIP2b

If you have enough time/resources, you could choose to use all these projections to make sure you have included the lowest and highest supply case. If you have limited resources choose one at each end of the range, understanding that they will represent the low/high end of supply results.

Using the chosen projections in a reservoir model will provide the upper and lower bounds of projected future average supply volume that the water supply manager has requested.



Box 3 – Using a subset of a set of projections

You may be able to use one, or a small number of projections to gain enough insight into how climate change affects your system. For such applications you could do one of the following:

- Use climate metrics that measure the climate characteristics that drive your water system to select a best- and worst-case projection (uses the storyline approach) to bookend your analysis, with consideration of implications if a future eventuates outside the bounds of these projections.
- Apply the precautionary principle, using your understanding of the links between climate and the water resource, you can use the storyline approach to select the climate projection that can be used to explore the most conservative projection (i.e. you expect a favourable outcome if the future climate is different from the projection you select) for water resource outcomes – this is a well-established approach to policy making in a risk-averse environment (note that this provides a deterministic outcome).
- Select one middle-of-the-road projection using storylines – in circumstances where it is enough to have a qualitative understanding of future climate uncertainty. This may be because your water resource response or decision is not as sensitive to the uncertainty in future climate as other factors and/or the consequences of a future that varies from the chosen projection are mild. This approach is not likely to be suitable when the projections do not agree on the direction of change of your hydroclimate variable.

We recommend you carefully consider whether selecting projections, and those you select for assessment are suitable for your application. And always consider the implications of a future climate outside the bounds of the projections you select.

Box 4 – Do previous decisions change based on the new climate projection information?

New and upcoming sources of climate change projections will continue to emerge from the latest generation of GCMs. You should review climate-related decisions periodically to capture the new information as it becomes available. Comparing datasets is not always straightforward. However, you can refer to the comparison of CMIP3 with CMIP5 for rainfall in Western Australia in Turner et al. (2024) – when available – for some insight into how to compare projections (see Chapter 7). You should consider whether any new projections may change the water resource decision. Or, if the projections are similar, you may be able to continue with your existing decision or planning without repeating the full modelling or assessment process.

Points to consider in a comparison include:

- Where does the previous climate information sit in relation to the new projections?
- Can you predict whether updating the climate information could result in a different decision being made?
- Have previous rules, policies, regulations and governance enabled you to achieve your desired water resource outcomes since your assessments were made?

Future climate water assessment

Climate assessment	• Use the chosen climate projections in a resource assessment.

In step four a climate assessment, usually involving some hydrological modelling, is carried out to explore the impacts of future climates on the water system. This step may be carried out concurrently with step three, depending on your analysis process.

The assessment should be completed by a qualified expert with consideration of hydrological parameters appropriate for the selected climate projections and sensitivity analysis. For the climate projections we recommend using the most up to date climate projections available and for WA this is currently the NHP, which are downscaled, application ready climate projections, which cover the whole state and are daily timeseries data. The assessment may be iterative depending on the results and the level of risk adopted for the decision, with additional projections potentially considered for the assessment based on the response of the water system (see Example 2).

Example 2 – Surface water supply volumes in the South West

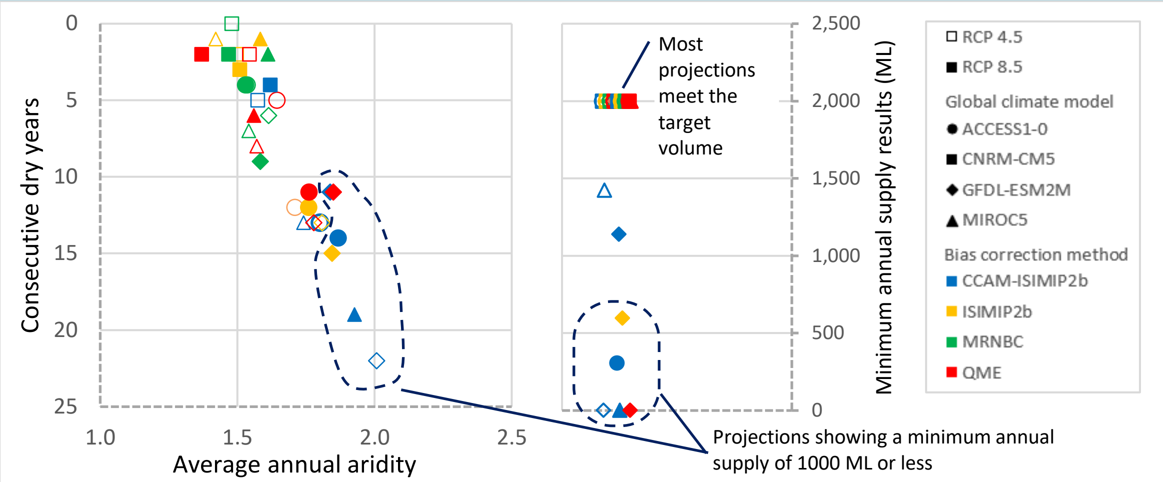
Picking up from Example 1, after examining preliminary results, the water manager now wants to provide 2,000 megalitres per year to a distributed irrigation supply. Each year the available supply must be at least 1,000 megalitres for the next 30 years.

The full set of projections from the NHP show that under most future climate projections, the full 2,000 megalitre supply can be achieved in every year. But five projections show at least one year with supply of less than 1,000 megalitres (minimum annual supply less than 1,000 megalitres).

Putting that in a storyline context, the future climate projections with a higher aridity index and greater occurrence of consecutive dry years result in at least one year with supply of less than 1,000 megalitres.

The manager needs to consider how to address that risk, namely:

- Find other water sources and/or redesign to lower the demand for water (additional sources, water efficiencies, adaptation) to supplement the supply or reduce the supply target.
- Design contingency plans to implement if these climate conditions eventuate. This may require iterating through parts of the framework to assess the contingency plans using the projections for which targets are not met and identify thresholds that will trigger the implementation of those contingency plans.



Future climate water assessment

Evaluate potential climate impacts	Use knowledge of impacts and consequences to: • assess range of consequences across the plausible futures • explore resilience of the water resource to impacts from different climate futures

Using the knowledge of impacts and consequences identified in the previous steps:

1. Assess the range of consequences shown across the plausible range of futures.
2. Ask: how resilient is the water resource to the climate futures depicted?
3. Ask: do different projections change the level of impacts and consequences?

If you used all the climate projections, assess each as a potential future. Use the futures with unacceptable outcomes in the ‘treat climate impacts’ step.

Note: we do not use model consensus to interpret the percentage of projections that give a particular result as the probability that the result will occur in the future. For example, with the NHP, if 16 of the 32 projections show a particular result, we need to be careful not to interpret this to mean there is a 50 per cent chance of the result occurring.

Future climate water assessment

Treat potential climate impacts	Use the connections made between climate change and the water resource to evaluate: • Adaptation options and management strategies for mitigating high risk outcomes. • Need for contingency plans. • Whether to redesign and re-evaluate to move the outcome into the desired risk zone.

Use the connections you have made between climate change and the water resource to evaluate and identify:

1. Adaptation options and changes to management strategies that will reduce severe consequences.
2. The need for contingency plans for tolerable consequences.
3. Trade-offs involved if different storylines eventuate.
4. Whether long-lasting transformational decisions or incremental changes as part of adaptive management approach are warranted.
5. If there are actions of ‘no regrets’ and/or with other benefits that can be implemented first.

Ideally most water planning decisions will be robust or adaptable to the full range of future climate possibilities. If this is not possible, then decision-makers should be informed about the residual risk and the likely performance of options under the range of projections. They need to be aware of the trade-offs involved in choosing one solution over another, or if a different storyline eventuates.

For example, if drainage design were based on a wetter projection, but not the wettest, then the policymaker needs to know if there is:

- a range of plausible futures that are wetter and may exceed the drainage infrastructure’s capacity
- a range of plausible drier futures where infrastructure could be overdesigned.

Or a water supply system may be reliable based on a dry projection, but with a trade-off: it might not make use of the water available if the future is wetter than the dry projection.

Communication

Communicate findings

- Use storylines to describe the modelling and assessment results.
- Different future climates will result in a range of impacts, risks and adaptation opportunities.
- Storylines help to communicate that the results are an exploration of potential outcomes – the outcomes that eventuate will depend on the future climate that unfolds.

Future climate information is just one part of decision-making processes, how decision-makers and policymakers communicate climate assessments is important for stakeholder understanding and acceptance of water resource decisions and adaptation options. Stakeholder acceptance on the use of the projections and consideration of future climate in the decision-making process will create confidence in their understanding of risk.

Effective communication should be clear and consistent, and tailors your message to your audience, for example:

- First Nations peoples: use Indigenous seasonal calendars to discuss climate
- all stakeholders and policymakers: explore realistic consequences for the range of plausible futures and work together to identify adaptation options.

Use storylines as the context to describe your water resource assessment and modelling results. For example, a drier and warmer future climate would result in one set of impacts, risks and adaptation opportunities, whereas a wetter and warmer future climate would result in another set. This helps to communicate that the results are an exploration of potential outcomes – the outcomes that eventuate will depend on the future climate that unfolds.

It is more powerful to communicate future storyline results with reference to past climate than using statistics from model results alone. Look for simple ways to present the results of climate projections and analysis of impacts, such as change maps for different variables, plots compared with a threshold, tables of results, trends, storyline charts and time-series plots (e.g. Example 1 and 2).

7 Comparing projections: CMIP3, CMIP5 and CMIP6 rainfall projections for Western Australia

Each generation of CMIP models (and associated modelling such as regional models) has the potential to give an increased understanding of climate change – both through different input scenarios and through changes in the models themselves.

The Bureau has compared rainfall across Western Australia in 2050 for CMIP3, which were the basis of the projections in DoW (2015), and the latest CMIP5 National Hydrological Projections (BoM 2022). You can read the comparison report on the AWO website when available (Turner et al. 2024).

The Bureau comparison focuses on two spatial scales – regional and local. To enable a fair comparison at the regional scale, it uses the same regions as DoW (2015). These are the South West land division and the Pilbara, Kimberley and Central West. The local-scale comparison uses specific locations within each of those regions, including Perth Airport, Morowa West and Scadden in the South West; Marble Bar in the Pilbara; Fitzroy Crossing in the Kimberley; and Gascoyne Junction in the Central West.

The Bureau uses a storyline approach (Shepherd et al. 2018) in the comparison. It selects four projections in each region that represent a range of hydroclimate changes that have become evident in recent years. Key findings of this study (Turner et al. 2024) at the regional scale are:

- **Seasonality of monthly precipitation is consistent** between NHP and DoW (2015) in all four regions. However, the NHP projected peak monthly precipitation differs in the South West region between May and October, and higher peak monthly precipitation in the Kimberley and Central West between November and March. In the Pilbara, all projections represent the monthly rainfall climatology, although peak precipitation varies between all NHPs.
- **For all regions larger cool season precipitation reductions are projected by the NHP compared with DoW (2015)**. In the Pilbara and Kimberley, an increase in cool season precipitation for a small group of projections highlights the need to investigate the range of seasonal changes and how they may differ at specific locations.
- **Very large increases and decreases in wet/warm season precipitation are projected across Western Australia**. Considerably larger than the spread of DoW (2015) projections, the spread of plausible futures under the NHP reflects uncertainty in the ability of GCMs to simulate tropical processes that influence summer precipitation in north Western Australia. For regions outside the South West, historical inter-annual and decadal precipitation variability exceeds the climate trend of the dry, median and wet scenarios in DoW (2015), and thus long-term precipitation records are more appropriate to use in

those regions. NHP allows the range of plausible futures to be explored across all regions of the state.

- **NHP projects larger precipitation peaks and troughs**. The pattern-scaling approach in DoW (2015) does not show differences in annual precipitation variability between the dry, median and wet scenarios as it simply scales observed variability. Large increases in warm season (November–April) precipitation variability are evident in the South West, although the warm season has low precipitation. Cool season (May–October) precipitation variability is projected to increase in the Kimberley region (Turner et al. 2024). In the Pilbara region, all NHP projections show a change in cool and warm season precipitation variability, although the direction and degree of change is not consistent between projections.
- **Aridity index and meteorological, hydrological and agricultural drought indicators** show the impact of projected precipitation changes on runoff and soil moisture in each region. For example, average annual aridity (total annual precipitation divided by total annual potential evapotranspiration) is projected by NHP to increase in the South West and Central West regions. Drought duration (average number of months) is highest in the South West, both in magnitude and spread across projections. The spread of projected change in drought intensity varies between each region and is greatest within the South West.

The CMIP6 downscaled climate projections are currently being created by the Climate Science Initiative for Western Australia. The differences in the latest generation of CMIP6 models is subtle or incremental compared to CMIP5, rather than a radical change in the climate change view they present. The latest set of global models show many of the same projected changes as previous generations, with just subtle or minor differences (Grose et al. 2020). Similarly, the set of internationally coordinated regional models, CORDEX, shows broadly similar projections as previous generations of models but with more regional detail. For example, the drying of the southwest has been a consistent finding for many generations of models since at least the 1990s. The ongoing agreement of models, as well as the mounting lines of evidence and understanding, has led to the incremental change in confidence, where IPCC Fifth Assessment Report found it *likely* (>66% chance), whereas the Sixth Assessment finds in *very likely* (>90%; Gutierrez et al. 2021).

Where a past decision has been made based on a previous generation of climate models it is important to compare datasets between different generations of GCMs or sources of projections to evaluate whether the climate metrics or indices (e.g. number of frost days or average rainfall) differ. If they differ, we must consider if the water resource decision and associated risk changes based on newer projections. If the difference is insignificant then it may not be necessary to update or re-do an assessment.

We recommend that you analyse the comparison report (Turner et al. 2024) when available, and similar assessments that cover the location and climate metrics of interest, before you re-do any climate assessments that used the previous projections. Chapter 6 is designed to guide you through your climate assessment.

8 Supplementary information

8.1 Climate Change Legislation

Climate Change Bill

The Western Australian Government is introducing climate change legislation to enshrine the state's long-term target of net zero emissions by 2050. It will create statutory requirements to set interim emission reduction targets and provide the basis for policies to reduce emissions and enhance climate resilience. The legislation also has provisions for the preparation of a climate adaptation strategy and sectoral adaptation plans for specified sectors.

The legislation will require the Minister for Climate Action to report annually to Parliament on Western Australia's net emissions and progress against the emission reduction targets.

8.2 Where to get help and more information

Knowledge brokers

Applying the climate science emerging from GCMs is a complicated exercise that requires skill and expertise. Knowledge brokers can facilitate knowledge sharing between researchers, practitioners and policymakers, as well as guide the use of climate projections for water resource applications. Our Science and Planning directorate is a first point of contact for assistance and can direct you to other sources of information: email hydroclimatescience@dwer.wa.gov.au.

International

The IPCC has an assessment cycle of about seven years. Its assessment reports provide the most up-to-date physical understanding of the climate system and climate change. These bring together the latest advances in climate science from multiple lines of evidence, for example: paleoclimate, observations, and global and regional climate simulations.

Each assessment report has the assessment cycle number attached to it and partly relies on the concurrent phase of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP): AR6 relies on CMIP6 and AR5 relies on CMIP5, but AR4 relies on CMIP3.

The 5th and 6th assessment reports have a synthesis report and three working group contributions:

- Working Group I (the physical science basis)
- Working Group II (impacts, adaptation and vulnerability)
- Working Group III (mitigation)

IPCC 5th assessment report (AR5)

www.ipcc.ch/assessment-report/ar5/

The Bureau's National Hydrological Projections are based on the global climate models associated with CMIP5.

IPCC 6th assessment report (AR6)

The AR6 synthesis report combines information from the three working group reports and findings from the three cross-working group special reports prepared during this assessment cycle:

- *Special report on global warming of 1.5ºC* (SR15, October 2018)
- *Special report on climate change and land* (SRCCL, August 2019)
- *Special report on the ocean and cryosphere in a changing climate* (SROCC, September 2019).

The IPCC has also released an online tool for displaying spatial and time-series analysis of the observed and projected climate change information from the Working Group 1 report. Australia is covered by four regions.

Western Australia's Climate Science Initiative will provide downscaled projections based on outputs from CMIP6 and interpretations following on from the IPCC's 6th assessment cycle. We will integrate this future climate information into our recommended approach for water resource applications as it becomes available.

Conference of the Parties

The Conference of the Parties (COP) is an annual meeting of the countries of the United Nations. It primarily focuses on mechanisms to stabilise atmospheric greenhouse gas concentrations (Kyoto protocol) and keep global average temperature rise as close as possible to 1.5°C above pre-industrial levels (Paris Agreement).

National – references and guidelines

There are several Australian sources of information about climate change and future projection data. When using future climate projections for water resource applications and water modelling, you may also find some useful information in national guidelines for those specific purposes.

Water modelling guidelines

Using the climate projections as inputs to water models introduces additional uncertainty – there are uncertainties in model conceptualisation, model parameters and other future non-climate stresses (e.g. future land use changes or future pumping regimes). While you also need to consider these uncertainties in the context of water resource management, they are outside of the scope of this guide.

The following national best practice modelling guidelines discuss how to undertake impact assessments for climate variability for:

- surface water: *Guidelines for rainfall-runoff modelling: towards best practice model application* (Vase et al. 2011)
- water resources: *Guidelines for water management modelling: towards best-practice model application* (Black et al. 2011)
- groundwater: *Australian groundwater modelling guidelines* (Barnett et al. 2012).

The Queensland Government (2020) has published a guideline for evaluating the ability of water models to incorporate climate variability and/or climate change.

Australian Rainfall and Runoff

Australian Rainfall and Runoff (ARR) is a national guideline document, data and software suite for estimating flood characteristics in Australia. It is used for water-related design such as road culverts and drainage (e.g. basins, channels, pipes) and to establish flood risk for the tributaries of major rivers. See Chapter 6 of the ARR guidelines for climate change considerations and Chapter 7 for the implications of climate change on generating daily and sub-daily rainfall sequences.

State of the Climate

The biennial *State of the Climate* report series published by the Bureau and CSIRO draws on the latest climate research, with observations, analyses and projections to describe year-to-year variability and longer-term changes in Australia's climate.

National emergency risk assessment guidelines

These guidelines provide an emergency-related risk assessment method consistent with the Australian Standard *AS/NZS ISO 31000:2018 Risk management – principles and guidelines* (AIDR 2015). It is designed for assessing emergency-related risks arising from sudden-onset hazards at various scales.

We have been working with the Bureau and the Department of Fire and Emergency Services for many years on major river flooding (a climate-related hazard) and the risk of flooding interacting with human and natural systems.

Non-hazard climate risk assessment and management is still emerging. Nevertheless, you can use the emergency risk management guidelines to support climate risk decision-making, predominantly for adapting to rapidly changing risks or transformational adaptation measures.

National Climate Risk Assessment Methodology

This report presents the methodology for the Australian national climate risk assessment framework, which is focused on identifying important national elements and systems at physical risk from climate change. The framework follows the risk management approach of standard ISO 31000 but is adapted to conceptualise complex risks.

The National Climate Risk Assessment will focus on physical climate risks and includes acute, chronic and slow onset events. To examine future risks, the framework uses policy-relevant Global Warming Levels (GWL's) of 1.5°C, 2°C and 3°C over different timeframes, rather than emission scenarios as described in this guide. However, the methodology does adopt the use of storylines to address national socio-economic scenarios to consider changes to society from 2020 to 2050 and 2090.

The methodology provides a comprehensive description of climate risk determinants, including the concept of complex risks, which relate to compounding risks from hazards occurring concurrently and multiple risks interacting, with risks transmitted through interconnected systems and across regions.

Climate Change in Australia – electricity sector climate information

The Climate Change in Australia website provides useful resources for conducting impact and risk assessments. It uses a process similar to the department's interim climate change risk management guide in that it establishes the context; assesses the risk in terms of identification, analysis and evaluation; and treats the risk. Throughout the process, it recommends monitoring and review as well as communication and consultation.

The *Electricity sector climate information* (ESCI) user guide provides a useful five-step approach to risk management. The approach can be applied to sectors other than electricity, including water. The five steps include:

1. Understand the context
2. Identify historical climate risk
3. Analyse future
4. Evaluate all risks
5. Treat climate risks

For a complete risk assessment, exposure and vulnerability need to be considered in addition to climate hazards. A hazard is defined as a change in a climate variable; for example, temperature is a variable, but an extreme temperature is a hazard (ESCI 2021).

The ESCI project recommends using a minimum of four datasets to represent four climate futures, and describing these in general terms like hot, wet, dry and warm. Depending on the region of interest, stakeholders can choose datasets that represent the range of possible future climate scenarios (ESCI 2021).

Figure 8 (below) illustrates the ESCI climate risk assessment framework.

Figure 8 Climate risk assessment framework from the electricity sector climate information user guide

National – CMIP5 climate information

Climate Change in Australia

In 2015, the Bureau and CSIRO released the (then) latest set of national climate projections for Australia. The Climate Change in Australia website makes all the results from this research available through a range of tools and downloadable reports. The website also provides many learning resources for those wishing to make use of climate projections. It is updated from time-to-time with new content and results from the latest research.

At present the website has information about both the CMIP3 and the CMIP5 generations of GCMs.

National Hydrological Projections

As discussed previously, these are Australia-wide projections for key water balance components – such as changes in precipitation, soil moisture, evapotranspiration and runoff – for a series of periods out to the end of the century (BoM 2022). These are the projections we recommend for water resource applications.

Climate Services for Agriculture (CSA)

The Climate Services for Agriculture (CSA) prototype has been designed to help Australian farmers adapt to climate variability and related trends.

It supports farmers to understand the historical, seasonal and future climate at a particular location to help inform their business decisions. It provides:

- historical data (1961–2020)
- future climate projections (2030, 2050, 2070).

The future climate projections in this tool originate from CMIP5 models sourced from Climate Change in Australia.

National – CMIP6 climate information

National Partnership for Climate Projections

The National Partnership for Climate Projections is a new collaboration that will guide delivery of a nationally aligned, sustainable and integrated approach to Australian projection science and information through a shared vision outlined in the Climate Projections roadmap for Australia. The roadmap aims to develop a consistent approach to deliver comparable, robust, fit-for-purpose future climate information to assess climate risks and inform adaptation planning.

National climate change projections

The Australian Government is working with state and territory governments, the Bureau, CSIRO, universities and other Commonwealth-funded initiatives such as the NESP Climate Systems Hub and the new Australian Climate Service to develop a set of national downscaled climate projections.

Australian Climate Service

The role of the Australian Climate Service is to support the emergency management sector to better understand the threats posed by a changing climate and natural hazards, to limit the impacts now and in the future. It will also consider floods.

CSIRO missions

CSIRO is working with the government, universities, industry and the community to develop and deliver a missions program to build Australia's long-term resilience. Some of the programs are:

- climate resilient enterprises
- drought resilience
- AquaWatch Australia.

NSW and Australian Regional Climate Modelling (NARCliM)

NARCliM began as an NSW Government initiative to generate detailed climate projections and data for eastern Australia in partnership with the ACT Government. The partnership has since expanded to include the governments of South Australia and Western Australia and is currently delivering CMIP6 climate projections across the country.

National Environmental Science Program (NESP) Climate Systems Hub

nesp2climate.com.au/

The Climate Systems Hub is one of four research hubs under the Australian Government's NESP. It is a collaboration between multiple Australian universities, research agencies, including the Bureau and CSIRO, and state governments to better understand our climate, its extremes, associated drivers, and how it is changing to inform climate adaptation. It is an extension of the previous NESP Earth Systems and Climate Change Hub.

The department has collaborated with the NESP on several climate- and water-related projects including:

- *Climate change impacts on the reliability of farm dams and environmental flow in south-west Western Australia* (DWER and NESP 2021)
- *Storylines of the Pilbara's future climate* (Narsey et al. 2023).

State (Western Australia)

Western Australian Climate Policy

In November 2020, the government launched the *Western Australian Climate Policy* with practical actions to enhance climate resilience and transition the state to a low-carbon economy. The policy outlines Western Australia's approach to reaching net-zero emissions by 2050.

Climate Science Initiative

The Climate Science Initiative (CSI) is a commitment under the Western Australian Climate Policy. The CSI will provide high-resolution downscaled climate projections for priority regions of Western Australia using the CMIP6 generation of climate models. The department is leading the CSI in partnership with Murdoch University and the NSW Department of Planning and Environment via the NARCliM and the Pawsey Supercomputing Research Centre.

The CSI will also provide guidance and communication materials to help governments, businesses and communities understand the projections, manage climate risks, and increase resilience.

We may update this guide as projections from the CSI become available.

Western Australian climate change risk management guide (interim)

The department has produced a climate change risk management guide (DWER 2022). The guide supports government agencies to do a first-pass assessment of physical climate risk to critical infrastructure and service delivery. First-pass risk assessments are high-level qualitative assessments that can be completed without detailed spatial local projections data. The corresponding level of climate information would be the *Western Australian climate projections summary* (DWER 2021) based on CCiA (CSIRO and BoM 2015a) or the climate-trend summary available in Section

3.2. We do not recommend the framework for sectoral or project-specific applications. It remains a useful document to refer to when conducting organisational climate risk assessments. It breaks up the risk assessment into four key areas:

1. Establish the context
2. Identify, analyse and evaluate risk
3. Treat the risks
4. Monitor and review

8.3 Useful policies and guidelines

Other policies related to water resource management and climate change exist but are administered by other government departments in Western Australia.

Water resources

Draft State Planning Policy 2.9 – Planning for water

The Western Australian Planning Commission has reviewed the state's water planning policy framework and released draft guidelines on water resources in land use planning strategies.

The policy's objectives are to:

- protect, conserve and enhance water resources that are identified as having significant economic, social, cultural and/or environmental values
- help ensure the availability of suitable water resources to maintain essential requirements for human and all other biological life with attention to maintaining or improving the quality and quantity of water resources
- promote and assist in the management and sustainable use of water resources.

Sea-level rise and coastal inundation

Coastal hazard risk management and adaptation planning guidelines

These guidelines are designed to assist statutory decision-makers, landholders and those conducting investigations on their behalf to:

- consider the risks arising from coastal hazards through evaluating their consequence and likelihood, and the vulnerability of specific assets
- identify risk management responses to those risks arising from coastal hazards
- prioritise and implement the risk management responses.

You should read these guidelines in conjunction with State Planning Policy 2.6 and its associated guidelines.

State Planning Policy 2.6 State Coastal Planning Policy

The purpose of State Planning Policy 2.6 is to guide decision-making within the coastal zone – to manage development and land use change, establish foreshore reserves, and to protect, conserve and enhance coastal values. This policy recognises and responds to regional diversity in coastal types and requires appropriate planning for coastal hazard risk management and adaptation. It encourages innovative approaches to managing coastal hazard risk and provides for public ownership of coastal foreshore reserves.

State Coastal Planning Policy guidelines

These guidelines provide detail on how land use and development is to be addressed when planning, designing and assessing a proposal in the coastal zone.

Flood risk management

Australian Disaster Resilience Handbook 7 Managing the floodplain: a guide to best practice in flood risk management in Australia (AIDR 2017)

Effective flood risk management can enable a community to become as flood resilient as practicable. This handbook and accompanying guidelines provide advice for those who plan and prepare for, respond to, and need to recover from flooding.

We use this handbook to help us prepare major river flood studies, understand flood behaviour, create strategies to manage the existing flood risk, and guide future development on floodplains. The community can use our floodplain mapping web tool and/or request site-specific advice to obtain information about flood risk in their area.

Other studies

Local governments may conduct studies on stormwater drainage, flooding, flood risk management, coastal vulnerability and coastal hazard risk management and adaptation planning for their local areas.

8.4 Climate change and your mental health

Practitioners and managers need to become comfortable with climate change and its impacts, and the uncertainty around future projections. In Western Australia's South West, we already have direct experience and increased awareness of climate-related change on the vulnerability of people and places. We can make use of this experience to motivate increased action, create greater resilience, and identify opportunities for adaptation in the water sector.

Working in the climate change area can be confronting. Help is available. The Australian Psychological Society has developed some information sheets that outline some useful behavioural, relational, cognitive and emotional strategies.

Appendix A – Requesting data from the Bureau of Meteorology

Access via the Bureau of Meteorology

Go to the Australian Water Outlook website for the latest information on how to access data from the Bureau. At the time of writing, you can send data requests to water@bom.gov.au. See Table 8 for the information you should send with your data request.

Table 8 Information to submit for Bureau of Meteorology Australian Water Outlook – National Hydrological Projections data requests

Data required for (location) (select one)	☐	Bureau weather station (for site information, see the Climate Data Online map search at bom.gov.au) Site number: ______ Site name: ______ Latitude (decimal): ______ Longitude (decimal): ______
	☐	Shapefile – for data averaged over shapefile area (attach a shapefile with request)
	☐	Point location – for data at the nearest grid Latitude (decimal): ______ Longitude (decimal): ______
Climate variables required (select all relevant)	☐	Precipitation
	☐	Temperature – minimum
	☐	Temperature – maximum
	☐	Solar radiation
	☐	Wind speed
	☐	Potential evapotranspiration (PET, Penman)
	☐	Soil moisture
	☐	Runoff
Time periods required (select all relevant)	☐	Historical (1900 until now unless specified; if PET is requested then historical PET should be from AWRA-L v6.1 and will start in 1911))
	☐	Future (2006 to 2099 unless specified)
Projections required	☐	All RCPs, GCMs, and bias corrections
	☐	A subset (please provide a list)
Additional comments (if required)		

Shortened forms

ACCESS1-0	Australian Community Climate and Earth System Simulator
AR4/5	Assessment Report 4/5
BoM	Bureau of Meteorology
CCAM	Conformal Cubic Atmospheric Model
CNRM-CM5	Centre National de Recherches Météorologiques – CMIP5 version
CMIP	Coupled Model Intercomparison Project
DoW	former Department of Water
DWER	Department of Water and Environmental Regulation (Western Australia)
ESCI	Electricity Sector Climate Information
GCM	general circulation model
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory – Earth System Model
IOCI	Indian Ocean Climate Initiative
IPCC	Intergovernmental Panel on Climate Change
ISIMIP2b	Intersectoral Impact Model Intercomparison Project
MIROC5	Model for Interdisciplinary Research on Climate Version Five
MRNBC	multivariate recursive nested bias correction
NCI	National Computational Infrastructure
PET	potential evapotranspiration
QME	quantile matching extremes
RCM	regional climate model
RCP	representative concentration pathway
SRES	Special Report on Emissions Scenarios

Glossary

Agricultural drought	When crops and farmland become affected by water resource deficits: caused by a prolonged period of rainfall deficit, soil moisture deficits on crops and vegetation, and the subsequent effects on livestock.
Bias	Difference between a modelled climate variable and the observed variable.
Bias correction	A process which attempts to match the percentiles (or quantiles) of the variable such as the mean and standard deviation.
Conformal Cubic Atmospheric Model (CCAM)	A global atmospheric model developed for climate modelling and regional climate downscaling.
Coupled Model Intercomparison Project (CMIP)	The CMIP is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models. The objective of the project is to better understand past, present and future climate changes arising from natural, unforced variability or in response to changes in radiative forcing in a multi-model context.
Climate scenario	A scenario which describes potential changes in climatic variables based on the results of ocean atmosphere modelling and assumptions about future greenhouse gas concentrations.
Climate period	The period of time that reflects the long-term weather pattern in an area, typically 20 or 30 years.
Climate projection	The simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols (through a representative concentration pathway), generally derived from running a global climate model. A projection differs from a prediction.
Climate variables	Variables that define the long-term average weather, such as rainfall, air temperature and potential evapotranspiration.
Dynamical downscaling	The method of using high-resolution regional simulations to extrapolate the effects of large-scale climate processes to regional or local scales of interest.

Emission scenario	The potential future releases of greenhouse gases and other pollutants into the atmosphere.
Ensemble	A group of climate model simulations used for climate projections.
Ensemble member	A single projection from the climate ensemble.
Global climate model or general circulation model (GCM)	Numerical models that represent the physical processes in the atmosphere, ocean, cryosphere and land surface, using the equations of physics. GCMs typically have a grid resolution about 150 x 150 km and require downscaling for local-scale applications.
Greenhouse gas	Natural and anthropogenic gases that absorb and emit thermal infrared radiation and cause the greenhouse effect in the atmosphere. Earth's atmosphere has water vapour, carbon dioxide, nitrous oxide, methane and ozone as the primary greenhouse gases.
Hydrological drought	When there are insufficient water resources in water storages, caused by prolonged periods of below-average rainfall and subsequent below-average runoff.
Intergovernmental Panel on Climate Change (IPCC)	The IPCC is an organisation of governments that are members of the United Nations or the World Meteorological Organization. The objective of the IPCC is to provide scientific information that can be used to develop climate policies.
Meteorological drought	When an area is subject to below average precipitation resulting in dry conditions.
Regional climate model (RCM)	A higher resolution limited area version of a global atmospheric model.
Representation concentration pathway (RCP)	A representation of the world's possible climate under different concentrations of greenhouse gas emissions. The number of the RCP represents the radiative forcing that is caused by additional atmospheric greenhouse gas concentrations by 2100.
RCP 4.5	A medium emission scenario where greenhouse gas emissions peak around 2040, and the CO_2 concentration reaches 540 ppm by 2100 (BoM 2022).

RCP 8.5	A high emission scenario which describes a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100 (BoM 2022).
Time horizon	A future point in time, often consider as a 20- or 30-year period.

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