Australia's National
Science Agency

# Plausible Hydroclimate Futures for the Murray-Darling Basin

## A report for the Murray–Darling Basin Authority

Lu Zhang, Hongxing Zheng, Jin Teng, Francis Chiew, and David Post

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# Executive summary

## Background

The hydroclimate of the Murray-Darling Basin (MDB) is changing. The future will be warmer and is likely to be drier with more severe droughts. These changes pose a threat to sustainable management of the Murray-Darling Basin as they are likely to have significant impacts on the Basin's water availability, agricultural production, communities and the environment. Water resources adaptation to climate change is challenging because (i) water is a cross-cutting issue connected to many sectors, (ii) there are competing needs from different water users, and (iii) projections of the Basin's water future are highly variable. To better understand the threat posed by climate change, policy makers require information about plausible future climate scenarios to evaluate the robustness of the water systems in the Basin, so they can plan accordingly.

## Study focus

The Murray-Darling Basin Authority (MDBA) is undertaking an initial scan of climate change vulnerabilities. To do so, they are examining climate change scenarios and exploring potential impacts on the objectives and settings in the Basin Plan. This will enable the MDBA and its stakeholders to better understand potential impacts and vulnerabilities and identify adaptation options to explore in the lead up to a review of the Basin Plan in 2026.

This *Plausible Hydroclimate Futures for the Murray-Darling Basin* study considered seven plausible climate scenarios – the historical climate and six future climate scenarios. These plausible hydroclimate futures (or storylines) are used to describe the change in climate variables and key hydrological metrics in each of the scenarios. These storylines can be used as a basis for communicating climate change risks on water security and the environment with stakeholders. The development of these scenarios is guided by the latest climate science, historical climate and streamflow data, paleoclimate data and projections from global and regional climate models.

## Climate scenarios and storylines

| Climate Scenario | Description | An example of the hydroclimate storylines<br>***using mean annual flow (total flow)*** |
|---|---|---|
| Historical climate (**Scenario H**) | Daily time series of temperature, rainfall, and potential evaporation (PET) from 1895 to 2018. | |

| | | |
|---|---|---|
| Historical climate but with more severe droughts **(Scenario $H_D$)** | Long-term average rainfall same as **Scenario H**, but with increased length and severity in multi-year droughts. | Decrease by up to 40% during the extended drought period |
| Warmer and wetter climate (**Scenario A)** | Daily temperature time series increased by 2˚C and daily rainfall time series increased by 10% compared with historical climate. | Increase by 20-30% |
| Warmer and drier climate (**Scenario B**) | Daily temperature time series increased by 2˚C and daily rainfall time series decreased by 10% compared with historical climate. | Decrease by 20-30% |
| Warmer and drier climate with more severe droughts (**Scenario $B_D$**) | Long-term average rainfall same as **Scenario B**, but with increased length and severity in multi-year droughts. | Decrease by up to 60% during the extended drought period |
| Warmer and much drier climate (**Scenario C**) | Daily temperature time series increased by 2˚C and daily rainfall time series decreased by 20% compared with historical climate. | Decrease by 40-50% |
| Warmer and much drier climate with more severe droughts (**Scenario $C_D$**) | Long-term average rainfall same as **Scenario C**, but with increased length and severity in multi-year droughts. | Decrease by up to 70% during the extended drought period |

*Mean annual flow shown above is one of eight hydroclimate metrics examined in this study. The others include overbank flows, freshes, replenishment flows, baseflows, cease-to-flow-days and dry spells. Full descriptions of these are found in Table 3 of the report.

Storylines based on the series of hydroclimate metrics describe a range of plausible future climatic and hydrological conditions for the Basin under the climate scenarios. The following are examples under different scenarios:

- A warmer and wetter climate (**Scenario A**) will lead to more favourable conditions with increases of up to 20% in key flow metrics and decreases in the length and severity of low flow and zero flow periods.
- Warmer and drier climate scenarios (**Scenarios B and C**) will lead to less favourable conditions with moderate to large decreases in key flow metrics (e.g. mean annual flow may decrease by 40-50% under Scenario C) and large increases in the length and severity of low flow and zero flow periods. High flow metrics generally show larger percentage reductions than low flow metrics (e.g. freshes decrease by up to 55% under Scenario C).
- An increase in the severity and duration of multi-year droughts (**Scenarios $H_D$, $B_D$, $C_D$**) can have a significant additional negative impact on flow metrics (e.g. mean annual flow may

decrease by up to 70% during the extended drought period. Again, the impact on high flow metrics is generally greater than that on low flow metrics (e.g. freshes decrease by up to 70% during the extended drought period).

## Next steps

The hydroclimate storyline approach with this small set of tractable climate scenarios is a useful way of representing and communicating uncertainty in climate. They can be used to identify system vulnerabilities under climate change and to develop adaptation options. It is envisaged that following this initial scan phase by the MDBA and stakeholders, more detailed scenarios will be examined, including developing datasets for hydrological modelling to assess adaption options and strategies to minimise climate change impact risk, to inform a Basin Plan review in 2026, and water reform more generally.

# 1 Context and Introduction

The climate and hydrology of the Murray-Darling Basin (MDB) are changing. Projections indicate a hotter and drier future, with more frequent drought periods and extreme weather events (CSIRO, 2012; CSIRO and Bureau of Meteorology, 2015; Potter et al., 2016, 2018). The changes in the Basin's climate and hydrology will have a substantial impact on water availability and river flow characteristics in the Basin (Chiew et al., 2017; Zheng et al., 2019), and the social, economic, cultural and environmental outcomes sought by the Murray-Darling Basin Plan.

The CSIRO is an industry expert and leader in hydroclimate science and adaptation. The Murray-Darling Basin Sustainable Yields project pioneered the first MDB-scale climate change impact on water assessment through the integration of 23 river system models. The future climate series is obtained by empirically scaling the long-term historical data, informed by global climate model projections, to reflect a wet, median and dry future climate (CSIRO, 2008). More recently, the CSIRO developed a climate risk management framework (Climate Compass) to support risk assessment and adaptation and planning in Commonwealth government agencies (CSIRO, 2018).

In 2019, the Murray-Darling Basin Authority (MDBA) released a discussion paper on likely climate risks, how they may have changed since the development of the Basin Plan, and the risks and challenges to maintaining a healthy Basin. Currently, the MDBA is undertaking an initial assessment of how vulnerable Basin Plan objectives are to the likely impacts of climate change, guided by Climate Compass 'Scan Phase'. This will help to identify adaptation opportunities and determine how best to direct future resources and investment via a 5-year climate change research program to inform the Basin Plan review in 2026.

Given recent advances in climate science and its application to water resources management, the MDBA is seeking CSIRO's assistance to provide climate scenarios to help inform future Basin water availability and provide advice on the MDBA's application of climate science to Basin water management. Specifically, the MDBA seeks CSIRO's expertise to: (i) provide an update on the latest climate science and projected impacts on runoff across the MDB, (ii) generate a small ensemble of future hydroclimate scenarios to support the 'Scan Phase', and (iii) provide advice on hydroclimate research needs to improve and communicate the knowledge for climate risk management in the MDB.

This is Milestone 1 Report of the project. It provides a brief summary of the projected climate change impacts on water availability in the Basin and describes the development of a small set of climate scenarios and hydroclimate narratives for the Basin to inform the 'Scan Phase'. It also provides a qualitative description of the changes in key hydroclimatic metrics for each climate scenario.  The Milestone 2 Report summarises current research knowledge and the research gaps and opportunities in hydroclimate science and hydrological modelling to support climate risk assessment and Basin water resources adaptation and planning. The Milestone 3 Report will provide a description of hydroclimate storylines for selected sites across the Basin, including quantitative values for a range of hydroclimate metrics.

Following this Introduction to this Milestone 1 report, Section 2 presents projections of water futures in the MDB, and the modelling components in estimating climate change impact on water and the sources of uncertainty. Section 3 describes the concept of scenarios and the rationale for developing a small set of tractable scenarios to enable the initial ‘Scan Phase’ communication, discussion and assessment of impacts and vulnerabilities to the different parts of the system and stakeholders and identify potential adaptation options. The development of the plausible scenarios is guided by the instrumental historical observations, constructed paleoclimate data and future projections from global climate models. Section 4 describes the development of the hydroclimate storylines or narratives. Section 5 then presents the storylines of changes to the climate variables and hydrological metrics for each of the seven scenarios considered here.

# 2 Projected climate change impacts on water availability in the Basin

Climate change will impact water availability in the Murray-Darling Basin and affect communities, agriculture, industries, and the environment (CSIRO, 2008; MDBA, 2010). The impact of climate change on water availability and river flow characteristics are generally assessed by combining climate change projections from global and/or regional climate models with hydrological models. The various modelling components and the sources of uncertainty are shown schematically in Figure 1. The key components or steps include: (i) selection of greenhouse gas emission scenarios; (ii) selection of global climate models (GCMs); downscaling of GCM outputs to catchment scale climate variables (including robust bias correction); and (iv) hydrological modelling (Chiew et al., 2009).

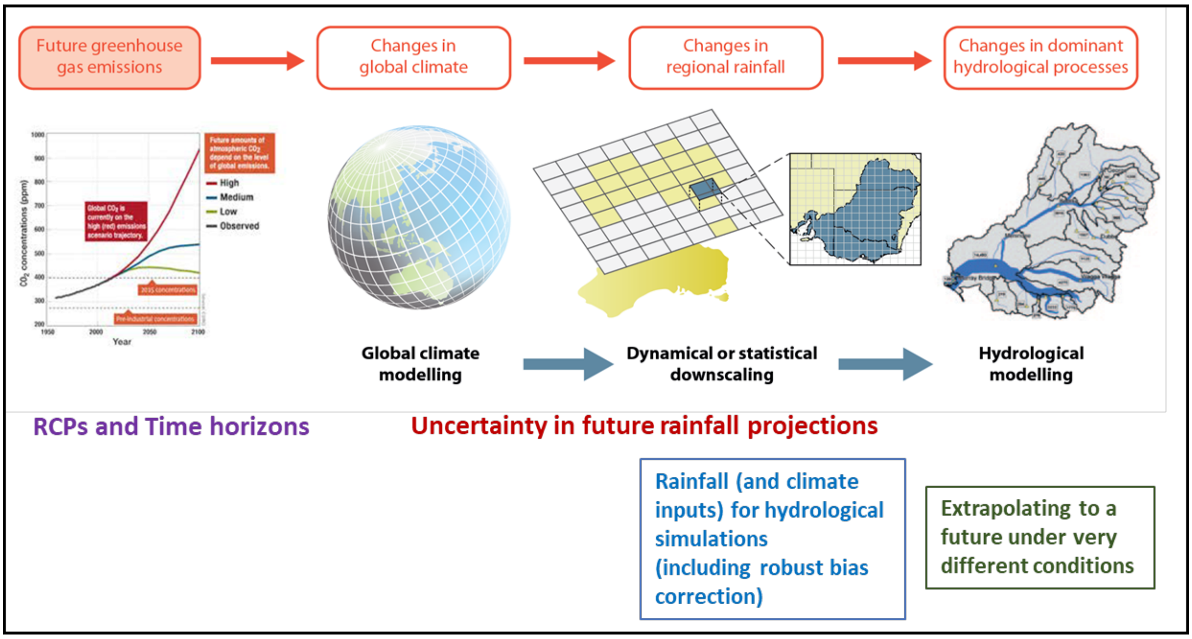


**Figure 1. Modelling components and uncertainty in projecting water futures.**

Figure 2 shows the projected change (median and the range) in future mean annual runoff across the Murray-Darling Basin. The projections are for 2046–2075 relative to 1976–2005 for RCP 8.5[1]. These projections come from hydrological modelling with the GR4J rainfall-runoff model, informed by the climate change signal from the 42 CMIP5 global climate models (GCMs) used in IPCC AR5 (Zheng et al., 2019). The projections can also be interpreted as the change in mean annual runoff

[1] RCP8.5 is Representative Concentration Pathways in which radiative forcing is stabilised at approximately 8.5 W $m^{-2}$ by 2100 and it represents high-emissions scenario.

for a 2.2°C global average warming relative to the IPCC AR5 1986–2005 reference period (IPCC, 2014).

The range in the projections largely reflect the uncertainty in the future rainfall projections across the 42 GCMs. Most of the GCMs project a drier winter in the future, which is consistent with observations of drier cool season rainfall in the past 30 years, and part attribution of winter rainfall decline to anthropogenic climate change (Hope et al., 2017; Post et al., 2014). Winter rainfall is therefore likely to decline, and more so further south. The direction of change in summer rainfall is uncertain.

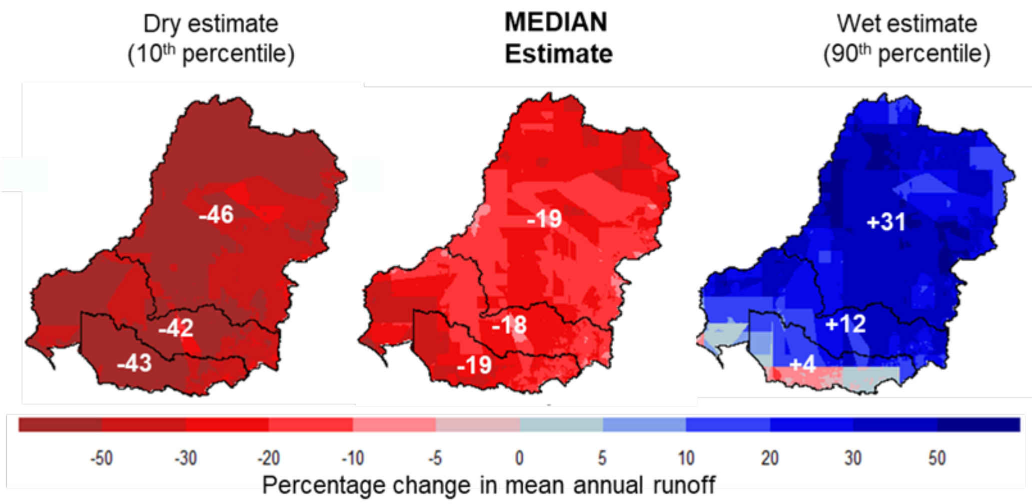


**Figure 2. Projected percentage change in mean annual runoff under 2.2°C global average warming (informed by climate change signal from 42 CMIP5 GCMs) relative to the IPCC AR5 1986–2005 reference period**

The main source of nation-wide climate projections for Australia is the CSIRO and Bureau of Meteorology 2015 projections for NRM (Natural Resource Management) regions (www.climatechangeinaustralia.gov.au; CSIRO and BoM, 2015), which largely reflects the range of projections from the 42 GCMs as used above for the hydrological modelling (Zheng et al., 2019). Climate change projections datasets have also been developed for specific regions and purposes, and these are summarised in Figure 3 (with their advantages and limitations summarised later in Table 1).

It should be noted that river flows in Australia (and the Murray-Darling Basin) exhibit very high inter-annual variability, where the runoff in a wet year can be more than 20 times greater than a dry year (see Figure 4). There is also high inter-decadal variability in the rainfall, which is amplified in the runoff, with long wet periods and long dry periods evident in the historical data (see Figure 4). Hydrologists, engineers and water managers design and manage systems to cope with this hydroclimate variability using the more than 100 years of instrumental record, and stochastic data generated based on the characteristics observed in the historical data. In the near-term (next 20 years), this natural hydroclimate variability will dominate. Further into the future, anthropogenic climate change will shift the averages, as well as the different climate and hydrological characteristics that impact water and related systems. In this context, the change signal presented and described above is generally applied to the long historical record (e.g. 1895 to the present), that is, the entire historical record (which encapsulates the range of variability and characteristics), is scaled by the 'delta' change signal, to reflect a future under a warmer world. An alternative approach is a transient simulation providing a trajectory from now into the future (which has advantages and limitations that are not discussed here). Another important consideration is the choice of baseline hydroclimate for near-term planning, particularly further south like in Victoria, where the past 20 years have been considerably drier than the long-term (see Figure 4).

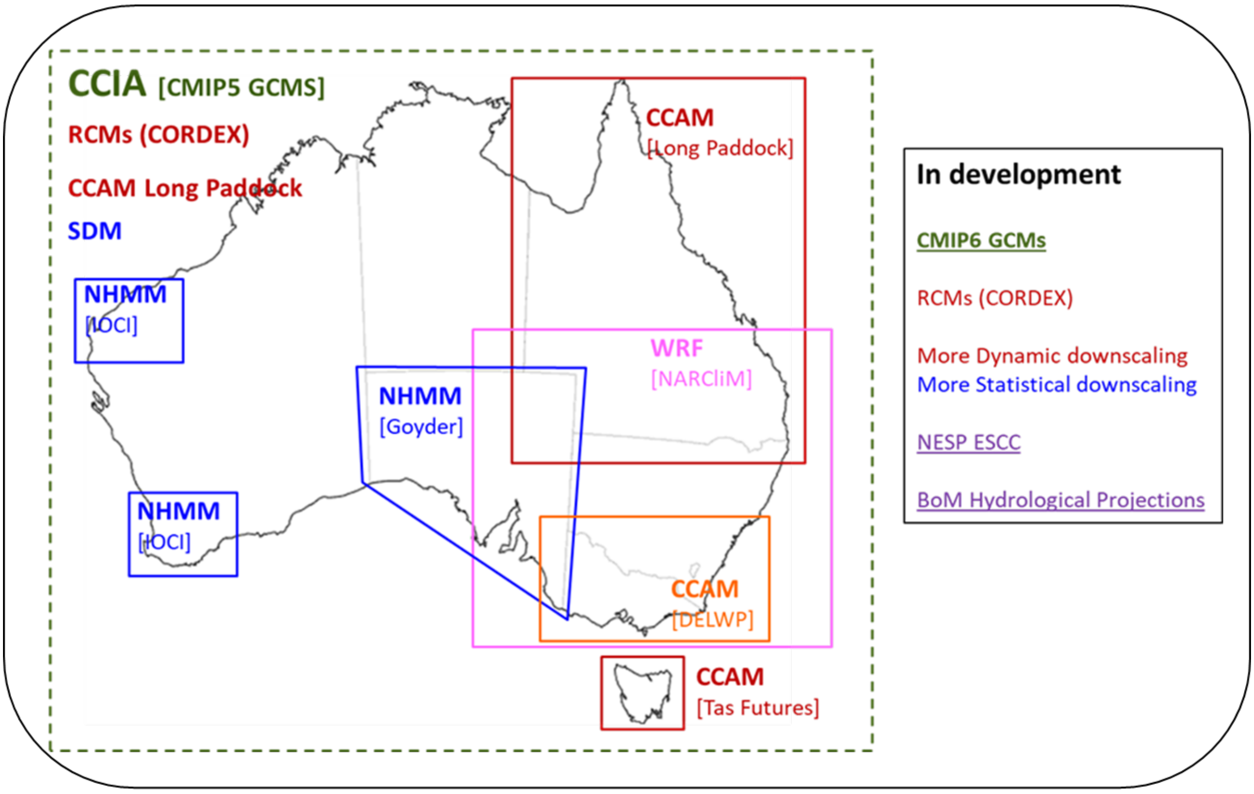


**Figure 3. Climate projections data sources**

The hydrological modelling discussed here comes from the GR4J daily conceptual rainfall-runoff model. The change signal in the long-term averages presented here, as well as the medium and high flow characteristics, from different rainfall-runoff models are likely to be similar (or relatively much smaller differences compared to the rainfall projections) (Chiew et al., 2018; Teng et al., 2012). However, it is much more difficult to accurately simulate the low flow characteristics, and therefore there is considerable uncertainty in the rainfall-runoff modelling of low flows as well as a larger range in the modelled impact on low flow characteristics (Chiew et al., 2018).

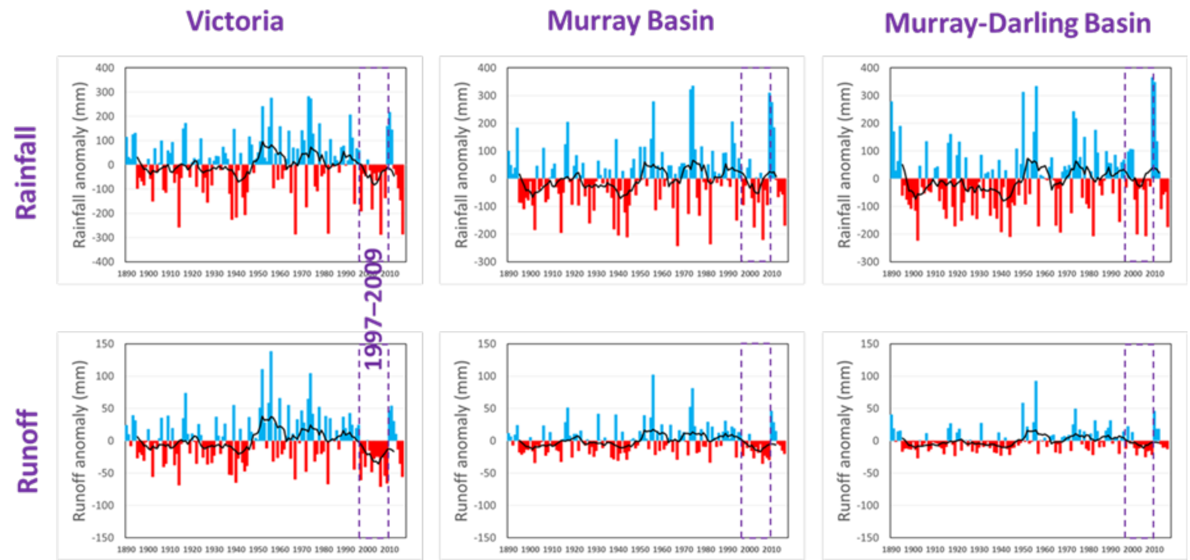


**Figure 4. Modelled annual rainfall and runoff anomalies, averaged across Victoria, Murray Basin and Murray-Darling Basin. The black line shows the 11-year mean. This is modelled using the GR4J rainfall-runoff model calibrated against observed streamflow at over 200 locations over the full period of data. The modelling approach is similar to that described in Zheng et al. (2019).**

Like practically all climate change impact on water studies, model parameters from calibration against historical record are used here to simulate the future. The modelling therefore only considers hydrological futures from the change in the input climate data. The modelling therefore does not consider potential changes in dominant hydrological processes under higher temperature, enhanced $CO_2$, and longer dry spells. Extrapolating hydrological models to predict the future, as is largely the current approach, is likely to underestimate the decline and range in the future hydrological projections (Chiew et al., 2014; Vaze et al. 2010; Saft et al., 2016). There is some research currently attempting to better understand how catchments respond to and recover from long dry spells (hydrologic non-stationarity) and adapt hydrological models to predict the future under changed conditions not seen in the past (Fowler et al., 2018, 2020).

For completion, some of the main (and by no means exhaustive) issues in developing hydroclimate projections are summarised in Table 1 (see Chiew et al. (2017) for a more detailed discussion).

**Table 1. Key issues in developing hydroclimate projections**

| Issues | Considerations |
|---|---|
| Sub-sampling projections data can provide more robust projection with reduced uncertainty? | Advantages: Use only the most suitable GCMs, as all the GCMs are not independent anyway.<br><br>Limitations: Choice of criteria to sub-select GCMs is dependent on application of study; Many papers show little difference in any case in the range of projections; Poor sub-sampling will under capture the full range of uncertainty. |
| More robust projection from dynamic downscaling? | Advantages: Higher resolution can capture important dynamics (e.g. orography, coastline).<br><br>Limitations: Limited runs constrained by limited host GCMs; Considerable differences in projections from different downscaling models; Challenges in robustly bias correcting dynamically downscaled rainfall and other climate variables for hydrological modelling. |

| | |
|---|---|
| Extrapolating hydrological models to predict the future? | • Traditional/current hydrological modelling do not consider potential changes in rainfall-runoff relationship and dominant hydrological processes (hydrologic non-stationarity) under longer dry spells, higher temperature, and ecohydrology under enhanced $CO_2$.<br>• Robustly bias correcting downscaled rainfall for hydrological modelling is challenging.<br>• Differences between hydrological models (relatively small difference in simulation of long-term averages and medium-high flows, but significant challenges and differences in modelling low flows). |

# 3 Developing climate change scenarios for the Murray-Darling Basin

There is a growing need to evaluate the impacts of climate change on regional water resources and a common method is to use downscaled future projections from multi-model ensembles of global climate models. However, large uncertainties exist in these future projections and it can be difficult to interpret them. As a result, an alternative preliminary approach is used here, in which regional impacts are conditioned on the occurrence of a small set of plausible future climate scenarios. This is called storyline approach and it describes the consequences or outcomes of the scenarios that can be used as a first step to assess potential systems vulnerabilities.

The storyline approach is a useful way to stimulate and communicate uncertainties in climate change impact assessment. In climate change literature, scenarios, storylines, and narratives have been used interchangeably. The term 'scenario' is often used in decision-making to represent an imagined future. The term 'narrative' is often used by social scientists to characterise people's views or perspectives (Shepherd et al., 2018). In this report, climate scenarios are essentially plausible and internally consistent descriptions about the future climate that can be used explicitly for investigating policy implications and options. They are the starting assumptions and used to develop climate storylines that provide narratives of what might occur to key hydroclimatic metrics under each scenario (see Figure 5).

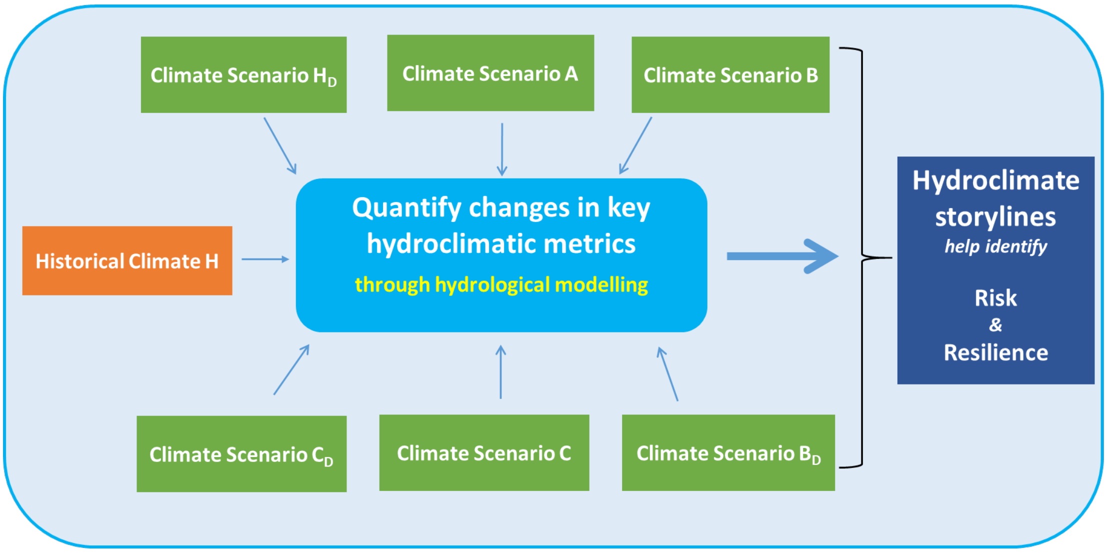


**Figure 5. Linking climate scenarios and hydrological modelling to generate hydroclimate storylines for the Murray-Darling Basin**

The purpose of climate scenarios is to help decision makers imagine and prepare for possible futures rather than attempting to predict the future. The intent of scenario development and analysis is to highlight the presence of uncertainty in the future and to reduce the possibility of inaction in the face of uncertainty. Development of climate scenarios is generally done by identifying a range of plausible futures that simultaneously considers multiple uncertainties. These scenarios can be used to identify adaptation options that best manage risk into the future and can be used to assess the effectiveness of different adaptation strategies.

The strength of scenario analysis is that it can be used to identify and examine how different factors and trends might play out in the future and help policy makers to build a shared understanding of how these key factors are likely to affect their adaptation strategies. Scenario analysis is not an attempt to predict what will happen in the future and it is designed to stimulate thought and identify some future opportunities and threats. Various methods have been used in developing climate scenarios and these include (1) climate model-based methods, (2) analogues of future conditions (both temporal and spatial) based on paleoclimate data and/or instrumental record, (3) incremental method, (4) stochastic weather generators, and (5) expert judgment (IPCC, 2001).

The choice of method for constructing climate scenarios should be determined by the intended application of the scenarios, for example, risk assessments, decision-making, or adaptation planning. In developing the climate scenarios for the Murray-Darling Basin, we considered the policy context and application of these climate scenarios and made best use of current understanding of climate projections science, instrumental records and paleoclimate data. The conceptual framework for the climate scenario development is shown in Figure 6.

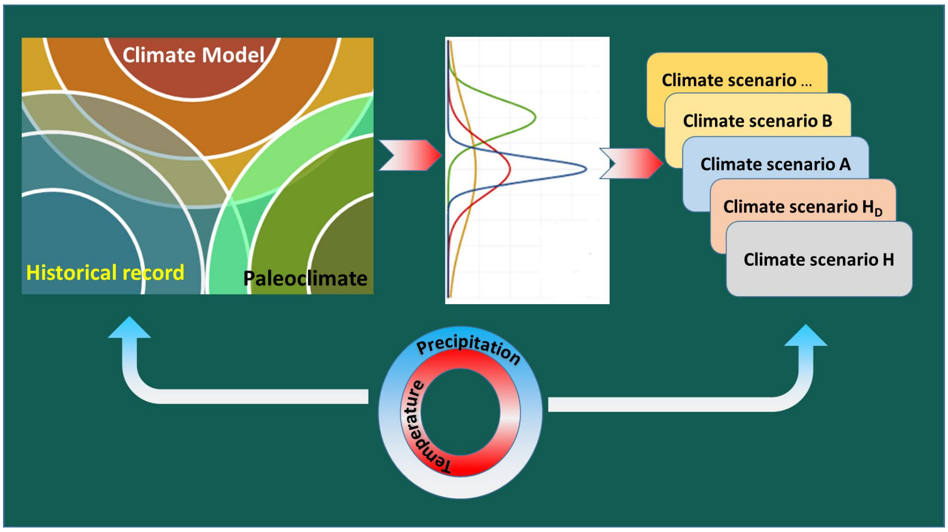


**Figure 6. Conceptual framework for developing climate scenarios for the Murray-Darling Basin by making use of current climate model projections, instrumental record and paleoclimate records. In developing the climate scenarios, key factors considered include changes in mean annual temperature and precipitation, and severity of multi-year droughts.**

Daily climate series from 1895–2018 is selected as the 'baseline period' for the historical data (**Scenario H**). This is consistent with the MDB Sustainable Yields and Basin Plan modelling. The 124 years of long climate sequence encapsulates the variability in the climate characteristics, which is needed to design and plan engineering and hydrological systems. It is worth noting that the long-term average annual rainfall averaged across the MDB for 1895–2018 is 460 mm, which is similar the long-term average over 1975–2018 (472 mm) but wetter than the recent period since the start of the Millennium drought (1997–2008) (443 mm).

Once the baseline historical climate is defined, the changes in mean annual temperature and rainfall for the 30-year period centred on 2050 are calculated from the CMIP5 climate models against the baseline values. Annual rainfall from paleoclimate records for the Murray-Darling Basin are also calculated as 30-year running means over the period of 1365-1899 relative to the baseline period (Figure 7).

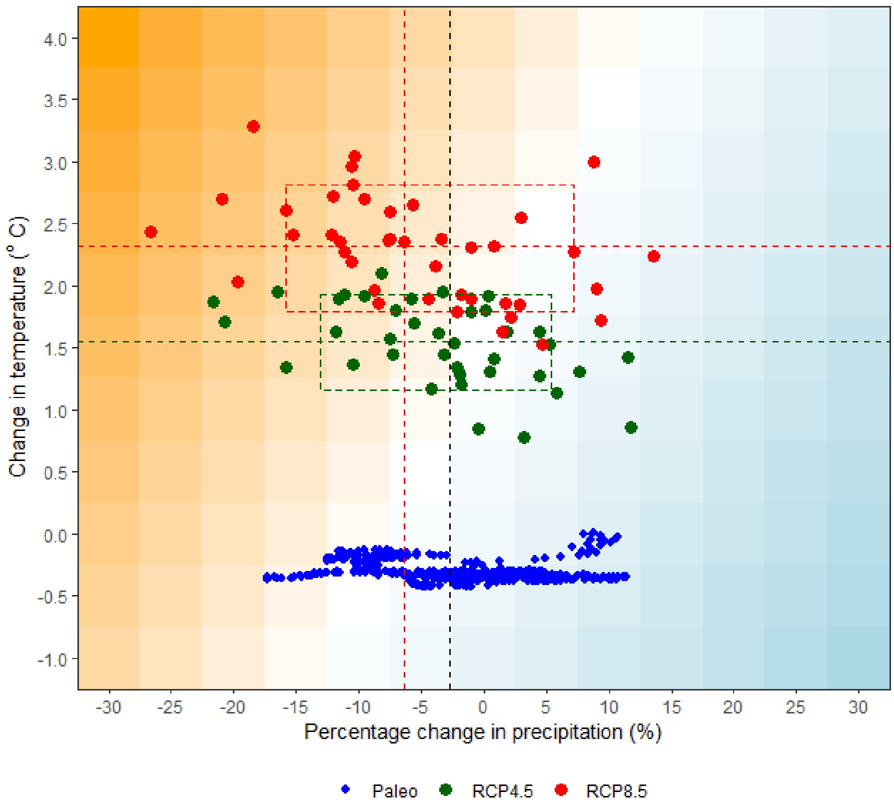


**Figure 7. Scatter plot of changes in mean annual temperature and precipitation by the CMIP5 GCMs for the 30-year period centred on 2050 relative to the historical period (1895-2018). Also shown are 30-year rainfall running means from paleoclimate records over the period of 1365-1899 relative to the historical period. Dash lines indicate the median values for temperature and precipitation changes. The box with dashed lines represents the 10th and 90th percentiles for temperature and precipitation projections by the GCMs for RCP4.5 and RCP8.5, respectively.**

Rainfall in the MDB is highly variable at multi-time scales and relatively short instrumental records do not provide adequate representation of long-term variability (e.g. over time scales of more than ten years) in the rainfall. Paleoclimate reconstructed rainfall indicate that both dry and wet epochs have persisted for longer periods than observed in the instrumental record (Ho et al., 2015). While it is useful to consider rainfall variability inferred from paleoclimate records, it should be acknowledged that there is considerable uncertainty in paleoclimate records and they do not represent changes in climate under enhanced $CO_2$ and global warming.

The mean annual rainfall and temperature over the period of 1895 to 2018 were calculated from SILO daily data to represent the historical climate. The paleoclimate data are available over the period of 1365 to 1899 for the Central Slopes of the Natural Resources Management Region (Freund et al., 2017). Annual rainfall and temperature reconstructed from paleoclimate records were calculated as 30-year running means and expressed as percentage change for rainfall and °C for temperature against the historical climate. The mean annual rainfall and temperature from each of the CMIP5 GCMs were also calculated for RCP4.5 and RCP8.5[2] for the 30-year period centred on 2050 and expressed as percentage change for rainfall and °C for temperature. These mean annual rainfall and temperature values obtained from the paleoclimate data and CMIP5 GCMs are shown in Figure 7.

The data shown in Figure 7 indicate that the change in mean annual rainfall compared with the historical climate ranges from +15% to -25% and the change in temperature ranges from -0.5°C to 3°C. The paleoclimate data exhibit a similar range in rainfall change to the CMIP5 GCMs. Based on the rainfall changes shown in Figure 7, four plausible climate scenarios are defined: 10% increase in mean annual rainfall (**Scenario A**), 0% change in mean annual rainfall (**Scenario H**), 10% decrease in mean annual rainfall (**Scenario B**), and 20% decrease in mean annual rainfall (**Scenario C**).

The severity of multi-year droughts is also an important factor to consider in water resources planning and management. The severity of multi-year droughts can be described in several ways (Palmer, 1965; Shafer and Dezman, 1982; McKee et al., 1993). Here we consider both total rainfall during a drought and its length. Droughts are defined here as the period with mean annual rainfall below the long-term average. Multi-year droughts (over one year, through to over ten years) were identified from the paleoclimate data and instrumental records, and the results are shown in Figure 8. Based on the changes in mean annual rainfall and severity of multi-year droughts, three further climate scenarios are considered: 0% change in mean annual rainfall but with more severe multi-year droughts (i.e. extending the length of the Federation drought, World War II drought, and Millennium drought by 2 years) (**Scenario $H_D$**), 10% decrease in mean annual rainfall with more severe multi-year droughts (**Scenario $B_D$**), and 20% decrease in mean annual rainfall with more severe multi-year droughts (**Scenario $C_D$**).

Table 2 summarises the main features of the seven climate scenarios. These climate scenarios were developed by considering *plausibility*, *policy relevance*, and *credibility*, and only represent changes in mean annual rainfall and multi-year drought severity. Other climate characteristics such as the likely increase in extreme daily rainfall intensity, changes in seasonality with greater decline in winter rainfall, and potential changes to sub-annual characteristics like dry spells are not considered here. The choice of these small set of seven scenarios is to promote discussion on what might happen to river flows in the Murray-Darling Basin and to identify potential system vulnerability under climate change in this 'Scan Phase'. More detailed modelling studies will be

[2] RCP4.5 and RCP8.5 are Representative Concentration Pathways in which radiative forcing is stabilised at approximately 4.5 W $m^{-2}$ and 8.5 W $m^{-2}$ by 2100 and they represent intermediate and high-emissions scenarios.

needed to robustly assess impact and adaptation options using the full suite of scenarios of projections, and these can be generated stochastically (guided by change signal in global and regional climate models, or robustly bias corrected directly from downscaled projections).

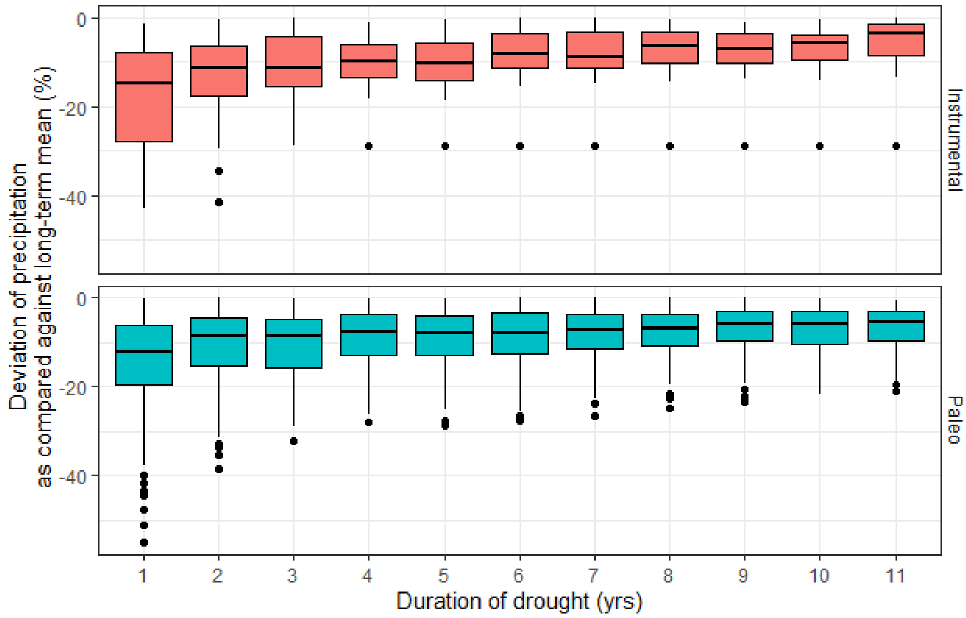


**Figure 8. Relationships between length of droughts and reductions in rainfall compared with long-term mean in the instrumental and paleoclimate records.**

**Table 2. Summary of the climate scenarios for the Murray-Darling Basin**

| Climate Scenario | Description |
|---|---|
| Historical climate (**Scenario H**) | Daily time series of temperature, rainfall, and potential evaporation (PET) from 1895 to 2018. |
| Historical climate but with more severe droughts **(Scenario $H_D$)** | Long-term average rainfall same as **Scenario H**, but with increased length and severity in multi-year droughts. |
| Warmer and wetter climate (**Scenario A)** | Daily temperature time series increased by 2˚C and daily rainfall time series increased by 10% compared with historical climate. |
| Warmer and drier climate (**Scenario B**) | Daily temperature time series increased by 2˚C and daily rainfall time series decreased by 10% compared with historical climate. |
| Warmer and drier climate with more severe droughts (**Scenario $B_D$**) | Long-term average rainfall same as **Scenario B**, but with increased length and severity in multi-year droughts. |
| Warmer and much drier climate (**Scenario C**) | Daily temperature time series increased by 2˚C and daily rainfall time series decreased by 20% compared with historical climate. |
| Warmer and much drier climate with more severe droughts (**Scenario $C_D$**) | Long-term average rainfall same as **Scenario C**, but with increased length and severity in multi-year droughts. |

# 4 Developing hydroclimate storylines for the Murray-Darling Basin

In this study, a “storyline” approach is used to provide descriptive ‘storylines” or narratives of plausible climate futures (Shepherd, 2016; Shepherd et al., 2018; Shepherd, 2019; Zappa and Shepherd, 2017). For each of the climate scenarios, changes in key hydroclimatic metrics that are relevant to the flow management tools in the Basin Plan are examined to assess system vulnerability and evaluate adaptation options (see Table 3). These metrics are the same as those used by the MDBA ecohydrology community of practice project. By examining changes in key hydroclimatic features under these climate scenarios, it will enable water managers to identify system vulnerability and evaluate different management options.

**Table 3. Hydroclimatic metrics used in the hydroclimate storylines for the Murray-Darling Basin**

| Hydroclimatic metrics | Description and policy relevance |
|---|---|
| *Temperature* | Temperature is a key climate variable and extreme temperatures can cause heatwaves, affecting people, ecosystem health and agricultural productivity.<br>All global climate models project an increase in temperature. |
| *Rainfall* | Rainfall directly affects runoff and water availability. It is the most important climate variable in water resources planning. Rainfall, particularly winter rainfall, is likely to decline, and more so further south in the Basin. However, there is considerable uncertainty and therefore a large range in the future rainfall projections from the global climate models. |
| *Potential evaporation (PET)* | Potential evaporation represents atmospheric and radiative conditions that determine the rate of evaporation from a surface with unlimited water supply. Potential evaporation is a commonly used variable in climate change impact assessment. Potential evaporation will increase because of the increase in temperature. |
| *Soil moisture index* | Soil moisture index is used to describe average relative catchment wetness and it can be calculated as the ratio of mean annual precipitation to potential evaporation. |
| *Mean annual flow* | Mean annual flow determines water availability and inflows for reservoirs. It is a primary variable considered in water resources planning and most climate impact studies report on changes in mean annual flow. |

| | |
|---|---|
| *Overbank flows* | Overbank flows can inundate floodplains to recover wetland functions and re-establish in-channel habitats for fish and other aquatic species. Overbank flows are calculated as the daily flows not exceeded 95% of the time ($Q_{95}$). Impacts of climate change on natural overbank flows are important to understand so that environmental watering can be planned to substitute for reductions in these natural flows and maintain wetlands and important ecological processes. |
| *Freshes* | Freshes (e.g. small-to-medium flows within the channel) maintain ecosystem productivity and diversity. They are generally short in duration and provide water for riparian vegetation and nutrients for in-stream habitats. Freshes are calculated as the daily flows not exceeded 75% of the time ($Q_{75}$). |
| *Replenishment flows* | Replenishment flows maintain downstream storages and refill pools and water holes in river systems. Replenishment flows are calculated as the daily flows not exceeded 25% of the time ($Q_{25}$). |
| *Baseflows* | Baseflows are important for aquatic habitat and their absence can lead to loss of diversity and biomass in plants and animals. Baseflows are commonly maintained by groundwater storage and are not directly affected by rainfall. Dam operations can considerably affect baseflows in regulated catchments. Baseflows are calculated as the daily flows not exceeded 5% of the time ($Q_5$). |
| *Cease-to-flow days* | Cease-to-flow occurs when the river stops flowing at a specific location and can lead to loss of connection and habitat. Cease-to-flow days are defined as number of days when flow is below a threshold value ($Q_1$). Under natural conditions, cease-to-flow days are generally decreasing with rainfall and catchment size. |
| *Dry spells* | Extended dry spells follow cease-to-flow events and can result in declining water quality and drying out of pools leading to death of plants and animals. Dry spells are defined as the longest consecutive days with flow below the baseflow ($Q_5$). |
| *Flow sequencing* | Flow sequencing is an important factor affecting ecosystem health and the same mean annual flow with different sequences of wet and dry spells can lead to different ecological outcomes. Changes in flow sequencing can be described using correlation coefficient against the baseline time series. |

Some of the hydroclimatic metrics described in Table 3 can be visualised using flow duration curve as shown in Figure 9.

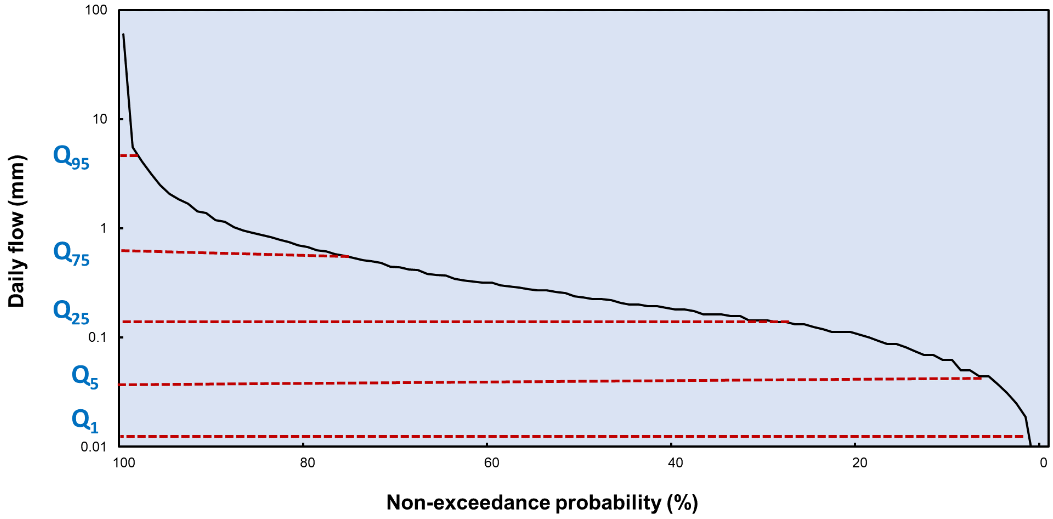


**Figure 9. Daily flow duration curve with overbank flow ($Q_{95}$), fresh flow ($Q_{75}$), replenishment flow ($Q_{25}$), baseflow($Q_5$), and threshold value for cease-to-flow ($Q_1$) shown.**

Once the climate scenarios are defined as shown in Table 2, it is necessary to generate daily time series of the key climate variables such as rainfall for each scenario to determine flow responses and a common method is to use a stochastic weather generator. It should be noted that, while stochastically generated daily rainfall time series could meet the conditions specified for a given climate scenario, they may introduce rainfall characteristics that are not part of the historical time series. For example, sequencing of stochastically generated daily rainfall may differ from the historical time series unless special effort is made to ensure consistency in sequencing. Hence, use of such stochastically generated daily rainfall time series would make it difficult to attribute changes in hydroclimatic metrics to changes in rainfall. However, the advantage of stochastically generated daily rainfall time series is to quantify the plausible uncertainty range in rainfall when a large number of samples are generated to conduct ensemble simulations. As the main purpose of this study is to develop high-level climate storylines that can be used to communicate with stakeholders on potential climate change risks, we selected one climate realization instead of stochastically generated rainfall ensembles for each scenario in order to enable direct comparison between plausible future climates and the defined historical climate conditions.

As all the climate scenarios are defined with respect to the historical climate (**Scenario H**), the new daily time series generated are the same as the historical time series except with the changes specified by the climate scenarios (e.g. 10% increase in mean rainfall for **Scenario A**). In generating the time series for **Scenarios A, B**, and **C**, all the daily historical rainfall is scaled by a constant factor and all the daily temperature is increased by a constant amount to generate a new/future daily climate series. The daily time series of potential evaporation (PET) are calculated with Morton's areal PET algorithms (Chiew and McMahon 1991) using daily values of radiation, humidity, and wind speed from the historical period with the scaled daily temperature. For **Scenarios $H_D$, $B_D$,** and **$C_D$**, the daily rainfall series from **Scenarios H, B,** and **C** are shuffled using the block shuffling approach to generate new daily time series with extended multi-year droughts (Schumann and Kantelhardt 2011).

The shuffling approach is based on the idea of shuffling a deck of cards, where each card corresponds to an annual rainfall value [Borgomeo et al., 2015]. The idea of shuffling a reference time series to generate new samples which preserve the statistics of the original series but have different sequencing is also at the core of bootstrap resampling strategies [e.g., Vogel and Shallcross, 1996; Lall and Sharma, 1996]. For block shuffling, we consider the daily time series of a year as a “block”, the blocks are then shuffled to meet the criteria set by a specific scenario (e.g. increasing the length of droughts). In this way, the block shuffling preserves the sequencing of daily precipitation for each year, as well as maintains the temporal association between precipitation and potential evaporation (PET).

For **Scenarios $\mathbf{H_D}$, $\mathbf{B_D}$,** and $\mathbf{C_D}$, several complete year(s) of daily rainfall series from **Scenarios H, B,** and **C** are switched to obtain a daily time series with longer and more severe multi-year droughts. This manipulation is carried out around each of the three historical droughts (Federation drought 1985–1902, World War II drought 1937–1945, and Millennium drought 1997–2009). Two extra below-average rainfall years are added to the end of each of the droughts, and all above-average rainfall years during the drought is replaced with data from below-average rainfall years. The below-average rainfall years are selected from below-average rainfall year closest to the above-average rainfall year. The entire year of daily rainfall record (in the below-average rainfall year and in the above-average rainfall year) are switched. This block shuffling is carried out to produce longer and more severe droughts than observed historically. This manipulation resulted in realistic multi-year droughts which are more severe than observed historically (top panel of Figure 8) but less severe than that in the paleoclimate data (bottom panel of Figure 8).

To project changes to the hydrological metrics, we use the daily conceptual rainfall-runoff model GR4J (Perrin et al., 2003), run using the daily time series from the seven scenarios. The GR4J model is based on a unit hydrograph principle which has been successfully applied to many catchments and studies globally. The model has four parameters representing maximum capacity of the soil moisture storage, interbasin water exchange rate, maximum routing storage, and time base of unit hydrographs.

To model runoff changes under each of the climate scenarios at the location/catchment of interest, we use parameter values obtained from GR4J calibration against streamflow from the nearest unregulated catchment to simulate the “natural” flow for the catchment of interest (Chiew et al., 2017; Chiew et al., 2018). The NSE-Bias objective function is used in the model calibration (Viney et al., 2009):

$$NSE\_Daily\_Bias = (1 - NSE) + 5[ln(1 + Bias)]^{2.5} \qquad (1)$$

where,

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{mod,i} - Q_{obs,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2} \quad (2)$$

$$Bias = \frac{(\overline{Q}_{mod} - \overline{Q}_{obs})}{\overline{Q}_{obs}} \quad (3)$$

where, $Q_{mod}$ is modelled daily streamflow, $Q_{obs}$ is observed daily streamflow, $\overline{Q}_{mod}$ is mean modelled streamflow, $\overline{Q}_{obs}$ is mean observed streamflow, and *n* is total number of days in the modelling period.

It is worth noting that the modelled changes in long-term averages and the medium and high flow characteristics from different rainfall-runoff models for a given change in the input data (the scenarios here) are likely to be relatively similar (relative to the large differences in the input climate series in the different scenarios). However, robustly modelling low flow is very difficult, and there is considerable uncertainty in rainfall-runoff modelling of low flow, and therefore also potentially very different modelled changes in the low flow characteristics from different rainfall-runoff models (Chiew et al., 2018).

# 5 Basin-scale hydroclimate storylines 2050

Based on the climate scenarios described in Section 2, basin-scale hydroclimate storylines for 2050 are described in this section with emphasis on changes in key hydroclimatic metrics that are relevant to the flow management tools in the Basin Plan.

For **Scenarios A**, **B**, and **C**, changes in the hydroclimatic metrics are reported over the 124 years baseline historical climate period (1895–2018). For **Scenarios $H_D$**, **$B_D$**, and **$C_D$**, changes in the hydroclimatic metrics are reported against the historical climate over the period of 1937 to 1947 (extended WWII drought). The World War II drought was selected to demonstrate how increased drought severity will affect hydroclimatic metrics and these changes describe the short-term (i.e. 11 years) hydroclimatic responses under these climate scenarios. The following categories are used for reporting.

| Slight increase | No change | Slight decrease | Moderate decrease | Large decrease |
|---|---|---|---|---|
| (0 to +10%) | (0%) | (0 to -20%) | (-20 to -50%) | (< -50%) |

**Basin scale**

## Summary of basin-scale hydroclimate storylines

The seven hydroclimate storylines provide a range of plausible future climate conditions for the Basin and can be used as a basis for communicating climate change risk on water resources planning and management with stakeholders. A warmer and wetter climate (**Scenario A**) will lead to more favourable conditions with improvement of up to 20% in the key flow metrics. A warmer and drier climate (**Scenarios B, C**) will lead to less favourable conditions with moderate to large degradations in key flow metrics (e.g. freshes will decrease up to 50%). High flow metrics generally show larger percentage changes than low flow metrics. Multi-year droughts (**Scenarios $H_D$, $B_D$, $C_D$**) can further degrade some of the flow metrics with up to 30% reduction in replenishment flows and increased drought severity.

| Hydroclimatic metrics | Historical climate but with more severe droughts (Scenario $H_D$) | Category |
|---|---|---|
| *Mean annual flow* | Mean annual flow will decrease by up to 40% during the extended drought period because of the more severe multi-year droughts. | Moderate decrease |
| *Overbank flows* | Overbank flows will decrease by up to 40% during the extended drought period because of the more severe multi-year drought. | Moderate decrease |
| *Freshes* | Freshes will decrease by up to 30% during the extended drought period because of the more severe multi-year drought. | Moderate decrease |
| *Replenishment flows* | Replenishment flows will decrease by up to 20% during the extended drought period because of the more severe multi-year drought. | Slight decrease |
| *Baseflows* | Baseflows will decrease by up to 5% during the extended drought period because of the more severe multi-year drought. | Slight decrease |
| *Cease-to-flow days* | No change in cease-to-flow days. | No change |
| *Dry spells* | No change in dry spells. | No change |
| *Flow sequencing* | Flow sequencing will be altered. | Slight change |

| Hydroclimatic metrics | A warmer and wetter climate (Scenario A) | Category |
|---|---|---|
| *Mean annual flow* | Mean annual flow will increase by 20–30% because of the 10% increase in rainfall. | Slight increase |
| *Overbank flows* | Overbank flows will increase (by up to 15%) because of the increase in rainfall and runoff. | Slight increase |
| *Freshes* | Freshes will increase (by up to 20%) because of the increase in rainfall and runoff. | Slight increase |
| *Replenishment flows* | Replenishment flows will increase (by up to 15%) because of the increase in rainfall and runoff. | Slight increase |
| *Baseflows* | Baseflow will increase by up to 10% | Slight increase |
| *Cease-to-flow days* | Cease-to-flow days in ephemeral streams will reduce. | Slight decrease |
| *Dry spells* | Dry spells will reduce in length. | Slight decrease |
| *Flow sequencing* | No change in flow sequencing. | No change |

| Hydroclimatic metrics | A warmer and drier climate (Scenario B) | Category |
|---|---|---|
| *Mean annual flow* | Mean annual flow will decrease by 20–30% because of the 10% reduction in rainfall and higher PET. Dry catchments will show a greater percentage reduction than wet catchments. | Moderate decrease |
| *Overbank flows* | Overbank flows will reduce (by up to 30%) because of the reduction in rainfall and runoff. | Moderate decrease |
| *Freshes* | Freshes will reduce (by up to 30%) because of the reduction in rainfall and runoff. | Moderate decrease |
| *Replenishment flows* | Replenishment flows will reduce (by up to 25%) because of the reduction in rainfall and runoff. | Moderate decrease |
| *Baseflows* | Baseflow will reduce (by up to 20%) (or become zero). [Note that in some rivers, baseflow is already zero]. | Slight decrease |
| *Cease-to-flow days* | Cease-to-flow days in ephemeral streams will increase. Perennial streams may become ephemeral. | Moderate increase |
| *Dry spells* | Dry spells will increase in length. | Moderate increase |
| *Flow sequencing* | No change in flow sequencing. | No change |

| Hydroclimatic metrics | A warmer and drier climate with more severe multi-year droughts (Scenario $B_D$) | Category |
|---|---|---|
| *Mean annual flow* | Mean annual flow will decrease by up to 60% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Overbank flows* | Overbank flows will decrease by up to 60% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Freshes* | Freshes will decrease by up to 50% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Replenishment flows* | Replenishment flows will decrease by up to 30% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought. | Moderate decrease |
| *Baseflows* | Baseflows will decrease by up to 15% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought. | Slight decrease |
| *Cease-to-flow days* | Cease-to-flow days in ephemeral streams will increase. Perennial streams may become ephemeral. | Moderate increase |
| *Dry spells* | Dry spells will increase in length. | Moderate increase |
| *Flow sequencing* | Flow sequencing will be altered. | Slight change |

| Hydroclimatic metrics | A warmer and much drier climate (Scenario C) | Category |
|---|---|---|
| *Mean annual flow* | Mean annual flow will decrease by 40 – 50% because of the 20% reduction in rainfall and higher PET. Dry catchments will show a greater percentage reduction than wet catchments. | Large decrease |
| *Overbank flows* | Overbank flows will reduce by up to 50% because of the reduction in rainfall and runoff. | Large decrease |
| *Freshes* | Freshes will reduce by up to 55% because of the reduction in rainfall and runoff. | Large decrease |
| *Replenishment flows* | Replenishment flows will reduce by up to 40% because of the reduction in rainfall and runoff. | Moderate decrease |
| *Baseflows* | Baseflow will reduce by up to 30% (or become zero). Note that in some rivers, baseflow is already zero. | Moderate decrease |
| *Cease-to-flow days* | Cease-to-flow days in ephemeral streams will increase. Perennial streams may become ephemeral. | Large increase |
| *Dry spells* | Dry spells will increase in length. | Large increase |
| *Flow sequencing* | No change in flow sequencing. | No change |

| **Hydroclimatic metrics** | **A warmer and drier climate with more severe multi-year droughts (Scenario $C_D$)** | **Category** |
|---|---|---|
| *Mean annual flow* | Mean annual flow will decrease by up to 70% during the extended drought period because of the 20% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Overbank flows* | Overbank flows will decrease by up to 70% during the extended drought period because of the 20% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Freshes* | Freshes will decrease by up to 70% during the extended drought period because of the 20% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Replenishment flows* | Replenishment flows will decrease by up to 50% during the extended drought period because of the 20% rainfall reduction and more severe multi-year drought. | Large decrease |
| *Baseflows* | Baseflows will decrease by up to 20% during the extended drought period because of the 20% rainfall reduction and more severe multi-year drought. | Moderate decrease |
| *Cease-to-flow days* | Cease-to-flow days in ephemeral streams will increase. Perennial streams may become ephemeral. | Large increase |
| *Dry spells* | Dry spells will increase in length. | Large increase |
| *Flow sequencing* | Flow sequencing will be altered. | Slight change |

# 6 Summary

The climate of the Murray-Darling Basin is changing, and projections indicate a warmer and drier future in the Basin. This decline in rainfall will be amplified in the runoff. The decline in water resources will impact agricultural, communities and the environment. To better understand the threat posed by climate change, policy makers require climate scenarios that can be used to evaluate the robustness of water systems in the Basin, management tools and water sharing arrangements under climate change. To facilitate such assessments, climate scenarios need to be developed with acknowledgement of climate projection uncertainty and should be tailored to specific policy and management issues.

The seven climate scenarios developed here provide the range of plausible climate futures in the MDB. The small and tractable set of scenarios provides a basis for communicating and assessing climate change risk on different aspects of the system and to identify potential adaptation options. Storylines or narratives on changes to climate variables and hydrological metrics for each of the seven scenarios are also presented to facilitate communication and discussion with the different stakeholders. The warmer and wetter climate scenario (**Scenario A**) will lead to more favourable conditions with improvements in the key flow metrics. The warmer and drier climate scenarios (**Scenarios B, C**) will lead to less favourable conditions with degradations in the key flow metrics. Multi-year droughts can further degrade the flow metrics and increase drought severity (**Scenarios $H_D$, $B_D$, $C_D$**).

The climate storyline approach is a useful way of communicating uncertainty in climate change and can help stakeholders to better understand the driving factors involved. The method does not require *a priori* probability estimates of climate scenarios. In the climate storyline approach, impacts of climate change are conditioned on a range of plausible scenarios. Stakeholders and researchers can work together to develop a shared understanding of the system vulnerability and identify flow metrics that are directly relevant to their management context.

The hydroclimate storylines can be used to better understand the sensitivity of water systems under a range of plausible future climate futures in the Basin. They are useful for capturing the range of risks from climate change. The hydroclimate metrics described here are the same as the metrics used in the MDBA ecohydrology community of practice project. The MDBA will use these hydroclimate storylines to undertake an initial scan of climate vulnerabilities in the MDB, with a focus on examining climate change impacts on the objectives and settings in the Basin Plan. This will enable the MDBA to better understand likely system risks to changing hydroclimate and identify adaptation options to be explored in the lead up to the review of the Basin Plan in 2026.

The MDBA is undertaking an initial scan of climate vulnerabilities in the MDB with an initial focus on examining climate change impacts on the objectives and settings in the Basin Plan. This will enable the MDBA to better understand likely future water availability and identify adaptation options to be explored in the lead up to the review of the Basin Plan in 2026. The climate storylines or narratives presented in this study can be used in communicating and engaging with stakeholders on likely climate futures and impacts.

It is likely that following this initial scan phase, more detailed scenarios will be needed including hydrological modelling of the system to assess potential impacts on specific (and connected) aspects of the system and to identify adaptation options to guide water management and planning. The expanded scenarios will also need to consider potential changes to other climate characteristics (e.g. increase in extreme high rainfall intensity, changed seasonality with winter rainfall decline, sub-annual dry spells and spatial patterns), which is not possible with the small set of tractable scenarios considered here.

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1300 363 400
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csiroenquiries@csiro.au
csiro.au

**For further information**

CSIRO Land and Water
Dr Lu Zhang
+61 2 6246 5802
Lu.Zhang@csiro.au
csiro.au/Research/LWF