MURRAY-DARLING BASIN ESSAY

Essay #1 in a series of nine by Australia's leading water experts

Hydroclimate of the Murray-Darling Basin

Lu Zhang, Francis Chiew and Tom Hatton

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Above: Aerial view of the Murray River around Mildura. fotofritz16, iStock.

EXECUTIVE SUMMARY

Zhang et al. advocate to develop a long-term hydroclimate management policy that best adapts to the climate change of the next 50 years by minimising the impact on the hydrological characteristics of the Basin region. Around 66% of the streamflow is generated from 12% of the Basin's area. Though MDB is typical of an arid inland river basin with low runoff and high evaporation losses, floods and droughts are very common due to very high spatial and temporal streamflow variability. Also, the Basin has warmed by one degree since 1910 and there is a risk of reduced average runoff (9% by 2030 and 23% by 2070). Zhang et al. also point out that there is an urgent need to invest in research to develop new knowledge and technologies for producing highly efficient projected water availability outputs. If implemented, policymakers will be able to develop future-ready action plans for a healthy and sustainable integrated Basin management system.

As climate change is already affecting the streamflow and degrading water quality, it is important to elevate water quality protection activities and management capabilities to meet future long-term water uses.

From: Radcliffe, John C and Flapper, Therese G (2024) (Eds), *A thriving Murray-Darling Basin in 50 years: Actions in the face of climate change*, Australian Academy of Technological Sciences and Engineering, Canberra ACT, 246 pp. DOI: 10.60902/he1w-gn75

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Abstract

As Australia's most important river basin, the Murray-Darling Basin (MDB) generates about 40% of the nation's agricultural income and supports important ecosystems with international significance. The agricultural water-use in the Basin accounts for two-thirds of the nation's agricultural water consumption and there is now a consensus that urgent actions are required to address the imbalance between consumptive and environmental water-use. The climate of the Basin varies considerably from the north to the south with about 90% of the Basin classified as arid or semi-arid. The hydrology of the Basin is typical of an arid inland river basin with low runoff and high evaporation loss. As a result, the MDB exhibits very high spatial and temporal streamflow variability with floods and droughts being common features.

Climate change is affecting hydrological characteristics of the MDB and impacting on the environment, economic and social development. The future of the MDB will be warmer and is likely to be drier with more severe droughts, yet the demand for water will increase, presenting major challenges for sustainable water resources management in the Basin.

An understanding of the hydroclimate of the MDB is highly important for developing long-term management policy to best adapt to climate change. This essay provides an overview of the hydroclimate of the Basin in terms of the spatial and temporal distribution of key climate variables and the hydrologic characteristics. It also presents the latest projections of future climate and water availability in the next 50 years and highlights the challenges and opportunities for sustainable management of the Basin. This essay is based on review and synthesis of recent literature on climate change impact on water relevant to the MDB.

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1. Introduction

The Murray-Darling Basin (MDB) is Australia's most important basin, covering over 1 million km^2, including parts of four states and all of the Australian Capital Territory (ACT). Agriculture is the dominant economic activity, making up around 85% of the total area, and generates around 40% of the gross value of Australian agricultural production. The MDB uses around two-thirds of the nation's agricultural water consumption. The MDB also harbours some of Australia's most important natural assets and supports a diverse array of ecosystems with international significance.

However, the MDB is also one of the most vulnerable basins in the world, subject to the simultaneous risks of climate change, water over-abstraction and pollution. 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). These 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, Whetton and Chiew, 2021), and the social, economic, cultural and environmental outcomes sought by the Murray-Darling Basin Plan (Basin Plan).

The Murray-Darling Basin Authority (MDBA) has been assigned the task of developing a high-level plan for the integrated management of water resources across the whole Basin. A main goal of the Basin Plan is to reduce consumptive water use to a more sustainable level through the establishment of sustainable diversion limits (SDLs). Key elements of the Basin Plan include long-term SDLs, basin-wide environmental watering strategy, water quality and salinity management plan, water trading rules, water resources plans, and monitoring and evaluation. At its core, the Basin Plan seeks to achieve a healthy working Basin and balance all interests. The development of the Basin Plan has been controversial with considerable community outrage and there are concerns that climate change has not been adequately addressed in the Basin Plan, leading to significant public discourse about this issue (Pittock et al., 2015, Alexandra 2016, Prosser et al., 2021). However, the Basin Plan is also designed to be adaptable and includes mechanisms for updating as new knowledge becomes available (Slater 2021). Climate change will be a key consideration in the upcoming review and update of the Basin Plan.

The Murray-Darling Basin Sustainable Yields project pioneered the first basin-scale climate change impact on water assessment through the integration of 23 models of the system's sub-catchments (CSIRO, 2008). It projected that water availability is likely to reduce across the entire Basin under climate change with a greater reduction in the south of the Basin. However, the impacts of climate change on water availability are highly uncertain mainly due to uncertainties in the global climate models. 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). Climate Compass has been designed to help management agencies to identify, prioritise and develop plans to manage the risks and opportunities merging from climate change by going through three guided cycles: *Scan cycle*, *Strategy cycle*, and *Project cycle*.

In 2019, the 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 (MDBA, 2019). Currently, the MDBA is undertaking an assessment of how vulnerable Basin Plan objectives are to the likely impacts of climate change, guided by the Climate Compass' 'Scan Phase'. The Commonwealth Government has also established the Water and Environment Research Program (WERP) to enhance knowledge for climate change adaptation. These will help to identify opportunities for adaptation and determine how best to direct future resources and investment.

Given recent advances in climate science and its application to water resources management, this essay provides an update on the current state of the hydroclimate in the MDB and projected changes in key hydroclimatic variables and water availability in the next 50 years. Following this Introduction, Section 2 provides a summary of the spatial and temporal distribution of rainfall and potential evaporation across the MDB. Section 3 describes the spatial and temporal distribution of hydrologic characteristics and water availability across the MDB, followed by projected climate change impacts on water availability in the Basin by 2070. Section 5 discusses the challenges and opportunities for adaptive management of the Basin with longer-term objectives and targets.

2. The spatial and temporal distribution of climatic variables across MDB

The climate of the Basin varies considerably with a sub-tropical climate in the north, arid or semi-arid climate in the west and mostly temperate climate in the south, with approximately 90% of the Basin classified as either arid or semi-arid. High variability is also a key feature of MDB's climate as the weather conditions are strongly influenced by many types of weather systems and their complex interactions.

Temperature

Temperature in the Basin has been increasing since 1910 and the warming has occurred in all parts of the Basin. The Basin-wide average increase over the period of 1910 – 2017 was 1.0 °C for daily mean temperature, 0.8 °C for daily maximum temperature, and 1.3 °C for daily minimum temperature (Whetton and Chiew, 2021). The warming has accelerated in recent decades with 2019 being the warmest on record (Fig. 1). Warming has been observed across the Basin for all seasons in daytime and night-time temperatures. There has also been a marked increasing trend in the frequency of hot years and a decreasing trend in cold years (Whetton and Chiew, 2021). Warming can be mostly attributed to anthropogenic climate change (e.g., greenhouse gases) with a little effect of natural external influences (e.g. changes in solar and volcanic aerosols) (Karoly and Braganza, 2005, Lewis et al., 2014).

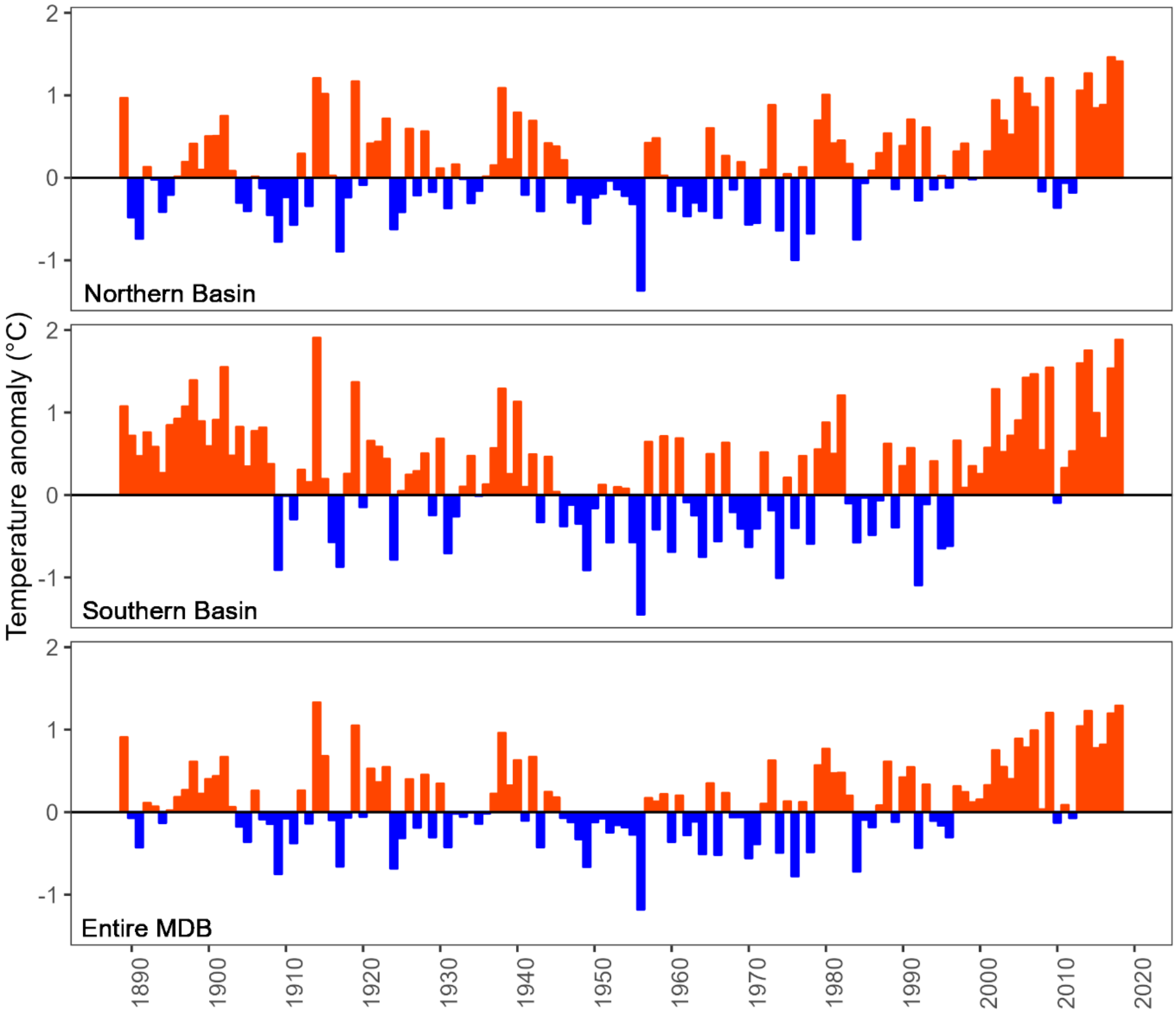

Fig. 1. Annual mean temperature anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Rainfall

Annual rainfall averaged across the Basin is about 467 mm (1889-2018). However, the rainfall exhibits large spatial variation (Fig. 2). The eastern side of the Basin has high average annual rainfall, up to 1,500 mm and in the south, snow falls for several months each winter on the peaks of the Great Dividing Range. The western side of the Basin is typically hot and dry, and average annual rainfall is generally less than 300 mm. Rainfall graduates from summer dominant to winter dominant from north to south. In the northern Basin, rainfall mostly occurs from tropical systems or interactions between tropical and extra-tropical systems (Wright, 1997; Sturman and Tapper, 2005). From December to April, tropical cyclones from the east Australian coast can contribute large rainfall totals to the northern Basin. Rainfall in the southern Basin is mostly extratropical in origin. Cut-off low pressure systems contribute up to 50% of rainfall. Frontal systems also contribute significantly to southern Basin rainfall totals (Pook et al. 2006).

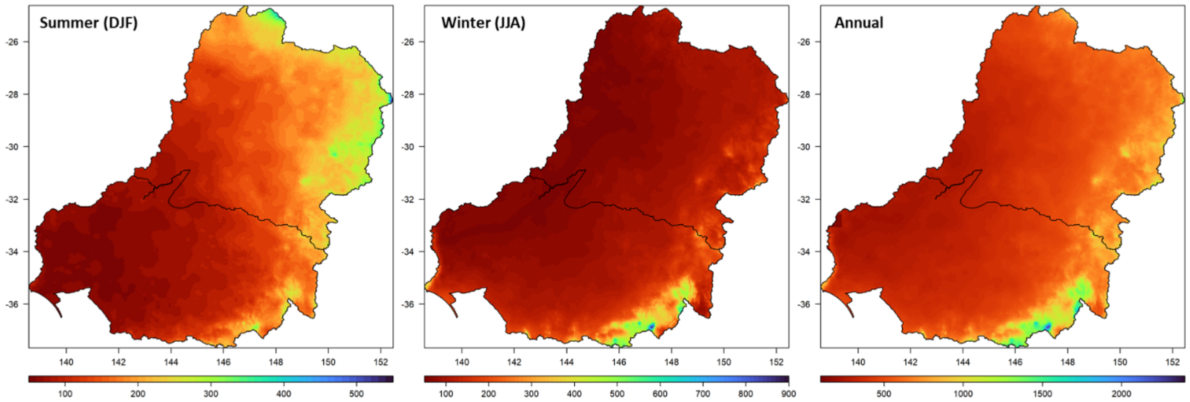

Fig. 2. Spatial patterns of mean annual, summer and winter rainfall in the Murray-Darling Basin (1889-2018) based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Rainfall in the Basin has shown large interannual to multi-decadal variations (Fig. 3). The standard deviation of rainfall is 117 mm and coefficient of variation is 0.25. During the first half of the 20th century, the Basin was relatively dry with rainfall deficits frequently exceeding 100 mm year^{-1} or 20% below long-term average. Over the period of 1900 – 2010, the Basin experienced several dry periods, including the “Federation Drought” (1895-1902), the “World War II Drought” (1937-1945), and the more recent “Millennium Drought” (1997-2010). The Millennium Drought was mainly confined to the southern Basin and was dominated by autumn and early winter rainfall declines stemming from both reductions in the number of rain days and rainfall intensity (Verdon-Kidd and Kiem, 2009). A key feature of the Millennium Drought was the low cool season (April to October) rainfall, which led to unprecedented declines in streamflow in the southern Basin and far south-east Australia as most of the runoff here occurs in winter and early spring (Chiew et al., 2014). This decline in cool season rainfall is evident up to the present (Whetton and Chiew, 2021; DELWP, 2020) and is associated with changes in global-scale circulation. Specifically, the expansion of the Hadley cell (i.e. large-scale atmospheric circulation in the tropics that produces the trade winds, tropical rain-belts and hurricanes) has pushed the cool season rainfall-bearing system further south, a phenomenon which has been partly attributed to anthropogenic global warming (DELWP, 2020; Post et al., 2014; Timbal and Hendon, 2011). As such, this decline in cool season rainfall is likely to persist and possibly intensify in the future.

The Basin has also experienced extreme high rainfall events, resulting in significant flooding and these include the 1956 floods, the 1974 floods, and the 2022 floods. The 1956 flood was the largest flood event in the instrumental record, with major floods in both the Darling River and the Murray River. These flood events significantly impacted properties, businesses and infrastructure in the Basin. Floods are generally more prevalent during La Niña years and negative phases of the Interdecadal Pacific Oscillation (IPO) (Kiem et al., 2003, Johnson et al. 2016).

During La Niña, the Pacific trade winds become stronger intensifying atmospheric circulation across the equatorial Pacific. This causes warm air to rise and increases moisture content and rainfall over much of Australia. La Niña exerts its strongest influence on eastern Australian rainfall during winter and spring. A negative phase of IPO is associated with more frequent La Nina and provides a wet background condition for La Nina. The La Niña conditions developed in the tropical Pacific in September 2020 persisted into 2022, resulting in the first triple-dip La Niña pattern in this century.

The El Niño–Southern Oscillation (ENSO) is the largest single source of interannual rainfall variability in the Basin and is responsible for over 20% of local annual rainfall variations (Nicholls, 1988; Risbey et al., 2009). Seasonal rainfall variations are strongly associated with ENSO events.

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Inter-annual variations in Southern Basin winter and spring rainfall are linked to Indian Ocean sea surface temperature anomalies and the Indian Ocean Dipole (IOD). During the positive phase of the IOD associated with cool east and warm west Indian Ocean Sea Surface Temperature (SST) anomalies, low winter rainfall over the southern Basin is likely and vice versa for the opposite phase of IOD (Meyers et al., 2007).

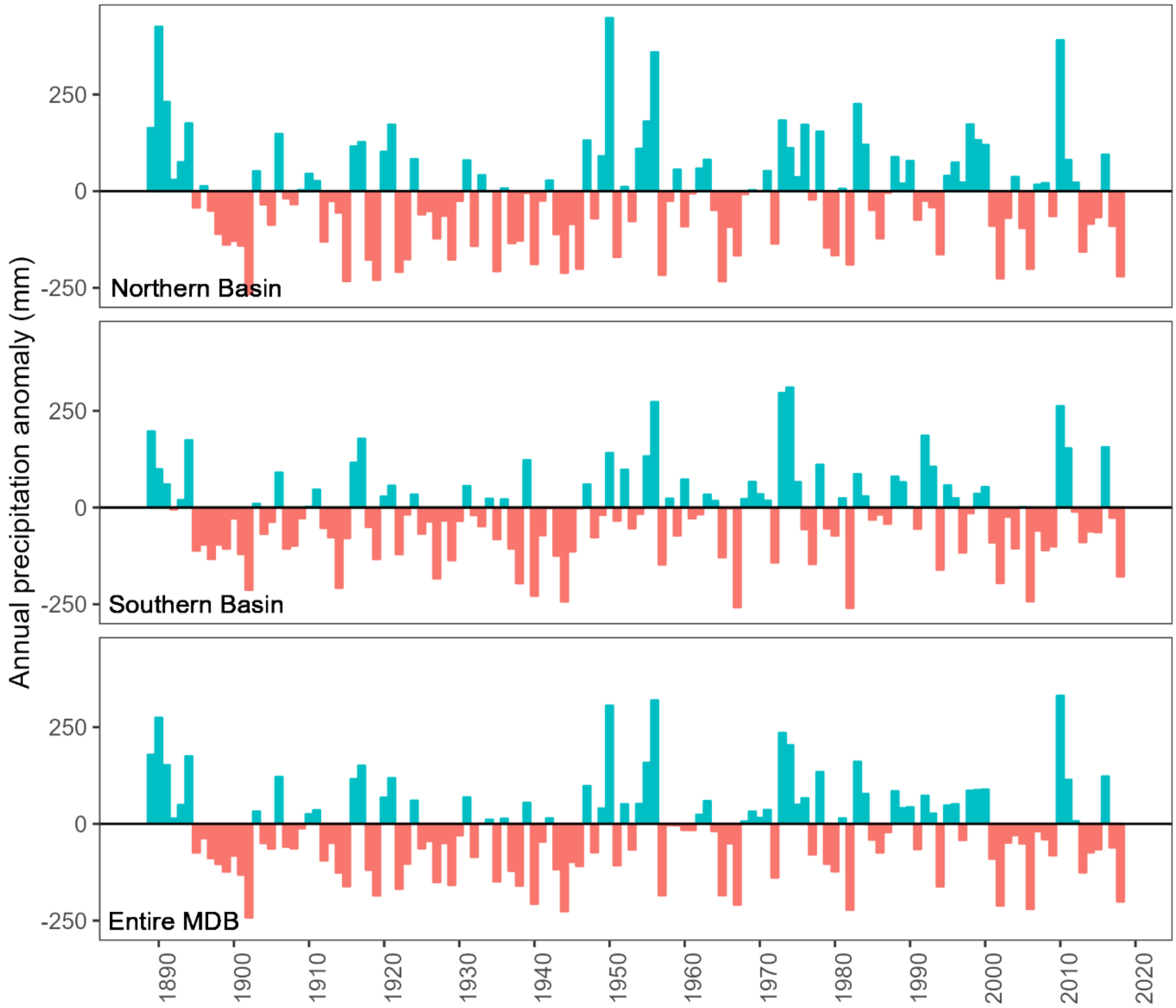

Fig.3. Annual rainfall anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Potential evaporation

Potential evaporation represents the maximal rate of evaporation from a homogeneous surface with ample moisture supply (Brutsaert, 1982). Potential evaporation is generally used to estimate actual evaporation and it is a key climatic variable for water resources management. The mean annual potential evaporation averaged over the Basin is 1,443 mm with a strong gradient - from 1,700 mm in the north to 1,000 mm in the south (Fig. 4) (CSIRO, 2008). Compared with rainfall, potential evaporation exhibits much smaller interannual variability (Fig. 5). Over the period of 1950 - 2018, potential evaporation showed an increasing trend across the Basin (see Fig. 5). However, pan evaporation measurements, representing potential evaporation, showed a decreasing trend over the period of 1975 – 1994 and an increasing trend in more recent time (1994-2016) (McVicar et al., 2012; Stephens et al.,2018; Ukkola et al., 2019). These trends have been attributed to changes in wind speeds and vapour pressure deficit.

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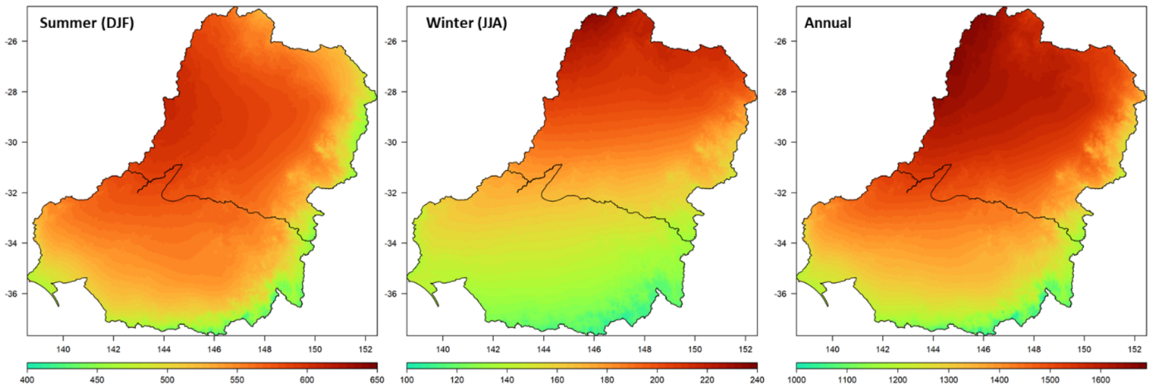

Fig.4. Mean annual potential evaporation in the Murray-Darling Basin (1889-2018) based on the SILO gridded daily climate dataset ([https://www.longpaddock.qld.gov.au/silo/gridded-data/)](https://www.longpaddock.qld.gov.au/silo/gridded-data/).

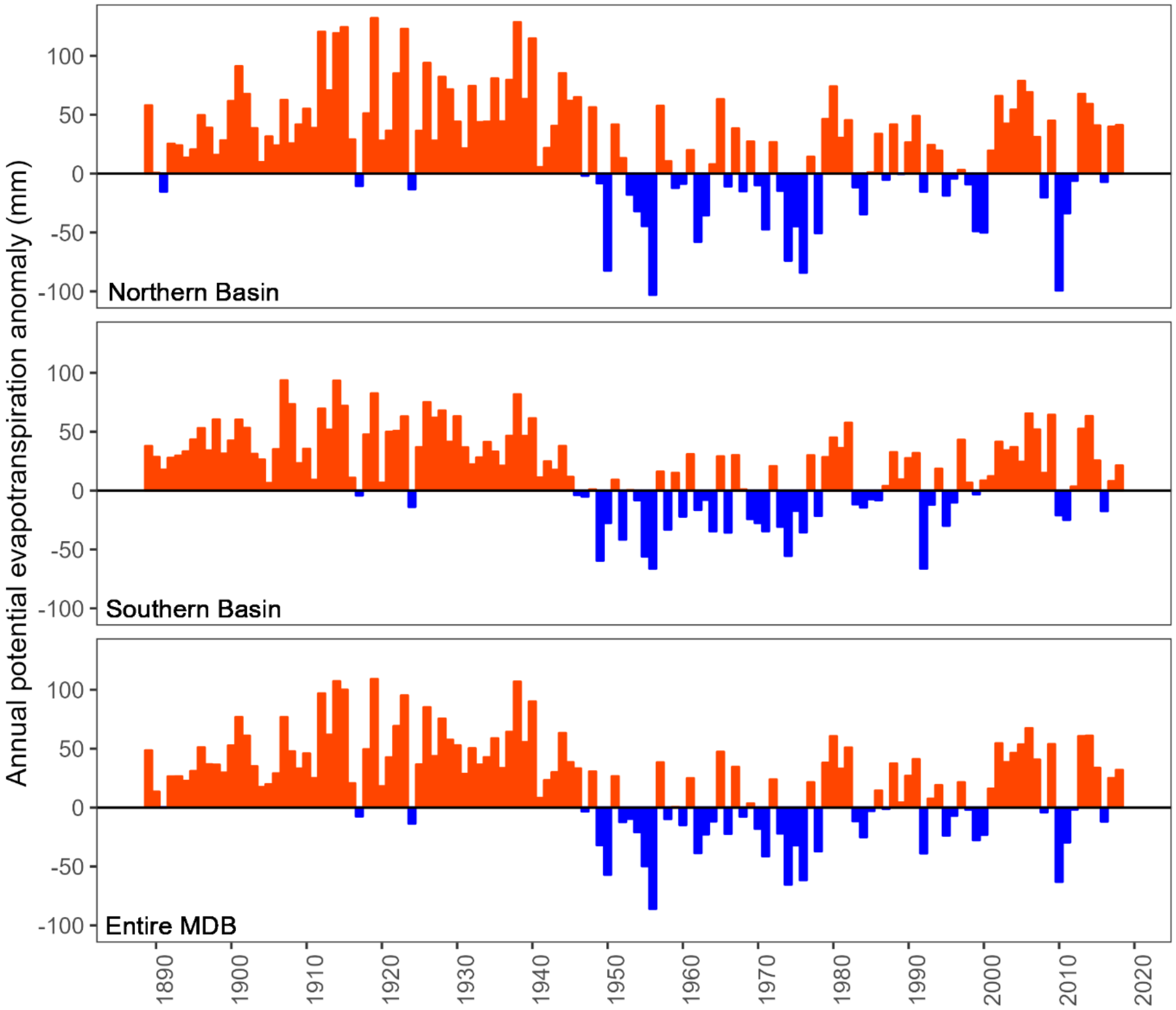

Fig.5. Annual potential evaporation anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/)

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3. The hydrologic characteristics of the Murray-Darling Basin

The Basin is the most iconic river basin in Australia. It covers a large range of climatic and hydrologic conditions. The hydrology of the Basin is typical of an arid inland river basin with low runoff and high evaporation loss. Despite its arid climate, there are over 30,000 natural wetlands across the MDB including 16 wetlands listed under the Ramsar Convention (see this ATSE essay series on Ramsar Wetlands). The MDB is a complex and interconnected river system. Due to its diverse climate and landscape, and hydrological characteristics, the Basin can be divided into two parts - the northern Basin and the southern Basin (Fig. 6).

The northern Basin includes the Darling River, the Darling Riverine Plain, and the Darling River upstream of Menindee. The northern Basin has a highly variable summer-dominated rainfall regime influenced by monsoonal weather systems. In the Darling system, rivers flow from higher-rainfall areas in the east into more arid regions in the west. The highly variable rainfall means that streamflow in the northern Basin exhibits large seasonal variations with frequent and long periods of very low flows. Hence water availability in the northern Basin is generally less reliable compared with the southern Basin.

The Murray River and its tributaries in the southern Basin flow from the south-eastern highland westward through the dry interior. The rainfall in the southern Basin generally is winter-dominated and the runoff is higher. In particular southern tributaries, including all the Victorian tributaries and the Murrumbidgee River, have their peak flows in the winter period with some minor influences of snowmelt in tributaries draining from the highest elevations of the Great Dividing Range.

Fig.6. Map of the Murray-Darling Basin showing the Northern Basin and Southern Basin. Source: Murray-Darling Basin Authority, https://www.mdba.gov.au/importance-murray-darling-basin/where-basin

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As with most inland arid river basins, much of the streamflow in the Basin is generated from temperate headwater catchments on the south-eastern and eastern boundaries of the Basin (CSIRO, 2008). It is estimated that around 66% of the streamflow is generated from 12% of the Basin's area (Fig. 7) (Donohue et al., 2011). Clearly, runoff in the Basin exhibits great spatial variability with the eastern upland headwaters contributing most of the streamflow for low-gradient rivers meandering through arid and semi-arid plains. The northern Basin with summer-dominated flows contributes to high flows in the Darling River. As a result, the MDB shows very high spatial and temporal streamflow variability with floods and droughts being common features.

To reduce risks of extreme floods and droughts, we need better planning to determine future water needs and develop improved flood forecasting systems so that operational responses and water sharing rules can be implemented across the Basin. This has important ecological and water resources management implications.

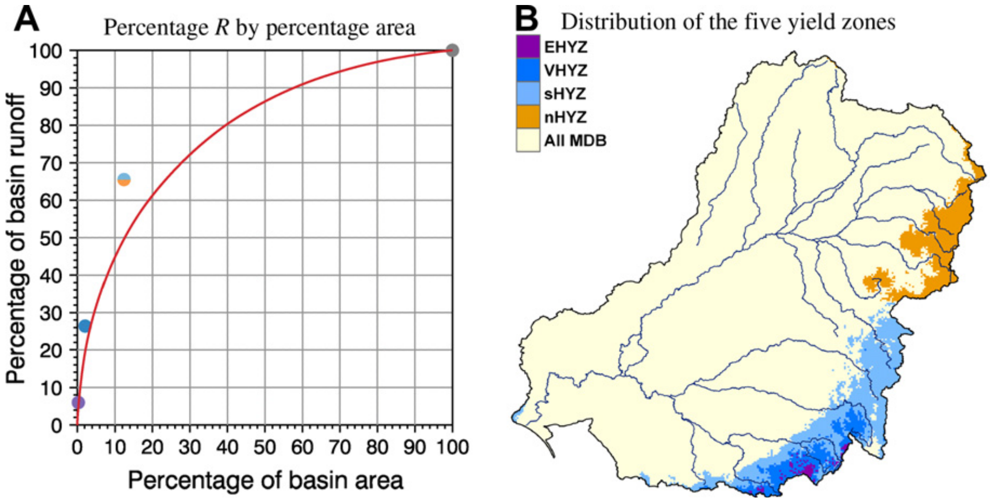

Fig.7. Areal distribution of basin runoff. Plot A shows percentage of basin runoff for a given percentage of basin. The red curve represents values derived by grid cell aggregation. Points represent values for the yield zones calculated using zonal averages. Plot B shows the distribution of the five Murray-Darling Basins Yield Zones: extremely high yield zone (EHYZ), very high yield zone (VHYZ), southern high yield zone (sHYZ), northern high yield zone (nHYZ), and whole Murray Darling Basin (All MDB) (From Donohue et al., 2011).

The MDB is large in area, but small in runoff. Average runoff across the Basin is around 27.3 mm per year, very low compared with other major river basins in the world. The mean annual runoff ranges from less than 10 mm in the west to over 200 mm in the southeast (CSIRO, 2008). Runoff in the Basin also exhibits large temporal variability and is among the most variable in the world (McMahon et al., 2007a, b; Peel et al., 2004; Chiew and McMahon, 2002). Over the period of records, the total streamflow from the Basin varied from 6,740 GL (in 2006) to 117,897 GL (in 1956) (MDB, 2010). As mentioned earlier, the Basin has experienced long multiyear droughts, including the recent Millennium Drought (1997-2010). During the 10-year period (1997-2006), rainfall was up to 20% lower than the long-term average and runoff reduced by over 50% in some parts of the Basin, unprecedented in the historical record (Potter et al., 2010). The cool season (April to October) rainfall has declined since 2001 partly attributed to climate change and resulted in significant reduction in streamflow. This is more evident in the southern basin.

River flows in the Basin exhibit very high interannual variability, where the runoff in a wet year can be more than 20 times greater than a dry year (see Fig. 8). 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 Fig. 8). The interannual variability of streamflow in the

Basin is about twice that of basins in similar climate regions elsewhere in the world (Peel et al., 2004). This large streamflow variability is in part due to the arid and semi-arid climate of the Basin and the strong ENSO influence in this region (Chiew and McMahon, 2002). The large variability presents a significant challenge for water resources management, and the strong ENSO-streamflow teleconnection has been used to forecast streamflow several months in advance (Robertson and Wang, 2013; Bennett et al., 2017; Tuteja et al., 2019) potentially helping with the management of this very variable system.

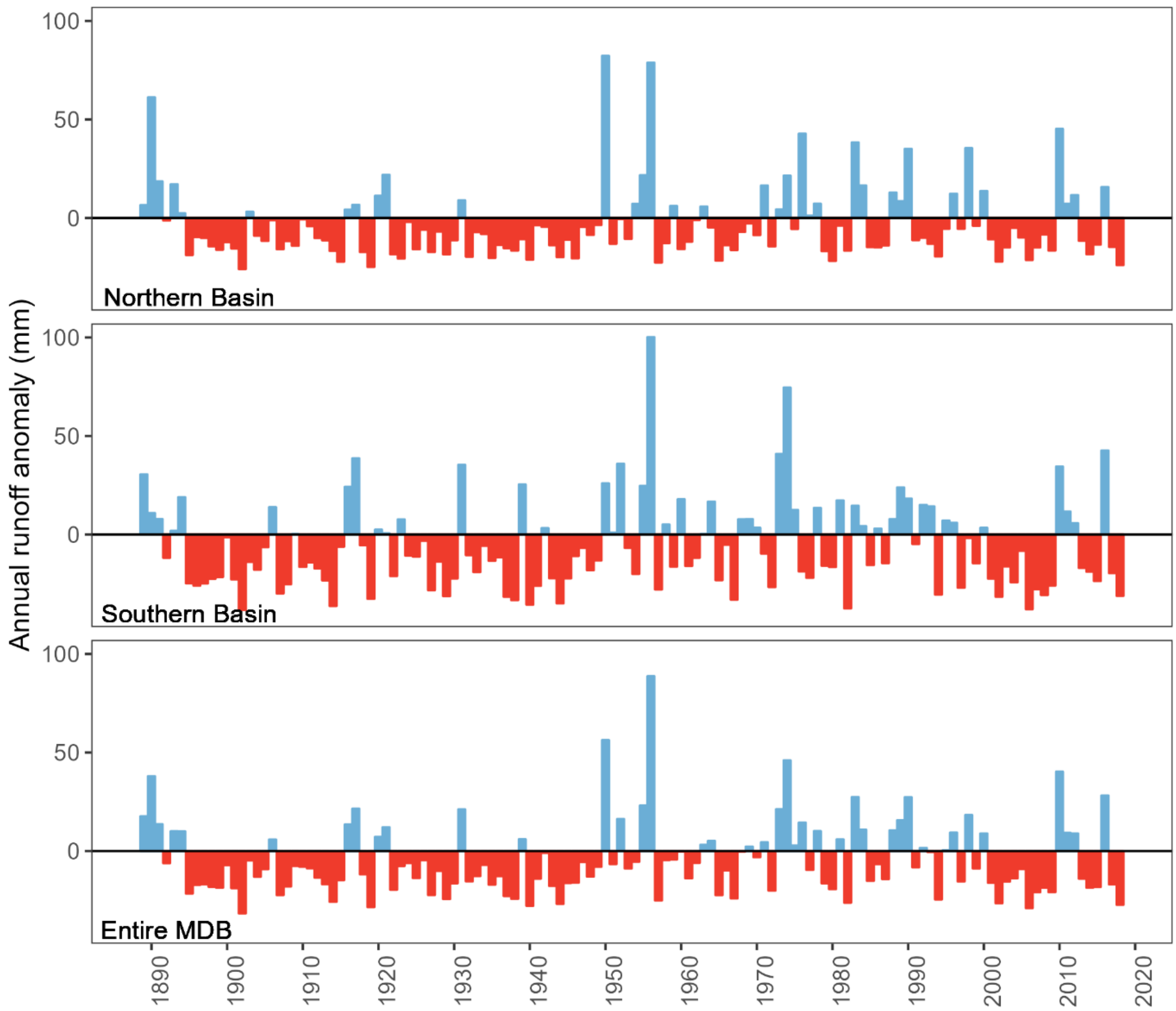

Fig. 8. Annual runoff anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on hydrological simulations using GR4J model and climate inputs from the SILO dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/)

There is large variation in the seasonal streamflow patterns across the MDB (CSIRO, 2008). However, the natural streamflow regimes in 24 of its 26 major catchments have been modified by water resources development such as construction of dams and weirs. The total water storage across the Basin is around 22,700 GL (MDBA, 2010), approximately 78% of historical mean annual streamflow. These developments have altered the seasonal streamflow distribution. The southern Basin was developed earlier than the northern Basin and includes the Basin's largest dams. As a result, the MDB is the most heavily regulated river basin in Australia, with significantly altered streamflow seasonality. In particular in the major southern rivers, high winter flows are captured by dams and released in the summer for irrigation, leading to seasonal inversion of flow downstream of major dams. Alterations to high and low flows, as well as the total flow volume, are also common in many catchments. Further downstream, flow seasonality is largely restored but the amplitude of the seasonal variation is greatly reduced due to consumptive water use (CSIRO, 2008). The heavy regulation of streamflow has affected flood- and flow-dependent ecosystems and caused major changes in geomorphological and ecological processes downstream of dams (Kingsford, 2000).

Another important feature of the Basin's hydrology is the complex spatial and temporal patterns of hydrological connectivity between the river channels and their floodplains (Stewardson et al., 2021). The hydrologic connectivity is affected by natural connectivity and the Basin development (i.e. water infrastructure). The level of hydrologic connectivity varies significantly across the Basin with the percentage of flow reaching the Murray Mouth ranging from 3% from the Warrego to 84% from the Murray (CSIRO, 2008). In wet years, rivers flow to the floodplains, lakes, and wetlands, while in dry years more water is lost through seepage and evaporation reducing the hydrologic connectivity. The construction of water supply infrastructure and flood levees has had a significant impact on flow distribution and hydrologic connectivity. It is also important to consider surface water and groundwater connectivity in managing Basin water resources as they are components of one system (see this ATSE series on surface water-groundwater connectivity).

Long-term average runoff depends chiefly on climatic conditions such as rainfall and is expected to change under climate change. However, catchments located in different parts of the Basin are expected to respond differently to climate change and it is important to understand the sensitivity of runoff to climate change.

Basin-wide runoff is expected to change by 2–3% for every 1% change in rainfall (Chiew, 2006), while the runoff sensitivity to potential evaporation is somewhat lower and in the opposite direction (Jones et al., 2006; Donohue et al., 2011). This means that in the high runoff generating catchments in the south-eastern part of the Basin runoff will decrease by 7 mm y^{-1} for a 10 mm y^{-1} reduction in precipitation, and to decrease around 4 mm y^{-1} for the same increase in potential evaporation. It is in these high yielding catchments where runoff is likely to change most under future climate change.

4. Projected climate change impacts on water availability across the Basin by 2070

The Basin has warmed by a degree since 1910 and the warming will continue (Whetton and Chiew, 2021). Climate change will impact water availability in the 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 key steps include: (i) selection of greenhouse gas emission scenarios; (ii) selection of global climate models (GCMs); iii) downscaling of GCM outputs to catchment scale climate variables (including robust bias correction); and (iv) hydrological modelling (Chiew et al., 2009).

The impacts of future climate change on water availability in the Basin were assessed by CSIRO (2008). Average annual runoff was projected to decrease 9% by 2030 and 23% by 2070 for the median of the 45 climate scenarios. There is a strong agreement in future rainfall reduction among the GCMs and hence reduction in projected runoff (CSIRO, 2008). However, the range of projected future runoff is mainly due to the large range in the future rainfall projections among the GCMs. The projected change in mean annual runoff ranges from -40% to +10% in the southern Basin mainly due to the projected cool season rainfall reduction. For the northern Basin, the projected change in mean annual runoff ranges from -45% to +30%.

Groundwater contributes 16% of the water used in the Basin, the proportion is much higher in the Darling Basins and during dry periods (CSIRO 2008). Diffuse recharge is the dominant recharge mechanism across the Basin as a whole. Diffuse recharge averaged across the Basin is projected to increase by 5% under the median future climate scenario, increase by 32% under wet climate scenario, and decrease by 13% under dry climate scenario (Crosbie et al., 2010). Such wide ranges of projected changes in runoff and groundwater recharge present challenges for the development of SDLs within the Basin Plan and management of climate change impact.

The climate scenarios and the hydrological projections developed by CSIRO (2008) are consistent with the findings of the latest research (Whetton and Chiew 2021). Fig. 9 shows the projected change (median and the range) in future mean annual runoff across the Basin. Also shown in Fig. 9 are projected percentage change in low flow days and increases in the number of 3-year hydrological droughts (Prosser et al., 2021). The projections are for 2046–2075 relative to 1976–2005 for RCP 8.5. 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 for a 2.0°C global average warming relative to the IPCC AR5 1976–2005 reference period (IPCC, 2014). Early CSIRO analysis indicate that hydrological modelling informed by recently released CMIP6 climate projections are similar to CMIP5, i.e. the MDB will be hotter and drier under climate change (Grose et al. 2020, Chiew et al., 2023), and the hotter and drier projections have been consistent through the different generations of IPCC, CMIP and national projections (Prosser et al. 2021, Chiew et al., 2023).

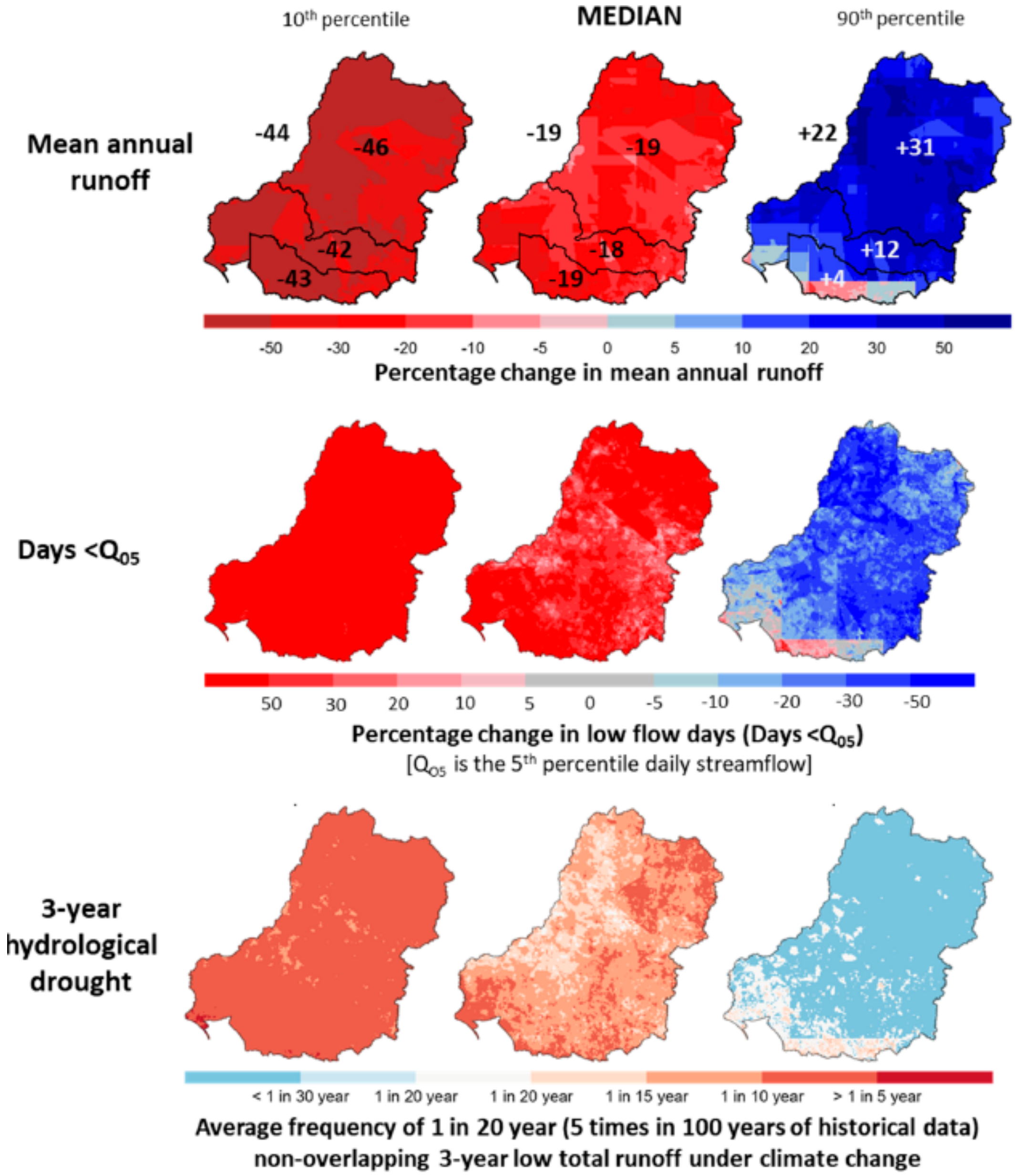

Fig. 9. Projected change in streamflow characteristics for 2046-2075 relative to 1976-2005 for the high RCP8.5 emissions scenario (from Prosser et al., 2021)

The range in the projections largely reflect the uncertainty in 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 partly attributed to winter rainfall decline as a result of 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. The magnitude of extreme high rainfall is expected to increase under climate change (Timbal et al., 2015, Wasko and Sharma, 2015). This will increase the risk of flash floods in built-up areas and small catchments. For large catchments, increases in extreme high rainfall events may not necessarily result in increased flood magnitude due to the effect of antecedent soil moisture conditions and attenuation of river flow (Wasko and Nathan, 2019).

Adaptation options to reduce flood risks include improved flood forecasting, developing temporary levee structures, maintaining floodplains, and water-sensitive urban design (Radcliffe et al., 2017).

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Given the large interannual variability in Basin's rainfall, 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. As a result, the change signal in rainfall 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. Another important consideration is the choice of baseline hydroclimate for near-term planning, particularly in the southern Basin, where the past 20 years have been considerably drier than the long-term (see Fig. 8).

Zhang et al. (2020) considered seven plausible climate scenarios – the historical climate and six future climate scenarios in assessing the impacts of climate change on streamflow regime. The development of these scenarios was guided by the latest climate science, historical climate and streamflow data, paleoclimate data and projections from global and regional climate models. They showed that:

- A warmer and wetter climate 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 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%) 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%).
- An increase in the severity and duration of multi-year droughts 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).

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. These hydroclimate metrics are directly relevant to the flow management tools used in the Basin Plan. The projected changes in these hydroclimate metrics can help the MDBA and stakeholders undertake climate vulnerability assessment with a focus on examining climate change impacts on the objectives and settings in the Basin Plan.

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).

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 changes 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). Over the last two decades, the science of hydroclimate projections has improved, but uncertainties in the projections will remain.

5. Challenge and opportunity for adaptive management of the Basin under climate change

The MDB has among the most variable hydroclimates in the world, making water resources management particularly challenging. The future will be warmer and is likely to be drier with more extreme weather events like the Millennium Drought and the 2022 floods. These changes pose a threat to sustainable management of the Basin as they are likely to have significant impacts on the Basin's water availability, agricultural production, communities and the environment. It challenges our science and calls for a more integrated and longer-term vision for the Basin with a healthy balance between agricultural water use and environmental water requirements.

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) there is considerable uncertainty in the future hydroclimate projections. 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. Management of the MDB under climate change will take policymakers and managers into 'uncharted territory' and would require the adoption of more flexible models of water governance and planning that consider multiple future pathways, as well as investment in new science and technologies (Hart et al., 2021).

There is no doubt that climate change is affecting hydrological characteristics of the Basin and impacting on our environment, economic and social development. There is an urgent need to invest in research to develop new knowledge and technologies to manage the risk posed by climate change. To facilitate assessments of climate change impact on water systems, climate scenarios need to be developed with acknowledgement of climate projection uncertainty and should be tailored to specific policy and management issues. This requires climate projections to be relevant and informative at the time and spatial scales of interest.

Climate impact assessments have been traditionally dominated by a "top-down" approach that begins with climate change projections followed by downscaling of GCM outputs and hydrological modelling. A complimentary approach to this model-driven 'top-down' approach begins with gaining an understanding of current exposures of the systems to climate, and then assess how these 'exposures' may change under different climate futures, a so-called 'bottom-up' approach. This approach focuses on identifying potential system vulnerabilities and relationships between the system performance and climate characteristics. *Research in 'bottom-up' approach is likely to yield more policy relevant information in the context of climate change and should be a future priority.* We also need to build stronger partnerships between research communities and management agencies to achieve the expected outcomes for the Basin.

Water resources planning and management needs to take into consideration not only average states of future hydroclimate but also extremes (e.g. increase in extreme high rainfall intensity, changed seasonality with winter rainfall decline, sub-annual dry spells and spatial patterns) with a longer-term (e.g. 50 years) planning horizon to identify actions that should be taken with development of new technology. To achieve this goal of sustainable development in the Basin, we need an integrated approach to include economic, social, cultural and environmental considerations at the whole of Basin scale.

What does a Future Ready MDB look like? In 2019, CSIRO ran a forum with 100 participants from diverse backgrounds to explore the future of the Basin through the lens of global trends, physical environment and regional communities and economics. The forum identified five key needs to achieve a future ready MDB with a longer-term vision (CSIRO, 2019):

- Understanding global drivers and their effect on the MDB;
- Engaging with communities to adapt to change;
- Investing in Aboriginal voices of the MDB;
- Strategic investments in new knowledge and technologies; and
- Building a system understanding.

Hart et al. (2021) articulated key priorities for improving the Basin Plan and the policy areas for sustainable water management in the Basin (see Fig.10). They call for more integrated catchment management with emphasis on climate change and community engagement. The Future Ready MDB needs are aligned strongly with the key priorities of Hart et al. (2021). The scientific community needs to work closely with policy makers and local communities towards development of shared vision and a whole-of-system view to support integrated basin management.

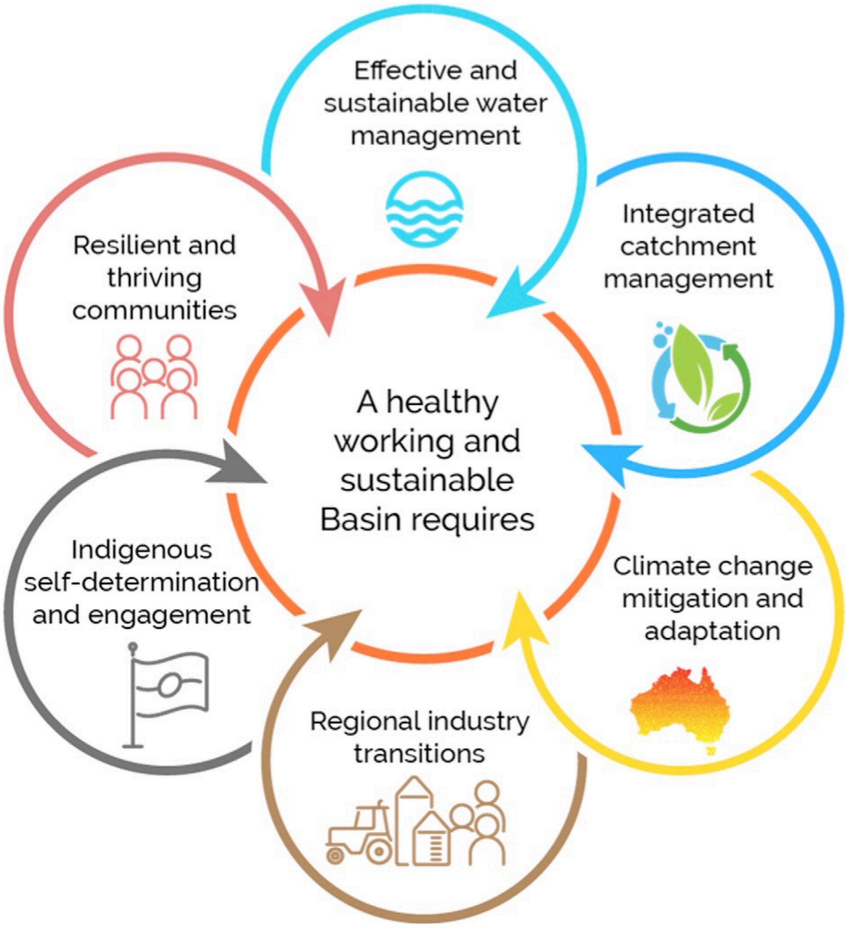

Fig. 10. Diagram showing the areas that need to be linked to achieve a healthy and sustainable working Basin (from Hart et al., 2021)

The historical development and management of the Basin reflects the realities of both coping with, and taking advantage of, the large natural variation in climate. With our growing understanding of how that climate is likely to change, particularly in likely extremes of both drought and flood, life in the Basin will inevitably have to adapt accordingly. This includes recognition that the landscape itself will change, for climate more than management determines the patterns and dynamics of the environment. Where we build, how we value, store and share water resources, what we grow and where, and how we insure or protect assets, livelihoods and heritage will either be anticipated and facilitated by long-term planning and policy or left to react to the changing vagaries of climate. Our understanding of the Basin's likely climate future merits an approach to planning and policy that gives industry, environmental managers and communities effective anticipation of the changing Basin.

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