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Evaluation of causes of reduced flow in the northern Murray–Darling Basin

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ERRATA This report was updated on 16 February 2023 to correct:

- an error across a number of pages related to the percentage of the proportional volume of surface water extraction due to floodplain harvesting from less than 10% to 20-25%
- typographical errors

Contents

EXECUTIVE SUMMARY

This Murray–Darling Basin Water and Environment Research Program (MD-WERP) tactical project was initiated by the Murray–Darling Basin Authority to evaluate the causes of reduced flow in the northern Murray–Darling Basin. The project was undertaken by synthesising knowledge from previous reviews and technical reports and enhanced with data analysis supported by a project in the MD-WERP Hydrology Theme.

The key findings are summarised below.

- Rainfall and streamflow in the past 50 years of living memory have declined across the Murray–Darling Basin, and south-eastern Australia generally. This is because the recent decades were dry and were preceded by wet decades. There have been similar long dry periods in the past like much of the first half of the twentieth century.
- Historical water resource development has also contributed significantly to the reduction in streamflow across the Murray–Darling Basin. Modelling indicates that development has reduced the flow volumes in the Barwon-Darling River by 40–50% compared to no-development conditions and has increased the frequency of low flow events. The impact of water resource development is accentuated in dry periods.
- Analyses of modelled and observed data indicate that the reduced streamflow in the Barwon-Darling River experienced over 2001–2019, relative to the wetter 1950–2000 period, can be attributed roughly equally to climate variability and to historical water resource development.
- Short and medium low flow periods (<6 months) are influenced by climate and development, and longer low flow periods (>1 year) are cause by prolonged dry period over the region.
- Flows are highly variable in the northern Murray–Darling Basin, resulting in the use of large on-farm storages to collect water when it is available. This provides visible evidence of water take on the landscape leading to more public scrutiny, particularly during dry periods when there are considerable volumes of water stored on-farm with little water visible in nearby rivers.
- Water resource development impact on low flow is largely caused by in-channel river extraction. Impact on overall flow volumes is caused by both in-channel river water extraction and floodplain harvesting. Averaged across the northern Basin valleys of NSW, floodplain harvesting is 20-25% of the total water take.
- There is considerable uncertainty in estimating the volume of water take into the on-farm storages, and this has led to scrutiny about whether and how much the water take is above what is intended in water resource management plans. Several initiatives have been recently established to address this, and they will improve knowledge and estimates of water take and management of water in the northern Basin.
- The Darling River contribution to the total downstream Murray River flow volume is much smaller than the contribution from the Murray River itself, with a long-term average contribution of about 15%.

There is a reasonably good general understanding of the hydrology and water resources in the northern Murray–Darling Basin, and most of the above findings have also been reported by MDBA and the Basin States. However, there are gaps in the knowledge, particularly for some water fluxes or components and at the detailed level required to better inform options to manage the river system more effectively especially in time of water stress. Recommendations to address the knowledge gaps are described in Section 5.2. There is also a need for more transparent engagement and communication with stakeholders to build confidence and trust in the knowledge, data and models, to enable positive engagements to seek solutions, make compromises and choices, and to adapt to changing conditions.

1. INTRODUCTION

1.1 Background

Flows in the Murray–Darling Basin in recent decades have been relatively low. Multiple recent reviews have highlighted a growing need to examine the causes (climate variability and water resource development) of reduced flows in the northern Murray–Darling Basin. These include the Interim Inspector General of the Murray–Darling Water Resources inquiry that recommended that "the MDBA should undertake further analysis of the causes of reduced inflows from the northern Basin and the extent to which this is affecting state water shares" (Interim Inspector General 2020). The panel examining the 2018/2019 fish deaths in the lower Darling made a series of recommendations to improve knowledge of northern Basin hydrology (Vertessy et al. 2019), and the Independent Panel assessing the NSW management of the 2020 northern Basin first flush event highlighted the lack of knowledge about the flows in the northern Basin (Craik and Claydon 2020). The MDBA 2020 Basin Plan evaluation also found indications of a step-change in the hydrological character of the northern Basin and recommended further research and modelling to enhance the hydrological knowledge (MDBA 2020a).

Systemic changes to flow have the potential to impact the long-term aims of the Basin Plan and the Water Act, and similar state-based water policy instruments. The reviews above, and analyses by the CEWO and MDBA, indicate that the observed changes to the flows in the northern Basin are significant, and are of the order of Basin Plan water recovery volumes in the northern Basin. There are numerous factors potentially contributing to the reduced flows in the northern Basin, including hydroclimate variability and climate change, catchment modification, irrigation development, floodplain harvesting, changes in river extraction rules, and non-compliance. The Interim Inspector General's inquiry highlighted that people are concerned that water theft, compliance, extraction rules and floodplain harvesting are having significant impacts downstream. The inquiry heard that understanding the relative influence of each of these factors is highly complex and has not been established.

The MDBA initiated this project to explain the causes of reduced flow in the northern Basin. This project is established as a tactical project in MD-WERP (Murray–Darling Water and Environment Research Program) and is also supported by a data analysis research project in the MD-WERP Hydrology Theme.

The definition of the northern and southern Basins, as used by the MDBA, is shown in Figure 1. The northern Basin is the entire Darling River Basin to just downstream of Wilcannia. The southern Basin is the Murray River Basin and the lower Darling. This boundary is used to aggregate rainfall and runoff across the northern and southern Basins presented in Section 3. The analyses of flows on the Barwon-Darling River in Section 4 also include gauges downstream of Wilcannia (at Weir 32 and Burtundy).

Figure 1. Northern and Southern Murray–Darling Basin.
[From Murray–Darling Basin boundary map | Murray–Darling Basin Authority (mdba.gov.au)**].**

1.2 Project aims and methods

The aims of the project are to:

- synthesise current hydroclimate and hydrological knowledge of the northern Basin
- identify limitations in the knowledge
- recommend methods that can overcome the limitation.

The project methods include:

- synthesising knowledge from previous reviews, technical reports and research papers
- engaging, learning and discussing with MDBA and Basin States technical and modelling experts
- enhancing the above through additional data analysis.

1.3 Process and governance

The project is established as a MD-WERP tactical project and is managed by the MDBA and MD-WERP leadership.

The steps in the project include:

- initial engagement with MDBA technical experts
- several presentations to the Basin Modelling Advisory Group (comprising MDBA and Basin States representatives)

- obtaining data and technical advice particularly from MDBA and NSW DPE
- reviews, synthesis and data analysis
- presentation to the MD-WERP Governing Panel
- producing a draft report that is reviewed by MDBA and Basin States
- completing a final report.

1.4 Report outline

Section 2 provides a background of the northern Basin communities, water resources and water uses. The section describes the history of water resource development, water resource planning and regulation, and scrutiny of water resource management in the northern Basin.

Section 3 presents the trends in climate and landscape rainfall and runoff across the northern Basin. This includes analysis of the characteristics of rainfall and gauged streamflow data, in particular the variability, declining trend and changing annual rainfall-runoff relationship over time.

Section 4 presents the trends and changes in the Barwon-Darling River. This includes analysis of flow volumes and low flow characteristics. Both observed and modelled data are used for the analysis.

Section 5 summarises the causes of reduced flow in the northern Basin and provides recommendations for addressing the knowledge gaps.

2. SYNTHESIS OF KNOWLEDGE AND REVIEWS ON NORTHERN BASIN DEVELOPMENT AND HYDROLOGY

2.1 Water resources in the northern Basin

The development of water resources in the northern Basin and the ongoing use, management and impact of the resources continues to see significant community, economic and political interest. In particular, how the water resources are accessed, used and managed and the subsequent effects on regional communities, environmental assets, downstream users and other Murray–Darling Basin stakeholders have been the subject of numerous reviews, studies, modelling and policy implementation.

The total catchment area of the northern Basin is about 600,000 km^2 and is formed through the catchments of eight major river valleys (Figure 2). The Barwon-Darling River system is the major delivery channel for waters out of the northern Basin into the southern Basin and Murray River (Figures 1 and 2). Contributions from upstream valleys and the tributaries that flow into the Barwon-Darling River have significant influence on the water flows (volume, timing, frequency) in the system, and it is therefore important to understand the way water resources in these valleys are managed.

From a hydrological and water resource perspective, the relative contributions from each of the tributaries provide an indication as to those that are likely to have the most impact on the Barwon-Darling River system. Figure 3 shows the runoff contribution (using the modelled runoff described in Section 3.1) and proportion area of the eight river valleys and the Barwon-Darling in the northern Basin. Runoff is highly variable spatially across the northern Basin, with 60% of the runoff coming from the Border, Gwydir, Namoi and Macquarie-Castlereagh River valleys that cover only 30% of the northern Basin area.

It is difficult to accurately estimate the inflows from these tributaries into the Barwon-Darling River because many of the valleys have terminal wetlands and floodplains that can retain significant amounts of water. This also highlights the importance of water resource management in the valleys to ensure there is sufficient water to meet the needs of ecosystems and environmental assets that exist throughout the valleys and at the end of tributary river systems as well as to provide inflows into the Barwon-Darling River system.

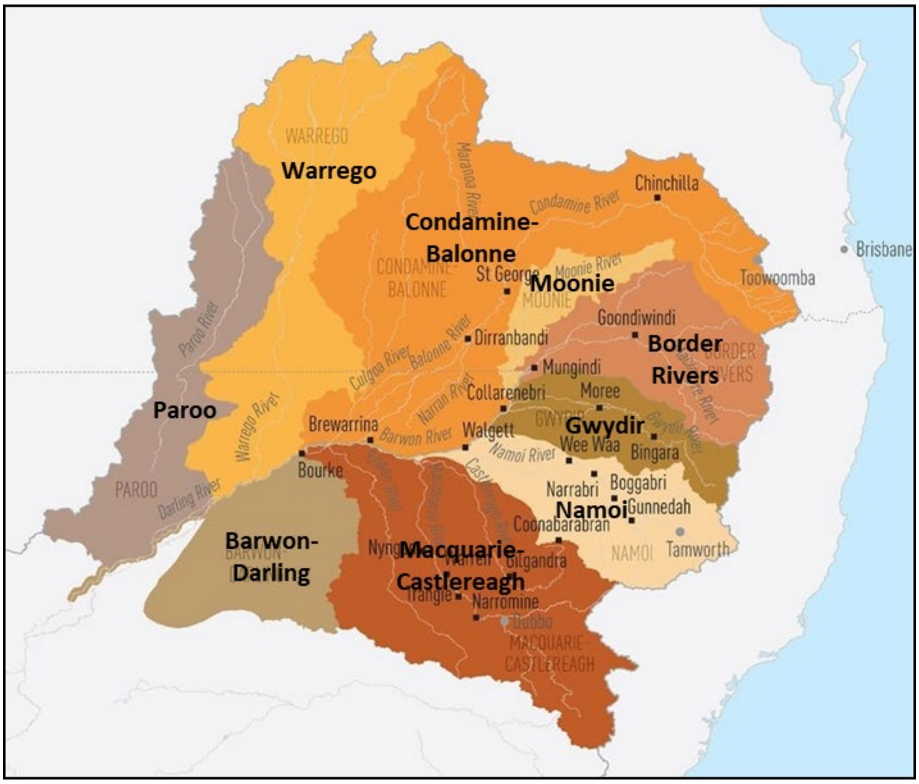

Figure 2. River valleys in the northern Basin.
[From Catchments in the Murray–Darling Basin | Murray–Darling Basin Authority (mdba.gov.au)].

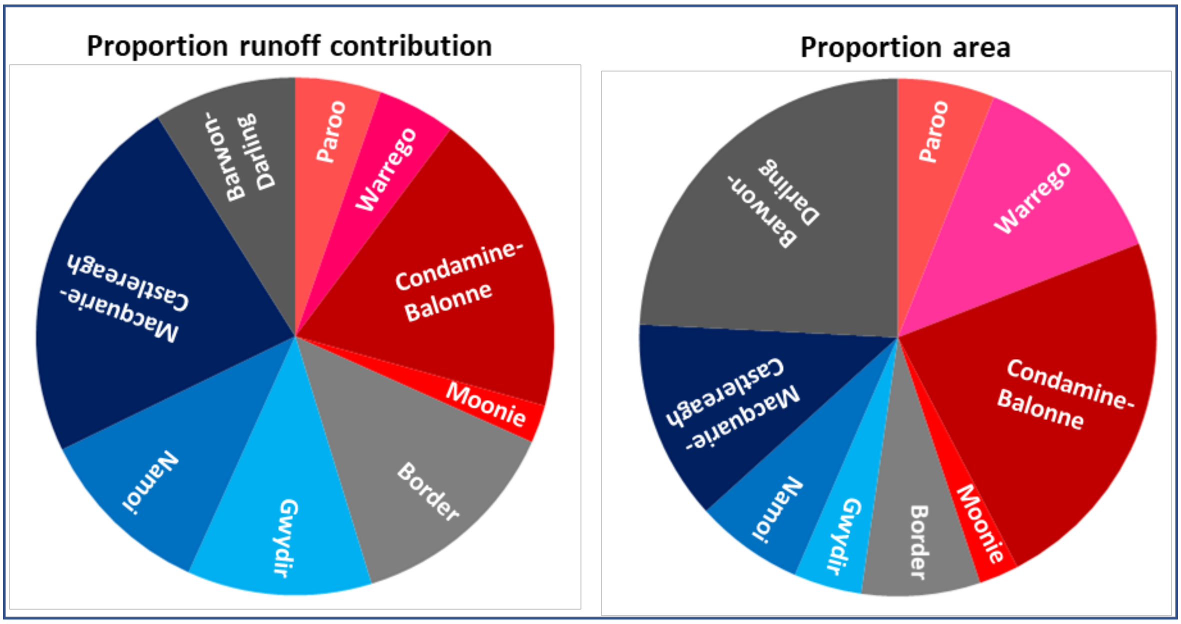

Figure 3. Modelled tributary contributions and proportion catchment area of river valleys in the northern Basin.

2.2 Northern Basin communities and water uses

The communities of the northern Basin, including First Nations Peoples, are dependent on the waters of the system for numerous economic, social and cultural uses. The management of the northern Basin is a frequent topic for discussion in many of these communities with the focus on tensions between the uses of water for agriculture, town water supply, downstream needs, cultural and social requirements and the environment. It is important therefore to understand how northern Basin hydrology provides for these water uses and where compromises, changed practices and constraints on water use may occur, now and into the future.

Across the Murray–Darling Basin, irrigated agriculture occupies only 3% of the total area but accounts for the majority of water use. Key agriculture activities in the northern Basin include cotton, cereals and grazing, with water extracted from groundwater, river (pumped and gravity fed) and overland flow (floodplain harvesting) (Water Use on Australian Farms, 2019-20 financial year | Australian Bureau of Statistics (abs.gov.au)).

2.3 History of water resource development in the northern Basin

Water resources in the northern Basin were relatively undeveloped until after World War 2, with most of the significant public headwater storages constructed between 1960 and 1985 (Figure 4). The northern Basin has much less public storage development compared to the southern Basin, contributing to only 20% of the reservoir storage capacity across the Murray–Darling Basin (Figure 5). This is partly because of the northern Basin's subdued topography, limiting the effectiveness of large storages and in-stream regulation.

In contrast to the southern Basin, water used for irrigation and other activities in the northern Basin is also extracted from rivers and from floodplains when they are available (during flow events) and stored in large private on-farm (or floodplain) storages. Figure 6 shows the current floodplain or on-farm storages and irrigated areas in the "unregulated" Barwon-Darling River system. Most of the floodplain storages were constructed between late 1980s and 2000 (Figure 7), as water availability from the reservoir storages constructed in previous decades meant that flows were more reliable than previously. Estimates of the total floodplain storage capacity in the Barwon-Darling floodplain management area ranges from 214 GL (Brown et al. 2022) to 283 GL (CSIRO 2008a).

Both Figures 6 and 7 show surface areas of floodplain storages from analysis of remote sensing derived water images (Ticehurst et al. 2022) and ancillary data (1 m digital elevation map from LiDAR data, land use map) (Peña-Arancibia et al. 2022a). The trend in the floodplain storage development in Figure 7 is the same as that reported and used for the Barwon-Darling River system modelling (NSW DPE 2022a). The analysis identified 107 large (>1,000 m^2 surface area) floodplain storages within the Barwon-Darling floodplain management plan area (NSW Government 2017). The same analysis can also identify open water area within the floodplain storages, as also shown in Figure 6, highlighting the variability of Barwon-Darling streamflow and the amount of water stored in the floodplain storages. Estimating the volume of water in the storages is much more challenging because most of the storages have steep walls resulting in significant variation of volume with little change in storage water level and the surface water area.

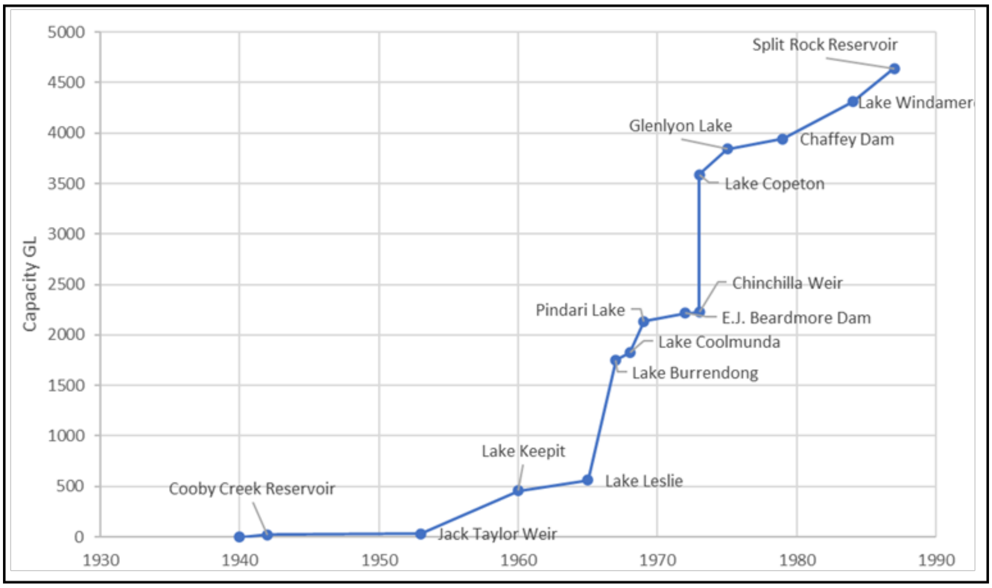

Figure 4. Cumulative capacity of major public headwater storages in the northern Basin.

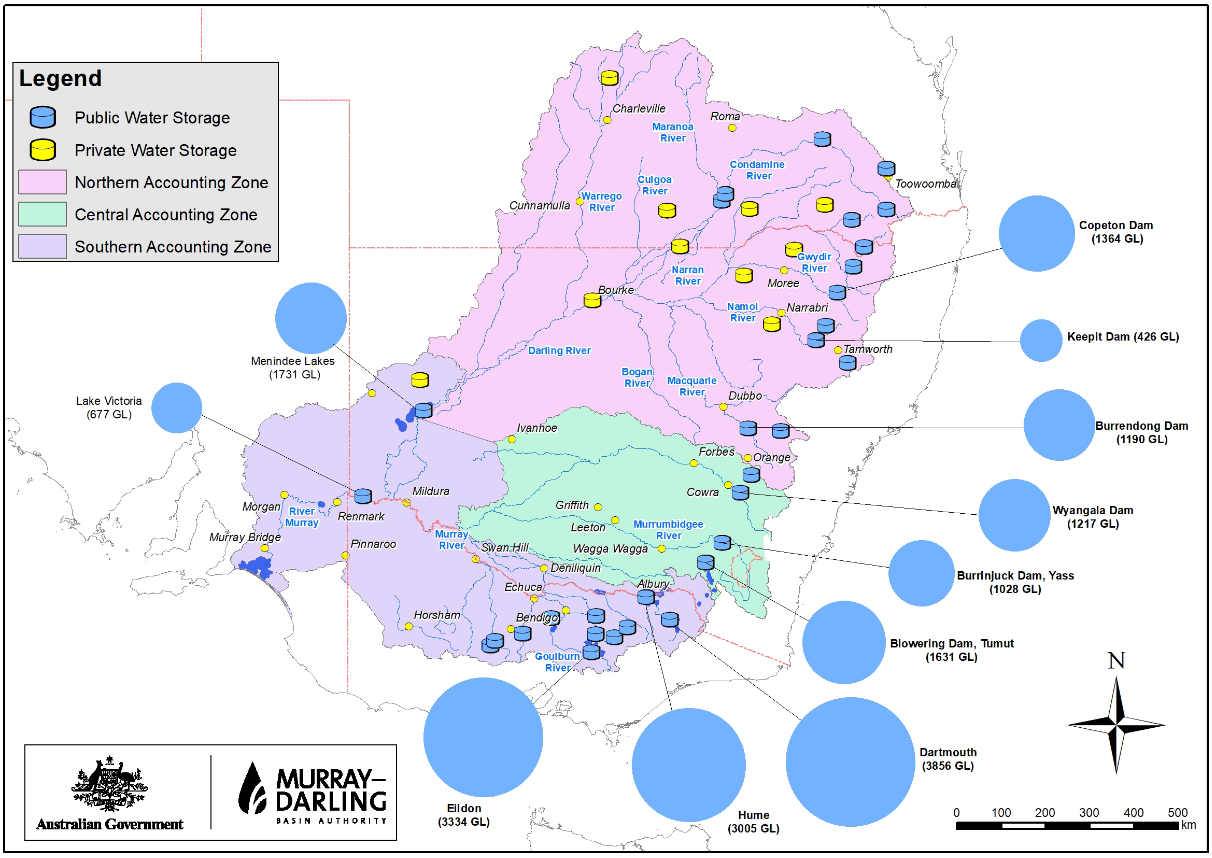

Figure 5. Major public storages in the Murray–Darling Basin.

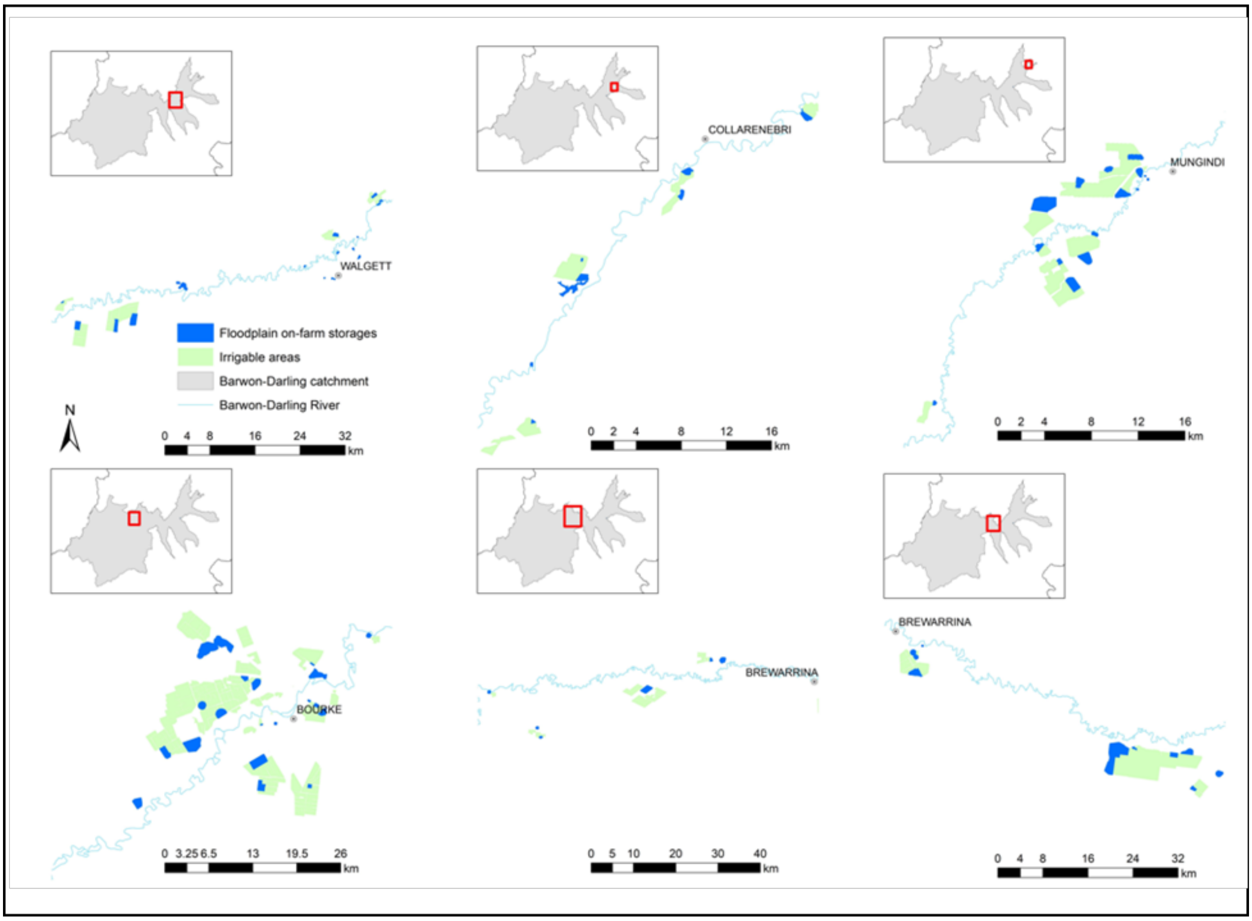

Figure 6. Locations of floodplain storages and irrigation areas within the Barwon-Darling River floodplain management plan area.
(Individual panels are organised from left to right following the direction of river flow).

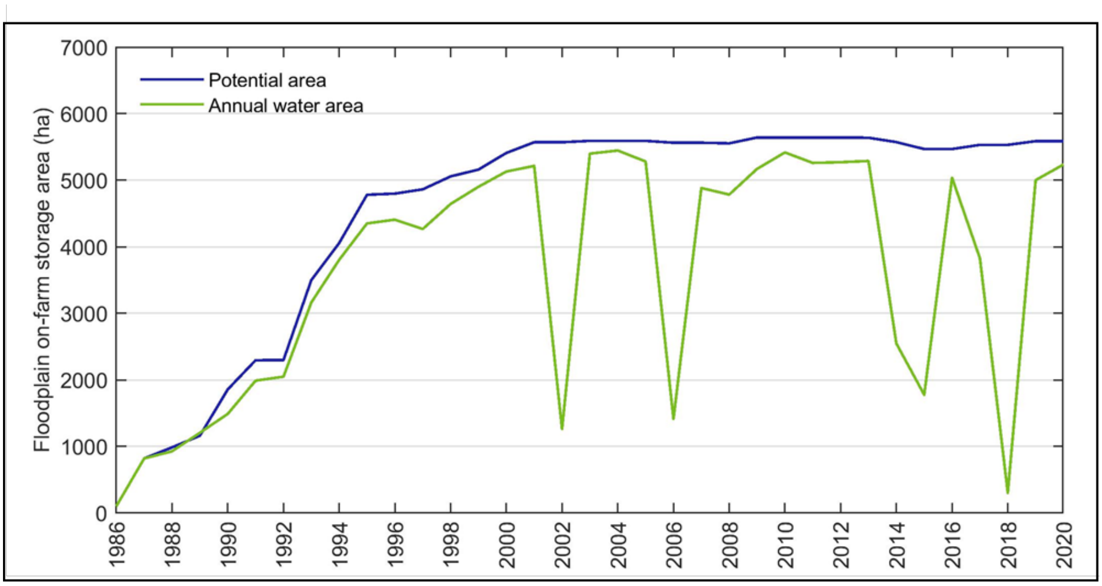

Figure 7. Potential surface area (capacity) of floodplain storages (blue) and annual time series of surface water area within the storages (green).
[Adapted from Peña-Arancibia et al. 2022a].

2.4 Planning and regulation of water resources in the northern Basin

Water resource management across the Murray–Darling Basin is a joint responsibility of the federal and state governments, with the Water Act 2007 (Water Act 2007 (legislation.gov.au)) providing the legislative framework for enabling the Murray–Darling Basin Plan and providing for the roles of agencies such as the Murray–Darling Basin Authority, the Commonwealth Environmental Water Holder and The Inspector-General of Water Compliance. In partnership with the water agencies in each of the Basin States, water resources are planned, managed, licenced and monitored across the Basin.

Water resources in the Basin are managed in order to (i) provide limits to the amount of water (both surface and groundwater) that can be taken each year, (ii) provide water for the environment, including recovery, planning and delivery to protect key ecosystems and environmental assets, (iii) plan and manage infrastructure development, operation and maintenance, (iv) maintain water quality (including salinity), (v) allow for water markets and trade, (vi) undertake monitoring, enforcement and compliance activities, and (vii) evaluate effectiveness of water management plans, policies and actions.

The key documents that outline the sharing of water across individual catchments or basins are accredited Water Resource Plans, enacted through Water Sharing Plans in New South Wales and Water Plans in Queensland. These outline the management measures to be put in place in order to ensure that the Sustainable Diversion Limit (SDL) for a particular catchment and across the Basin is not exceeded over the long-term average. They are intended to work in partnership with other state-based arrangements for water management.

2.5 Modelling of water resource system

River system models have been developed for all the river valleys across the Murray–Darling Basin to support development of policy and regulatory instruments in managing the water resources of the Basin and to evaluate compliance with the Basin Plan. These models have been developed progressively over several decades and through successive model frameworks and are now being brought into a consistent eWater Source modelling platform (Welsh et al. 2013, Ewater Source - eWater). To ensure some consistency in modelling across the Basin, the MDBA, in collaboration with Basin States, has established guidelines and protocols for the modelling (Australian Modelling Practice - eWater Online Community - eWater Wiki).

The river system models operate over a number of scales. Figure 8 shows an example of modelling at the farm or property scale. This conceptually represents one or more properties that access water through common points and/or use water in similar ways. Figure 9 shows an example conceptualisation of the river reach scale and water fluxes into and out of the river reach. River system models are typically constructed through the compilation of numerous reach scale "sub-models", each of which will have groups of farm scale models. They are then brought together as an integrated network within the modelling platform to form a whole of valley system model. The river system models also have rules on how reservoirs and river system are managed and how water is allocated, as well as algorithms simulating water take and water use.

The models require many different types of input data and use parameters and algorithms to describe the various processes (e.g., landscape runoff generation, transmission losses, overbank flow). Input data include daily time series of climate and streamflow, measured extraction from the river, and physical system characteristics (e.g., river network, irrigation area, floodplain storages and infrastructure). Some of these have a relatively higher degree of certainty, like rainfall and observed streamflow. Some of the data, although not measured directly, like crop water use and number and volume of on-farm storage can be estimated reasonably by putting together or developing relationship with secondary datasets such as remote sensing data, landholder records or targeted experimental assessments.

However, despite the significant progress in modelling, including integrating information from multiple sources such as on-ground measurements, remote sensing and anecdotal evidence, there remains significant gaps and considerable uncertainty in estimating some of the fluxes. This includes the estimation of catchment runoff in arid and semi-arid landscapes of the region, floodplain harvesting volume at farm level, total river water extraction beyond that which is licensed or measured, amount of overland flow that returns to the river, transmission losses, surface-groundwater exchange, and low flow characteristics (Weber and Claydon 2019).

Models cannot perfectly reproduce the complex natural and human-related behaviour of a river system, but they are vital tools for testing policy and regulatory framework development. The appropriate use of models recognises their uncertainties and assumptions, and also the need to cultivate policy maker and community buy-in regarding the value of models as a policy development tool. This has led to State and Commonwealth agencies to use multiple lines of evidence to supplement modelling, to be more transparent through improving model documentation and explaining model outputs, and engaging with stakeholders in the model development process, to improve overall understanding and confidence in the interpretation and use of the models (NSW DPE 2022a, 2022b, and NSW modelling reports for most of the river valleys).

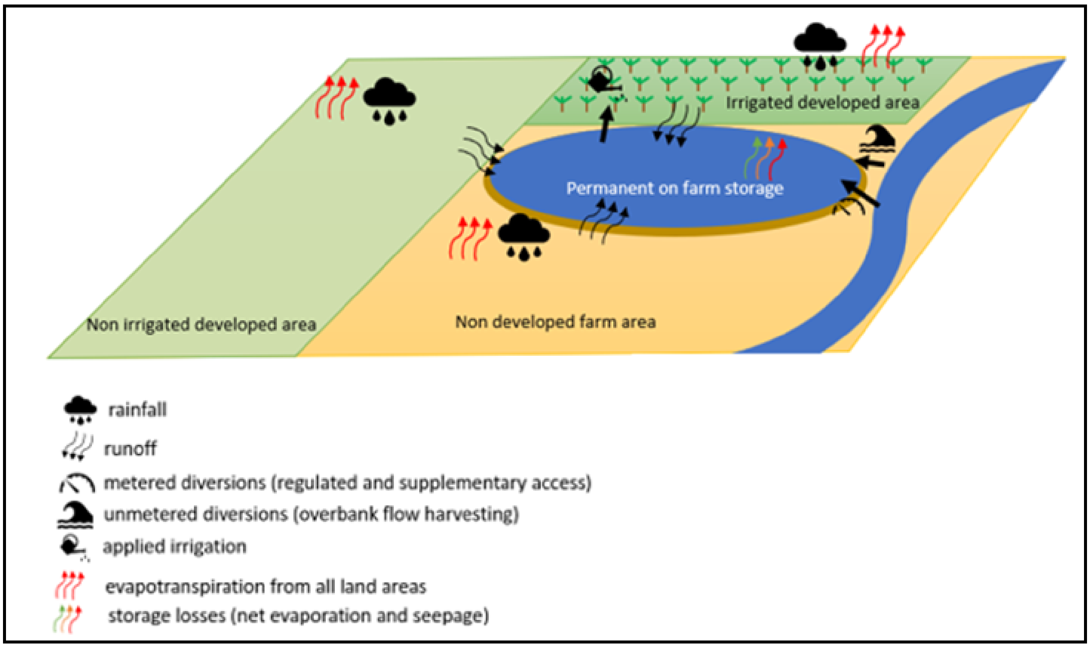

Figure 8. Property or farm scale conceptualisation in river system modelling. [From NSW DPE 2022a].

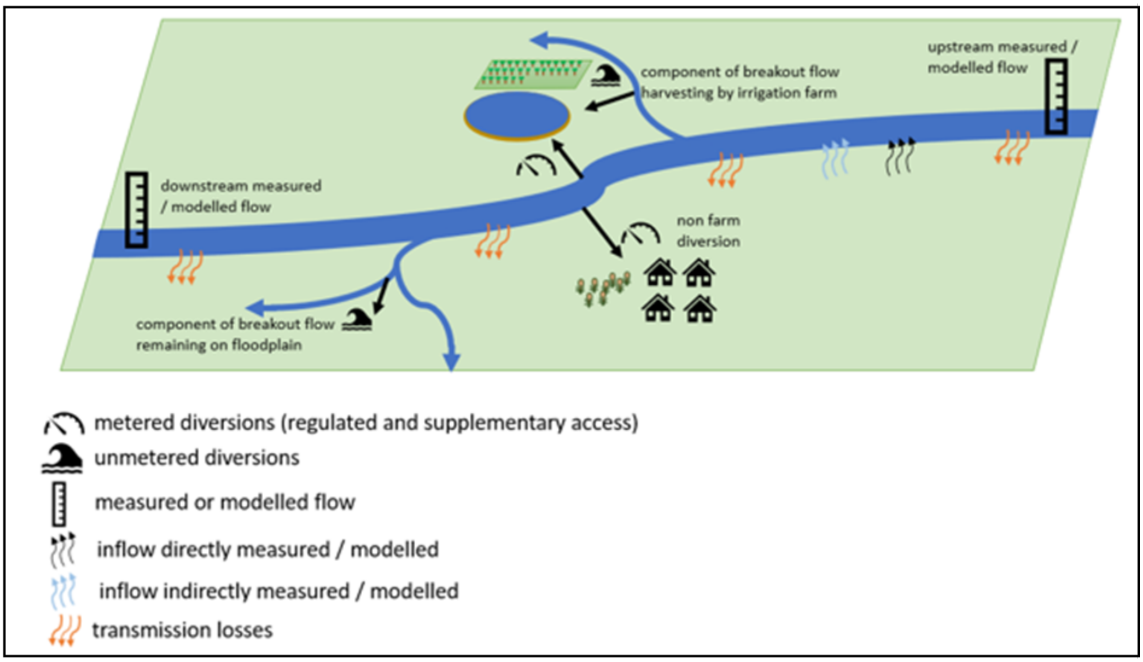

Figure 9. River reach scale conceptualisation in river system modelling. [From NSW DPE 2022a].

2.6 Scrutiny of water resource management in the northern Basin

There have been ongoing tensions amongst water users across the whole of the Murray–Darling Basin since the early 1900s with the development of water infrastructure, ongoing droughts and variability in available water and the need to coordinate governance and management across five states and territories in order to provide for equitable access to water. To a large extent, policies such as the Basin Cap, the Living Murray, and the Basin Plan have worked to address the underlying issues behind such tensions, but many remain especially in time of water scarcity. These tensions have led to a number of significant enquiries at the state and federal levels associated with ongoing management of the resources (e.g., South Australia Murray–Darling Basin Royal Commission, Walker 2019) and as a response to key crises like the fish deaths in the lower Darling (Vertessy et al. 2019) and water availability and sharing during droughts (Interim Inspector General 2020). The MDBA completed a review of Basin Plan settings in the northern Basin in 2016 (MDBA 2016), which resulted in a change to the Basin Plan and the adoption of the northern Basin toolkit in 2017.

Largely, these reviews have focussed attention on the availability of water and the proportionate share of water use within the northern Basin and between the northern and southern Basins. The importance of the northern Basin hydrologic characteristics is often raised, with considerable variance in the assumptions as to the quantum of water available, its timing, the influence of agricultural development on water availability and the extent to which climate variability and climate change are having an effect on these.

Flows are more variable in the northern Basin compared to the southern Basin, with many more of the northern Basin rivers experiencing long periods of low flows, both prior to water resource development and afterwards. The higher streamflow variability in the northern Basin has resulted in the need to use large private floodplain on-farm storages to collect water when it is available and keep this water on-hand for use when it is needed for agriculture and other activities. This provides visible evidence of water take on the landscape resulting in more public scrutiny, especially during dry periods when there are considerable volumes of water stored on-farm with little water visible in nearby rivers. This visual contrast does not occur in the southern Basin where water is stored in large public reservoir far away in the upper pats of the catchments.

The hydrology of the northern Basin, defined by longer periods of dry weather when river systems cease to flow, followed by large flow and flood events where runoff is plentiful, means that the take of water needs to be finely balanced between that available for consumptive use and that which passes downstream. This brings a number of key issues into focus on a regular basis, including:

- the relationship between water uses in upstream tributaries or valleys and main river channels of the northern Basin where flow is more sporadic or intermittent compared to the perennial rivers in the southern Basin providing a higher water reliability
- the taking of water over short periods (in-channel water extraction during flow events and floodplain harvesting of overland flow) requires large storages to provide for consumptive water use during periods of little flow

- the requirements for environmental watering and the timing and frequency of those requirements are often in conflict with periods when water harvesting may also be possible, especially after extended periods of dry conditions
- the water use and how water is harvested in the upstream tributaries/valleys impact end-of-valley conditions and flows into the Barwon-Darling River.

In the Interim Inspector General (2020) report into water sharing arrangements for the River Murray system, it was acknowledged that the natural river flow regimes in the Murray–Darling Basin are highly variable from year to year, and the River Murray inflows in the past two decades were significantly lower than in the preceding decades. This places increased importance on how flows and water availability in the northern Basin will be able to assist in provision of water to downstream users.

Periods of acute water stress are also times when large-scale ecological impacts are felt, such as the 2018-2019 fish deaths in the lower Darling, when the combined effects of low water flows, high temperatures and significant algal blooms resulted in conditions that led to hypoxia across the whole water column from which the large fish population could not escape. The findings of the Independent Panel (Vertessy et al. 2019) into this event highlighted both the need for ongoing water reform in the northern Basin, and the need to better understand runoff response changes after recent droughts, the effect of water extractions from tributaries of the Barwon-Darling River and from the Barwon-Darling River itself, especially during periods of low flows and the changes in frequency, magnitude and duration of low flows due to the effects of water diversions and “carry-forward” arrangements.

Overall, this continued high level of interest in the role and effect of the northern Basin on water sharing, acute and chronic water quality impacts and the relationships between water users across the Basin means that continued efforts to better understand the hydrological characteristics of the system are of considerable importance.

2.7 On-farm storages, riverine extraction and floodplain harvesting

The floodplain on-farm storages in the Barwon-Darling River (Figure 7) and across the northern Basin were largely constructed between the late 1980s and 2000. Nevertheless, there has been some growth in the floodplain storage capacity through raising wall heights and deepening borrow pits (Peña-Arancibia et al. 2022a, Brown et al. 2022) as well as consolidation and decommissioning of some storages (e.g., small reduction in surface area capacity after 2010 in Figure 7). Floodplain works that provide access to overland flow have also developed increasing the ability to take water from the floodplain.

The total volume of take of riverine water (pumping or diversion from the river) is larger than floodplain harvesting. The river water extraction occurs much more frequently than floodplain harvesting which can only happen during very high flow events when the river overflows to the floodplain. Averaged across the northern Basin valleys of NSW, floodplain harvesting is 20-25% of the total water take (NSW DPE 2021e and the NSW model scenario reports). There has been some growth in floodplain harvesting, and some of this is likely to be compensated by a reduction in riverine water extraction because any water take will reduce the airspace in the storage for water take from another source. For example, the floodplain harvesting in the unregulated Barwon-Darling River has doubled in the recent decades, but is now still less than 15% of the total water take in the Barwon-Darling valley (NSW DPE 2022b).

There is considerable uncertainty in estimating the volume of water take into the on-farm storages, and this has led to scrutiny about whether and how much the water take is above what is intended in water resource management plans. Nevertheless, there have been several recent initiatives to address this challenge, like floodplain licensing policies, metered measurements of water take and storage level, and using new remote sensing technology. These, and further information collected through them over the next couple of years, will no doubt improve knowledge and estimates of water take and management of water in the northern Basin.

3. TRENDS IN CLIMATE AND LANDSCAPE RAINFALL AND RUNOFF

3.1 Hydroclimate trend and variability in the northern Basin

- **Rainfall and runoff in the northern Basin exhibit high inter-annual, multi-year and decadal variability.**
- **The past two decades in the Murray–Darling Basin have been relatively dry.**
- **The low rainfall is amplified in the percentage reduction in Basin runoff and inflows.**

The climate and streamflow data, averaged across the northern and southern Basins, over the past 120 years, are presented here to provide an indication of the climate signal or impact on runoff and therefore water resources. The annual time series of rainfall and runoff averaged across the northern and southern Basins are shown in Figure 10. For the northern Basin, the annual water year from July to June is used because most of the rainfall here occurs in summer and early autumn. In this report, the water year for a specific year is defined from July of the year to June the following year (i.e., data for 1970 covers the period from July 1970 to June 1971). For the southern Basin, the calendar year is used as rainfall and runoff here is winter dominated. Data for the northern Basin in Figure 10 covers the period 1900 (from July 1900) to 2020 (up to June 2021). Data for the southern Basin covers the period from 1900 (from January 1900) to 2021 (up to December 2021).

The source of the rainfall data is the 5 km gridded dataset from the Australian Bureau of Meteorology (http://www.bom.gov.au/metadata/catalogue/19115/ANZCW0503900380). The modelled runoff series comes from the GR4J lumped conceptual daily rainfall-runoff model (Perrin et al. 2003). The GR4J model is calibrated against gauged streamflow data from the Bureau of Meteorology Hydrologic Reference Stations (www.bom.gov.au/water/hrs/) (see Section 3.2) which have continuous daily data over the past 40 years in most catchments (Zheng et al. 2019, Zhang et al. 2016). Parameter values from the closest gauged catchment are used to model all the 5 km grid cells across the Basin. The largely unimpaired (low development) gauged catchments are located mainly in the upland areas where most of the runoff is generated, and therefore there is considerable uncertainty in the modelled runoff for the lower landscapes. As there is relatively little development in these upland catchments (see Section 3.3), the modelled runoff in Figure 10 largely reflects the rainfall impact (and to a lesser extent potential evapotranspiration) on runoff. Rainfall-runoff modelling to provide broad scale regional assessment is a matured science and practice (Chiew 2020, Bloschl et al. 2013), and simulations from different rainfall-runoff models (including the Murray–Darling Basin Sustainable Yields modelling (Chiew et al. 2008, CSIRO 2008b) and Bureau of Meteorology Australian Landscape Water Balance (http://www.bom.gov.au/water/landscape/#/sm/Actual/day/-28.4/130.4/3/Point////2022/4/19/)) show similar broad scale annual and decadal characteristics (Zheng et al. 2019).

Rainfall in the northern Basin is highly variable (Figure 10). The mean annual rainfall averaged across the northern Basin is 480 mm, and the coefficient of variation of annual rainfall is 0.25. This high rainfall variability is amplified in the runoff variability. The mean annual runoff averaged across the northern Basin is 21 mm (less than 5% of rainfall), and the coefficient of variation of annual runoff is 0.8 (more than 3 times the inter-annual rainfall variability). Runoff in the wettest years can be more than 20 times higher than runoff in the dry years. This high runoff variability is a feature of Australian rivers, which exhibit higher inter-annual variability compared to rivers in similar climate regions in other parts of the world (Peel et al. 2004, Chiew et al. 2002).

The plots in Figure 10 show that the period from 1900–1945 was relatively dry in both the northern and southern Basins. This was followed by many wet years in the 1950s and 1970s. The recent 2 decades have been relatively dry, but unlike the first half of the century, is broken by several wet years in between. The recent dry periods include the 1997–2009 Millennium drought (which is much more evident in the southern Basin, see also Section 3.2) and 2017–2019 being the driest 3-year period in 100+ years of instrumental rainfall record in much of New South Wales (Figure 10). As the past two decades were relatively dry with wet decades preceding this, any assessment using data from only the recent history would accentuate the recent dry conditions. For example, Figure 11 shows the declining rainfall trend from 1970 across much of eastern Australia. For context, analysis starting from 1940 onwards all show a clear declining rainfall trend across the MDB. The trends are less obvious for analysis with earlier start dates because of the dry periods in the first half of the 20th century.

The temperature in the Murray–Darling Basin has risen by about 1.4^{o}C over the past 100 years, with most of the increase occurring after 1970 (Figure 12). The higher temperature would increase potential evapotranspiration (PET) accentuating the reduction in runoff. It is worth noting that in PET formulations, the increase in PET largely comes from the increase in vapour pressure deficit driven by higher temperature. Despite increases in temperature, decreases in pan evaporation have been reported around the world (commonly referred to as the ‘pan evaporation paradox’), and this has been attributed to reductions in wind speed and solar radiation (McVicar et al. 2012). However, this trend has plateaued and reversed in recent decades (Stephens et al. 2018). Increasing vapour pressure deficit has become more dominant, resulting in an increasing pan evaporation trend since 1994, and PET would continue to increase with higher temperature under climate change.

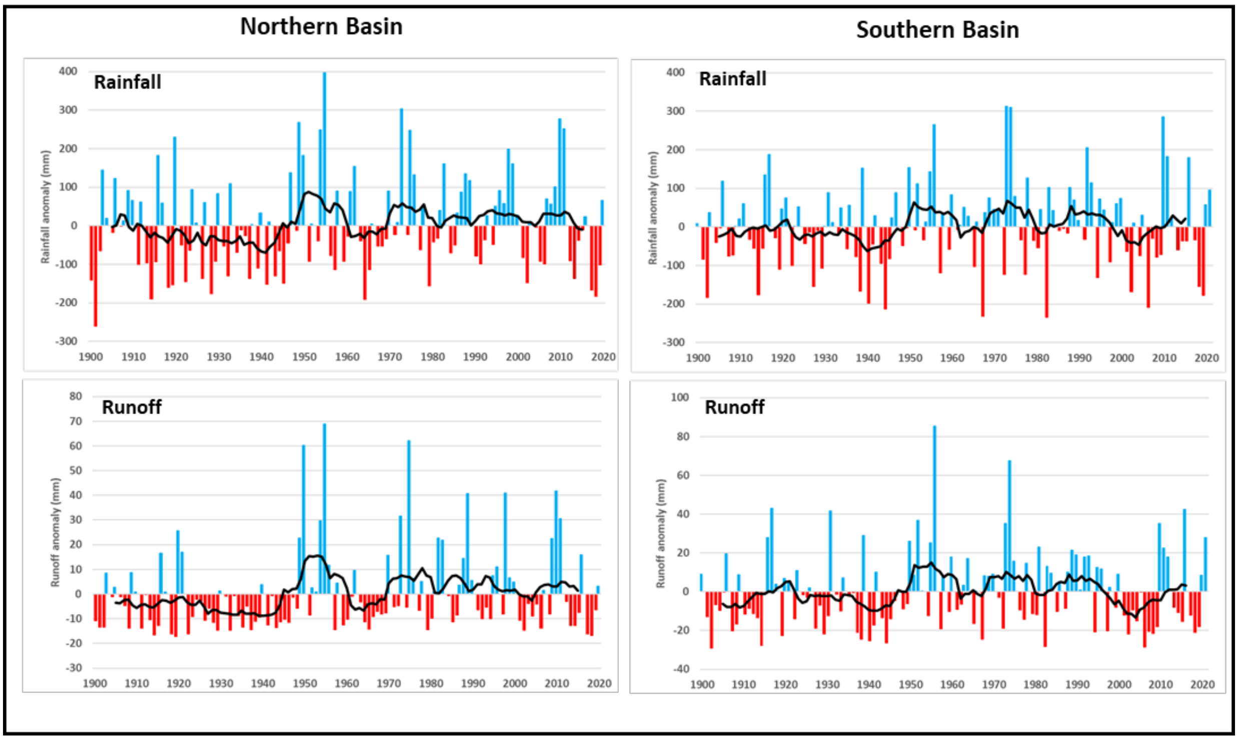

Figure 10. Annual rainfall and runoff series averaged across the northern Basin and southern Basin (blue and red colours show anomalies above and below the long-term average respectively, black lines show 11-year moving average centred at the mid-point).

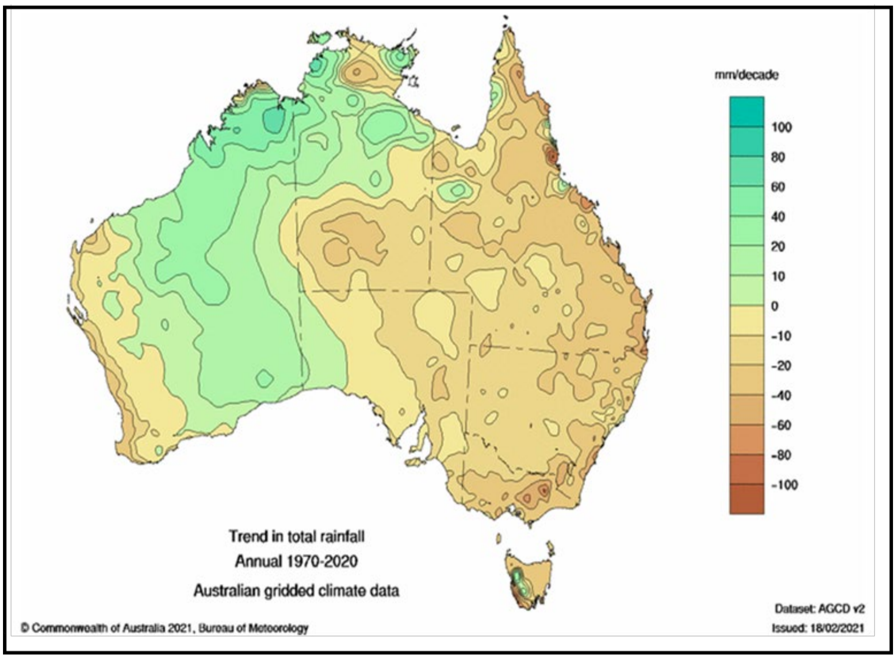

Figure 11. Rainfall trend from 1970 to 2020. [From Bureau of Meteorology website, accessed 6 Sep 2022].

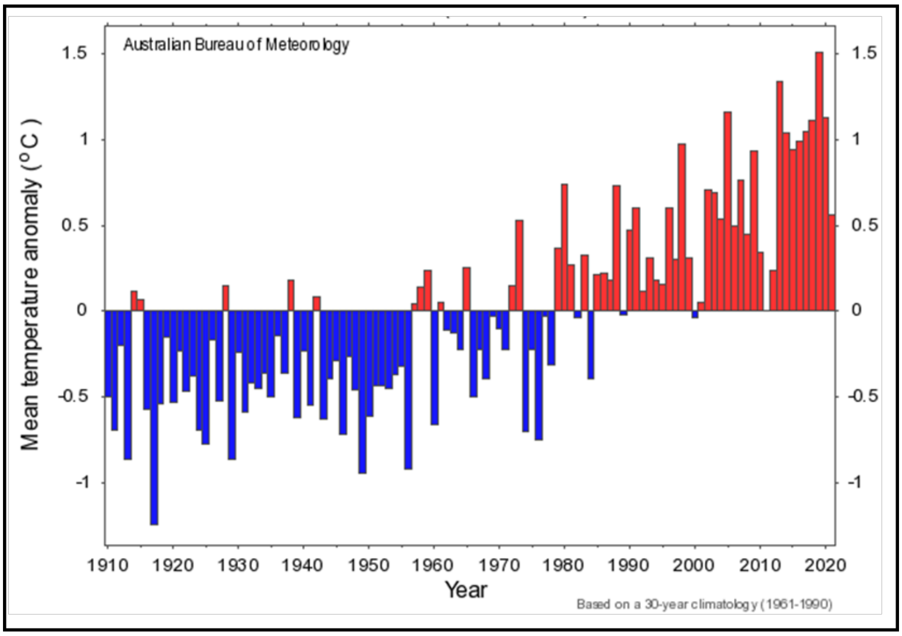

Figure 12. Annual temperature series for the Murray–Darling Basin from 1910 to 2021. [From Bureau of Meteorology website, accessed 6 Sep 2022].

3.2 Trends in observed rainfall and streamflow data

- **Rainfall and streamflow records across the Murray–Darling Basin show a declining trend over the past 50 years of living memory, as the relatively dry past two decades were preceded by wet decades.**
- **The Murray–Darling Basin is likely to be hotter and drier under climate change, with lower mean annual streamflow and more frequent hydrological droughts in the future.**

The plots in Figure 13 show the trends in the observed rainfall, streamflow and runoff coefficient in the 133 Hydrologic Reference Stations (HRS) catchments across the Murray–Darling Basin from 1970 to 2020. There are 37 HRS catchments in the northern Basin and 96 HRS catchments in the southern Basin. These are largely unimpaired catchments, and are therefore mainly located in the upland areas, with better spatial coverage in the high runoff areas in the south-eastern parts of the Murray–Darling Basin. The catchment areas range (10^{th} to 90^{th} percentile) from 120 to 2,600 km^2. The background shading in the plots shows the linear trend from 1970 to 2021. The statistical significance shown in Figure 13 is for the slope of the linear regression (correlation above 0.28 for the 51 data points or years (1970–2020) indicates that the trend is statistically significant at a < 0.05). Trend detection using the range of parametric and non-parametric tests also show similar results. The results are also consistent with the analyses of Zhang et al. (2016) for streamflow across Australia and the analyses by Bureau of Meteorology (2020) for rainfall and streamflow in the Murray–Darling Basin.

For the northern Basin, 84% of the 37 HRS catchments show declining trend in rainfall, but none of them is statistically significant (at a < 0.05). The declining trend in in rainfall is amplified in the streamflow, where 92% of the catchments show a declining trend with 22% being statistically significant. Consistent with the above rainfall and streamflow trend, 95% of the catchments show a declining trend in the runoff coefficient with 27% being statistically significant. Averaged across the northern Basin, rainfall and runoff since 1970 have been declining at 16.6 mm and 2.2 mm per decade respectively (Figure 13).

The declining trend in rainfall and in particular streamflow is more significant in the southern Basin compared to the northern Basin. Some of the catchments in the southern Basin show a statistically significant declining trend in the rainfall, and almost all the catchments show a statistically significant declining trend in the streamflow and runoff coefficient (Figure 13). This is because the 1997–2009 Millennium drought is much more severe in the southern Basin with some catchments experiencing streamflow reduction of more than 50% (DELWP 2020, Saft et al. 2016).

The main feature of the Millennium drought is the reduction in the cool season rainfall (March to October) which has persisted even after the drought. The impact of the Millennium drought on runoff is greater in the southern Basin (and even greater in Victoria) because the reduction in rainfall is higher further south and because most of the runoff further south occurs in winter and spring. This reduction in cool season rainfall has been partly attributed to changes in general atmospheric circulation under a warmer climate pushing the cool season storm tracks further south (Timbal and Hendon 2011, Post et al. 2014, Rauniyar and Power 2020, DELWP 2020) and practically all climate models project a drier future cool season across south-eastern Australia (CSIRO and BoM 2015, Zheng et al. 2019, Grose et al. 2020).

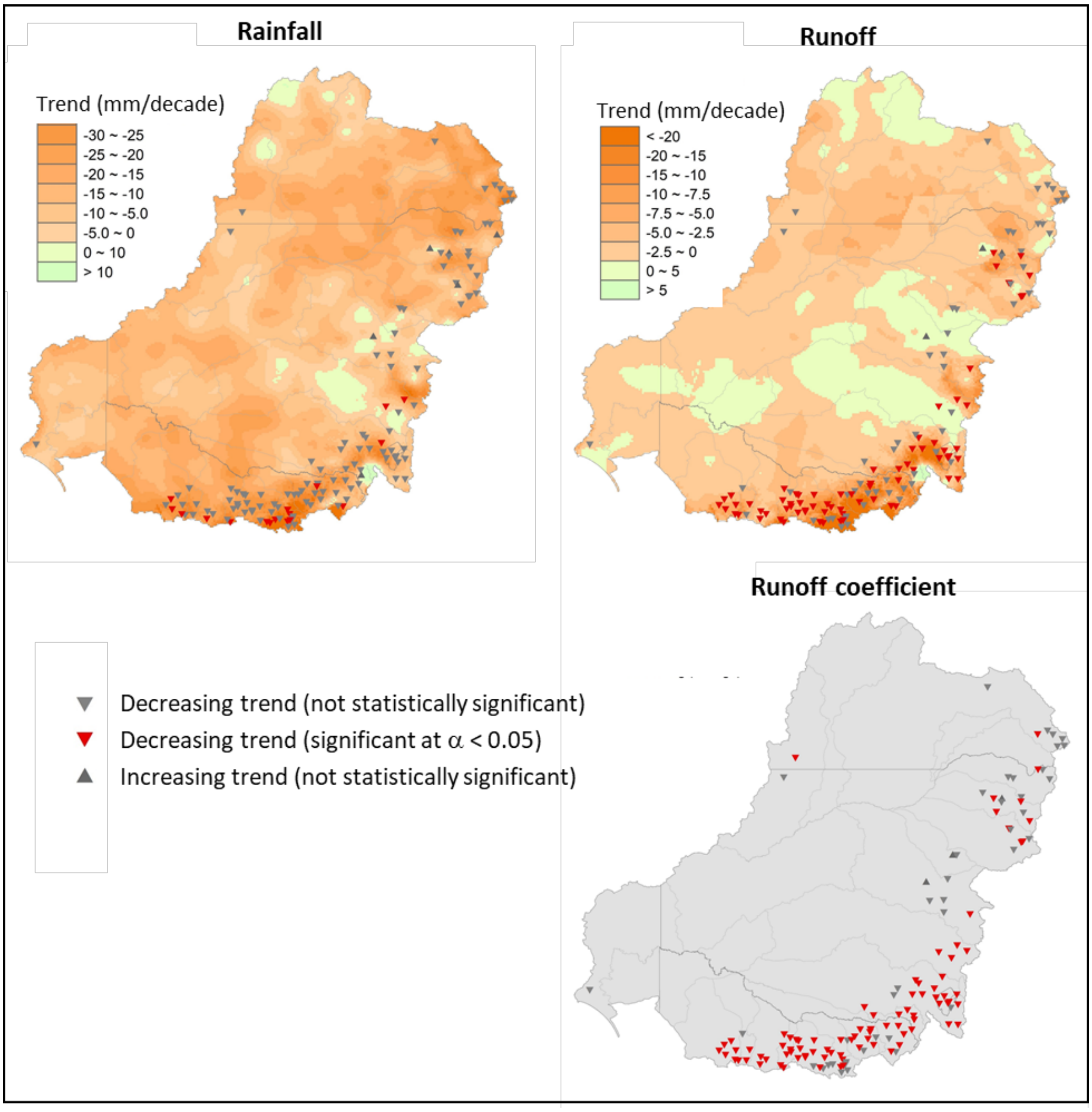

Figure 13. Trend in rainfall, streamflow and runoff coefficient from 1970 to 2020 (results are shown for 133 catchments, background shading shows the linear trend).

Hydroclimate projections modelled by rainfall-runoff models informed by climate change signal from global climate models indicate that mean annual rainfall and runoff is likely to decrease across the Murray–Darling Basin. The median projection under 2°C global average warming indicates a 20% decrease in mean annual runoff (and therefore future water resources) across the Basin (Figure 14, Zheng et al. 2019, Whetton and Chiew 2021). However, there is a large range in the future runoff projections, largely because of the large range or uncertainty in future rainfall projections. The projected change in mean annual runoff in the southern Basin (which is strongly impacted by the projected reduction in cool season rainfall) under a 2°C global average warming range from (10^{th} to 90^{th} percentile) -40% to +10%. The projected change in mean annual runoff in the northern Basin (which is also driven by warm season rainfall for which the direction of rainfall change is less certain) has a large range from -45% to +30%.

Hydroclimate variability in the future would remain high, and long wet periods and long dry periods would continue to be experienced. The downward shift in the mean rainfall and runoff would be reflected in more frequent and severe droughts. The projections indicate that hydrological droughts that are experienced in the historical data could occur twice as frequently in the future. These projections are shown in Figure 14, together with projected changes in high flow and low flow characteristics for the Basin. The projections for low flow are indicative because it is difficult to define suitable low flow metrics (particularly for the ephemeral and intermittent rivers in the northern Basin), it is difficult to reliably model low flows, and unlike for medium and high flows, low flow projections developed using different models and approaches can be quite different (Chiew et al. 2018). The climate change signal used in the above hydrological modelling is consistent with the CSIRO and BoM (2015) projections (www.climatechangeinaustralia.gov.au). Dynamical downscaling simulations supported by Queensland, New South Wales and Victorian state water agencies also project a declining trend in future rainfall (Chiew et al. 2021, 2022).

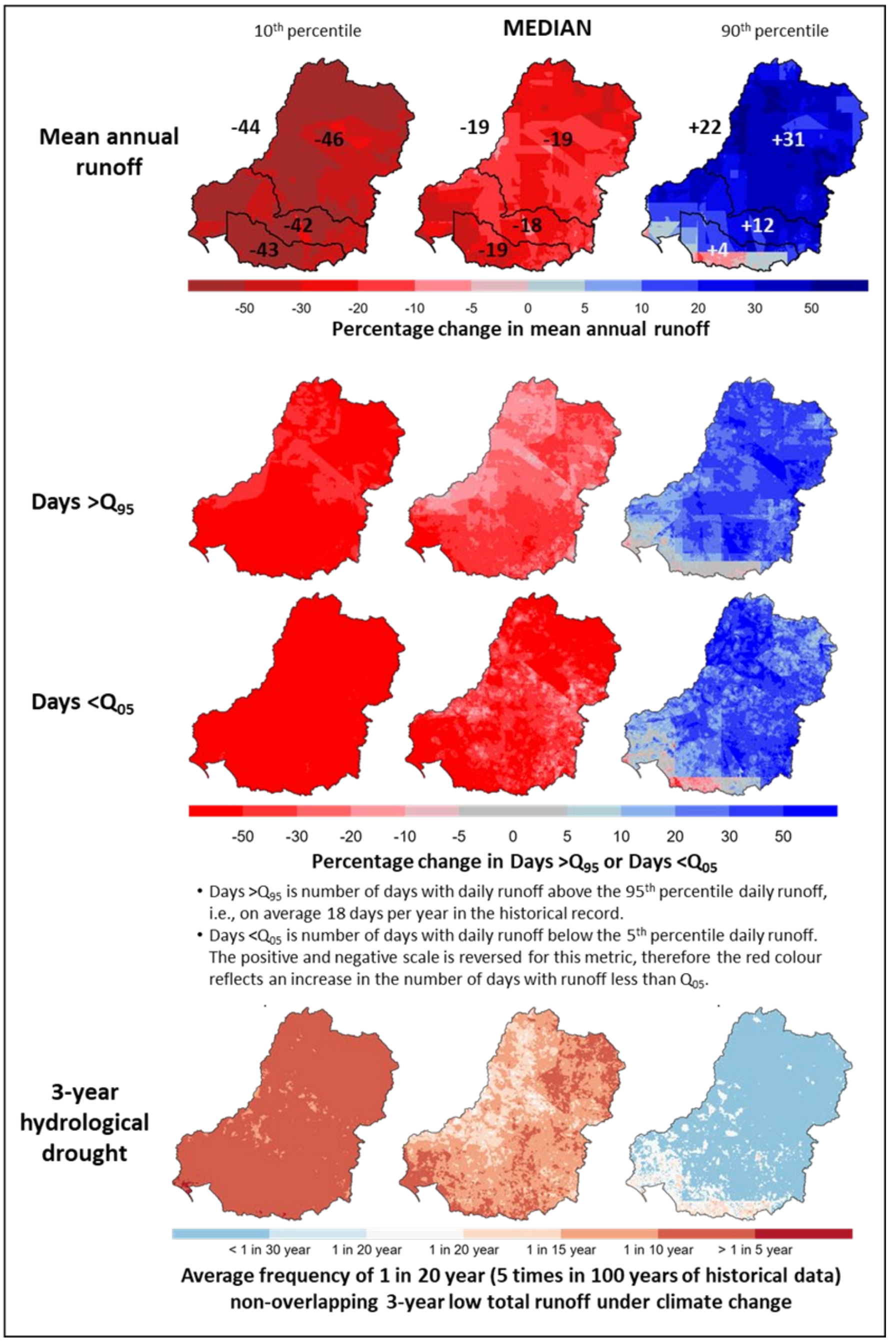

Figure 14. Projected change in mean annual runoff and hydrological characteristics under 2oC global average warming for the Murray–Darling Basin.

In summary, rainfall and streamflow records over the past 50 years of living memory show a declining trend, more so in the southern Basin than in the northern Basin. This is because the past two decades were relatively dry and were preceded by wet decades. In fact, the observed reduction in streamflow (over the short 20-year recent period) is greater than the median projected reduction in mean annual streamflow (over a long period, >50 years) under 2°C global average warming. The reduction in rainfall and streamflow over the relatively short recent period is part of the high natural hydroclimate variability in the Basin (for example, the first half of the 20st century was relatively dry). Nevertheless, hydroclimate projections indicate a drier future in the Murray–Darling Basin under climate change, and therefore the dry periods in the historical data including in the past several decades are likely to occur more frequently in the future.

3.3 Hydrological non-stationarity and landscape development

- **Hydrological non-stationarity, resulting from long dry spells and landscape development, has reduced the annual runoff generated from the same amount of annual rainfall.**
- **The impact of hydrological non-stationarity on water resources can be significant, particularly under climate change, although it is likely to be much smaller compared to water extraction from rivers.**

Like the southern Basin, the northern Basin also exhibits non-stationarity in the rainfall-runoff relationship where less annual streamflow is generated during the 1997–2009 Millennium drought and in the more recent dry periods for the same annual rainfall compared to the pre-drought hydroclimate (Figure 15, Saft et al. 2016, Vaze et al. 2012, Chiew et al. 2014). Extensive studies in the southern Basin and Victoria indicate that the change in the annual rainfall-runoff relationship is likely due to changes in surface-groundwater interaction, subsurface water availability and vegetation water use during long dry spells impacting runoff generation (Fowler et al. 2022a, Peterson et al. 2021, DELWP 2020).

Changes in weather systems and sub-annual rainfall characteristics can also impact runoff generation (Fu et al. 2021, DELWP 2020, Pepler et al. 2021). Analysis of rainfall data from a limited number of stations in the northern Basin by MDBA (2018a) indicates that the dry season has become drier leading to less favourable antecedent conditions for runoff to be generated in the following wet season. The same analysis also shows increased dominance of low to medium intensity rainfall and fewer high intensity rainfall events.

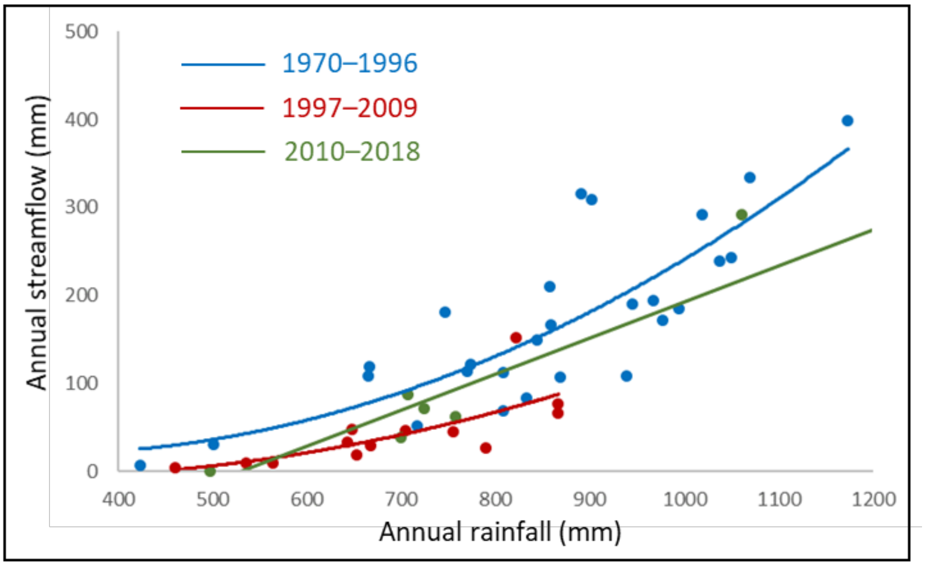

Figure 15. Annual streamflow versus annual rainfall in different hydroclimate periods for Catchment 418027 Horton River at Horton Dam Site in the Gwydir River basin.

Development on the landscape, like farm dams, plantations and land clearing, and changing farming practice can also impact catchment runoff. For example, Figure 16 shows farm dam density across the Murray–Darling Basin, most of which were constructed before 2010 (Malerba et al. 2021, Pena-Arancibia et al. 2022b). The proportion of runoff intercepted by farm dams and plantations would be higher in dry years and under climate change with projected hotter and drier conditions (Chiew et al. 2008, Robertson et al. 2020). The impact of landscape development or modification when averaged over river valleys or regions is likely to be relatively small compared to water extraction from rivers (van Dijk et al. 2007, Chiew et al. 2008), but can be significant locally.

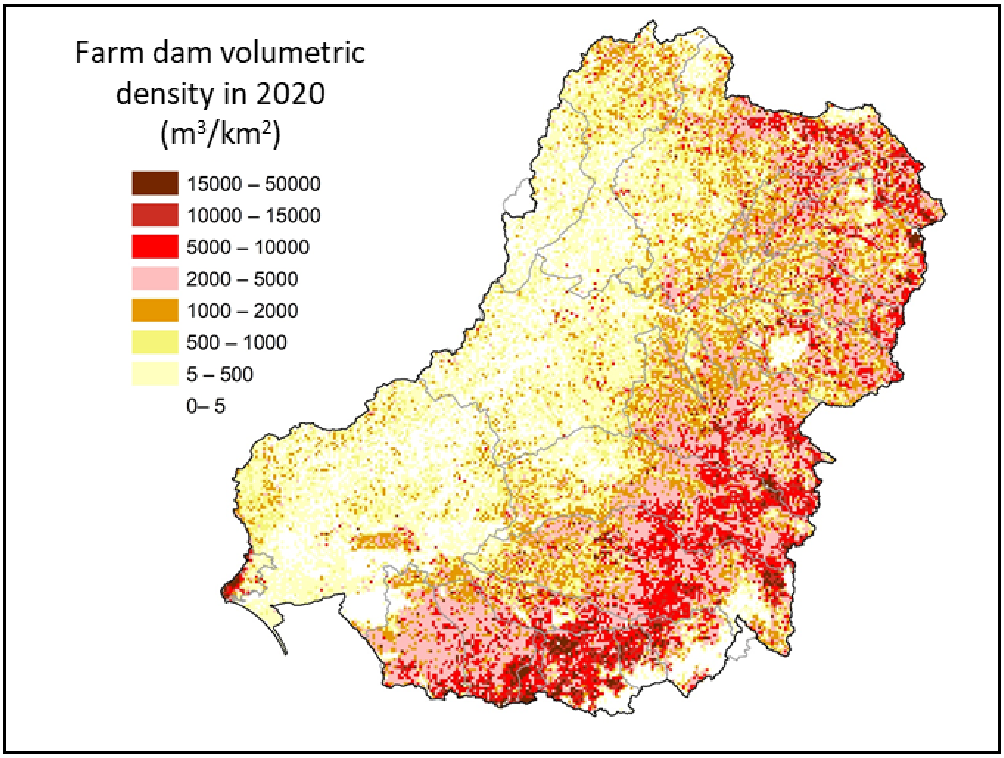

Figure 16. Density of landscape farm dams in the Murray–Darling Basin.

The term "hydrological non-stationarity" is used to describe changes in the annual rainfall-runoff relationship driven by (i) changes in dominant hydrological processes under different hydroclimate conditions, (ii) changes in sub-annual rainfall characteristics (e.g., seasonal distribution, weather systems), and (iii) landscape development or modification. In particular, relating to (i) above, hydrological models developed, conceptualised and parameterised against historical data (e.g., pre-Millennium drought data) are deficient when used to model conditions that have not been experienced in the historical data (e.g., Millennium drought period, and more frequent and severe dry spells under climate change).

Compared to the southern Basin, there have been much fewer studies on the impact of hydrological non-stationarity on catchment runoff in the northern Basin. More research is needed here, particularly with the opportunity provided by longer and new datasets becoming available, and significant advancements in remote sensing technology, interpretation and application. Understanding and modelling hydrological non-stationarity is important particularly when hydrological models are extrapolated to predict a future under conditions that are not seen in the historical data like higher temperature, more severe dry spells, and higher atmospheric CO_2 concentration (Chiew et al. 2014, Zheng et al. 2022, Fowler et al. 2022b, Bloschl et al. 2020).

4. TRENDS AND CHANGES IN BARWON-DARLING RIVER AND TRIBUTARY FLOWS

4.1 Annual time series of Barwon-Darling River flow characteristics

- **Irrigation development and water extraction across the northern Basin have also significantly reduced flow volumes and increased the number of low flow days in the Barwon-Darling River.**
- **Both climate variability and water resource development have caused the reduced flows in the Barwon-Darling River, but it is difficult to quantify their relative contributions because of the high streamflow variability and the relatively short period of instrumental data.**

The previous section presents analyses of hydroclimate data in the northern Basin landscape, informed by observed rainfall and streamflow data from the upland catchments, and gridded rainfall and modelled runoff across the Basin. This section presents analyses of streamflow data from the Barwon-Darling River, and to a lesser extent tributary inflows into the Barwon-Darling River, which have undergone flow modification from irrigation development and river water extraction.

The analyses here use streamflow data from the WaterNSW public web portal (Real-time water data (waternsw.com.au)) and the much longer NSW DPE (Department of Planning and Environment) extended and gap filled daily dataset for five gauging stations on the Barwon-Darling River (NSW DPE 2021a, All Water Data – Barwon Darling Cease Flows 2021 | Anzlic_Dataset | SEED (nsw.gov.au)). The five gauged locations are Walgett (Station 422001), Brewarrina (422002), Wilcannia (425008), Weir 32 (425012) and Burtundy (425007) (Figure 17). Other observed streamflow data presented here, including the Darling River at Bourke (425003), comes from the WaterNSW web portal.

The NSW DPE (2021a) extended the Water NSW publicly available streamflow data by digitising archived paper-based records. The NSW DPE also produced a binary daily low flow dataset indicating whether the daily flow is either below or above the low flow threshold. The low flow thresholds defined by NSW DPE (2021b) are 326 ML/day for Walgett, 468 ML/day for Brewarrina, 450 ML/day for Bourke, 200 ML/day for Wilcannia and 200 ML/day to 350 ML/day for the different months for Weir 32 and Burtundy.

This low flow dataset has also been gap filled and corrected for obvious errors (mainly equipment failure, missing data recorded as zero flow, and incorrect application of rating curve) by inspecting the flow hydrograph and informed by streamflow data from upstream and downstream gauges. As such, the low flow dataset is largely continuous and almost complete. This is not the case for daily flow volume where missing data when the river is flowing is difficult if not impossible to infill. The NSW DPE Weir 32 data combines the data from Menindee Town gauge (installed in late 1880s) and Weir 32 gauge (commenced in 1960s). Although archived paper-based records are also available for Bourke, the NSW DPE did not extend the Bourke dataset because of large amounts of missing data and inconsistent gauging over time. For this reason, the analysis here only presents the WaterNSW data for Bourke from 1970.

The investigation in this project indicates that the NSW DPE and WaterNSW data are relatively similar when they are concurrently available, the NSW DPE adjustments to low flow data are relatively infrequent, and the reasons documented in the log file for the adjustments and gap filling appear sensible. The gap filling for low flow analyses here is also helped by the Barwon-Darling River having little local catchment runoff contribution resulting in a high correlation between upstream and downstream gauges especially during low flows. This long NSW DPE dataset is extremely useful to assess trends and changes in flow characteristics through time and the causality of these trends, and it is worth exploring if other datasets across the northern Basin can also be reliably extended.

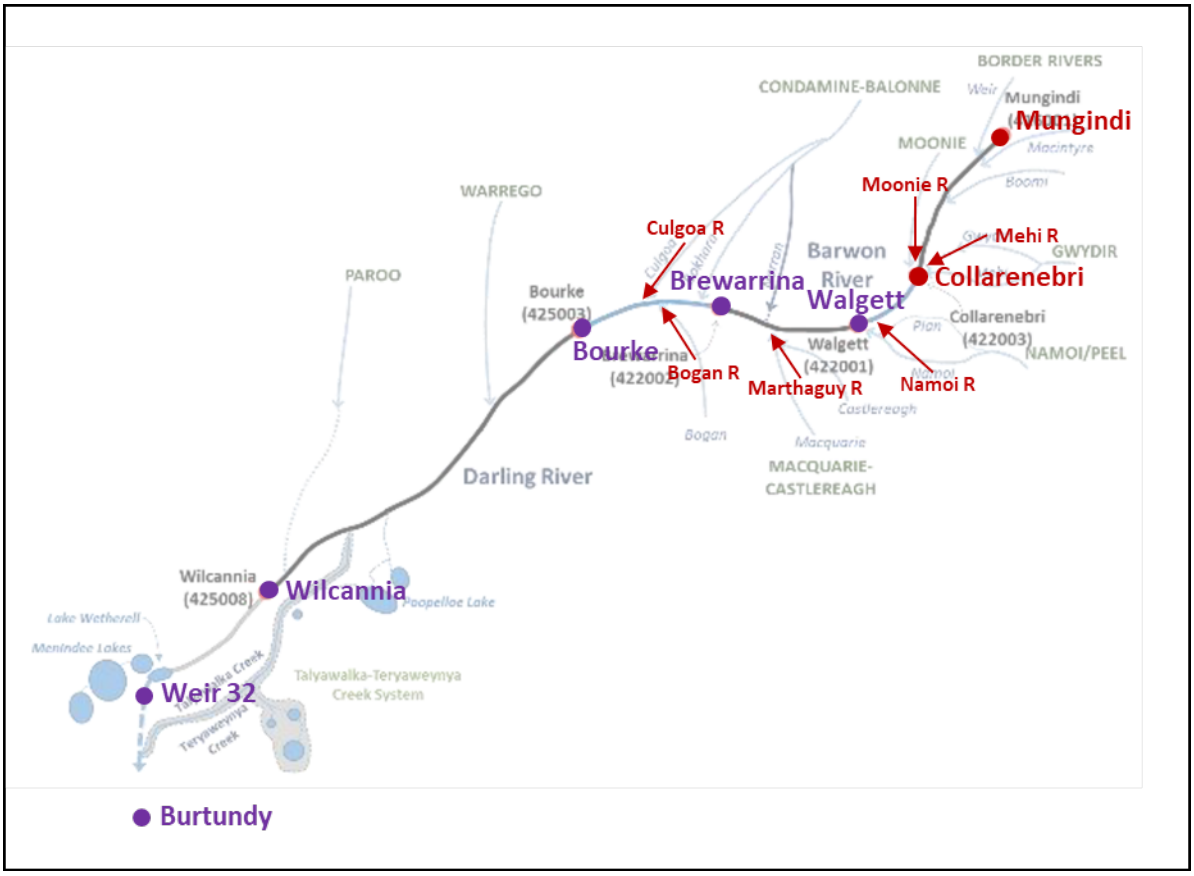

Figure 17. Barwon-Darling River system and locations of streamflow gauges (streamflow data from locations shown in purple are analysed here, streamflow data from locations shown in red are not analysed but plotted in Figure 18a).

The plots in Figures 18, 19 and 20 show the annual time series of flow volume, number of low flow days and peak daily discharge, respectively, at the six gauges on the Barwon-Darling River. The water year from July to June is used throughout, and data for a specific year are from July of the year to June the following year (i.e., data for 1970 covers the period July 1970 to June 1971).

Like the Section 3 data for landscape runoff across the northern Basin, the plots in Figures 18, 19 and 20 also show high inter-annual, multi-year and decadal variability in the Barwon-Darling streamflow. The plots also show the drier conditions at all the sites between 1895–1949 and 2001–2019 and wetter conditions between 1950–2000. The mean annual values over these 3 periods are also shown in Figures 18 and 19. The 1950 and 2001 breakpoints used here are reflective of the dry and wet periods indicated by the data and are consistent with that used in many NSW DPE reports (e.g., NSW DPE 2021b) and factsheets.

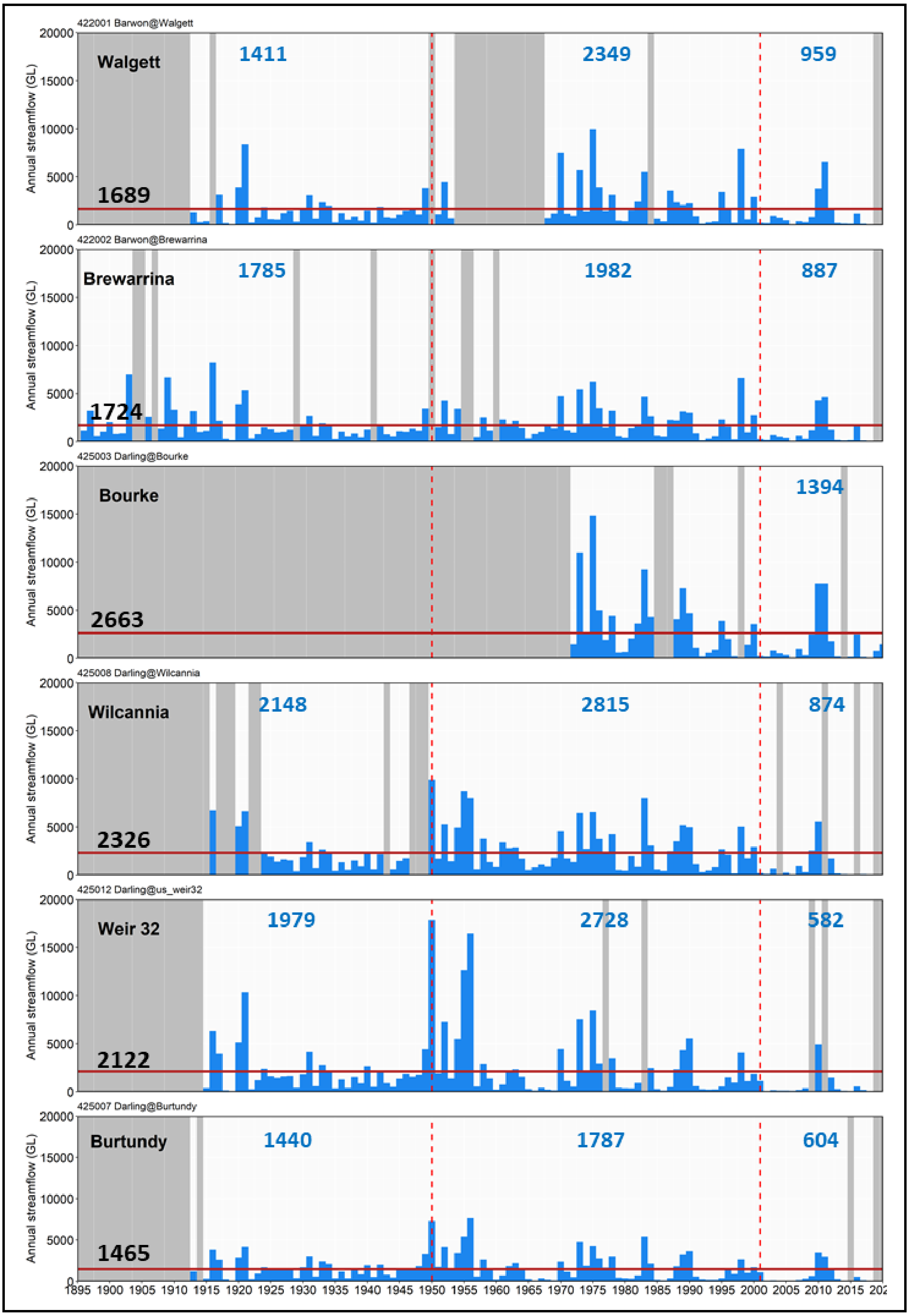

Figure 18. Time series of annual streamflow for gauges on the Barwon-Darling River (numbers show mean annual values over the entire period (red line) and the 3 sub-periods, grey shadings indicate missing data).

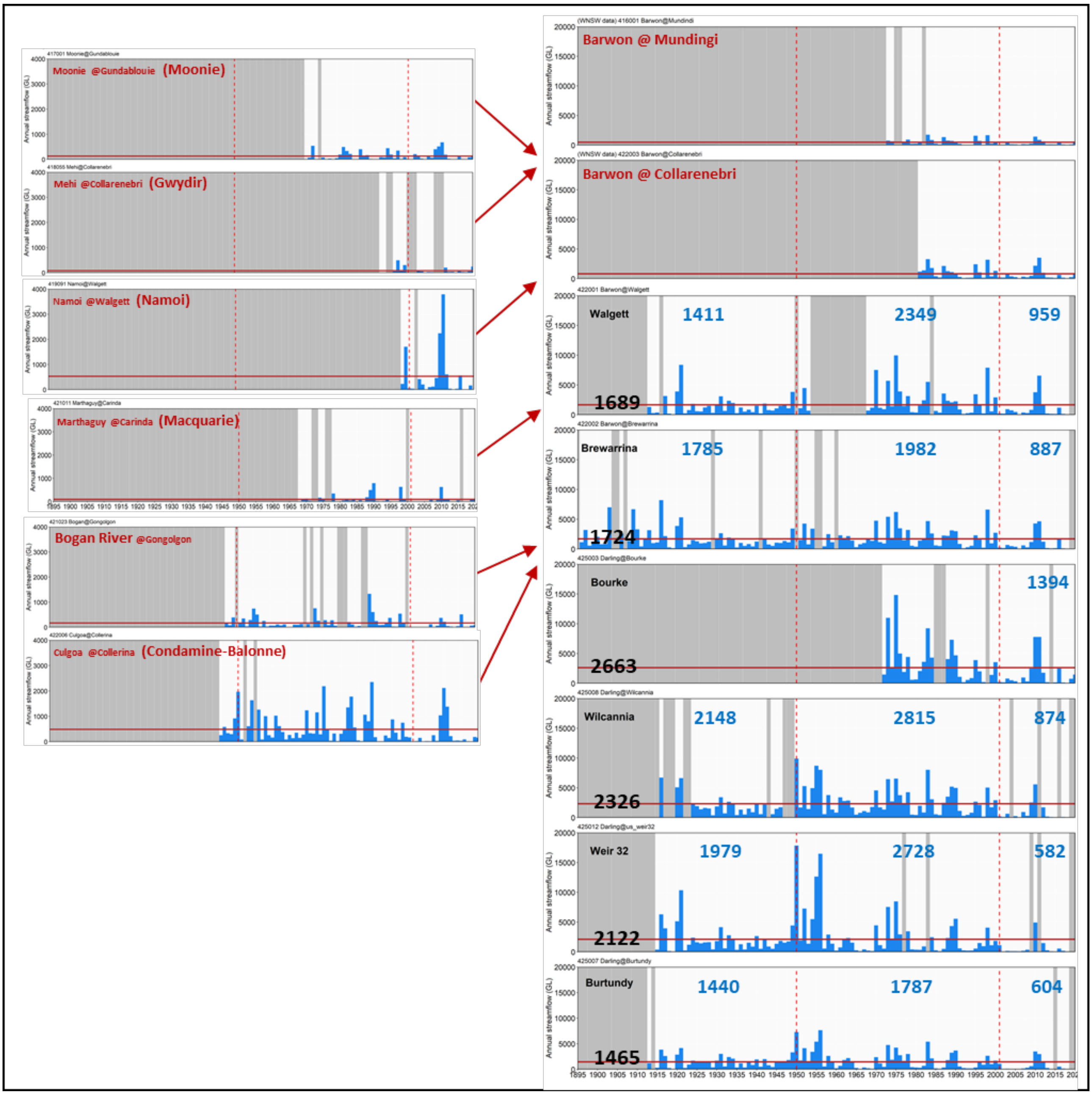

Figure 18a. Time series of annual streamflow for the Barwon-Darling River and selected valley outflows (gauges in addition to Figure 18 are highlighted in red, the same y-axis scale is used for all the gauges on the Barwon-Darling River, and another same y-axis scale is used for the tributary gauges).

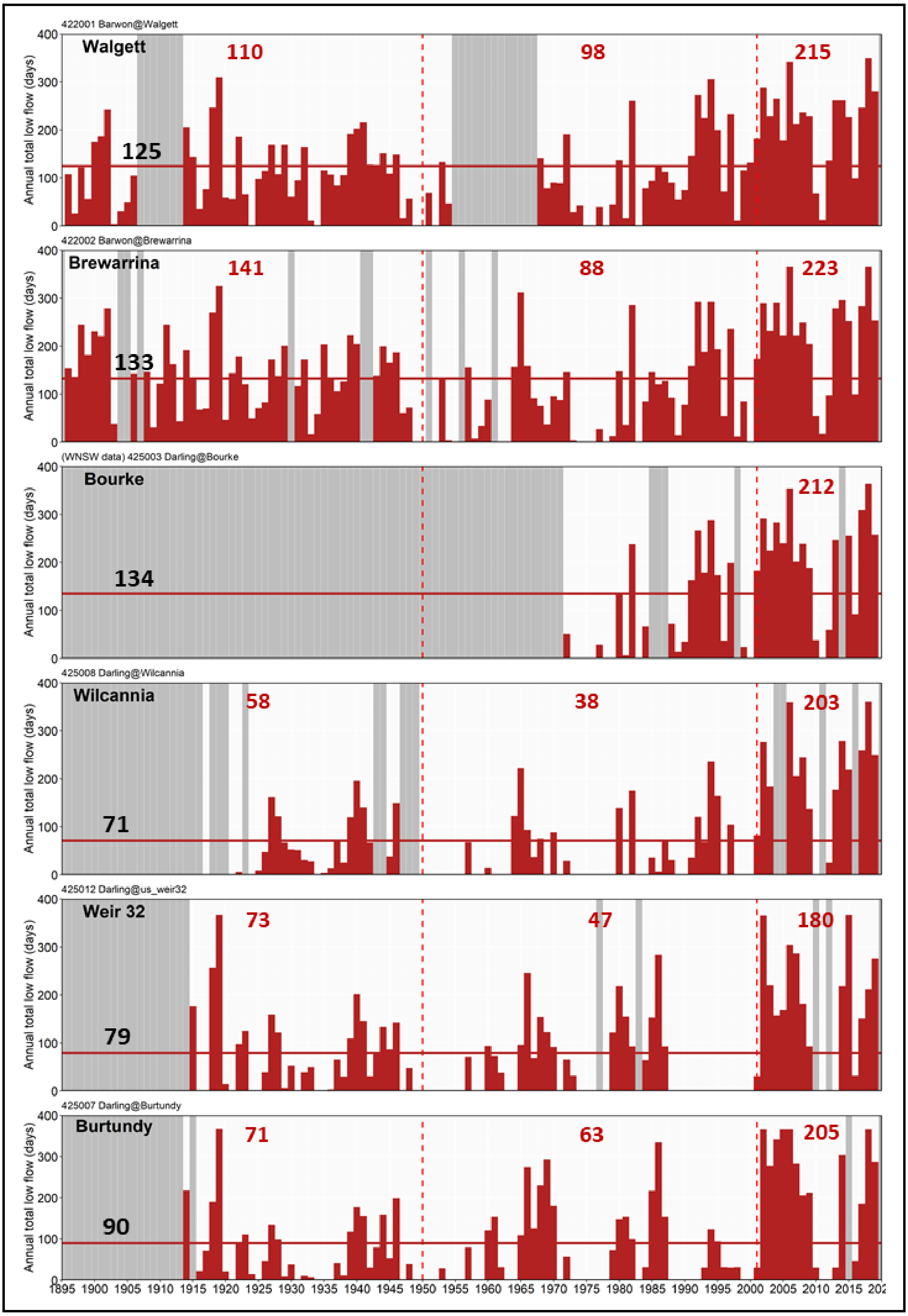

Figure 19. Annual time series of low flow days for gauges on the Barwon-Darling River (numbers show mean annual values over the entire period (red line) and the 3 sub-periods, grey shadings indicate missing data).

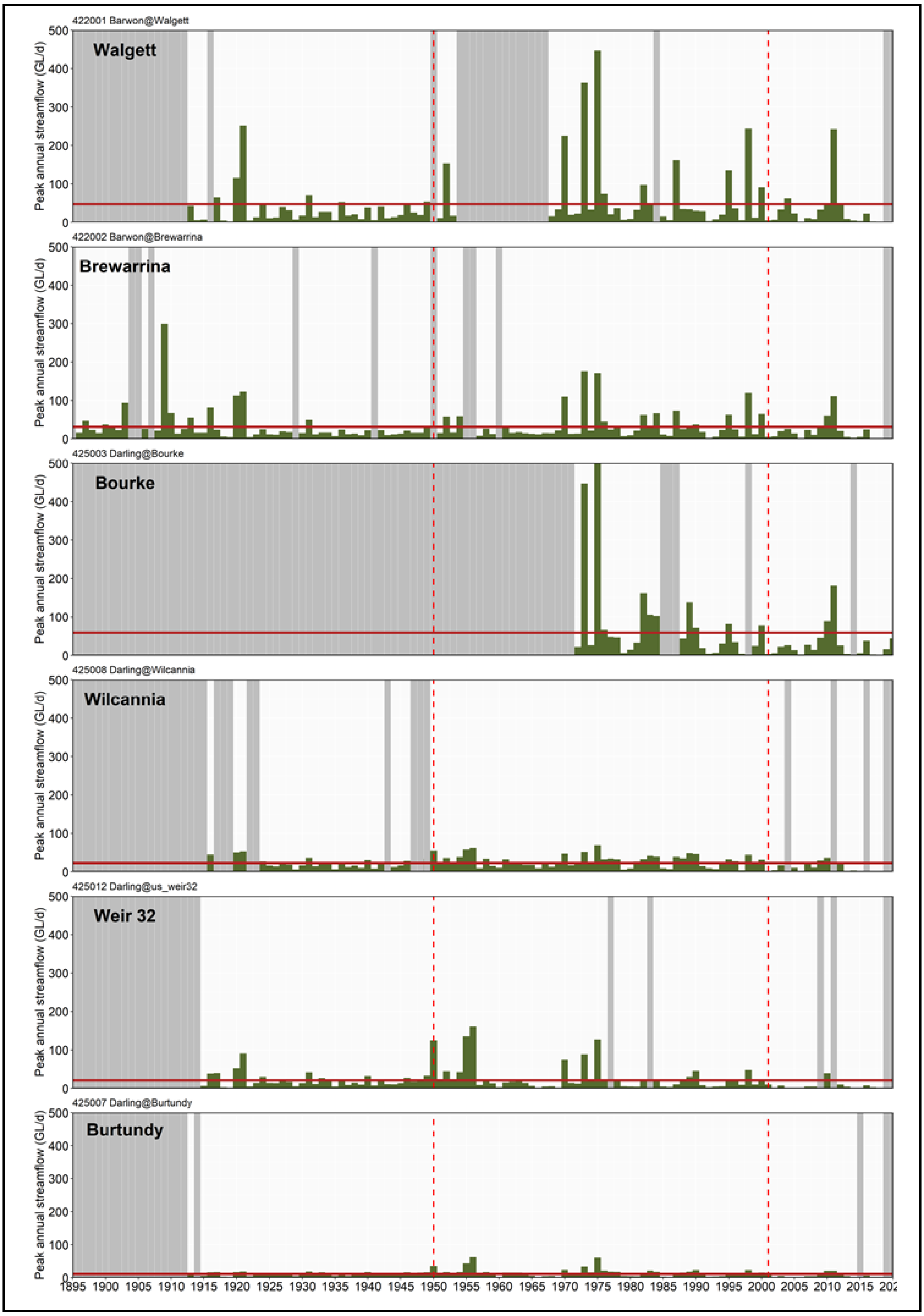

Figure 20. Annual time series of peak daily discharge for gauges on the Barwon-Darling River (grey shadings indicate missing data).

The plots in Figure 18 show that streamflow volumes in the drier recent post-2001 period are, as expected, significantly lower than the wet 1950–2000 period. The post-2001 streamflow volumes are also significantly lower than the dry pre-1950 period. The relative difference between the mean annual streamflow in the different periods is shown in Table 1. In contrast, mean annual rainfall averaged across the northern Basin in the post-2001 period is similar to the pre-1950 period, and the "unimpaired" mean annual runoff in the post-2001 period is 15% higher than the pre-1950 period (Figure 10). The data here, as expected, and noting that the recent 20-year period is compared to 50-year periods, show that irrigation development and water extraction across the northern Basin have significantly reduced the streamflow volume in the Barwon-Darling River.

Water resource development has also significantly increased the number of low flow days (Figure 19 and Table 2). The number of low flow days post-2001 are significantly higher than in the dry pre-1950 period. The impact is particularly large in Wilcannia where the post-2001 period has more than twice the number of low flow days compared to the similarly dry pre-1950 period, and 4 times more low flows days compared to 1950–2000.

The plots in Figure 20 also indicate that the annual peak daily discharge is lower in the post-2001 period.

Table 1. Streamflow volume (mean annual streamflow) in 2001–2019 relative to volumes in 1950–2000 and in 1900–1949.

	Percentage change	
	2001-2019 relative to 1950-2000	2001-2019 relative to 1900-1949
Walgett	-59	-32
Brewarrina	-55	-50
Wilcannia	-69	-59
Weir 32	-79	-71
Burtundy	-66	-58

Table 2. Number of low flow days in 2001–2019 relative to number of low flow days in 1950–2000 and in 1900–1949.

	Percentage change	
	2001-2019 relative to 1950-2000	2001-2019 relative to 1900-1949
Walgett	119	95
Brewarrina	153	58
Wilcannia	434	250
Weir 32	283	147
Burtundy	225	189

The analyses here clearly show the significant impact of water resource development on river flows and is consistent with that reported in the NSW DPE (2021b) low flow analysis. Both the drier climate and development have caused the recent reduction of flows in the Barwon-Darling River. However, it is difficult to quantify the relative attribution of reduced flows to climate variability versus development because of the high variability in the streamflow and because of the relatively short period of record (apart from the presentation here, most gauges only start recording after the 1980s).

For completion, the annual time series of flow volume from several gauges in the WaterNSW dataset are also shown in Figure 18a. These include Mungindi and Collarenebri on the Barwon-Darling River, and gauges with the largest flows from each of the valleys. It should be noted that the proportion of this volume that flows into the Barwon-Darling River from some valleys could be relatively small because of terminal wetlands and floodplains between the gauged locations and the Barwon-Darling River. The plots here further indicate the high streamflow variability and the relatively short period of record for detailed analysis of causality of reduced flows on the Barwon-Darling River and in the valleys.

4.2 Analyses of modelled streamflow data for the Barwon-Darling River

- **Modelling indicates that water resource development across the northern Basin has reduced streamflow volumes in the Barwon-Darling River by 40–50% compared to no development conditions.**
- **Water resource development has also increased the frequency of low flow events.**
- **Short and medium low flow events (<6 months) are caused by climate variability and water resource development, and longer low flow events (>1 year) are caused by drought across the region.**

4.2.1 Modelled annual streamflow time series

The use of modelled streamflow data can help overcome the challenge of trying to separate the relative impact of climate variability and water resource development on streamflow from the short period of instrumental data. This is analysed here using data from hydrological and river system modelling by NSW DPE and MDBA (All Water Data – Barwon Darling Cease Flows 2021 | Anzlic_Dataset | SEED (nsw.gov.au), NSW DPE 2022a). The daily modelled data used here reflects the climate inputs from 1895–2019 for two static system conditions, no water resource development (ND) and pre-Basin Plan water resource development and rules (PBP). Note that for Weir 32, results from modelling for new annual permitted take (APT) rules, which are relatively similar to PBP, are used because there were no modelled PBP data for Weir 32.

There are many limitations in river system modelling, particularly the considerable uncertainty in estimating catchment runoff and accounting for system losses, water extraction and use, and floodplain processes, and these are discussed in Section 2.5. As such, analyses of modelling results can only provide broad indications of the relative causality of reduced flow in the Barwon-Darling River. Prior to the analyses described here, simple investigations were carried out to explore the representativeness of the modelling. The investigation confirmed that the modelled streamflow volumes from the ND and PBP modelling are consistent relative to each other and when compared to the observed gauged data. However, it is more difficult to consistently interpret the modelled low flows as is further discussed below. The modelled data analysed here are similar to that reported in the Murray–Darling Basin Sustainable Yields (CSIRO 2008b) and MDBA Basin Plan modelling (MDBA 2012).

The plots in Figures 21, 22 and 23 show the annual time series of flow volume, number of low flow days and peak daily discharge, respectively, at the five gauges on the Barwon-Darling River from the ND and PBP modelling. The mean annual streamflow and number of low flow days over the different time periods are tabulated in Tables 3 and 4.

The modelled data for streamflow volume and peak daily discharge is consistent with the observed data. This is illustrated in Figures 18 and 20 indicating that observed streamflow volume and peak daily discharge in the more recent period are significantly lower because of the dry climate and water resource development, and in Figures 21 and 23 indicating that modelled streamflow and peak discharge under current development conditions (PBP) are significantly lower than under no development conditions (ND). Averaged over the 125 years of modelling period, the streamflow volume under PBP compared to ND ranges from about 40% lower in Bourke, Wilcannia and Weir 32 to about 50% lower in Walgett and Brewarrina (Table 3).

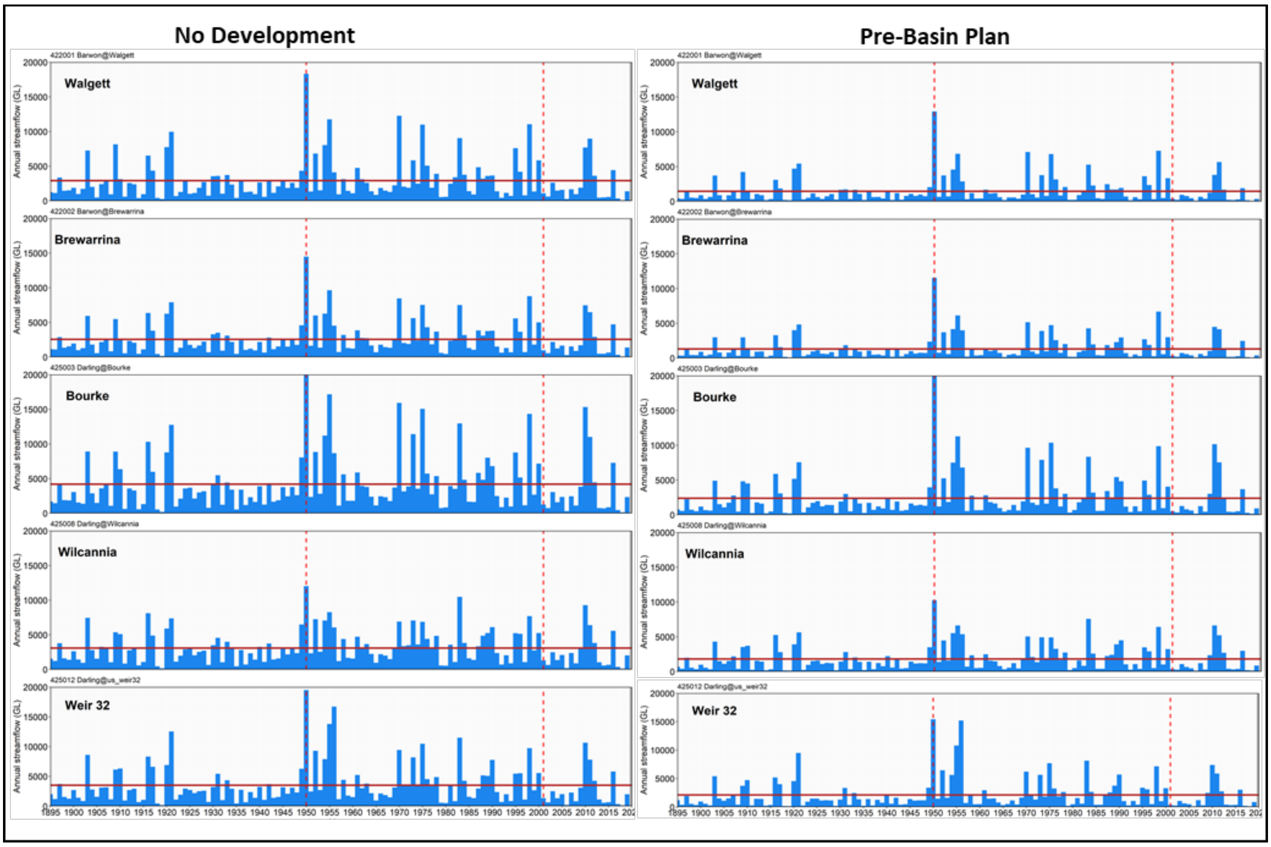

Figure 21. Annual time series of streamflow volume from modelling for No Development and Pre-Basin Plan conditions.

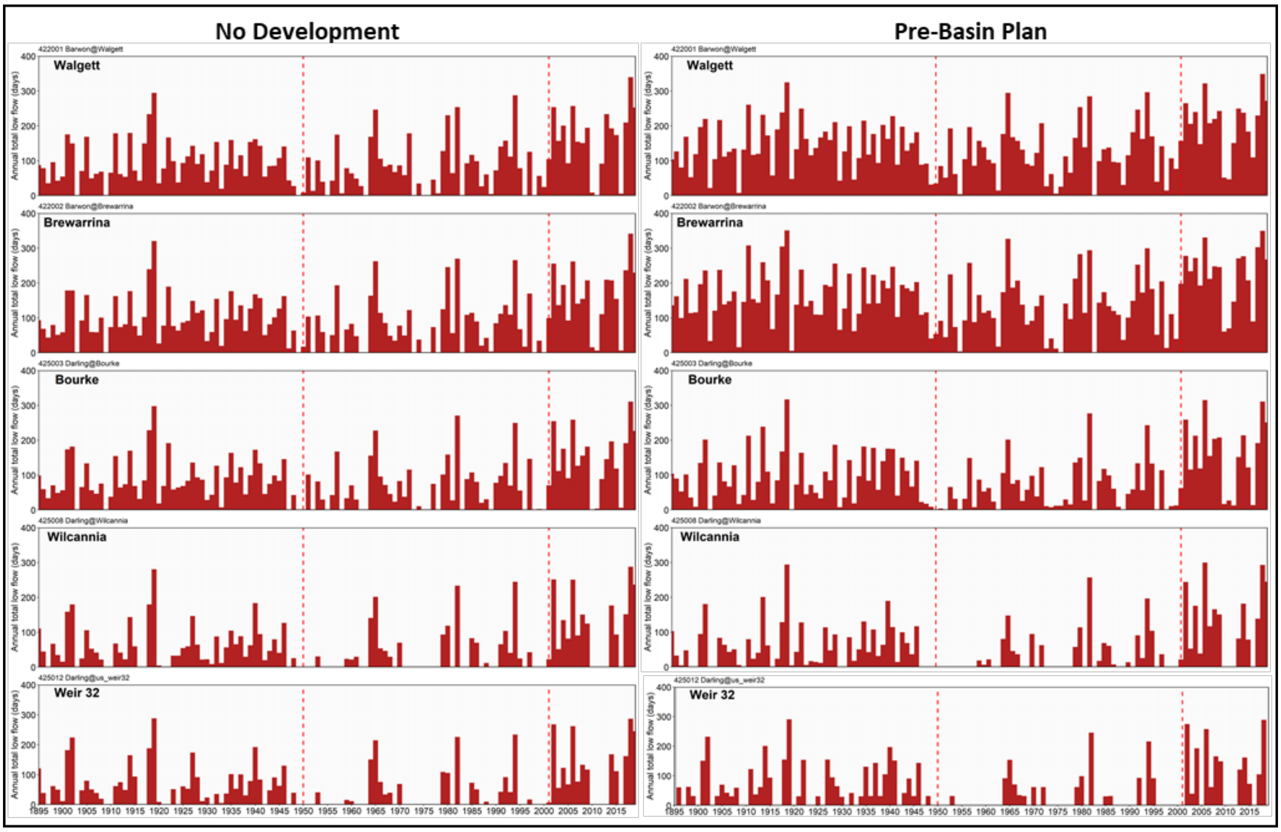

Figure 22. Annual time series of low flow days from modelling for No Development and Pre-Basin Plan conditions.

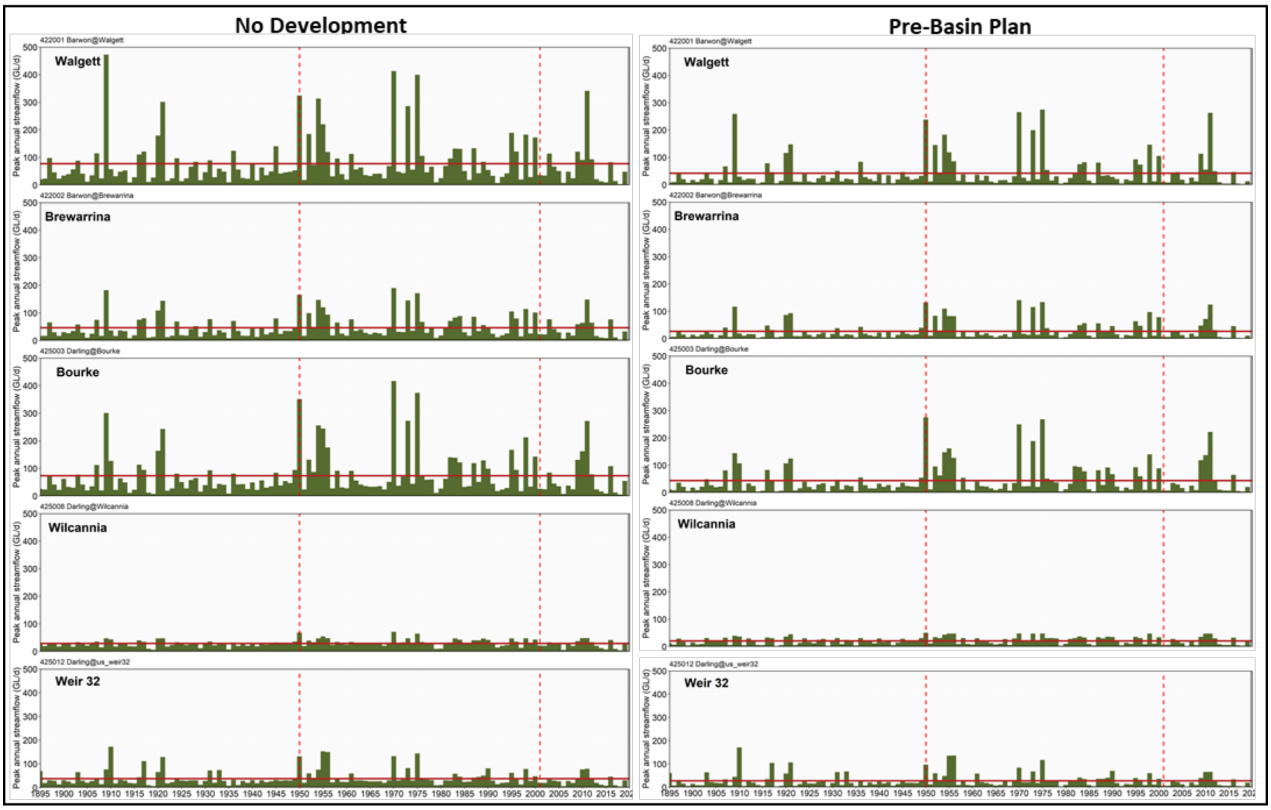

Figure 23. Annual time series of peak daily discharge from modelling for No Development and Pre-Basin Plan conditions.

Table 3. Modelled streamflow volumes in the different time periods for No Development and Pre-Basin Plan conditions.

No Development				
	Mean annual streamflow (GL)			
	1895-1949	1950-2000	2001-2019	1895-2019
Walgett	2381	3812	2078	2919
Brewarrina	2107	3293	1856	2553
Bourke	3301	5562	3134	4196
Wilcannia	2667	3836	2287	3086
Weir 32	2859	4608	2454	3511
Pre-Basin Plan				
	Mean annual streamflow (GL)			
	1895-1949	1950-2000	2001-2019	1895-2019
Walgett	1067	2042	983	1452
Brewarrina	950	1861	908	1315
Bourke	1691	3354	1804	2387
Wilcannia	1408	2413	1362	1811
Weir 32	1550	2962	1434	2109

Table 4. Modelled low flow days in the different time periods for No Development and Pre-Basin Plan conditions.

No Development				
	Mean number of low flow days per year			
	1895-1949	1950-2000	2001-2019	1895-2019
Walgett	94	78	161	98
Brewarrina	99	75	161	99
Bourke	87	63	142	85
Wilcannia	58	35	110	56
Weir 32	61	32	109	57
Pre-Basin Plan				
	Mean number of low flow days per year			
	1895-1949	1950-2000	2001-2019	1895-2019
Walgett	143	118	204	142
Brewarrina	161	126	223	156
Bourke	93	62	155	90
Wilcannia	58	30	120	56
Weir 32	65	27	112	57

The low flow modelling for Walgett and Brewarrina also shows the significant impact of water resource development on the number of low flow days (Figure 22). The number of low flows days over the 125 years of modelling for Walgett and Brewarrina is about 50% more under current development condition (PBP) than for no development (ND) (Table 4).

However, contrary to the results for flow volume, there is little difference in the modelled low flows days for PBP versus ND in Bourke, Wilcannia and Weir 32 (Figure 22 and Table 4). The relatively small difference between PBP and ND is only evident for the 2001–2019 period, being about 10% more low flow days under PBP compared to ND in Bourke and Wilcannia, and 3% more low flow days in Weir 32 (Table 4).

The modelling therefore indicates that water resource development has significantly reduced streamflow volume in Bourke, Wilcannia and Weir 32, but only has a small impact on low flow days at these sites. These results are inconsistent compared to the observed data which show significantly more low flow days in the 2001–2019 period (Figure 19 and Table 2). This highlights limitations and complexity in the modelling of low flows, with the modelled data suggesting that the model has likely underestimated water resource development impact on low flows.

The difficulty in reliably measuring and modelling low flows is well acknowledged, both in natural landscapes, and more so in developed systems like the Barwon-Darling River, where many model assumptions need to be made relating to the simulation of in-channel river water extraction, water use and transmission losses. Most modelling, including in the Murray–Darling Basin Sustainable Yields (CSIRO 2008b), focusses on the streamflow volumes with less attention given to the low flow characteristics. It is envisaged that targeted model calibration against low flow characteristics (e.g., observed low flow days in Figure 19), as well as improved model conceptualisation for low flows (e.g., bed storage conceptualisation, surface-groundwater interaction, transmission losses), would improve the low flow simulations.

4.2.2 Low flow events

The low flow events are explored here using the modelled data for No Development (ND) and Pre-Basin Plan (PBP) conditions. The plots in Figures 24 and 25 show the total number of low flow events and cease to flow events from the ND and PBP modelling. Four categories are used to describe the low flow and cease to flow event durations, 5–30 days, 1–3 months, 3–6 months, and greater than 6 months. The low flow and cease to flow thresholds defined by NSW DPE (2021b) are used for the analysis. The low flow thresholds are 326 ML/day for Walgett, 468 ML/day for Brewarrina, 450 ML/day for Bourke, 200 ML/day for Wilcannia and between 200 ML/day to 350 ML/day (for the different months) for Weir 32. The cease to flow thresholds are 25 ML/day for Walgett, 20 ML/day for Brewarrina, 0 ML/day for Bourke, 20 ML/day for Wilcannia and 5 ML/day for Weir 32. For the purpose of the analyses here, one day above the flow threshold is considered sufficient to separate the events, but there must be at least five days below the flow threshold for it to be defined as a low flow or cease to flow event. The relative number of low flow days and low flow events between locations are not directly comparable because of the different low flow thresholds used for the different locations. However, the relative modelled results for the different periods and under different development conditions for each location can be compared to provide an indication of the drivers and causality of low flows at the location.

The plots in Figure 24 indicate that water resource development has increased low flow events for all event durations in Walgett and Brewarrina. However, the modelled data indicates that there is little difference in the <3 months low flow events under PBP compared to ND in Bourke, Wilcannia and Weir 32. This is consistent with the annual time series analyses in Section 4.1 which also show little difference in number of low flow days under PBP and ND (Figure 19 and Table 4), and the subsequent discussion on the modelling underestimating water resource development impact on low flows.

All the modelled data show water resource development impact on the 3–6 months low flow events, with about 40% more low flow events of this duration at Bourke and Wilcannia under PBP compared to ND, and more than 60% more low flow events of this duration at Walgett and Brewarrina (Figure 24). The modelled data also show that >6 months low flow events under PBP compared to ND increased by more than 50% at Walgett and Brewarrina, but there is little difference at Bourke, Wilcannia and Weir 32.

The plots in Figure 25 indicate that cease to flow events (except for <1 month event in Walgett and Brewarrina) have reduced under PBP compared to ND. This is because dams are operated to avoid cease to flow periods for as long as possible, potentially prolonging low flows (NSW DPE 2021b).

The analyses presented throughout Section 4.2 show similar results as reported in NSW DPE (2018b). However, the definition of low flow events here, although similar, are not exactly the same as that used by NSW DPE, and results are shown here for each of the five locations whilst NSW DPE (2018b) presented aggregated results from all the locations (which showed a larger impact on low flows than the results presented here).

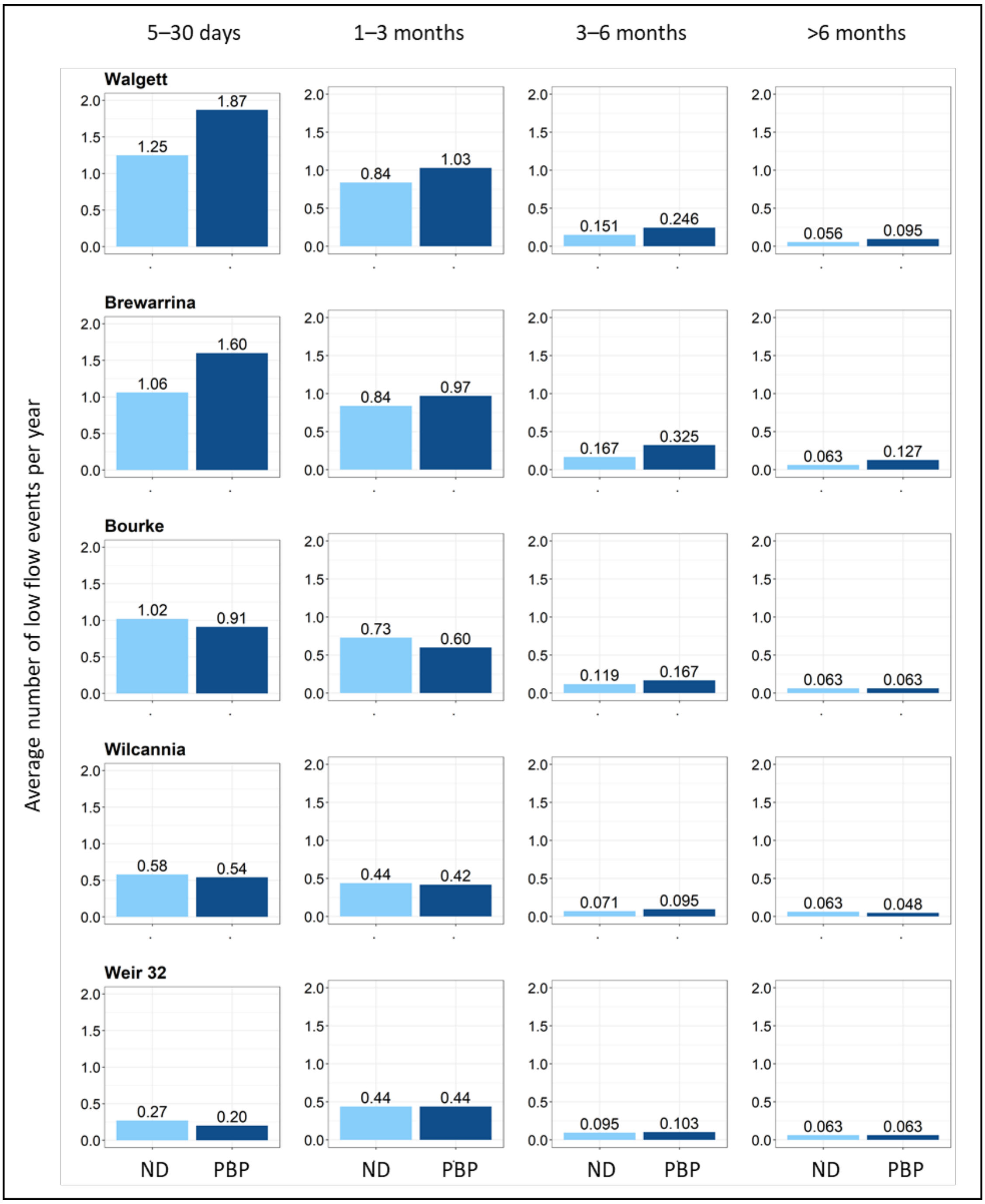

Figure 24. Number of low flow events from modelling for No Development and Pre-Basin Plan conditions.

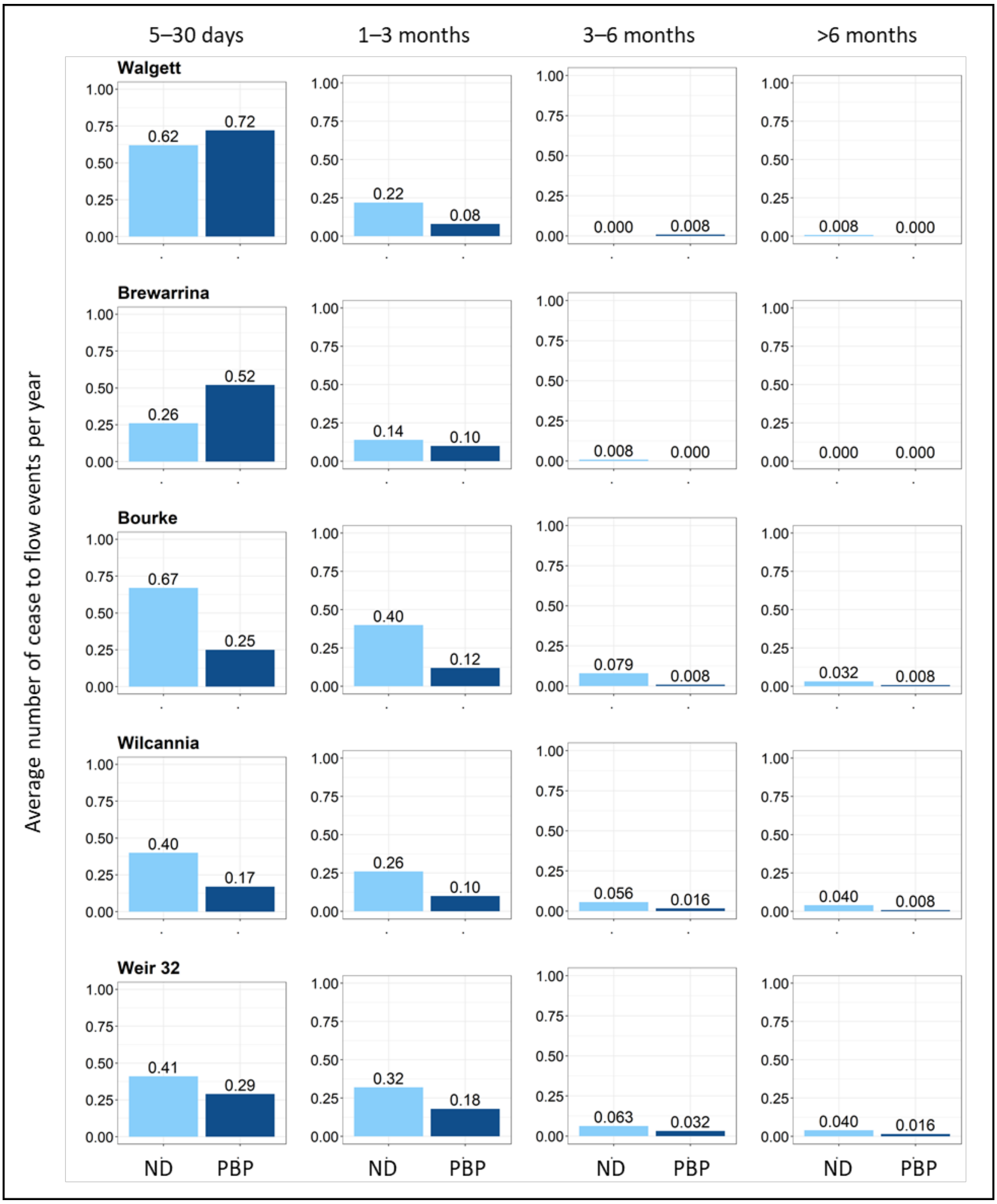

Figure 25. Number of cease to flow events from modelling for No Development and Pre-Basin Plan conditions.

4.3 Climate variability, water resource development and relative streamflow volumes in the Darling and Murray rivers

- **Analyses of modelled and observed data indicate that the reduced streamflow in the Barwon-Darling River experienced over 2001–2019, relative to the wetter 1950–2000 period, can be attributed roughly equally to climate variability and to historical water resource development.**
- **The impact of water resource development is accentuated in dry periods.**
- **The Darling River contributes, on average, about 17% to the total lower Murray River flow volume under pre-development conditions and about 13% under current development conditions. The Darling River contributes more than 25% to the total lower Murray River flow in only 10% of the years.**

4.3.1 Impact of climate variability and water resource development on Barwon-Darling River flow

The modelled data for 2001–2019 versus 1950–2000 are further analysed here to provide an indication of the impact of climate variability and water resource development on the reduction in Barwon-Darling River flow. The analyses for modelled streamflow volume are summarised in Table 5. The orange box quantifies the 2001–2019 streamflow volume relative to the 1950–2000 streamflow volume from the No Development (ND) and Pre-Basin Plan (PBP) modelling results. The modelled data for ND indicates that streamflow volume is about 44% lower (averaged across the five locations) in the drier 2001–2019 period compared to the wet 1950–2000 period. The modelled data for PBP indicates that streamflow volume is about 49% lower (averaged across the five locations) in 2001–2019 compared to 1950–2000 suggesting that development exacerbates the impact of climate on flows.

The green box quantifies the PBP versus ND results for the 2 climate periods. The modelled data indicate that streamflow volume is about 40% lower (averaged across the five locations) under PBP compared to ND over the wet 1950–2000 period and about 46% lower over the dry 2001–2019 period. The modelled data here also show higher impact from development in the drier period.

The above estimates of impact from the different climates in the 2 periods (orange box) and from water resource development (green box) are not independent. The numbers in the orange and green boxes in Table 5 are near-equal, indicating that the relative impacts of climate and development are also approximately the same. However, to put more quantitative rigour around the attribution of relative impact, the estimates for 2001–2019 versus 1950–2000 for ND (impact from climate, first column in orange box) are compared with the estimates for PBP versus ND for 2001–2019 (impact from development, first column in green box). This is shown in the blue box in Table 5, calculated as ratios of climate impact (first column in orange box) and development impact (first column in green box) respectively to the sum of both values. The estimates in the blue box in Table 5 indicates that the reduced streamflow experienced over the 2001–2019 period relative to the 1950–2000 period can be attributed roughly equally to the prevailing climate conditions during

2001–2009 and the historical water resource development that has occurred across the northern Basin (largely before 2000, see Figure 7).

The analyses of modelled data presented here, while not a precise disentanglement of the relative effects of climate and development, can provide a broad indication of their relative impact on the reduced streamflow over 2001–2019 compared to 1950–2000 (i.e., "living memory" over the past 70 years). However, it should be noted that there is considerable uncertainty in any modelling, and therefore the estimates here can only provide a rough quantification of the attribution and should be interpreted cautiously.

A recent study by Grafton et al. (2022), using observed streamflow data at Wilcannia, also showed the significant impact of water extraction on the reduced streamflow. The analysis compared the reduction in mean annual streamflow for 2001–2020 relative to 1981–2000 in the observed data versus the expected climate-driven reduction estimated from the Budyko relationship (relationship between mean annual streamflow versus mean annual rainfall and PET developed from global datasets). The analysis indicated that only one third of the reduction in the 2001–2020 streamflow in Wilcannia relative to 1981–2000 can be attributed to the drier climate in 2001–2020. The Grafton et al. (2022) study also showed that ecosystem resilience is much lower in the developed Darling River system compared to the largely unmodified Paroo River. The Grafton et al. study, the analysis presented in Table 5, and the NSW DPE reports (NSW DPE 2018b) highlight the significant impact of water resource development on the Barwon-Darling River flows in addition to the drier climate over the recent decades.

The same analysis for streamflow volume in Table 5 is presented for low flow days in Table 6. Consistent with the low flow analysis presented and discussed earlier, the modelled data show a much smaller impact from water resource development on the low flows compared to the influence on streamflow volume. For example, about 80% of the increase in low flow days in 2001–2019 relative to 1950–2000 is attributed to climate variability and 20% to water resource development in Walgett and Brewarrina, and the increase in low flow days in Bourke, Wilcannia and Weir 32 is largely attributed to the dry conditions (Table 6).

Table 5. Impact of climate variability and water resource development on Barwon-Darling River streamflow volume.

	Percentage change (2001-2019 vs 1950-2000)		Pre-Basin Plan vs No Development		Impact attribution 2001-2019 versus 1950-2000	
	No Development	Pre-Basin Plan	2001-2019	1950-2000	Climate	Development
Walgett	-45	-52	-53	-46	46	54
Brewarrina	-44	-51	-51	-43	46	54
Bourke	-44	-46	-42	-40	51	49
Wilcannia	-40	-44	-40	-37	50	50
Weir 32	-47	-52	-42	-36	53	47

Table 6. Impact of climate variability and water resource development on Barwon-Darling River low flow days.

	Percentage change (2001-2019 vs 1950-2000)		Pre-Basin Plan vs No Development		Impact attribution 2001-2019 versus 1950-2000	
	No Development	Pre-Basin Plan	2001-2019	1950-2000	Climate	Development
Walgett	106	73	27	51	80	20
Brewarrina	115	77	39	68	75	25
Bourke	125	150	9	-2	93	7
Wilcannia	214	300	9	-14	96	4
Weir 32	241	315	3	-16	99	1

The much smaller impact of development relative to climate variability on low flows (Table 6) compared to on the flow volumes (Table 5) is largely because of the modelling underestimating the development impact on low flows as discussed in Section 4.2. Nevertheless, water resource development is likely to impact flow volume more than low flows because flow volume is impacted by large in-channel river water extraction and floodplain harvesting during high flows, whilst low flows are only impacted by in-channel river extraction during small and medium flow events.

4.3.2 Streamflow volume in the Darling River compared to the Murray River

The mean annual modelled streamflow volumes from the Darling River and Murray River are summarised in Table 7. These come from the MDBA synthesis from river system models run by the MDBA and Basin States, similar to the modelling reported in the Murray–Darling Basin Sustainable Yields (CSIRO 2008b) and MDBA Basin Plan modelling (MDBA 2012). The modelling covers the period from July 1895 through to June 2009 and were run for no development, pre-Basin plan and post-Basin plan conditions. The Murray River data are from the model node at Mildura, while Darling River data are the sum of the model nodes at Burtundy and the Great Darling Anabranch.

The modelled data show that under a no development scenario, the long-term average inflows to the lower Murray from the Darling River is about 17% of the total lower Murray flow, with the remaining 83% coming from the Murray River and its tributaries upstream of the junction with the Darling River. This is also consistent with the landscape runoff described in Section 3.1 where most of the runoff in the Murray–Darling Basin comes from the high elevation areas in the south-eastern parts of the Basin.

Climatic conditions can vary widely between the northern and southern Basins. As a result, the relative contribution is different in different years with the Darling River contributing less than 1% in some years and up to 50% in years with large volumes of water coming down the Darling River coinciding with drier conditions in the southern Basin (Figure 26). The 10th to 90th percentile range of Darling River contribution to the total lower Murray River flow in the different years is 5 to 25%. The Darling River contributes more than 20% to the total lower Murray River flow in only 25% of the years, and more than 25% in only 10% of the years.

Under the Pre-Basin Plan model run, flows in both rivers reduced, but this decline was proportionally more in the Darling River, and as a result, the Darling River only contributes 14% to the total lower Murray River flow. Under a Post-Basin Plan scenario, flows in both rivers increase but with a larger proportional increase in the Murray River, resulting in the Darling River contributing 13% to the total lower Murray River flow (Table 7).

It should be noted that in very wet years in the northern Basin, the MDBA controls Menindee Lakes and releases water to supply the lower Murray River. However, in most (dry and medium) years, when the Menindee Lakes capacity is low, the Menindee Lake system is operated primarily to provide for the needs of the lower Darling.

In summary, the Darling River contributes much smaller, but not insignificant, inflow compared to the Murray River. Over the long-term, the Darling River contributes, on average, about 17% to the total lower Murray flow under no development, and about 13% under the Basin Plan. Observed data from the Darling River at Burtundy and Murray River at Lock 10 (immediately downstream of the junction with the Darling River) also supports the conclusions drawn from the modelled data. An analysis of the available observed data from 1988 to 2014 (when data are available at both locations) shows that the average Darling River contribution to the Murray River system for this 27-year period was 18%, ranging from a minimum of less than 1% in 2006 to a maximum of 55% in 1999.

Table 7. Mean annual Darling River and Murray River flows under No Development, Pre-Basin Plan and Basin Plan modelling scenarios (averaged over 1895–2009).

	No Development	Pre-Basin Plan	Basin Plan
Darling River inflow to the lower Murray River (GL)	2,304	1,070	1,185
Murray River flow (GL)	11,621	6,400	8,128
Darling River contribution to lower Murray River total flow volume (%)	17	14	13

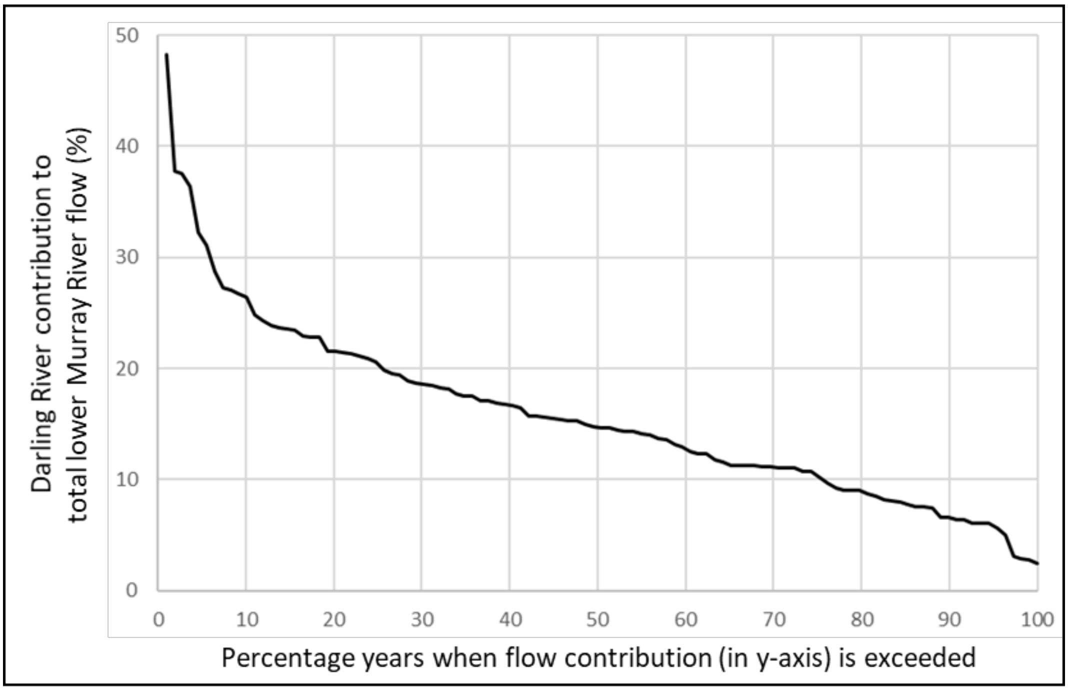

Figure 26. Darling River contribution to total lower Murray River flow in different years.

4.4 Related studies on northern Basin flows

- **Several other studies and technical analysis also indicate the significant impact of water resource development on northern Basin flows.**
- **The impact on low flows is largely caused by in-channel river water extraction.**
- **Both in-channel river water extraction and floodplain harvesting impact flow volumes.**

4.4.1 Low flow studies

The MDBA (2018b) presented analysis of low flow and small fresh events using 1980–2017 streamflow data observed at six gauges on the Barwon-Darling River (Mungindi, Collarenebri, Walgett, Brewarrina, Bourke, Wilcannia). The main analysis presents the attenuation of censored low flow events (<2,000 ML/day) between the downstream and upstream gauges. The results indicate that low flow and small fresh events between Collarenebri and Walgett and particularly between Walgett and Brewarrina are heavily attenuated post-2000 compared to pre-2000. Some of the events observed at Walgett attenuated to zero with no corresponding flow recorded downstream at Brewarrina. Most of these flow attenuations often occurred in pairs (Collarenebri-Walgett and Walgett-Brewarrina reaches), occurred only after 2002, and often around the end of the calendar year.

The MDBA (2018b) further analysed the length of dry spells of very low flow (<20 ML/day). The dry spell length is greatest in the lower Barwon-Darling reaches downstream of Bourke. The average dry spell length in the mid-reaches (between Collarenebri and Bourke) is lowest and lower than the upper reaches because of tributary inflows breaking some of the dry spell events. The analysis show that the average length of dry spell is higher post-2000 compared to pre-2000 and have doubled at Brewarrina and Walgett. This is further supported by Sheldon's (2017) analysis using the same data which identified 2001 as a break point where the "natural" correlation between dry spells and the Southern Oscillation Index diverged.

The above analysis was carried out by the MDBA (2018b) following the Northern Basin Review recommendation to reduce water recovery volume and implement a range of "toolkit measures" (MDBA 2016). The toolkit measures specify the need to protect ecologically significant low flows which are critical for communities and the environment. The MDBA analysis is consistent with the more detailed analysis by NSW DPE (2021b) and in Sections 4.1 and 4.2, indicating the impact of the dry climate and historical water resource development on low flows in the Barwon-Darling River post-2000.

The impact on low flows is largely caused by in-channel river water extraction, with floodplain harvesting of overbank flows (which occurs only during large flow events) having little impact. The need to mitigate this impact has been recognised by NSW's recent changes in water sharing plan rules to enhance low flow outcomes in the Barwon-Darling River. The changes include revised A-class access thresholds (increasing the flow threshold before river water extraction can occur), resumption of flow rules (increasing the number of days after flow threshold is exceeded before water extraction can commence to allow first flush event to flow downstream), and limiting daily water extraction volumes (NSW DPE 2019a, 2019b, 2020).

4.4.2 Impact of floodplain harvesting on low flows and streamflow volumes

Floodplain harvesting occurs only during large flow events when the river overflows its bank. As such, floodplain harvesting is unlikely to significantly impact low flows. This assertion is supported by the analysis of the timing of floodplain harvesting events in the northern Basin and cease to flow periods in the Barwon-Darling River by NSW DPE (2021c). The analysis compared the modelled floodplain harvesting diversions across the Border Rivers, Gwydir and Namoi valleys and the observed streamflow at Walgett over the past 30 years. The results show that floodplain harvesting does not occur during cease to flow events and does not contribute significantly to starting the cease to flow period sooner or extending existing cease to flow periods.

Although floodplain harvesting has little impact on low flows, it can significantly reduce flows to downstream floodplains and wetlands during higher flow events. Averaged across the northern Basin valleys of NSW, floodplain harvesting is 20-25% of the total volume of water extracted (Section 2.7). Floodplain harvesting is difficult to effectively control and measure, and together with the uncertainty in measuring and quantifying the volume of riverine water extraction, has led to community disquiet about water theft, compliance and extraction rules (Interim Inspector General 2020, Weber and Claydon 2019). Nevertheless, recent NSW policy and reform to more effectively regulate and formally account for floodplain harvesting (NSW DPE 2021d, 2021e), together with advancements in quantifying floodplain water (through direct measurement, remote sensing and modelling), is a significant progress towards better managing floodplain water and water resources generally to enhance downstream outcomes.

4.4.3 Environmental watering in the northern Basin

The Murray–Darling Basin Plan requires the recovery of 320 GL for the northern Basin to be managed by the Commonwealth Environmental Water Holder. Furthermore, as a result of investigations and discussions undertaken through the Northern Basin Review, Basin governments have committed to implement a series of toolkit measures to enhance environmental outcomes in the northern Basin (MDBA 2016). The 2020 Basin Plan evaluation (MDBA 2020a), through analysis of flow metrics reflecting longitudinal river connectivity and lateral connectivity combined with inputs from technical experts and stakeholders, concluded that the Basin Plan is having some positive impact on the northern Basin environment. The evaluation noted that the Basin Plan has been crucial for sustaining water-dependent ecosystems during the recent drought, particularly in regulated rivers where water can be delivered from storages.

The Wentworth Group (2020) compared post-2012 observed streamflow against pre-2012 analogues that also accounted for antecedent conditions. The analysis suggests that 20–30% of water expected under the Basin Plan did not flow past key sites in the northern Basin. The Wentworth Group (2020) identified possible reasons for this including higher than expected losses, upstream extraction of environmental water, undermining of water recovery efforts, and the Basin Plan not being fully implemented yet. Both the Basin Plan evaluation (MDBA 2020a) and

Wentworth Group (2020) analyses suggest that the Basin Plan is having some positive impact for the environment but is likely to have fallen short of Basin Plan expectations. The Basin Plan evaluation also notes that the Basin Plan is unlikely to be sufficient to achieve long-term outcomes unless further implementation and other actions are fast-tracked. The major fish death events in 2019 also demonstrate the need for whole-of-system management (Vertessy et al. 2019).

There are limitations in both the above assessments, and the results of these and other studies are not always consistent, leading to speculations on the causality of flow reduction in the northern Basin and whether the Basin Plan has achieved its intended outcomes. This highlights the need to assess river flows (for different events and time scales, and specific locations), with best-available models, observed data, and counterfactual modelling, to support environmental watering decisions and to then monitor if the intended flow outcomes have been achieved.

5. SUMMARY AND RECOMMENDATIONS

5.1 Summary

The low streamflows in the northern Basin in recent decades, and challenges in managing water for competing uses in the northern Basin as well as across the Murray–Darling Basin, have led to concerns that water resource development has significantly impacted flows, and more so than what is intended in water resource management plans. The scrutiny is enhanced in the northern Basin because the use of large on-farm floodplain storages to collect water when it is available provides visible evidence of water take on the landscape particularly during dry periods.

The syntheses of knowledge from previous reviews, commentaries and technical reports, enhanced with data analyses in this project, indicate that there is a relatively good and reasonably consistent understanding of the hydrology and water resources of the northern Basin. However, communicating the different aspects and issues of a complex system can be difficult, leading to different interpretations and distrust in the knowledge and limiting effective water resource management, policy development and adaptation to changing conditions.

The synthesis and evaluation of causes of reduced flow in the northern Basin are summarised below.

- Rainfall and runoff in the northern Basin exhibit high inter-annual, multi-year and decadal variability. The past two decades in the Murray–Darling Basin have been relatively dry. The low rainfall is amplified in the percentage reduction in Basin runoff and inflows. [Section 3.1].
- Rainfall and streamflow records across the Murray–Darling Basin show a declining trend over the past 50 years of living memory, as the relatively dry past two decades were preceded by wet decades. The Murray–Darling Basin is likely to be hotter and drier under climate change, with lower mean annual streamflow and more frequent hydrological droughts in the future. [Section 3.2].
- Hydrological non-stationarity, resulting from long dry spells and landscape development, has reduced the annual runoff generated from the same amount of annual rainfall. The impact of hydrological non-stationarity on water resources can be significant, particularly under climate change, although it is likely to be much smaller compared to water extraction from rivers. [Section 3.3].
- Irrigation development and water extraction across the northern Basin have also significantly reduced flow volumes and increased the number of low flow days in the Barwon-Darling River. Both climate variability and water resource development have caused the reduced flows in the Barwon-Darling River, but it is difficult to quantify their relative contributions because of the high streamflow variability and relatively short period of instrumental data. [Section 4.1].
- Modelling indicates that water resource development across the northern Basin has reduced streamflow volumes in the Barwon-Darling River by 40–50% compared to no development conditions. Water resource development has also increased the frequency of low flow events. Short and medium low flow events (<6 months) are caused by climate variability and water

resource development, and longer low flow events (>1 year) are caused by drought across the region. [Section 4.2].

- The impact on low flows is largely caused by in-channel river water extraction. Both in-channel river water extraction and floodplain harvesting impact flow volumes. [Section 4.4].
- Analyses of modelled and observed data indicate that the reduced streamflow in the Barwon-Darling River experienced over 2001–2009, relative to the wetter 1950–2000 period, can be attributed roughly equally to climate variability and to historical water resource development. The impact of water resource development is accentuated in dry periods. [Section 4.3].
- The Darling River contributes, on average, about 17% to the total lower Murray River flow volume under pre-development conditions and about 13% under current development conditions. The Darling River contributes more than 25% to the total lower Murray River flow in only 10% of the years. [Section 4.3].

5.2 Recommendations

There is a reasonably good general understanding of the water balance in the northern Basin, that is, water inputs and outputs in the system at different time scales and at different locations, from measurements, modelling and integrating multiple types of information. However, there are gaps in knowledge, particularly for some water fluxes or components and at the detailed level required to address issues that have been discussed. While addressing these gaps may not significantly change the quantum of the larger volumetric assessments, it would better inform options to manage the river system more effectively especially in times of water stress. Recommendations are described below to help overcome some of these knowledge gaps.

Equally important is the need for more transparent engagement and communication with communities and stakeholders to build confidence and trust in the knowledge, data and models. This will then shift the conversation from about uncertainty and debates on the broad knowledge to a more positive engagement and discussion about solution, choices and adaptation to overcome challenges in providing a scarce and limited resource to multiple uses.

- <u>In-channel water extraction</u>
  Most of the water in on-farm storages comes from diverting or pumping from rivers and tributaries. Whilst most of these are measured, further improvements to monitoring, in ensuring compliance, or understanding and accounting for non-compliance can improve the uncertainty in this large water balance component (particularly as measurement technologies and data assessment approaches improve). Basin governments have made significant investments in this area over recent years, and it is important that this momentum is maintained.

- <u>Characteristics of flow events</u>
  A well-constructed formal analysis of individual flows on an event-by-event basis can improve the understanding of impact of water take and flows through the system, particularly when combined with developments in satellite remote sensing (see below). This includes how the timing and volume of upstream water take, transmission through the various river systems, and

river management and operation, impact downstream hydrographs for the different types of events.

- <u>Low flows</u>
  It is important to understand and quantify cease to flow and recommencement of flows in the Barwon-Darling River and tributaries, particularly with regards to how these affect transmission losses, rewetting of channels, connectivity of refuge ponds and impact on instream ecosystems, and how they have changed over time. Measurements, in-depth event analysis, modelling and integrating different types of data (remote sensing of river connectivity, streamflow, groundwater, controlled flow release) can enhance the understanding to inform policies and management.

- <u>Floodplain volumes</u>
  It is difficult to reliably estimate the components of the water balance that make up overbank flows – volume of floodplain harvesting, losses to evaporation, infiltration and groundwater recharge, and in particular water that returns to the river either soon after the event or through the groundwater system weeks or months later. This is a significant knowledge gap that can be improved through measurement of harvested water, floodplain storage depth and volume, remote sensing of water inundation and depth, analysis of falling limb of the hydrograph, and modelling.

- <u>Landscape development, hydrological non-stationarity and changing climate</u>
  Hydrological non-stationarity, resulting from long dry spells and landscape development, can reduce annual runoff generated from the same amount of annual rainfall. Compared to the southern Basin, there has been very few studies in the northern Basin on the impact of hydrological non-stationarity on catchment runoff and inflows into rivers. Research is needed here, particularly with the opportunity provided by longer and new datasets becoming available, significant advancements in remote sensing technology, interpretation and application, new modelling capabilities including machine learning, and building on knowledge from the extensive research in the southern Basin. In addition, current management responses to recovery after significant droughts may need to consider how the system may be changing and how the responses may need to be adapted to the changes.

- <u>Satellite remote sensing</u>
  Satellite remote sensing can be used to estimate development and land use change on landscapes over time. Satellite remote sensing can also be used with irrigation classification methods (Peña-Arancibia et al. 2014) and hydrological modelling (Peña-Arancibia et al. 2016) to estimate irrigation development, paddock-scale water use, and potentially floodplain storages over time (depth, volume and capacity). With the rapid advancement of remote sensing application in agriculture and hydrology, it is essential to increasingly use remote sensing data, either directly or to inform and constrain hydrological and water resources modelling.

- <u>Data and monitoring</u>
  Existing data should be examined to explore if they can be enhanced, through digitising old datasets (e.g., extension of Barwon-Darling streamflow data by NSW DPE), developing relationships with other data sources (e.g., farm scale water use, storage data, infrastructure

data, remote sensing data) and using other non-water data sources (e.g., socio-economic data from Australian Bureau of Statistics). New measurement initiatives (e.g., floodplain harvesting), advancements in telemetry, and new technology like the growing use of unmanned aerial vehicles in agriculture and environmental assessments can enhance datasets for the northern Basin.

- Floodplain on-farm storages
  There is considerable uncertainty in current knowledge and quantification of water take in on-farm storages. The most direct method to quantify this is metered measurements of diversions and water depth in the storages. This can be supplemented with new satellite technologies to estimate the storage capacity and in the near future also the storage water depth (Peña-Arancibia et al. 2022a). Recent initiatives like licensing policies, compliance monitoring, and implementation of direct measurements, will significantly improve the quantification and management of water take in on-farm storages.

- Water resource modelling
  Modelling has continued to improve over several decades, and new knowledge from the research outlined above combined with integrating models with remote sensing and new and longer data sets, will reduce the "residual terms or losses" in models (i.e., improving the quantification, causality, and prediction of the different water fluxes) over the coming years. Modelling should also explore whole of river system or river valley application (or calibration or parameterisation), and combine this with the current practice of reach application, and embrace quantification of uncertainty. This will allow causality and processes to be more explicitly conceptualised and parameterised, enhancing the ability of models to better predict outcomes from different data input and management scenarios.

- Transparency, communication and engagement
  Reviews and political discourse have consistently reported on the distrust of modelling and the inability to understand policy formulation and water resource management decisions. While this is partly reflective of the complexity of the water system, it also highlights the need to improve engagement and communication, especially of the complex elements, using better techniques such as participatory modelling, improved visualisation and alternative engagement approaches to those used previously. This requires a better understanding of the types of engagement and communication approaches that are appropriate for basin stakeholders, and how the use of alternative techniques to facilitate these may improve transparency and understanding.

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