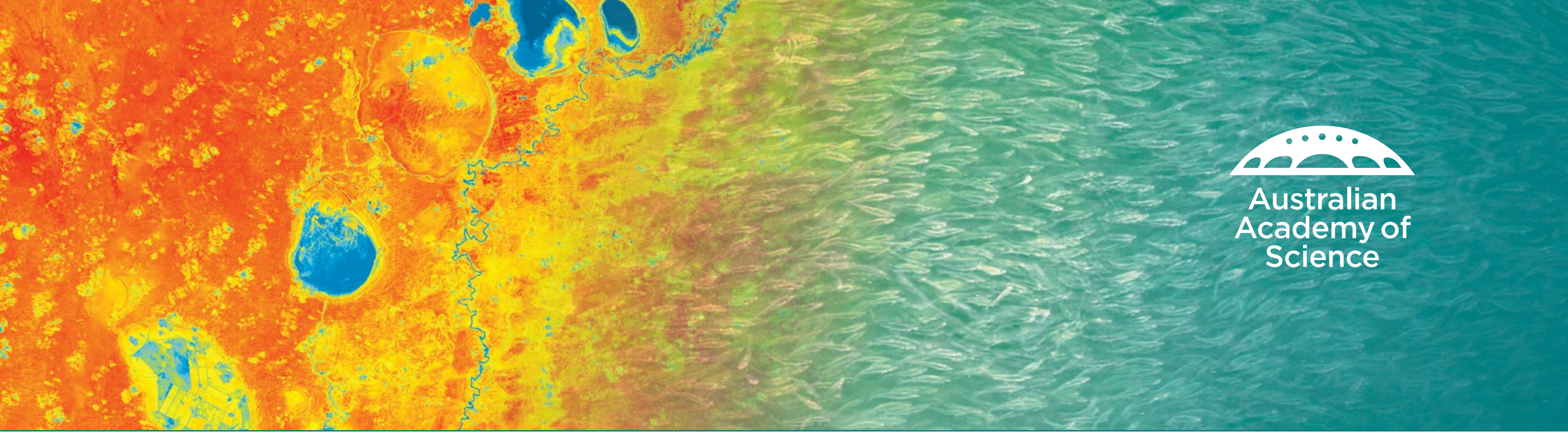

Australian Academy of Science

INVESTIGATION OF THE CAUSES OF MASS FISH KILLS IN THE MENINDEE REGION NSW OVER THE SUMMER OF 2018–2019

AUSTRALIAN ACADEMY OF SCIENCE

18 FEBRUARY 2019

ACKNOWLEDGEMENTS

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Additional thanks

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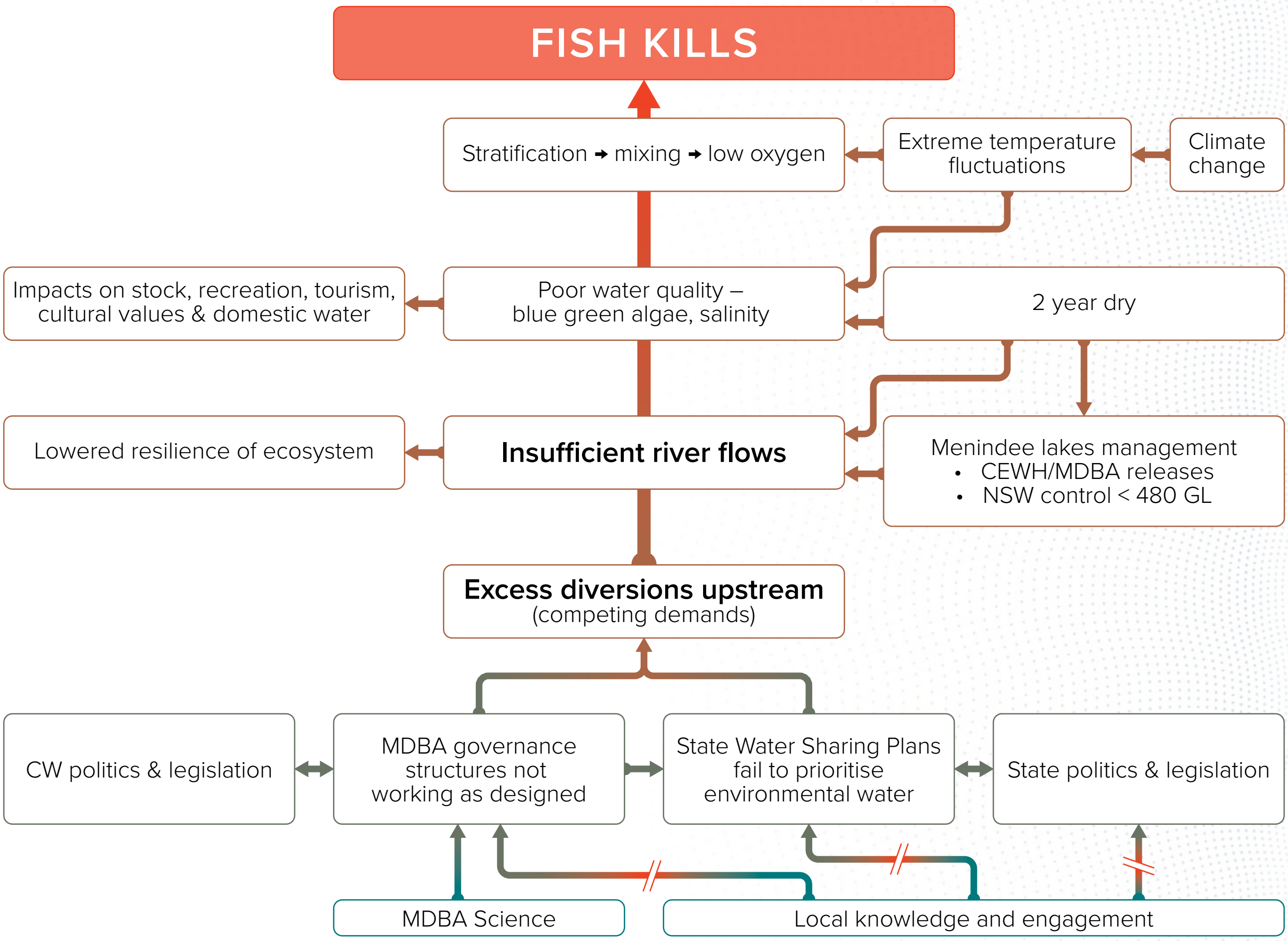
EXECUTIVE SUMMARY

On 15 December 2018 tens of thousands of dead fish were reported along a 30 km stretch of the Darling River near the town of Menindee in New South Wales. High numbers of dead fish were seen in the vicinity of the Old Menindee Weir and Menindee Pump Station. A second, larger fish kill event involving hundreds of thousands of fish was reported on 6 January 2019 on the same stretch of river. A third event followed on 28 January, killing millions of fish. Members of the panel witnessed the beginnings of a fourth event on 4 February 2019.

Many different sectors of Australian society, and of the Menindee region itself, are distressed knowing that fish have been dying en masse, and are concerned about the implications for the health of the river. In addition, these fish are of high cultural significance to Indigenous communities in the region, including those holding Native Title rights.

In response to the first two kills, the Academy was requested by the Leader of the Opposition, the Hon. Bill Shorten MP to provide advice on the immediate causes, as well as exacerbating circumstances from water diversions, agricultural runoff or climate change, and to provide recommendations.

Figure 1



Summary chain of causes leading to the fish kills. Red barriers refer to poor ratings for use of information.
MDBA – Murray-Darling Basin Authority; CW – Commonwealth; CEWH – Commonwealth Environmental Water Holder.

SUMMARY FINDINGS

The Academy Panel made the following findings, illustrated in Figure 1:

1. The three fish kills that occurred in rapid succession over December 2018 and January 2019 were unusual in the combination of their severity, impact on large, 20-year-old and older Murray cod, and association with low flows.
2. The immediate cause of the fish deaths was stratification and then mixing of a large volume of oxygen-depleted bottom water with the smaller oxygenated surface layer. Conditions such as low- and no-flows and hot temperatures favoured growth of large blue-green algae blooms as well as separation of water layers. As the blooms died and sank they fed bottom layer microorganisms, which used up all available oxygen. Sudden drops in temperature then triggered mixing between the surface and bottom layers, lowering the overall concentration of oxygen in the water beyond the ability to support respiration of the fish. The extreme maximum temperatures, among the hottest on record, are as expected under anthropogenic warming.
3. The conditions leading to this event are an interaction between a severe (but not unprecedented) drought and, more significantly, excess upstream diversion of water for irrigation. Prior releases of water from Menindee Lakes contributed to lack of local reserves.
4. **The root cause of the fish kills is that there is not enough water in the Darling system to avoid catastrophic decline of condition through dry periods.** This is despite a substantial body of scientific research that points to the need for appropriate flow regimes. Similarly, engagement with local residents, Indigenous and non-Indigenous, has been cursory at best, resulting in insufficient use of their knowledge and engagement around how the system is best managed.
5. The panel strongly supports the objectives of the *Water Act 2007* and the framework of the Murray-Darling Basin Plan (2012), which were developed with bipartisan political support and intended to increase water for the environment. However, the findings summarized above and detailed in the following sections point to serious deficiencies in governance and management, which collectively have eroded the intent of the *Water Act 2007* and implementation of the Murray- Darling Basin Plan (2012) framework.

The freshwater systems of the Darling are already listed as endangered (NSW, 2007) and include multiple fish species listed as threatened by the Commonwealth. Failure to act resolutely and quickly on the fundamental cause—insufficient flows—threatens the viability of the Darling, the fish, and the communities that depend on it for their livelihoods and wellbeing including the traditional owners, who have recognised rights and responsibilities

SUMMARY RECOMMENDATIONS

The Academy expert panel recommends that responsible authorities:

1. Within 6 months, take urgent steps to ensure that there is sufficient flow—considering both quality and quantity of water—in the Darling River to prevent stratification and blue-green algal blooms.
2. Within 6 months, establish a Menindee Lakes restoration project, to determine sustainable management and operation of the lakes system and the Lower Darling and Darling Anabranch
3. Initiate a community planning process in the Lower Darling to restore river health and sustain local livelihoods
4. Improve meaningful engagement with river-based communities, including Indigenous peoples
5. Improve the health of the Darling River, through adequate and effective planning, which is scientifically informed
6. Return to the intent of the 2012 Murray-Darling Basin Plan to avoid increasing risks of more fish kills and other environmental problems for the Darling River
7. Invest to fill high priority knowledge gaps as the MDBP continues to be implemented, and then reviewed in 2026
8. Commission within 12 months an independent scientific panel to review progress in implementing the above recommendations.

Important detail is provided for each of these recommendations in Section 8—Academy Panel Recommendations.

1. INTRODUCTION

TERMS OF REFERENCE

In response to fish kills in the Menindee region on 15 December 2018 and 6 January 2019, the Australian Academy of Science was requested by the Leader of the Opposition, the Hon. Bill Shorten MP to assemble a multi-disciplinary panel to provide advice on:

1. How the fish kills took place and what caused the magnitude of the event
2. Whether water diversions and/or water management practices in the Murray-Darling system have caused or exacerbated the scale of this disaster
3. Whether chemical and fertiliser use may have contributed to the event
4. What immediate steps can be taken to improve the river system's health and management within the Basin Plan framework
5. Whether there has been a step change in inflows due to climate change or whether more work is required in this research area.

PROCESS

The Academy convened an expert panel comprising Fellows of Australia's Learned Academies, with additional scientific expertise recruited as necessary. The expert panel consulted with other experts, scientists and researchers to ensure comprehensive coverage of the issues relating to the fish death events. The panel members drafted sections of the report according to their expertise, and these sections were synthesised into the final report. The panel also sought additional data from relevant government agencies, including the Murray-Darling Basin Authority, the Commonwealth Environment Water Holder, and the relevant NSW water agencies including the Department of Primary Industries, the Land and Water Division of the Department of Industry and the Office of Environment and Heritage. The panel considered data and reports provided up to midnight on 13 February.

The expert panel operated closely with the Independent Panel to Assess Fish Deaths in the Lower Darling, initiated by the Australian Government and chaired by Professor Robert Vertessy, including sharing data and reciprocal review of findings. Both panels were briefed by the Murray-Darling Basin Authority and the Commonwealth Environmental Water Office on 1 February 2019. The draft report was assessed by seven independent reviewers, including one international reviewer, who collectively have expertise appropriate to the scope of the findings and recommendations.

While relying primarily on published evidence and publicly-available government reports, the panel also sought local knowledge on river conditions past and present from the Menindee region community, including pastoralists, irrigators, local residents, and Indigenous people. Indigenous perspectives are especially relevant given the 2015 determination of Native Title (Barkandji and Malyangapa people) over affected areas. Members of the expert panel met with the Broken Hill Mayor, and with the Menindee community including traditional owners on 5–6 February 2019.

The membership of the expert panel and review panel are provided in Appendix 9. Details of the consultations are provided in Appendix 10. The expert panel is very grateful to all who contributed and to the Australian Academy of Science staff who tirelessly supported the expert panel as they undertook their work.

SCOPE AND STRUCTURE OF THIS REPORT

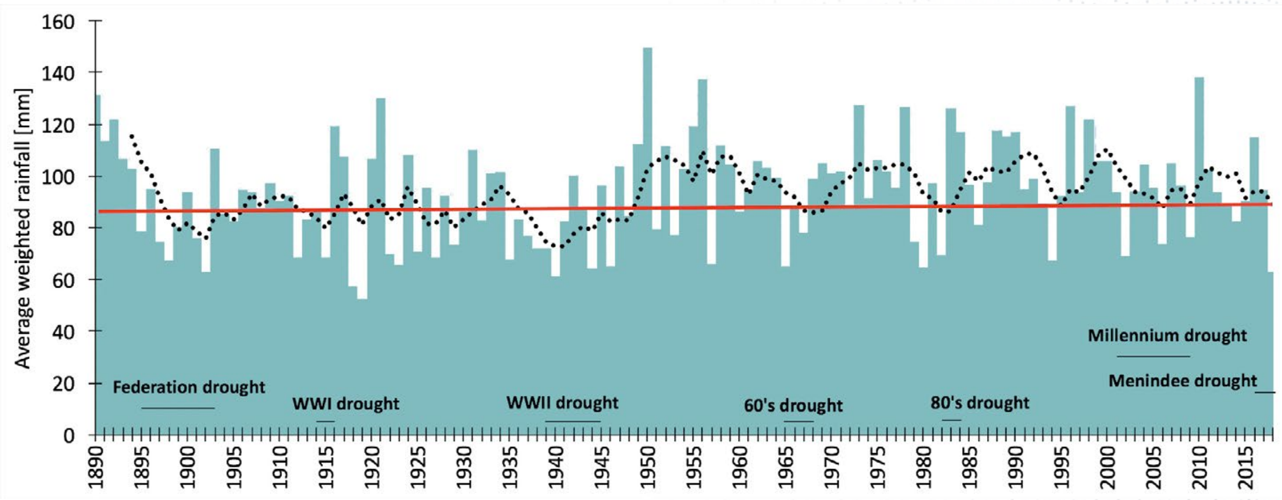
The fish kills were not caused by the recent drought alone, stressful as that was. Rainfall deficits as severe or worse occurred across the catchment during the Millennium and previous droughts (Figure 2), but some of the larger Murray cod were from 17 to 25 years old[1] and so evidently survived the more recent of these. It follows that these kills reflect the poor ecological condition of the Menindee Lakes region and of the Darling River itself. This finding required the expert panel to investigate (i) how the Darling, and the upstream catchments (ie. Northern Basin) that provide 99% of the water in the Darling, have been managed under the Murray-Darling Basin Plan leading up to this event, and (ii) how recent changes to water allocations in the Northern Basin will affect the likelihood of such kills occurring again.

The health of the Darling, and the broader Murray-Darling system, reflects hydrological and ecological processes across space and time—the ecological connections across floodplains and the main channel systems—and how flows change over years. Simultaneously, the health of the river system impacts local and regional communities, including Indigenous responsibilities and rights. Hence, this report considers the fish kills and associated poor condition of the river in this broader socio-economic context.

This report presents our findings in the following sequence: What caused the kills and their magnitude (TOR1); did chemicals or fertiliser use contribute (TOR3); did water diversions and/or water management practices exacerbate the scale of the kills (TOR2); has climate change caused a step change in inflows (TOR5); and what immediate steps can be taken to improve the system's health (TOR4). The panel's investigation of these terms of reference also led to findings on overarching issues about governance and management that are directly pertinent to TORs 2 and 4. Because they require understanding of how water across the Murray Darling Basin is governed and managed, this material is presented as a separate section following those addressing individual TORs.

Each of the sections in the main text of the report has accompanying Appendices that contain the detailed analyses of evidence; these should be referred to for the detailed evidence supporting the findings and recommendation of the panel.

Figure 2



Annual and 5-year rolling average (dotted line) rainfall across the Darling system, based on total cumulative data from rainfall stations in the tributary catchments, reflecting the relative contribution of the rivers to flows in the Darling River. The red line compares the current 5 year average to that in previous droughts.

1 https://www.dpi.nsw.gov.au/fishing/habitat/threats/fish-kills/Fish-death-interim-investigation-report.pdf

2. HOW THE FISH KILLS TOOK PLACE AND WHAT CAUSED THE MAGNITUDE OF THE EVENTS

TERMS OF REFERENCE 1

(See Appendices 1 and 2)

On 15 December 2018, tens of thousands of dead fish were reported along a 30 km stretch of the Darling River near the town of Menindee in New South Wales. Inspections by New South Wales Department of Primary Industries (DPI) fisheries staff observed high numbers of dead fish in the vicinity of the Old Menindee Weir and Menindee Pump Station.

A second, larger fish kill event was reported on 6 January 2019 on the same stretch of river. DPI inspectors reported hundreds of thousands of dead fish. A third event, even larger, followed on 28 January 2019, killing millions of fish. Members of the panel witnessed the beginnings of a fourth event on 4 February 2019; 20 of the affected Murray cod were subsequently removed to a captive breeding facility.

The NSW Department of Primary Industries investigated the two first large fish kills and concluded in a preliminary report (NSW Department of Primary Industries; 2019) that the fish died because there was insufficient dissolved oxygen in the water for them to survive. This occurred through the development and subsequent breakdown of thermal stratification, combined with large cyanobacterial (blue-green algae) blooms, driven by low or no flows and abundant nutrients that provided the large amounts of organic material, and which then led to massive oxygen depletion due to microbial activity. A visual summary of the conditions and range of factors leading to the fish kills is provided as a conceptual diagram in Figure 3. These conditions and processes—the thermal stratification and algal blooms—are the combined outcome of low river flows as a result of regional drought and the regulation of flows by responsible authorities. These aspects are considered under TOR2 in Section 4.

Based on the information available to us, the panel supports the finding of the NSW Department of Primary Industries (NSW Department of Primary Industries; 2019), with additional observations below. Additionally, the panel notes that the release of water into the Darling River from the upstream Lake Pamamaroo, which contained high concentrations of blue-green algae, could have fuelled the downstream blooms.

Several factors combined to lower the amount of dissolved oxygen in the water. First, a layer of warm water formed over deeper, colder water—a phenomenon known to anyone swimming during summer, when sunlight warms surface waters. The upper layer is more oxygenated due to the presence of oxygen-producing blue-green algae (cyanobacteria) which thrive in warm water overlying cold water. Extremely hot weather was almost certainly a major contributor. Warm water holds much less oxygen than cold water.[2] A small amount of oxygen in the warm water also comes from the atmosphere via turbulence created by wind and rain. The deeper, colder layer is very low in oxygen because, as blue-green algae, and other aerobic organisms die, they sink to the bottom, joining other organic matter. Microbes in the sediment consume this organic matter, using up *all* the oxygen. More oxygen cannot cross the boundary

2 For example, oxygen saturated water at 10 °C contains around 11.3 mg/L of oxygen; this falls to 9.1 mg/L at 20 °C, and only 7.6 mg/L at 30 °C.

between the warm and cool water, stopping oxygen from the upper surface warm water entering the deeper water. Even though blue-green algae produce considerable amounts of oxygen during the day when they are photosynthesising, they also consume oxygen at night when respiration dominates. So large concentrations of cyanobacteria can deplete oxygen levels in water at night.

Then a cool change cooled the warmer upper layer, allowing the warm upper and cool lower water bodies to mix. As this happened, the oxygen in the warm layer was diluted in the whole water body, and was quickly used up and the fish died (see Figure 4). Different weather events triggered the various fish kills. In 15 December 2018, it was hot still conditions followed by cold snaps and rainfall.

For the 6 January 2019 kill similar large temperature fluctuations combined with strong south winds. For the 28 January 2019 kill, there was a similar severe temperature drop—from maximum temperatures of 49˚C (following temperatures of above 40˚C in 14 of 17 preceding days) to 23˚C. Further, a feedback loop may have developed following the first mass mortality, where further depletion of oxygen occurred due to bacterial breakdown of blue-green algae and dead fish in the lower layer when stratification was re-established.

Figure 3

ISSUE

- Extensive Fish Kills in the Darling River at Menindee, NSW during December 2018 and January 2019

DIRECT CAUSE

- Low concentrations of dissolved oxygen (DO) extending along a large section of the lower Darling River

IMMEDIATE FACTORS

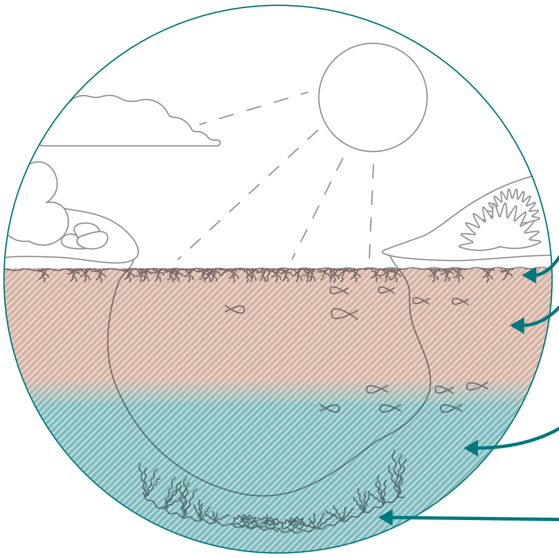
- Thermal stratification (layering) of waterbody over large area
- Turnover (mixing of layers) brings low DO water from bed to surface
- Large area affected and bariers mean fish cannot escape to high DO refuges
- Strong winds, drop in temperature, rainfall and flow create turnover
- Prior hot, still conditions and low flow drives stratification and algal blooms
- Large algal blooms drive increase in organic material on riverbed
- Microbial respiration of organic material on riverbed drives low DO

LONG TERM DRIVERS

- Poor catchment management = high nutrient inputs = algal blooms
- Poor water management and drought = low water levels and low or no flows
- High temps and nutrients and low water levels and no flows = algal blooms and stratification

Conceptual diagram of fish kill causes

Figure 4



Thermal Stratification

Blue Green Algal Bloom
Algal flourish in warm and still conditions, particularly in the absence of high flow.

Surface Water Layer
Warm, high nutrient load from run off. Oxygen production from photosynthesis by day, depletion overnight. Limited fish habitat.

Deep Water Layer
Cooler, high nutrient load from organic matter, low light penetration. Low dissolved oxygen (hypoxia). Poor fish habitat.

Decomposition of organic matter
Depletes dissolved oxygen.

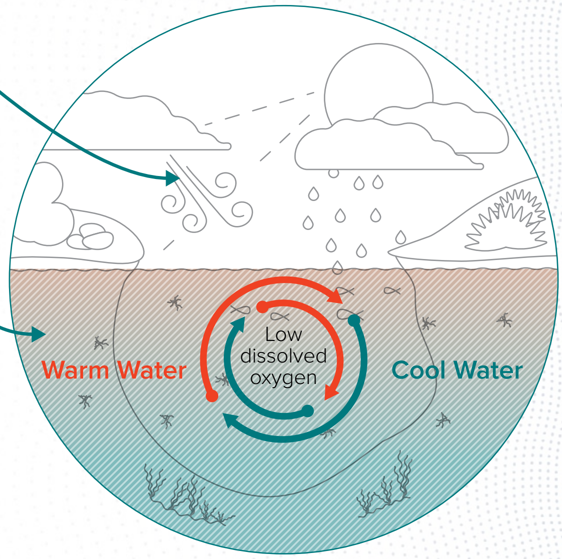
Destratification (“mixing”)

Sudden weather events or increases in flows above the threshold required for water column mixing
Mixes the warmer surface water and cooler deep water – breaking down the temperature stratification.

These changes can mix the warmer oxygenated surface water with cooler and low oxygen deep water.

Algal blooms may also be disrupted, potentially increasing decomposition (and further reducing oxygen).

This means even at the surface dissolved oxygen levels can become critical, killing fish.



Stratification/algal bloom, mixing and further deoxygenation
Source: Adapted from New South Wales Department of Primary Industries (NSW Department of Primary Industries, 2019).

Other causes of the fish kills have been proposed, including poisoning by cyanobacterial toxins and cyanobacterial bloom die-offs triggered by cold snaps. No toxins have been detected and the temperature change was well below any threshold for cyanobacterial mortality. Given our present knowledge, it seems that low oxygen conditions associated with the breakdown of thermal stratification was the most probable cause, exacerbated by the die-off of blue-green algae and associated decomposition of a large amount of organic material on the riverbed (including dead fish). Continuous recording of water temperature, dissolved oxygen concentration, conductivity, pH, chlorophyll *a*, cyanobacterial species and toxins over a range of depths, along with other data, is needed in weir and river pools, if we hope to predict fish kills and act before they occur. Investigation into the pathology of the fish killed would also help.

SCALE OF THESE FISH KILLS—IS IT UNUSUAL?

The most recent large fish kill in the Darling system was in 2004, primarily caused by low quality of water released from the Menindee Lakes, lowering oxygen levels through microbial decomposition of high loads of carbon (Ellis and Meredith 2004). Unlike the 2018/2019 fish kills, the 2004 fish kill on the Lower Darling primarily only affected Murray cod, not the same extensive impacts across the whole of the fish community of the 2018/2019 fish kills. The 2004 fish kill affected an estimated 3000 Murray cod, not vast numbers across multiple species of native fish, as did the 2018/2019 fish kill (see Table 1).

The repeated events on the Darling River over the summer of 2018/2019 are unusual in the combination of their association with extreme temperatures and low flows in the Darling, involving millions of dead fish, and including numbers of large (some more than 20-year-old) Murray cod. The loss of iconic and keystone species, such as Murray cod and golden perch, and the death of large, old fish, is particularly worrying. Some of these older fish have survived through many other adverse environmental events such as the Millennium drought. Fish will normally swim away from low oxygen waters to better oxygenated ones (refugia). But in the recent fish kills, oxygen depletion occurred over such a large area that no refugia were left: there was no escape. To make matters worse, even if there was better quality water nearby, the fish cannot get there because of physical barriers—the weirs themselves. The loss of such important breeding stock, along with very high numbers of small-bodied fish such as bony herring, will likely deplete aquatic and terrestrial food chains in the region. Cumulatively, these kills included substantial numbers of threatened species—notably silver perch and Murray cod. They also included large numbers of golden perch, which could be of broader significance as the Menindee Lakes is an important nursery area for the Lower Murray population.

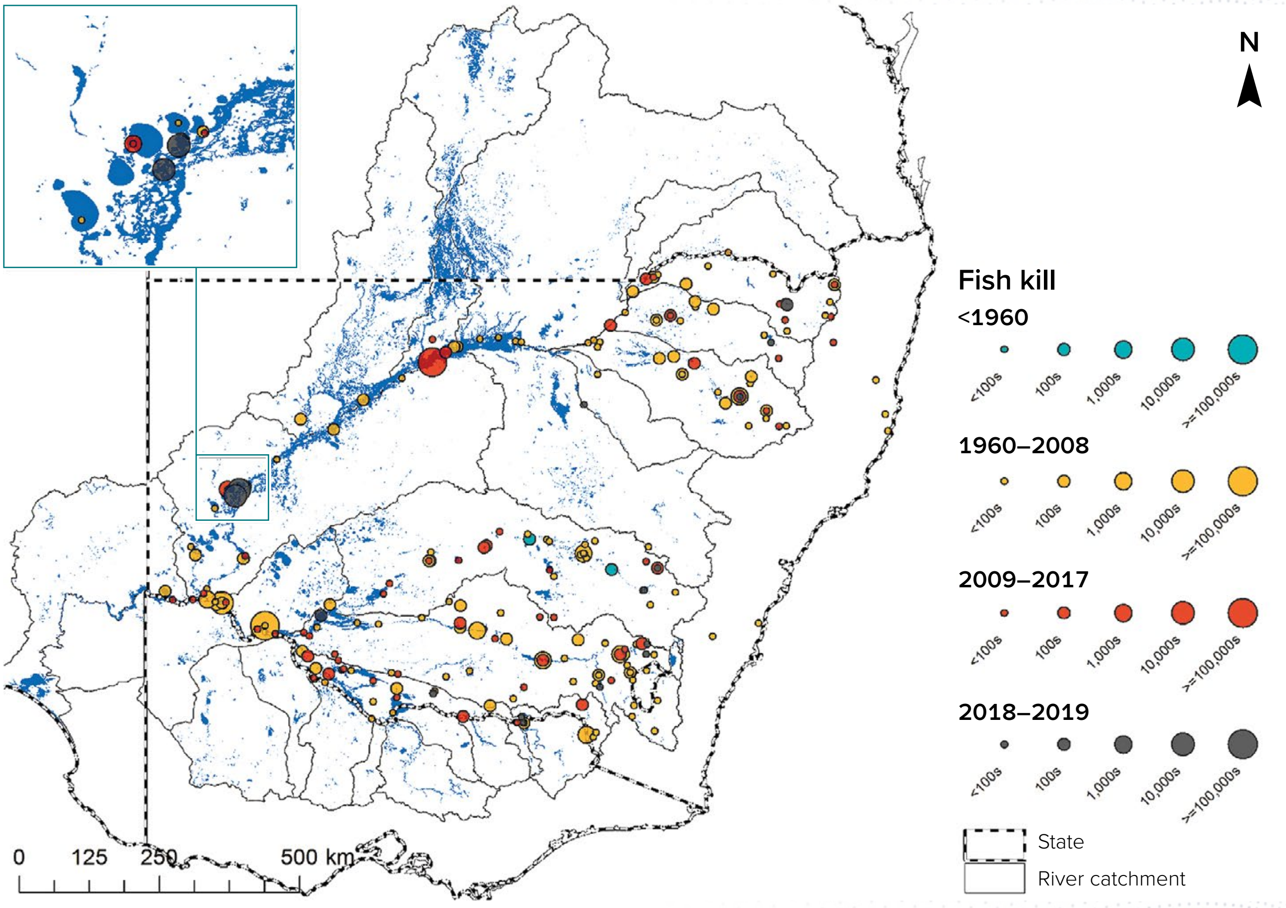
The increased flow and connectivity of the 2016 flood stimulated wide ranging breeding of native fish species throughout the Menindee Lakes and the Darling River. In winter of 2016, there was widespread spawning of golden perch followed by spring spawning of 2016 Murray cod, as the flow pulse came through (D'Santos et al. 2017). Bony herring also probably bred in large numbers, given their responsiveness to flow pulses and floods (Lintermans 2007). To ensure wide dispersal of native fish, the releases of water by the Murray-Darling Basin Authority were managed to promote dispersal of golden perch in late 2016 (see Section 4, p31). The presence of large numbers of newly recruited native fish could have amplified the scale of the fish kills. However, the data available to this panel on the size and age structure of the fish killed is inadequate to test this hypothesis.

Fish kills occur reasonably frequently in the Murray Darling-Basin, illustrated by the many events in the NSW part of the Murray-Darling Basin (Figure 5). Records in the NSW Department of Fisheries fish-kill database and historical data indicate that large fish kills occurred in the hundreds of thousands and millions on the Darling River and River Murray previously (Figure 5, Table 1). They have also occurred on Menindee Lakes and the Lower Darling. There are three principal reasons for fish kills: stranding of fish when there is no water, usually in lakes (such as occurred at Menindee Lakes in 1984, Table 1), low flows producing low oxygen, and high flows (blackwater events[3]), also producing low oxygen conditions. There is some evidence that the latter causes are increasing over time (see Appendix 3), with more large fish kills in the last few decades although this

3 Blackwater is the black appearance of water due to release of dark coloured carbon compounds (notably but not exclusively tannins) from organic matter decay—like adding tea leaves to water

may also be due to reporting bias. It is also clear that both fish kills when rivers are low and fish kills during blackwater events are also linked to river management and the effects of diversions and river regulation on the rivers. The low flows, which are increasing in the Darling River as a result of increased diversions (see Section 4), will increasingly cause blue-green algal blooms, increasing the risks of large fish kills in the river and other rivers in the Murray-Darling Basin. The low oxygen conditions caused by high flow events (blackwater events) are also increasingly related to impacts of river regulation and increased diversions on the river. The increases in organic matter (leaves and dead branches) are widespread and related to floodplain forests dying across the floodplains of the Murray-Darling Basin as a result of receiving insufficient flooding (Mac Nally et al. 2014, Horner et al. 2009, Mac Nally et al. 2011, Catelotti et al. 2015). This creates considerable dead plant material which, during a large flood, will start to break down and contribute to low oxygen in the river that has caused fish kills (Thiem et al. 2017, Kerr et al. 2013, Whitworth et al. 2012, King et al. 2012).

Figure 5



Fish kills recorded for the NSW part of the Murray-Darling Basin over time and in each river, from various causes, sorted by periods including before water resource development (1960), 1960–2008 (main period of water resource development) and 2009–2017 (water recovery period) (see Table 1 for details on large fish kills).

CURRENT STATE OF FISH POPULATIONS IN THE DARLING RIVER

The fish of the Darling River are important for economic, social, recreational, cultural, biological and scientific reasons. The 2012 Sustainable Rivers Audit rated the Darling River as poor, reflecting a fish community that had lost half of its native fish species richness. Five native fish species dependent on river flows in the Darling River are listed as threatened with extinction under national and state legislation. These include one critically endangered (silver perch) and the vulnerable Murray cod, species listed under national legislation and directly impacted by the recent fish kills. Reflecting declines in the fish community, the lowland part of the Darling River is listed under NSW legislation as an *endangered ecological community*[4], including a significant part of the Darling River. This determination includes all native fish species and invertebrates and was made because of the major changes caused by regulation of the river system by dams and weirs, which has *'altered the flow regime, reduced channel complexity and has stopped fish migrations upriver…'*[5]. Further, the determination cites the altered floodplain as a problem and *'…water extraction has decreased flows in many parts of the system to levels detrimental to ecosystem function'*. In particular, the development of the Barwon-Darling River through these threats has reduced opportunities for native fish, especially small fish that live less than five years, to breed and move along the river (Murray-Darling Basin Authority, 2018).

The native fish species affected by the recent fish kills in the Darling River are indicators that the condition and resilience of the river ecosystem has deteriorated. Their loss in the kills provide a clear measure of overall river stress, not just from drought but from long term reductions in river flows. Fish populations are highly dependent on natural flow regimes to stimulate spawning and successful recruitment. Different flow components are particularly important, including different sized pulses and inundation of habitats. Understanding how different fish populations are connected throughout the system remains a critical knowledge gap; this gap includes modelling metapopulations and predicting the importance of different flow regimes for recruitment and dispersal. In addition, understanding how these fish populations can survive dry periods is clearly critical. It would assist in identifying volumes of water required for contingencies when flushing flows are required, particularly to mitigate the build-up of algal blooms and low oxygen risk.

4 https://www.dpi.nsw.gov.au/fishing/species-protection/what-current/endangered/darling-river-eec
5 https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/636498/FR22-Darling-River-EEC.pdf

Table 1

RIVER	LOCATION	DATE	QUANTITY	SPECIES	CAUSE / CATEGORY / DESCRIPTION
Bogan	Willamarra, near Gongolgin	9/12/90	Millions	Carp (millions)	Unknown
Darling	Darling River (Main Weir to Weir 32 (Concentration at Texas Downs & Weir 32)	28/1/19	Millions	Silver perch 100s, bony herring 100,000s-millions, golden perch (1,000s), Murray cod (10s), carp 100s	Low dissolved oxygen
Darling	Darling River (Main Weir to Weir 32 (Concentration at Texas Downs & Weir 32)	6/1/19	100,000s	Silver perch (100s), Bony herring (1,000s), golden perch (1,000s), Murray cod (10s-100s), carp (100s)	Low dissolved oxygen
Darling	Darling River (Main Weir to Weir 32)	15/12/18	10,000s	Silver perch (100s), bony herring (1000s), golden perch (1000s), Murray cod (100s)	Low dissolved oxygen. Above 40 degrees for consecutive days; Rain event then low temperatures Significant crash in dissolved oxygen. Possibly due to algae, weather or a combination of the two
Darling	Menindee Lakes (7 km of Menindee Lake shoreline)	28/2/84	10,000s	Bony herring (10,000s)	Unknown
Darling	Menindee Lakes (town weir pool)	2/6/11	10,000s	Golden perch (1,000s) and bony herring (10,000s).	Black water resulting from inundation of local floodplains
Darling	North Bourke Bridge to Weir flowing south (15 km)	11/3/11	Millions	Mainly bony herring and carp are gasping for air. Some carp dead.	Low dissolved oxygen
Darling	Thegoa lagoon	16/1/98	100,000s	Not specified	Potentially drought related (e.g. declining water levels, lagoons drying out, deteriorating water quality)
Murray River and Darling Rivers	Euston-Cullulleraine and Darling River at Wentworth	13/7/00	10,000s	Bony herring	Infection or disease (protozoan, virus, possibly fungal infection, given filamentous fungus attached on some)
Murray River and Darling Rivers	Lake Benanee (northern shoreline)	19/9/04	Millions	Bony herring	Unknown. Possibly cold water die-off. No evidence of infection or pesticides
Murray River and Darling Rivers	Murray River (100 km upper Murray, Indi and Swampy Plains rivers, below Khancoban)	10/1/88	10,000s	Not specified	High temperature/heat stress
Lachlan	Lachlan River (Lake Forbes, 5 km2)	6/1/84	10,000s	Silver perch, freshwater catfish (10–100), redfin (10–100), golden perch (1,000s)	Low dissolved oxygen, due to inflow of surface waters high in organic matter
Macquarie	Macquarie Marshes (Back Swamp)	18/3/11	100,000s	Carp (100,000s) and goldfish (10,000)	Low dissolved oxygen
Macquarie	Cudegong River (immediately downstream of Windamere Dam)	25/2/03	10,000s	Golden perch	Related to operation of dam
Macquarie	Duck creek (near Warren)	31/12/90	10,000s	Carp (10–100), golden perch (10,000s)	Suspected release of tail water from cotton farm
Namoi	Lake Keepit (western to southern shoreline)	21/8/08	10,000s	Bony herring	Low Temperature/cold stress
Murrumbidgee	Lake Albert (entire perimeter of artificial lake in golf course, Wagga Wagga)	28/2/08	10,000s	Goldfish	Unknown
Murrumbidgee	Gooragal Lagoon	19/12/02	10,000s	Carp	Drought related (e.g. declining water levels, lagoons drying out). Lagoon had dried out and fish were stranded
Murrumbidgee	Burrinjuck Dam (backwaters in Hume Park-Goodhope area)	2/4/75	10,000s	Carp	Miscellaneous

Large (>10,000 individuals) recorded fish kills in the Murray-Darling Basin part of NSW, (NSW Fisheries Fish kill database), their locality (river, location), size, species and potential causes, where assessed.

FINDINGS FOR SECTION 2

The sequential fish kills in the same place on Darling River at Menindee are unusual, with (i) millions of dead fish, (ii) including hundreds of large Murray Cod, some of more than 20 years of age, and (iii) associated with drought, high temperatures and low flow conditions, over the preceding 2 years.

The fish were killed by insufficient oxygen, caused by mixing of previously stratified, anoxic bottom water with a smaller layer of oxygenated surface water.

Severe blue-green algal blooms from December led to these condition. Blue-green algae are the main contributor of oxygen in the relatively shallow surface water layer and on their death contribute substantially to decomposition of organic matter by microbes in the sediment, resulting in deoxygenation of bottom waters.

The large spatial extent of this stratification reflects very low flows to the Menindee town weir along with the very hot and still conditions preceding the kills.

The immediate cause of the mixing events was repeated cycles of rapid cooling air temperatures from extremely hot conditions, sometimes accompanied by strong wind and rain.

The fish were unable to escape low-oxygen conditions because of the large extent of the deoxygenated water and physical barriers to movement, especially the weirs, and general lack of other connected aquatic habitats.

There is no evidence that toxins from blue-green algae contributed to the fish kills.

The magnitude of this Darling River fish kill is potentially connected with large populations of small native fish generated by large recruitment events in the 2015/16 floods. It is possible that reduced ecological resilience, due to shifts in flow regimes and altered food webs has also contributed, but more data is needed to confirm this hypothesis.

3. WHETHER CHEMICAL AND FERTILISER USE MAY HAVE CONTRIBUTED TO THE EVENT

TERMS OF REFERENCE 3

Application of fertilisers, clearing of vegetation near rivers, and allowing stock access to waterways can all contribute to the inflow of nutrients that can contribute to algal blooms. At present, there is insufficient information to know how important these factors might have been as contributing factors to the fish kills.

CARBON AND OXYGEN

Cyanobacteria (also known as blue-green algae) are the photosynthetic bacteria that lead to blue-green algal blooms (algal blooms). Photosynthesis is the process where the energy of light (in the environment this is sunlight) is used to synthesise organic compounds from carbon dioxide.

Cyanobacteria tend to be slow growing (relative to green algae), and grow best in stratified weir pools during low flows. They can be suppressed by flow management; still waters can be detrimental to river health. Cyanobacteria produce oxygen as a by-product, and some species can position themselves via buoyancy features at the surface of turbid or cloudy water to best avail themselves of the light. The cyanobacterium *Dolichospermum circinale* (formerly known as *Anabaena circinalis*), which was the abundant species in the 1991 cyanobacterial bloom on the Darling River (Donnelly et al. 1997), has this buoyancy capacity. When they die, they fall to the bottom where their decomposition by sediment microbes contributes to oxygen depletion.

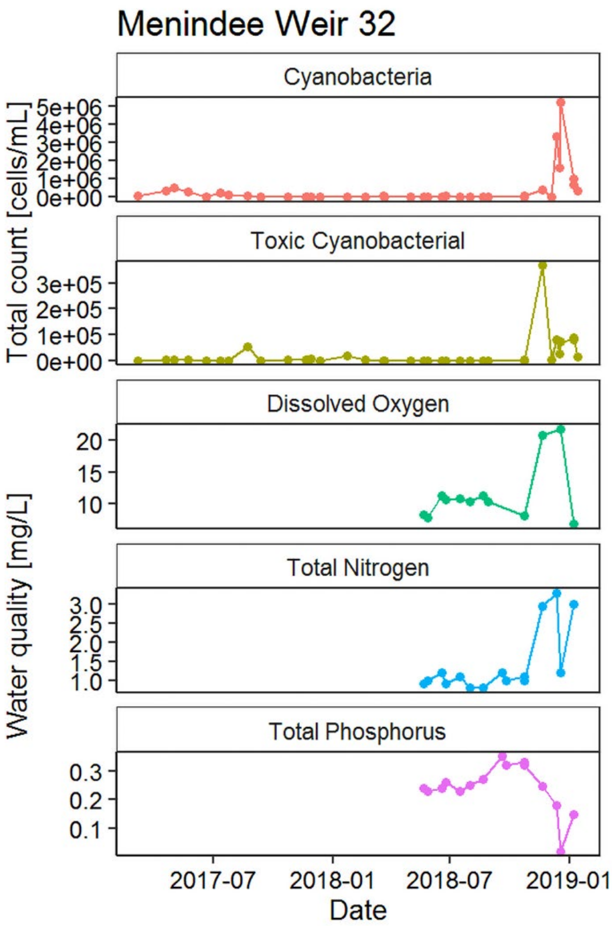
PHOSPHORUS AND NITROGEN

Cyanobacteria need essential nutrients to grow—without enough phosphorus and nitrogen, there cannot be the large-scale cyanobacterial growth that leads to a blue-green algal bloom. Fertilisers may contain phosphorus or nitrogen in forms that the cyanobacteria can use, but naturally occurring sources of these nutrients cannot be overlooked. Studies of earlier cyanobacterial blooms on the Darling River showed that phosphorus rather than nitrogen was the limiting nutrient. This can be explained by the fact that atmospheric nitrogen (N_2) can be fixed to ammonia by some cyanobacteria, including *D. circinale*. Conditions of low fixed nitrogen will select for species with innate nitrogen-fixing ability. Hence, these organisms will grow independently of added nitrogen (e.g. fertiliser) to the ecosystem. Phosphorus needs to be in the form of phosphate for cellular uptake and utilisation, and excessive amounts of phosphate lead to large cyanobacterial blooms. In addition to anthropogenic sources, basalt rocks in the Namoi River catchment (Oliver et al., 1999) provide a large natural source of phosphorus to the Darling River.

IRON

Waterway and weir pool sediments can store nutrients that are later released under anoxic (lacking oxygen) conditions. All catchments in the Murray-Darling Basin are rich in iron, and hydrated ferric (iron(III)) oxides are very efficient at adsorbing phosphate from the water column, essentially keeping phosphate levels low in the water. When the water becomes anoxic, bacteria switch to alternate electron acceptors than oxygen, one of which is insoluble iron (ferric). This process converts ferric iron to soluble ferrous iron (iron(II)), liberating phosphate. The phosphate then diffuses upwards through the water column, providing this resource for cyanobacterial growth, stimulating and enlarging the cyanobacterial bloom.

Figure 6



Changes (2017–2019) in cyanobacterial numbers and the nutrients, oxygen, nitrogen and phosphorus, measured at Weir 32 on the Darling River (note oxygen levels at night will be lower, with respiration of blue-green algae and microbial assemblages). Increasing cyanobacterial numbers leads to saturation of the water with oxygen (less than 20 mg/L), increased nitrogen (via their nitrogen fixation and release), and depletion of phosphorus as they grow.

SULFIDES AND THE REPORT OF A 'SULFUR SMELL'

The sulfur smell reported at some sites in the Menindee lakes is presumed to be hydrogen sulfide, also known as rotten egg gas. If so, this confirms the long-term anoxia of the bottom water and at the water–sediment interface. Sulfate-reducing microorganisms use sulfate as an electron acceptor in their respiratory metabolism, producing sulfides.

The most likely scenario is that once oxygen is depleted, microorganisms will use the 'next best' electron acceptors. First, any nitrates and nitrites will be reduced to ammonia. Next, ferric iron is reduced to ferrous iron (releasing phosphates as described above), and then sulfate to sulfide. In addition to the generation of hydrogen sulfide gas with its characteristic odour, some insoluble iron sulfide, known as pyrite, will be formed, and if the sediments were examined we would expect to see a blackening because of this compound.

Where does sulfate come from? Likely this comes from salt intrusions into the river from many salt aquifers perched along the river and extending widely across the MDB. The salt water provides sulfate (for reduction to sulfide), and also facilitates coagulation of fine particles in the water column, which can now sink as their aggregate size increases. This allows greater light penetration and enhances cyanobacterial growth and blooms.

WATER FLOW

The amount of flow required to prevent stratification depends on the individual river weir pool. Flow facilitates a well-mixed water column with dissolved oxygen throughout the column all the way to the sediment surfaces. Without stratification, anoxia—and the resultant fish kills—is extremely unlikely. The flat topography of the Darling system means that flows tend to be slow and with lower energy than water flowing in steeper topographies. The modification of the Darling River from a natural river to a contiguous weir pool system has increased the amount of flow required for natural oxygenation of the water

SUMMARY

Given the existence of multiple sources, it is likely that there is enough phosphorus in the Darling River to facilitate a cyanobacterial bloom at any time of the year. However, light availability is also a limiting factor for algal growth. Highly turbid waters (those with high amounts of suspended sediments, e.g. fine clays) impede the cyanobacterial growth via light attenuation, even if sufficient phosphorus is available. However, during low river flows, the suspended particles contributing to turbidity can slowly settle leaving a sufficiently illuminated surface layer allowing more cyanobacterial growth via greater photosynthesis. Inflows of saline groundwater can also favour the development of algal blooms through an increase in light availability, resulting from the flocculation (clumping) of fine clay particles.

Some land management practices will lead to soil and fertiliser entering the river, potentially increasing the levels of phosphorus, nitrogen and sulfur. Runoff from farms should be monitored to assess the potential for this runoff to exacerbate algal blooms.

FINDINGS FOR SECTION 3

There is insufficient information on nutrients and their sources to know whether the nitrogen, and especially phosphate, needed to promote algal blooms has come from fertilisers or stock.

The panel notes that there is likely to be sufficient phosphate to promote algal blooms in the system from natural and historic sources, independent of recent inputs from land-users.

4. WHETHER WATER DIVERSIONS AND/OR WATER MANAGEMENT PRACTICES IN THE MURRAY-DARLING SYSTEM HAVE CAUSED OR EXACERBATED THE SCALE OF THIS DISASTER

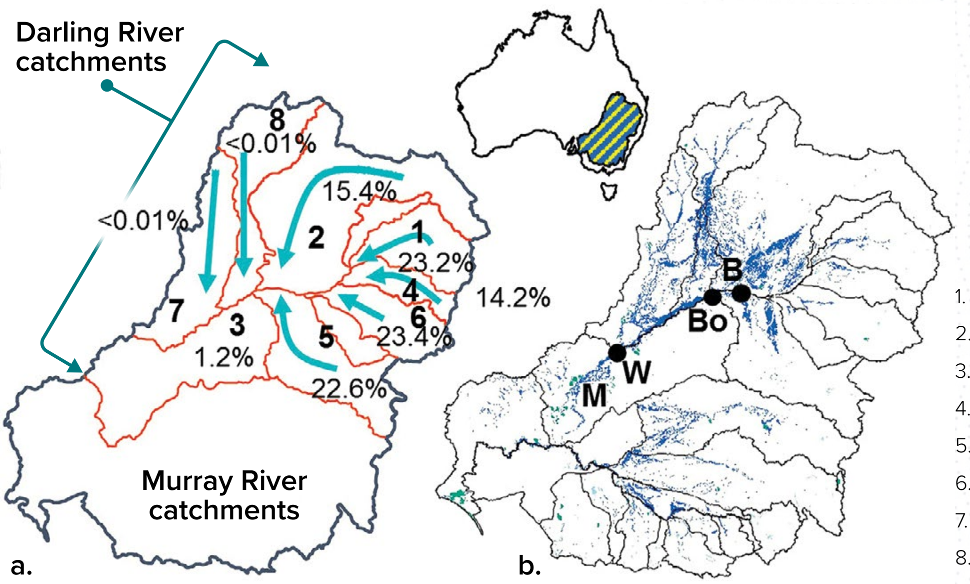
TERMS OF REFERENCE 2

(See Appendix 3 and 4)

THE DARLING RIVER SYSTEM

Responding to this term of reference requires an understanding of the Darling River and its tributary river catchments (Figure 7). The Darling River is one of Australia's largest, flowing from northern New South Wales to Wentworth in the state's west, where it joins the Murray River. The Darling has high cultural significance to both Indigenous and Australians as the lifeblood of its arid and semi-arid regions. It has been occupied for at least 45,000 years and the ecosystem has responded strongly to climate change from that time to the present (Box 1). This river is fed by nine major tributary river systems, with their upper catchments in the Great Dividing Range (Figure 7) in south-eastern Queensland and north and central New South Wales. The great majority of the Darling's flow comes from rainfall in the catchments of these tributary rivers. Water flows slowly down the Darling. It can take months for water at Bourke ('Bo' in Figure 7) to reach the Menindee Lakes (M).

Figure 7



1. Border River and Moonie Rivers
2. Condamine-Balonne
3. Darling River
4. Gwydir
5. Macquarie-Bogan / Castlereagh
6. Namoi / Peel
7. Paroo
8. Warrego

a. Flow contributions of tributaries flowing into the Darling River (CSIRO 2008) within the Murray-Darling Basin (inset) and; b. the distribution of wetlands across the Murray-Darling Basin (see Kingsford et al. 2004), showing the location of fish kills on the Darling River near Menindee Lakes (M) and flow gauges on the river at Brewarrina (B), Bourke (Bo) and Wilcannia (W) used to analyse changes to flow regimes.

Box 1 Environmental and human history of the Darling River and Menindee Lakes region

The first people to settle on the Darling River and Menindee Lakes arrived around 45,000 years ago. At that time, the region was very different from what it is today. Carbon dioxide levels in the atmosphere were around half present concentrations, restricting plant growth, and average temperatures were around 6 °C lower than the historic average. A diverse fauna of giant marsupials, including rhino-sized diprotodons and gigantic short-faced kangaroos was either still present, or recently extinct (Cupper and Duncan 2006). There were few trees in the region, but saltbush and bluebush flourished, as did herbfields in which various kinds of daisies abounded. Parts of the Darling and its tributaries flowed along different courses from those followed today. These earlier courses are marked by now abandoned channels, the size of which indicate that during this period much more water flowed down the Darling than during the historic period (Hesse et al. 2018).

Over the millennia following initial colonisation, average temperatures continued to decline. By around 20,000 years ago atmospheric concentrations of carbon dioxide had fallen to 160 parts per million, restricting plant growth and lowering temperatures. Globally, at higher latitudes, ice sheets reached their maximum extent, and contained so much water that the oceans were 120 metres lower than they are today. On the Darling, average temperatures were 9 °C cooler than at present: it was a frigid, windy and dusty environment, lacking trees and populated by organisms typical of deserts. Yet paradoxically, water flows in the Darling rivers were far greater than experienced during historic times, and at times the Menindee Lakes may have been permanently full. Fish and freshwater mussels were major resources, and human populations probably clustered around the waters.

Throughout the millennia rivers continued to alter their courses, abandoning sections of their channels and leaving some lakes dry. This, and a changing climate, may have left some fish populations susceptible: archaeological evidence indicates that around 19,000 years ago people harvested large numbers of golden perch from a drying Lake Mungo, perhaps made vulnerable by low oxygen levels in the water (Long et al. 2014).

By around 11,000 years ago carbon dioxide concentrations had risen and the Earth had started to warm. Woodlands expanded, colonising the herbfields and becoming dominant habitats in the region. With the warming, flows in the Darling began to decline, and the Menindee lakes started to dry out. Before humans began diverting water into the Menindee lakes (in the 1960s), they filled only four or five times per century during floods (Balme and Hope 1990).

At the time of European exploration in the early 19th century, Aboriginal populations along the lower Darling were dense, while more scattered populations utilised the resources of the surrounding dry country. As documented in a rich archaeological record, many cultural changes had occurred during the 45,000-year-long human occupation, helping people to adapt to the extraordinary environmental changes that had occurred in the region.

References

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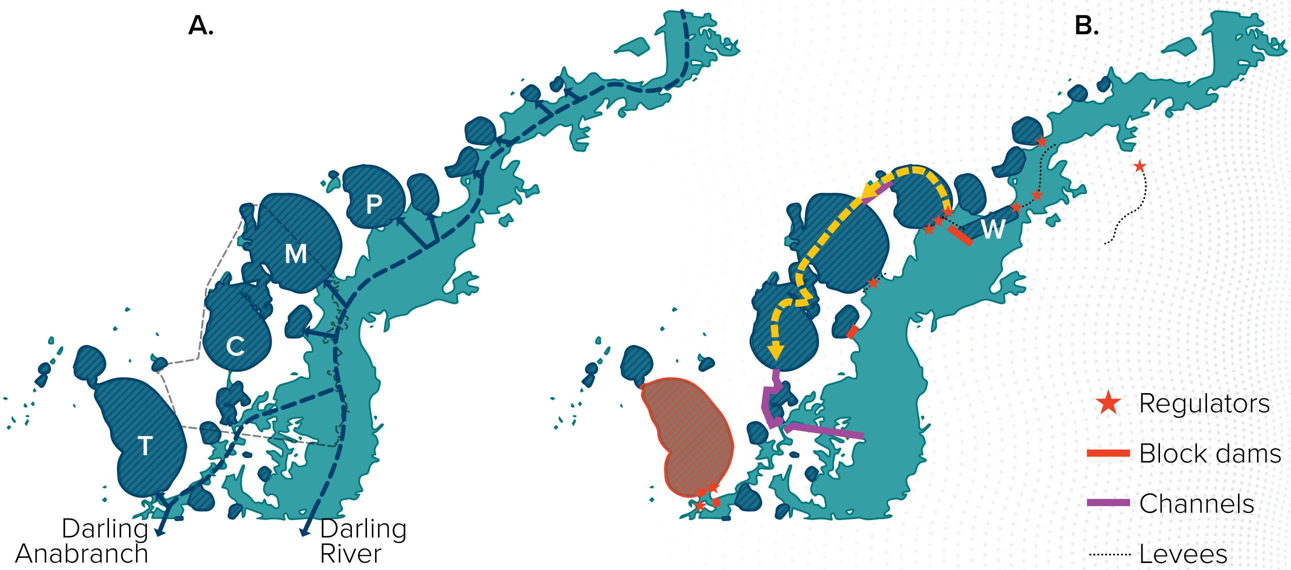
Flows in the Barwon-Darling[6] are largely unregulated by large government-built dams, in comparison to flows further upstream.

The Darling's channels contain permanent water even at the driest times. Its wetlands—billabongs, claypans, creeks, flood-outs, floodplains, lakes, lagoons, marshes, overflows, swamps, and waterholes—can also contain water in aquatic refugia for long periods. But they rely on replenishment in periods when water flows over the banks of the Darling into these varied wetlands.

The flows in the Darling are a complex reflection of the flows from the tributary catchments, influences of temperature, and the past patterns of flooding and drying. The Darling's flows fluctuate considerably between periods of high flow to periods of very low, or even no flow. Generally large floods occur about every decade, but there are a number of small, medium and large floods (called freshes) which connect the waterholes, billabongs and wetlands. One of the major wetland systems reliant on river flows is the Menindee Lakes system.

The Menindee Lakes system consists of nine large lakes (Figure 8). In the 1960s, governments decided to use some of the lakes as water storages, building a large weir (Main Weir) to divert water into lakes Pamamaroo, Tandure and Bijijie. Levees, block dams and channels were built to regulate the flow of water in the system. There is relatively little information on the flooding regimes of the lakes before they were regulated (dammed) in the 1960s but they were undoubtedly highly productive and important wetland systems. Local resident A.F. Cudmore remarked in relation to the flooding of Menindee and Tandou lakes in the 30 year period 1870–1900, that the lakes were dry only a *'half a dozen or more times'* (Commissioners of the Royal Commission on the River Murray, 1902). This indicates water frequently flowed into the lakes when the flows were sufficiently high in the river.

Figure 8



a. Menindee Lakes (main lakes: P-Pamamaroo, M-Menindee, C-Cawndilla and T-Tandou), with the Darling River floodplain (green) before river regulation, showing the boundary of Kinchega National Park, and b. Menindee Lakes today, a regulated system with Main Weir forming the dam known as Lake Wetherill (W), regulators, block dams, channels and levees designed to control and hold water in Menindee Lakes and Lake Tandou converted to an irrigation area.

6 The Barwon River is one of the tributaries to the Darling. It merges with the Culgoa River upstream of Bourke, and the river channel becomes the Darling. The Barwon and the Darling are in the same catchment, so they are often referred to together as the Barwon-Darling River or the Barwon-Darling system.

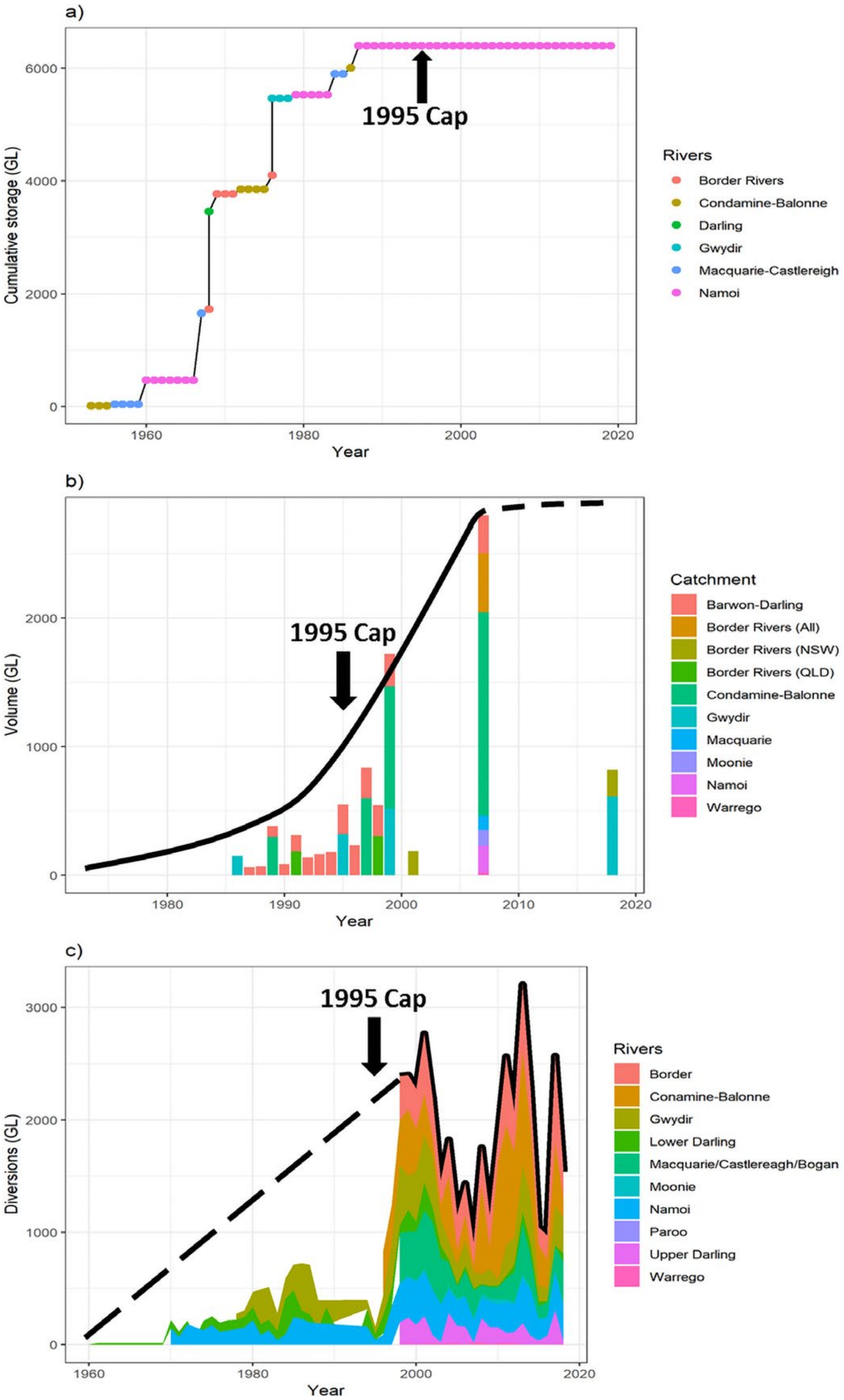
WATER DIVERSIONS

Water diversions have occurred over a reasonably short period in the Darling River catchments compared to the Murray River catchments, since the first government-built dams were constructed in 1960. The history of this development is important in outlining changes to river flows and likely effects on fish kills and other environmental problems in the river. Water resource development, including the building of dams, diversion of river flows and development of dams, levees and channels and agriculture on floodplains (Kingsford et al. 2016), primarily for irrigated agriculture, mostly began in 1960 when Keepit Dam on the Namoi River was built (Webb 2007), followed by Burrendong Dam on the Macquarie River and the Menindee Lakes Scheme (Kingsford and Thomas 1995, Water Conservation and Irrigation Commission 1971, Kingsford 1995b). These large government-built dams in the Great Dividing Range (e.g. Burrendong Dam, Pindari Dam, Keepit Dam) 'capture' floods in the upper reaches of the tributary catchments and store the water, which can then be later released for irrigation and communities downstream, regulating the flows in the river (Kingsford 2000a; Kingsford 2015, Figure 9a). Most of the water diverted for use in the Darling River catchments is for irrigation, mostly to grow cotton[7].

After the building of large dams by governments between the 1950s and 1980s in most of the catchments (Kingsford 1995a), the next stage of water resource development involved diverting water from the rivers of the Darling River. This was to build private dams or off-river storages (also called ring-tanks) on the floodplains from the mid 1980s onwards (Kingsford 2004) (Figure 9b). This allowed downstream irrigation enterprises to 'capture' flows that were from unregulated tributary rivers downstream of major dams, spills of major dams and floodplain inundation into these off-river storages. Data for the growth in off-river storages or current volumes remains poor, with only one full assessment of more than 3.3 million megalitres of storage across all of the Darling River and its tributary catchments available for 2007 (Figure 9b; Webb, 2007). Further, where there is evidence, increases have occurred in off-river storage volumes since 2007. For example, current estimated volumes that can be held in floodplain storage in the Gwydir and Border rivers (NSW) respectively are about 614 GL and 207 GL (Figure 9b; NSW Department of Industry, 2018). Development of off-river storages has continued after the agreement of all state governments and the Australian Government to a Murray-Darling Basin Cap in 1995, at 1993/1994 levels of development for NSW, Victoria and South Australia and 1999/2000 levels of development for Queensland (Figure 9b). The only reliable estimate current available for the Barwon-Darling of 1993/1994 levels of development was 189 GL, not accounting for floodplain harvesters, provided to the Ministerial Council Audit report into water use across the Basin (Murray-Darling Basin Ministerial Council, 1995).

7 https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4618.02016-17?OpenDocument

Figure 9



Trajectories of water resource development in the Darling River and its tributary catchments (Figure 7), beginning when the first government-built dams were built in 1960: a. cumulative storage capacity of government-built and owned storages; b. cumulative storage capacity of private off-river storages (ring-tanks, see Appendix 3 for data availability and sources) and c. reported annual diversions from each of the river catchments, which does not adequately report floodplain harvesting, non-compliance or diversions not measured. Arrows indicate when all states and the Australian Government committed to the Murray-Darling Basin Cap (at 1993/1994 levels of development for NSW, VIC and SA and 1999/2000 levels of development in QLD).

A recent report to the Commonwealth Environmental Water Office (Simpson 2017) underlines continuing diversions of water from the Darling. In relation to management of the Murray-Darling Basin Cap and understanding within governments: *'It was well recognised that development had continued beyond the 1993/94 levels, and that long-term diversions were likely to be in excess of the 1993/94 Cap on diversions'* (Simpson 2017). Further, the creation of new Unregulated River Access Licences under the NSW *Water Management Act 2000*, *'allowed users with works approvals for larger pumps (generally B and C class users) to link to their own A Class licences or purchase and link other A Class licences with those pumps'* (Simpson 2017). Simpson (2017) recommended that to achieve the identified low flow targets in the Barwon-Darling will require managers to address the significant risk posed by the significant take of water (namely A Class licences, and take by B Class licences in the upper sections between Mungindi and Walgett), and the relaxation of existing channel capacity constraints in the lower sections of the regulated tributaries.

During flood periods, extensive areas of off-river storages can be filled, as in 2016 compared to a dry year such as 2018 when few storages were filled (see Appendix 3, Figs A3.1 and A3.2). Floodplain diversions are sometimes referred to as floodplain harvesting, although these private off-river storages are also used for holding regulated water and pumping water directly from the main part of the river under licence (e.g. Darling River). A few off-river storages also capture groundwater, connected to river flows. In addition, there are large questions regarding groundwater take and connectivity within the system. Low stream flows are exacerbated by take of water from the floodplain that would otherwise discharge to rivers, particularly in low-flow conditions. Take of groundwater, which discharges to rivers and provides critical 'baseflow' during dry periods, is particularly significant in this context. Take of groundwater also affects other groundwater-dependent ecosystems, like springs and wetlands, more generally. Australian water law—and particularly NSW water law—tends to allow groundwater pumping to have relatively large impacts on rivers. The Menindee Lakes are located within the Western Porous Rock Water Resource Plan area for groundwater (known as 'GW6' in the Basin Plan). Groundwater in this area feeds the Menindee Lakes and other riparian and floodplain ecosystems that have been assessed as having 'very high' ecological value. Current Basin Plan provisions allow a very substantial increase in the volume of groundwater that may be extracted from this area: from 63.1 GL per year. Some forms of groundwater use, particularly stock and domestic use, are also unmetered: no government agency can be sure of the current volume of withdrawals or keep a close eye on how these withdrawals might affect rivers.

Currently, the amount of floodplain water diverted from the rivers and their floodplains is not captured well in reporting diversion statistics. The intent of the NSW Floodplain Harvesting Policy in 2013 is to bring existing floodplain harvesting extractions into the water entitlement system. The current proposal is to estimate current long-term average level of extractions of unregulated floodplain harvesting, equal to the lower value of the new modelling estimates for the extraction levels in the 1993-1994 and 1999-2000 water years. If the estimated current level of extractions is higher than this, the entitlements of all landholders who had approved works in place as of July 2008 will be allocated so that they face an equal reduction in extraction volumes.

Measurement of volumes diverted remains poor in many places and there are issues of compliance (NSW Ombudsman 2018, Matthews 2017, Murray-Darling Basin Authority 2017, New South Wales Ombudsman 2017). Allegations regarding water theft and corruption on the Darling River were a catalyst to eight government inquiries. The Senate Committee report on the integrity of the water market (2018 p. 4–5, 8–9) details the allegations; Section 7 and Appendix 4 of this report provide more overview. Enforcement of water use rules by NSW has come under increasing scrutiny since, and legal action has been taken for both the theft of water and fraud (relating to claims made under water efficiency projects). According to the MDBA, in the Northern Basin between 25% and 51% of surface water is metered. On this point, the recent Senate Committee concluded that to implement effective water compliance and enforcement regimes, it is vital that appropriate water metering and monitoring systems are in place (Senate Committee, 2018, p.37). In June 2018, the NSW Government responded to the issues of water theft and inadequate monitoring of water licence conditions identified by a range of inquiries, with a package of amendments to the NSW *Water Management Act 2000*. NSW noted that under the 2009 National Framework for Non-urban Water Metering, the northern Basin had until 2020 to install meters. Nonetheless, NSW instituted a range of responses which included provisions for comprehensive water metering for all licence extractions and proposed metering for all licensed users with pumps, pipes, or offtakes of 100 millimetres or larger for surface water or bores of 200 millimetres or larger for groundwater. Anyone who holds a licence that currently requires a meter will be required to keep and maintain that meter.

The amount of water diverted from the Darling River tributaries and the Darling River has increased considerably since development began in the 1960s, largely due to the establishment of large dams to store water and off-river storages, channels, levees and pump infrastructure (Figure 9). It took some time before the water in large government-built dams was fully utilised and irrigation licences were fully activated. In the 1960s, 1970s and early 1980s, large government-built dams frequently spilled because the water was not used for irrigation and there was limited development of off-river storages to capture floodplain flows on the floodplain. The effects on river flows were not fully established until about the early 2000s when the Queensland Government instituted the Murray-Darling Basin Cap (Figure 9). Despite this commitment, development and growth in diversions continued in Queensland and New South Wales as more floodplain flows were captured by dams, levees and channels on the floodplain, as well as water theft. The NSW Government's floodplain harvesting policy aims to assess floodplain harvesting earthworks (i.e. channels, levees and off-river storages) on or before 3 July 2008, with potential authorisation of these works if an application was made under the *Water Act 1912* or the *Water Management Act 2000* was required (NSW Department of Primary Industries, 2013). This effectively 'grandfathers' development, after the Murray-Darling Basin Cap. These trends in structures and diversions to collect water could also be compared to metered water extraction data to determine long-term trajectories of change in flows, as recommended in a recent report to the Commonwealth Environmental Water Office (Carlile, 2017).

EFFECTS OF WATER DIVERSIONS ON FLOW IN THE DARLING RIVER AND MENINDEE LAKES

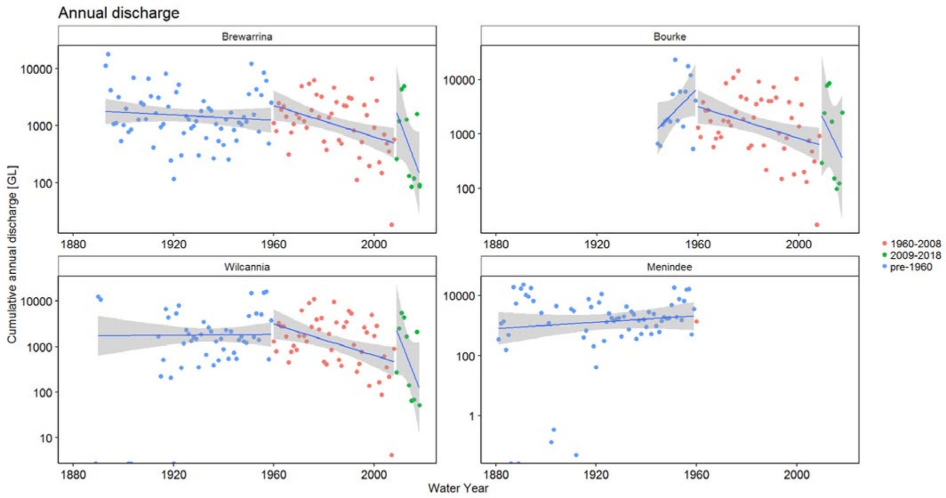
The year 1960 is a useful point for analysis of the effects of water diversions on flows, given this was when the first large dam was built in the Darling River tributary river catchments (Figure 7). Analysis of these changes can focus on different phases of development of the river: 1. before 1960, a predevelopment phase when there was little water diverted from the Darling River or any of its tributaries; 2. 1960–2008, a period when there was increasing growth in diversions, particularly up to 2000, despite policy responses to constrain growth and; 3. post 2009, a water recovery phase during which the Murray-Darling Basin Plan was gazetted. This latter period does not capture the full impact of water recovery for the environment, reaching 2118.4 GL/year in September 2018[8], with more to be achieved.

With the regulated water stored in large dams and water pumped from the river and connected groundwater and harvested from floodplains, flows in the rivers of the Darling River tributaries have continued to decline, reducing flows along the Darling River. There were reductions in total volumes of annual flows at the flow gauges where sufficient data exists (Brewarrina, Bourke, Wilcannia) (Appendix 3). For the Brewarrina gauge on the Darling River (Figure 10), there was a significant reduction in annual flow volume (see also Tables A3.7 and A3.8) of 49.06%, comparing annual flows before 1960 to the most recent period 2009 to 2018 (Table A3.8). For the next flow gauge down the Darling River, the Bourke gauge (Figure 10), there was a larger significant reduction in annual flow volume (Tables A3.7 and A3.8) of 55.78%, comparing annual flows before 1960 to the most recent period 2009 to 2018 (Table A3.8). For Wilcannia, differences between these periods was a reduction of 46.74% in total annual volume (Figure 10, Tables A3.6–A3.8). Inflows from the Paroo and Warrego Rivers, which occur downstream of Bourke and upstream of Wilcannia are reduced by about 12% in the Warrego River (CSIRO 2008), but as the last free-flowing river in the Murray-Darling, flows in the Paroo River remain at natural levels with no significant diversions. This probably reduces the impacts of water resource development on this part of the river.

These reductions were also clear in a comparison between actual flows at the three river gauges (Brewarrina, Bourke and Wilcannia, Figure 11) and modelled data without development (Murray-Darling Basin Authority model). The proportion of flows reaching gauges tended to be highly variable but oscillating around a one to one relationship which would be expected prior to the beginning of water resource development in 1960 (Figure 11). There were some points (e.g. Wilcannia) where there were significant differences with observed flows (Figure 11), much higher than modelled flows. These coincided with the floods of the 1950s and highlights potential challenges in measuring inflows from the Paroo and Warrego Rivers. After 1960, there was increasing development of water resources with increasingly higher amounts of flow captured from the rivers or diverted upstream (Figure 9). This resulted in a declining proportion of flows reaching each of the three gauges, compared to the no development scenario.

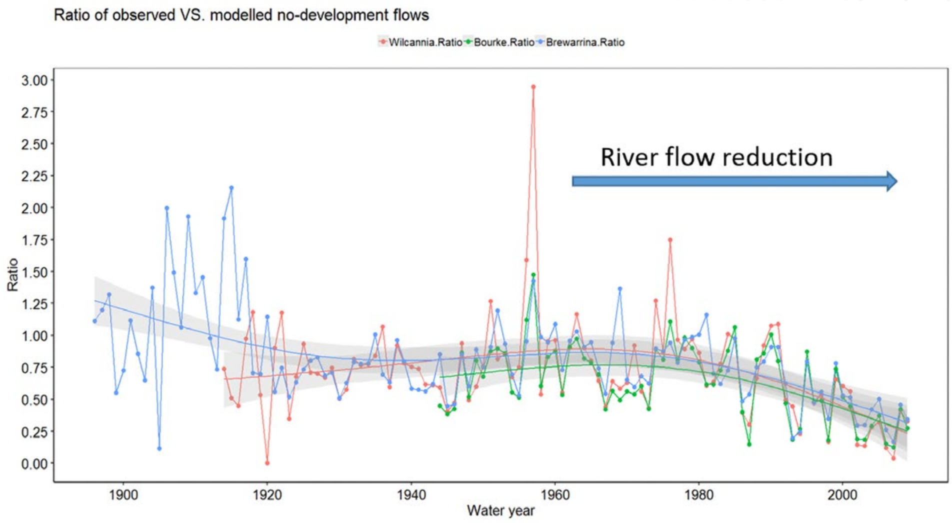
8 https://www.mdba.gov.au/progress-water-recovery

Figure 10



Trajectories of change (lines) in annual flow volumes in the Darling River at Brewarrina, Bourke, Wilcannia and Menindee over three periods: pre-1960 (before river development), 1960–2008 (main period of river development), 2009–2018 (water recovery phase).

Figure 11

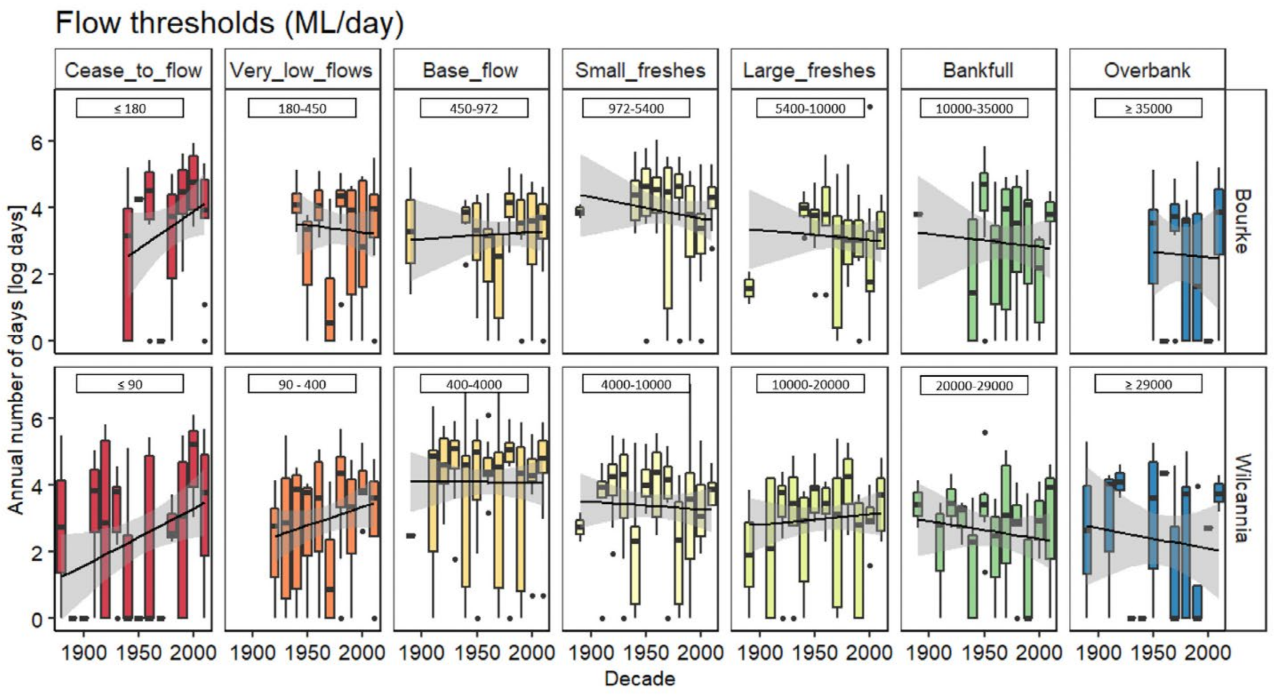


Relative proportion of observed annual flows, flows without development (Murray-Darling Basin Authority modelled data, only available to 2009) in the Darling River at Brewarrina, Bourke and Wilcannia, 1886–2009 (main period of river development after 1960, with river reduction), with lines showing long-term trends.

To analyse long-term changes to daily river flows at relevant ecological thresholds, daily observed flow data were collated for two of the flow gauges on the Darling River with long periods of information available and reasonably proximate to Menindee: Bourke and Wilcannia (Figure 7). Daily flow data were then analysed for long-term changes at different thresholds, equating to key flow stages which trigger movements and breeding of native fish species and overbank flows for wetlands, including floodplains and lakes (Appendix 3). Specified flow thresholds corresponded to periods of no flow (cease to flow); very low flows; base flows; small freshes, large freshes; bankfull and overbank flows. Very low flows, base flows, small freshes, large freshes and bankfull are all windows measuring the changes to flows within the main channel of the river.

There were major changes to different flow thresholds (Figure 12), reflecting the decreasing volumes of water flowing down the Darling River (Figs 10 and 11). In particular, there were increasing numbers of days of no flow (cease to flow), increasing low flows, particularly at Wilcannia and decreasing, small freshes, bankfull flows and overbank flows at both gauges (Figure 12). Base flows and large freshes were reasonably stable at both flow gauges (Figure 12). These changes in actual flows were not as easily observable in differences in the modelled flows (Figure 11; see also Figures A3.5–A3.7), comparing flows without development, baseline (development in 2008), benchmark (Murray-Darling Basin Plan) and Northern Basin Adjustment (Murray-Darling Basin Plan but with the reduction of 70 GL).

Figure 12



Changes to different levels of daily flow at Bourke and Wilcannia, showing trends, in relation to different mutually exclusive levels of flows, related to fish ecology and floodplain ecology (Appendix 3; Table A3.6).

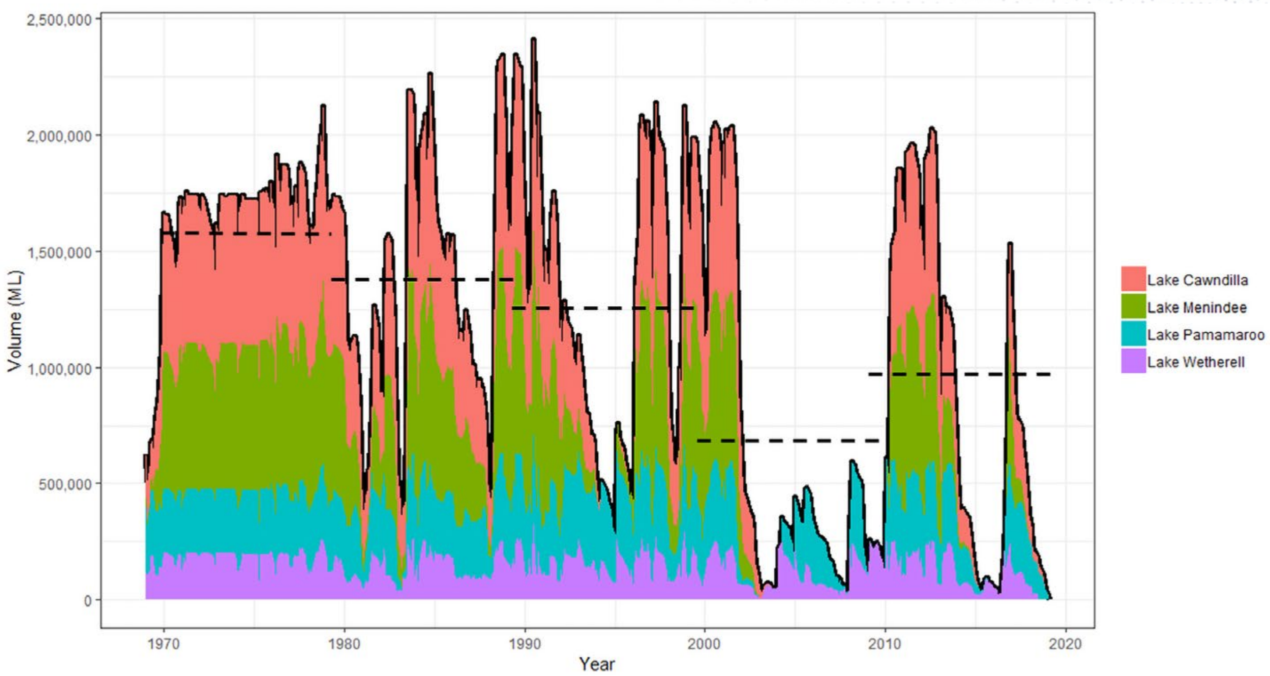
As a result of water resource development in the Barwon-Darling and its tributary catchments, maximum dry periods between low flow events have doubled and are sometimes 10 times longer, severely stressing ecosystems (Murray-Darling Basin Authority 2018). Even in relatively recent times, periods of low flow or no flow have increased downstream of Bourke after 2000, compared to before 2000 (Murray-Darling Basin Authority 2018). In particular, low flows (<2000 ML per day) have been affected. These are critical to the ecology of the river, providing physical habitat, maintaining refuges for water-dependent organisms and providing longitudinal connectivity for the river (Thoms et al. 1996, Rolls et al. 2012). A recent report to the Commonwealth Environmental Water Office identified that low flows were reduced by 70% across most sections of the Barwon-Darling since 1990, on average 74% loss from 1990–2017 and 70% loss from 2012–2017 (Carlile 2017). In some parts of the river, reductions were higher after 2012, when the water sharing plan was in place (Carlile 2017). Under very low flow or cease to flow conditions, the probability of blue-green algal blooms developing increases. Saline groundwater can also exacerbate water quality issues by intruding into river pools.

Low flow periods are important in ensuring that native fish and invertebrate populations survive during dry periods and upstream and downstream connectivity is maintained. They also ensure that during periods of floods, there is an increased probability of inundation, given that large flows do not need to fill water holes or connect the river if low flows have occurred. The flows in the Barwon-Darling River inundate these benches at different levels, reflecting the size of the river flows. Most of the in-channel benches occur in the Brewarrina to Bourke and the Tilpa to Wilcannia parts of the Barwon-Darling River (Murray-Darling Basin Authority 2018). Analyses of 600 of these benches showed that flows of 500 ML per day inundated 5–20% of these benches (Murray-Darling Basin Authority 2018).

There is unfortunately only one threshold for overbank flows, reflecting the poor measurement and understanding of the relationships between river flows and the extent and duration of inundation on the floodplain. There are few assessments of impacts to any of the Darling River and its tributaries floodplains, although there is increasing understanding of the importance and linking of flows to floodplain inundation (e.g. Macquarie Marshes; Thomas et al. 2015). There is less water in the river at all times than under natural conditions. As a percentage of natural river flows, CSIRO (2008) estimated that there was moderate to extremely high levels of diversions in the Darling River catchments: moderate (10–20%, Warrego), moderately high (20–30%, Macquarie-Castlereagh, likely to be an underestimation (Ren and Kingsford, 2011)), high (30–40%, Moonie, Border Rivers, Namoi), very high (40–50%, Gwydir) and extremely high (50–60%, Condamine-Balonne).

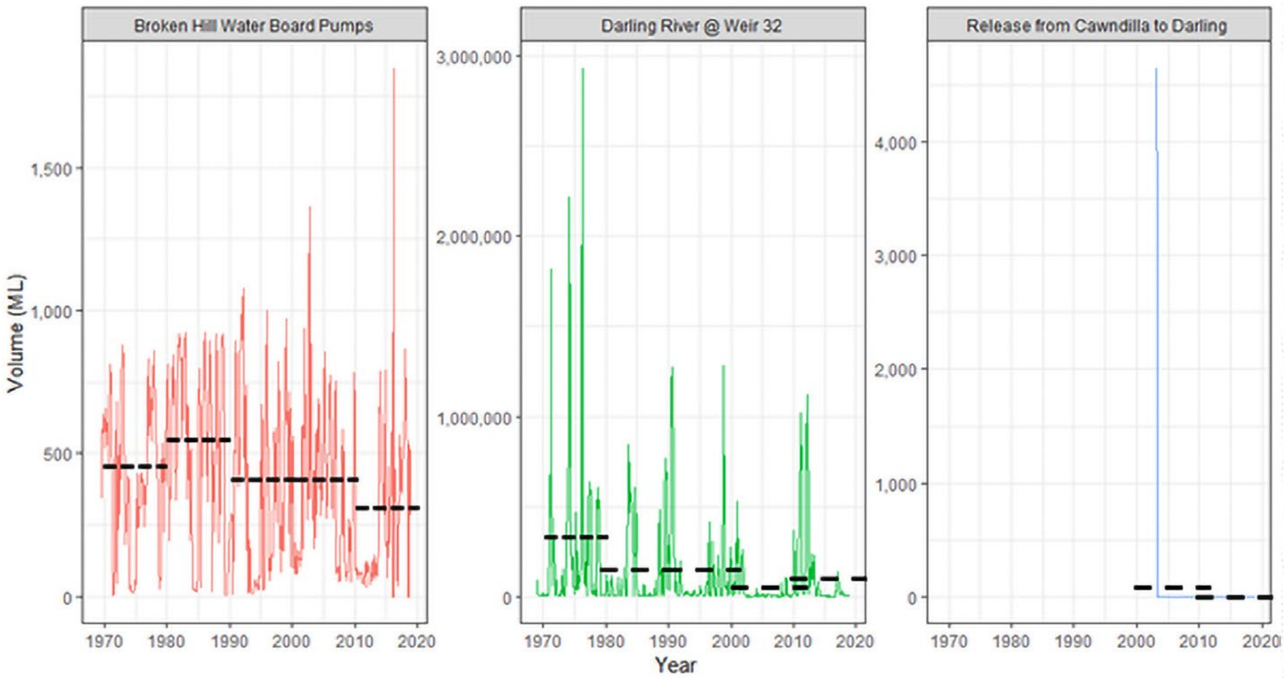
These reductions in flows down the Darling River were reflected in declining long-term storage patterns in Menindee Lakes, with increasing drying over the last decade, shown by the decadal averages (Figure 13). Release patterns have also showed declines (Figure 14).

Figure 13



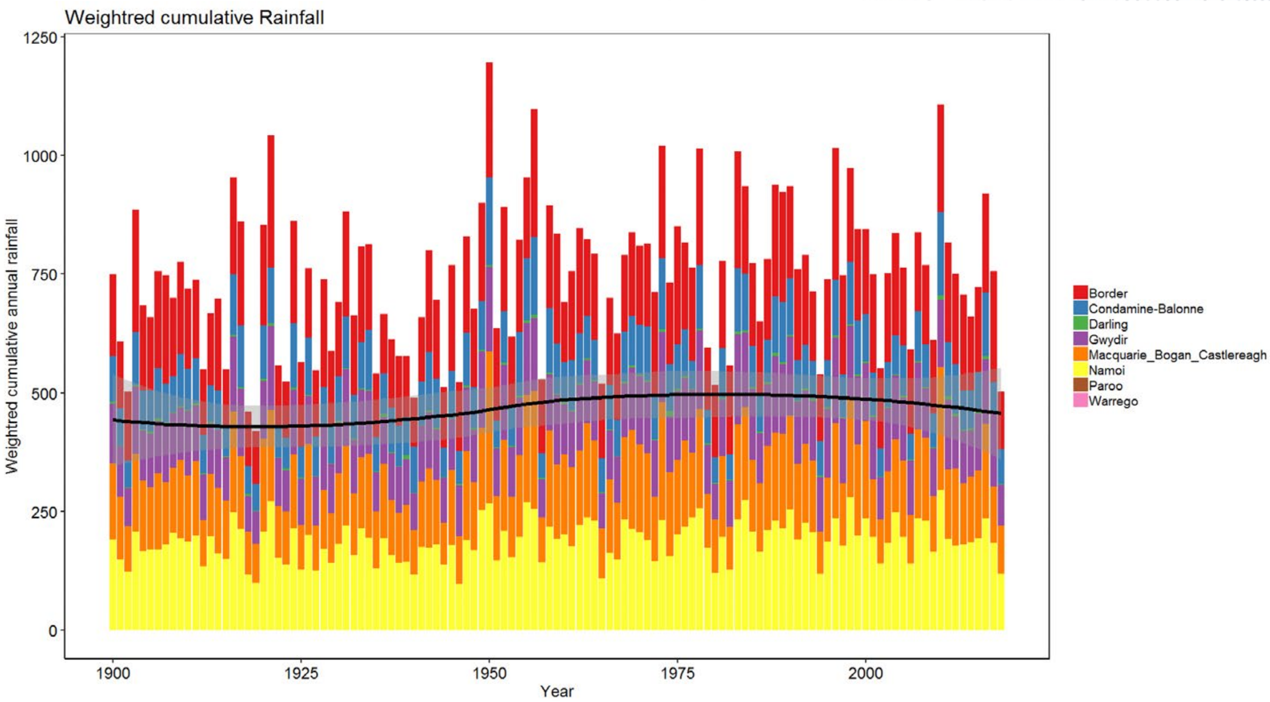
Changes in monthly flow volume of Menindee Lakes over time, with volumes of the major lakes, showing decadal averages (dashed lines).

Figure 14



Flow releases and pumped volumes for Broken Hill from Menindee Lakes, showing decadal averages (dashed lines). Few data were available for releases from Cawndilla.

Figure 15



Long-term cumulative annual rainfall patterns (1900–2018) in the upper reaches of each river catchment (see Figure 7), weighted for the contribution of each catchment to total flows into the Darling River (CSIRO, 2008), see Figure 7; see also Fig A3.9 for unweighted values, see Figure 3.9 for annual rainfalls of each tributary catchment). Black line depicts a Local Polynomial Regression Fitting (loess) to illustrate trend.

RAINFALL PATTERNS IN THE DARLING RIVER AND ITS TRIBUTARY CATCHMENTS

Over more than a century, there was a only slight oscillations in total annual rainfall contributing to flows into the Darling River, despite the severe current drought of 2017–2018 (Figure 15). These minor oscillations likely reflect the extended WWII drought and the overall wetter period across the 1960's and 1970's. This rainfall measure or index reflects the different contributions of tributary catchments to Darling River flows, with those catchments contributing few flows (e.g. Paroo, Warrego), correspondingly not contributing much to the index. Further, rainfall did not change significantly between the periods pre vs. post substantial water development (before vs after 1960, Figure A3.10; Tables A3.13–3.14).

STATE OF THE DARLING RIVER AND MENINDEE LAKES

The Lower Darling and Menindee Lakes are in poor ecological condition. There is widespread loss and degradation of wetlands in the Murray-Darling Basin (Kingsford 2000a), considerably more than in the other 11 major river basins in Australia. Importantly, the ecological sustainability of the Darling River depends heavily on its irregular flows: the system needs not just regular inundations through flooding but also maintenance of low level flows between flood events. This is described by some ecologists as the 'pulse' of the river system. Plant, invertebrate and microbe species are adapted to, and depend on, the wet-dry pattern, and these organisms form the 'food web' for higher level organisms such as fish, turtles, frogs and waterbirds. Further, recent research (Thoms and Delong 2018) found that the food webs have changed in a way that suggests that the ecological resilience of the system has declined. Changes to sedimentation processes result in less deposition on floodplains and river bench channels leading to reductions in productivity (Thoms 2003). Similarly, river flows transport invertebrates that hatch out of floodplain soil, increasing secondary production and connecting invertebrate communities along different parts of the river (Jenkins and Boulton 2007).

Periods with no flow stress the ecosystem and reduce the resilience of the river, causing declines in abundance and distribution of many aquatic species. Flow regulation also affects the amount of carbon present in river systems. With increased degradation of floodplain forests, the concentrations of dissolved organic carbon rises as more leaves and branches degrade. This can result in hypoxic blackwater events which can cause widespread death of fish and invertebrates (Section 2; Whitworth et al. 2012; Baldwin and Mitchell 2000; Thiem et al. 2017). Additionally river regulation, including diversions of environmental flows, may reduce carbon input into rivers altering them to algal-dominated systems (Robertson et al. 2001). Blue-green algal (cyanobacteria) blooms occur when there are high nutrients and low flow. Their toxicity (Baker and Humpage 1994) and effect on water quality disrupt drinking supplies, and pose a risk to livestock, wildlife and human health because some species of cyanobacteria produce neurotoxins[9]. Reductions in nutrients, and flow manipulations (i.e. increased flow), can disperse blooms. In the summer of 1991, the Darling River had the longest blue-green algal bloom recorded in the world, affecting more than 1000 km of the river (Bowling and Baker 1996, Donnelly et al. 1997). In the Darling River, flow and turbidity were more important than nutrients and seasonal temperatures in determining variations in

9 https://www.mdba.gov.au/managing-water/water-quality/blue-green-algae

density and community composition (Hotzel and Croome 1994). In the Darling River at Bourke, concentrations of cyanobacteria decreased with increasing flows, with large blooms occurring when flows were less than 500 ML per day (Oliver et al. 1999). Flows of 300 ML per day as an environmental flow were effective in removing established cyanobacterial blooms (Mitrovic et al. 2010).

Fish refuges vary in their persistence, depending on their depth. They are affected by the frequency of low flows which replenish and connect refuges, enabling animals to move up and down the river. Water-dependent biota will not survive if refuges dry out. Additionally, water quality may become so poor (including elevated water temperatures, low dissolved oxygen concentrations and elevated salinities) during the drying out phase that aquatic species cannot survive. Reductions in flooding also cause declines in affected water-dependent organisms, including vegetation, invertebrates, fish, amphibians and birds, including waterbirds.

MANAGEMENT OF MENINDEE LAKES

In the 1960s, governments decided to use the naturally flooding and drying Menindee Lakes as river storages by 'capturing' as much of the uncontrolled water flowing down the Darling River and holding this in the main lakes, particularly Lakes Pamamaroo, Tandure and Bijijie. This was done by building a large weir (dam wall) in the middle of the river which formed a dam (Lake Wetherill), allowing water then to be diverted and held in the lakes (Figure 8). In addition, there was a range of levees, block dams and channels built to regulate water in this system. The engineering works were completed in 1968. The Menindee Lakes when full cover 457 km2, with a total operating capacity of 1731 GL, although they can be surcharged to 2050 GL[10]. The system is owned and operated by the NSW Government's water agency.

Management of the lakes depends on the volume of water held in the lakes. Their management is governed under the Murray-Darling Basin Agreement (Joint Venture) between the governments of NSW, Vic, SA and the Commonwealth. The agreement has been in place since the Menindee Lakes Scheme was completed in the late 1960s and is a schedule in the *Water Act 2007*. The 'joint venture' aspect means that the states involved and the Australian Government empower the Murray-Darling Basin Authority to manage the lakes above the level of storage of 640 GL. When the volume held in the scheme drops to 480 GL, the NSW Government water agency takes control. Between 640 GL and 480 GL, there is joint management. Despite about 28% of the lakes making up Kinchega National Park, management by the NSW Conservation Agency only occurs when the lakes are dry, despite their considerable aquatic biodiversity values.

When the Murray-Darling Basin Authority is managing the lakes, it does so cooperatively with the partner governments through coordinating committees and strategic and operational plans. NSW remains a prominent partner in this decision-making. Management of the water held in storage and its release has remained similar throughout the period during which the agreement has been in place. The Menindee Lakes water is managed with the entire River Murray, particularly the main headwaters on the River Murray (Hume Dam and Dartmouth Dam) to meet river orders (towns, irrigation, industry, environment, South Australia commitment of 1850 GL per year). The water in Menindee Lakes is usually preferentially used relative to stored water in the upper catchment storages, because water agencies and the Murray-Darling Basin Authority have been concerned about reducing the

10 https://www.waternsw.com.au/supply/visit/menindee-lakes

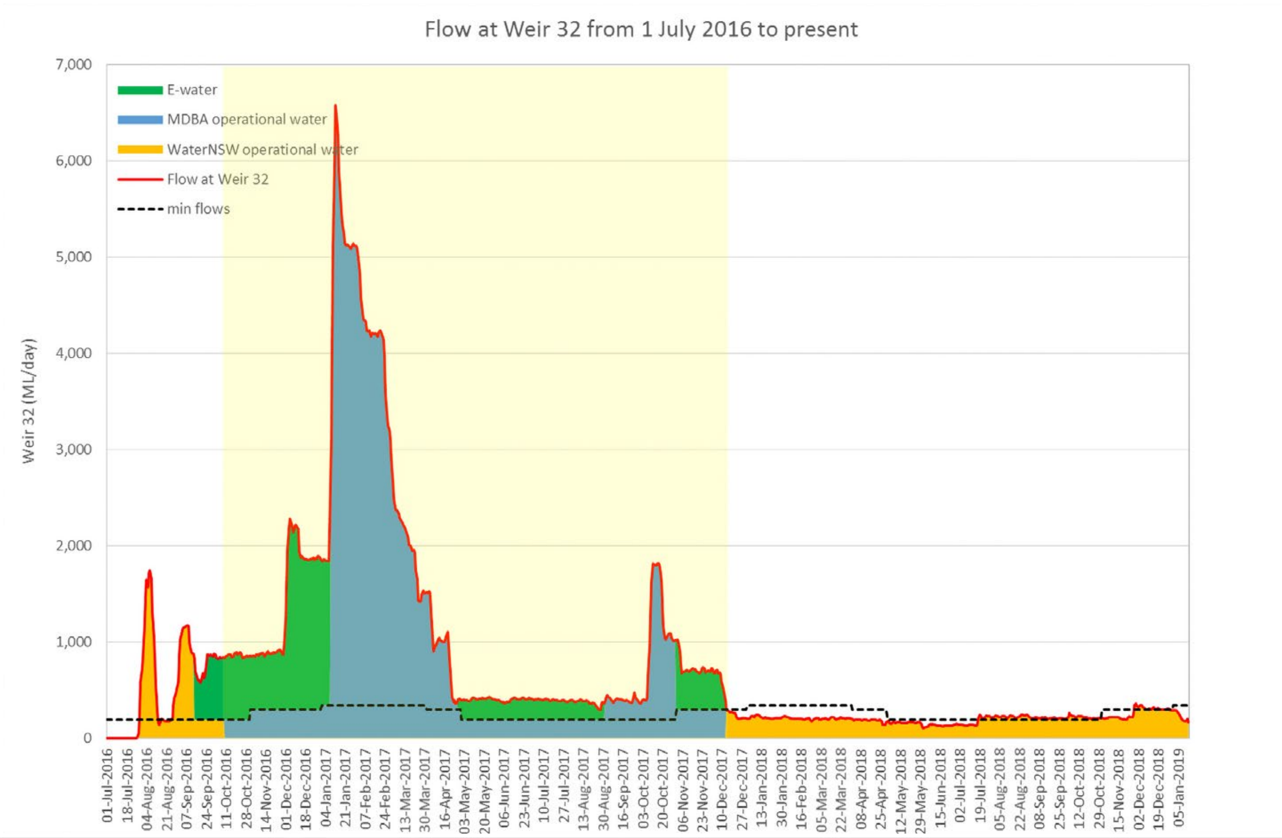
amount of water lost to evaporation, estimated to be 700 GL a year from Menindee Lakes (MDBA pers. comm). Water releases are primarily accounted for at Weir 32 on the Darling River (the site of the recent fish kills) and flows down the Darling Anabranch, downstream of Lake Cawndilla at Packers Crossing. Menindee Lakes water is also used to provide water to Broken Hill. A key management trigger was to ensure there was sufficient water supply in the lakes for two years.

Under the Murray-Darling Basin Plan, the upper lakes (especially Pamamaroo) provide water locally and to Broken Hill (future arrangements will involve a pipeline). They also hold water reserves allocated to local and shared water flows. The lower lakes (Cawndilla, Tandou) hold reserves for flows to the Darling Anabranch. The agreement has been in place since the Menindee Lakes Scheme was completed in the late 1960s and is a schedule in the *Water Act 2007*. Management of the lakes depends on the volume of water in them.

MANAGEMENT OVER 2016–2019

Government agencies have been actively and dynamically managing the Northern Basin region in the lead up and in response to the 2018–2019 fish kills. The following summary is based on a briefing given to the panel by Murray-Darling Basin Authority and Commonwealth Environmental Water Office officials on 1 February 2019, and the MDBA (2019) report on management responses to the Menindee (and other) fish kills. During 2016, the Menindee Lakes filled as a result of widespread rains in the tributary river catchments of the Darling River and subsequent flows into Menindee Lakes. The MDBA managed releases from the Menindee Lake system over August-September 2016 and then January to April 2017 (Figure 16). Releases began in the middle of 2016, with operational releases, followed by an environmental flow release which assisted and triggered widespread breeding of Murray cod and golden perch (D'Santos et al. 2017). This release combined environmental flows (210 GL) and operational water for total of 450 GL released from Weir 32. The agencies also released a 100 GL environmental flow from Lake Cawndilla through Darling Anabranch to enable fish emigration from Lake prior to drying. Following these releases, the Murray-Darling Basin Authority released large volumes of flows to meet South Australian requirements (done preferentially to using water from Dartmouth Dam and Hume Dam), environmental flows in South Australia and other operational requirements. **These releases were predicated on near-term natural inflows to the lakes that did not come to pass.** By January 2018, the Menindee Lakes dropped to <480 GL, and so to NSW Water management. Since this period, WaterNSW has released small amounts of water to meet downstream user requirements. Management of the releases from the lakes is primarily governed by the Murray-Darling Agreement which does not account for dry conditions upstream of the lakes and reduced inflows.

Figure 16



Time series of releases of different classes of water from the Menindee Lakes from winter of 2016 to early summer of 2017. Source: MDBA briefing to panel, Feb. 2019

Responses to subsequent drought

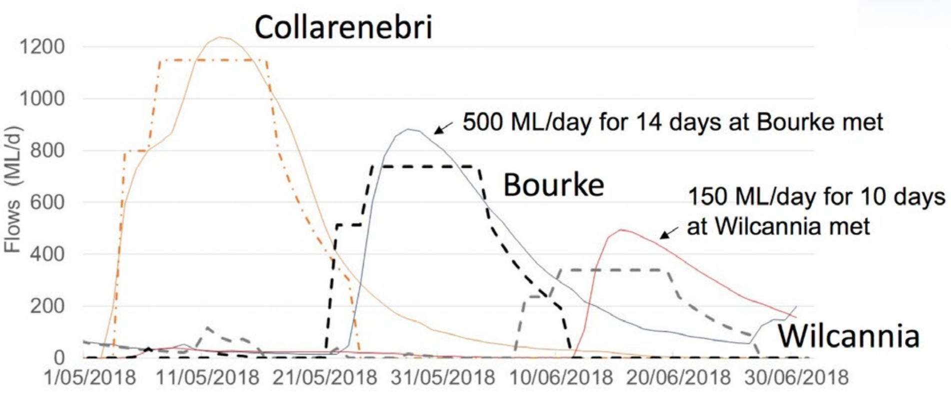
The current dry has extended for two years and followed high inflows to the Menindee region in the summer of 2017. In mid 2017, the lower Menindee Technical Advisory group concluded that the best option was to retain environmental water in the lakes as a key refuge for fish in the region. From late 2017, water was no longer able to be accessed in accord with WaterNSW needs for drought management.

From early 2018, authorities were aware of a rapid decline in river condition with cease-to-flow already covering large sections of the Darling—at Wilcannia in early January and Brewarrina soon after. Algal blooms commenced over summer of 2018, ranging from moderate to severe across monitoring sites on the Darling.

In response, from February 2018, a cross-agency Lower Darling Technical Advisory Group commenced meeting to develop ‘critical incident responses’, including enhanced monitoring to provide weekly updates on algal blooms. This led to rapid Commonwealth/state planning for a managed and embargoed environmental flow from northern catchments to the Darling, the ‘northern connectivity event’; all this depending on strong local community support and strong cross-agency cooperation. Stated aims included refreshing fish refugia and promoting dispersal. This resulted in releases from upstream catchments over April-June (23 GL including 17 GL from the Commonwealth Environmental Water Holder and the balance from the NSW Office of Environment and

Heritage), with flows of 17 GL reaching Wilcannia in June 2018. Encouragingly, the observed and modelled flows are congruent, indicating that the environmental water was not subject to substantial extraction (Figure 17).

Figure 17



Modelled (solid line) and observed (dashed line) flows following released of upstream water in the 'northern connectivity event' in mid 2018. Source: CEWO briefing to panel, 1 February 2019.

Water did reach the upper Menindee Lakes after two months; local information is that the water was very salty and remained so for as long as the flow was maintained.

Several positive lessons can be learned from this planned flow:

- Cross-jurisdiction/agency releases of environmental water can be planned and executed in a short-time frame, in this case four months. This is encouraging for intent to move to event-based management in Northern Basin WRPs.
- Embargo, or 'shepherding' of environmental water flows can work with cross-agency cooperation and support from local communities. This again demonstrates that this mechanism can deliver environmental benefits, as assumed in the NSW Toolkit approach to managing the Northern Basin.

The negative outcome is that, even with optimal timing and protected water, only a very small flow of low quality water made it to the Menindee region. This is consistent with the finding from the Northern Basin Review (MDBA 2017) that it cannot deliver sufficient water to restore the lower Darling. It also underlines the panel's general conclusion that there is not enough available environmental water in the system to refresh the lower Darling without also compromising important environmental objectives upstream.

Management responses during and after the Menindee Lake fish kills

From mid-January onwards, that is, subsequent to the first two fish kills, senior operational and government officials met to consider immediate responses to these events. It was concluded that there is no available water, either in the lakes themselves or upstream, to initiate the flows needed to refresh the system. They also found that remaining large fish below weir 32 are too stressed to be relocated. Given that, immediate responses are to (i) increase surveys of remaining fish refugia and assess their condition, including local knowledge, and (ii) use mechanical aeration to increase oxygen levels in selected refugia.

The Murray-Darling Basin Authority (2019) report also states that there is:

- in-principle support across agencies to implement a 'first-flush' rule to protect the first significant flows such that the system is flushed, while also managing that flow to minimise the risk of further fish kills (as occurred in 2004)
- intent to scope and implement a basin-wide recovery strategy for native fish
- intent to increase community and traditional owner involvement in native fish recovery planning and actions.

The expert panel appreciates the efforts taken by officials in response to the fish kills and strongly supports the initiatives outlined above.

Future management of Menindee Lakes

There is a water efficiency project under development which aims to reduce evaporation from the Menindee Lakes and save this water for adjusting the sustainable diversion limits estimates. There is an estimated 700–800 GL of water lost to evaporation each year from the lakes. There are clearly opportunities for water savings in management and reconfiguration of structures in the lakes that regulate water.

However, there is a lack of clarity and rigor available in the modelling of water savings, with little information about the uncertainties or variation with changes in evaporation, temperature and climate. This is needed to provide an auditable assessment of the volume of water likely to be saved in any reconfiguration of the Menindee Lakes scheme and likely value for the Sustainable Diversions Limit adjustment.

There is also poor documentation or analysis of the ecological costs and benefits of the water efficiency project in terms of native fish movements, breeding and recruitment. This is particularly important for golden perch that breed in Lake Cawndilla, which is expected to be dry for long periods of time. There is no analysis of the likely impacts on the ecology and populations of waterbirds and in particular migratory species for which Australia has international obligations. These are critical objectives under the *Water Act 2007* and the Murray-Darling Basin Plan. There is little assessment of floodplain and native vegetation impacts with altered flow regimes. Despite much of the area being incorporated in Kinchega National Park, of which 28% is wetland, there is no reference or assessment of the long-term impacts of the water efficiency project on the natural and cultural heritage values or other socio-economic impacts such as effects on tourism.

To improve ecological management of the lakes, they should be allowed to function with a restored wetting and drying regime. It will be important to continue to regulate water for downstream use and hold water primarily in Lake Pamamaroo, Lake Wetherill and Lake Tandure; based on local advice, we suggest that the system be managed to maintain at least 400 GL of accessible water in these upper lakes. However, it would be possible to reinstate natural flows and inundation regimes into Lake Menindee and Lake Cawndilla to allow natural drying and wetting process to occur, in keeping with the values and objectives of management of Kinchega National Park. This more ecologically sustainable approach would not deliver as much water savings, but would improve environmental outcomes under the Murray-Darling Basin Plan, specifically targeting the range of different organisms and ecological processes, including conservation of habitat for native fish species and waterbirds, including migratory shorebirds.

It is critical to engage on such options with the local community, given limited local consultation currently on the proposed water efficiency project. Restructuring of the project would provide benefits but there may also be costs if downstream requirements for water are modified through structural adjustment.

NORTHERN BASIN MANAGEMENT PRACTICES LEADING TO LOW FLOWS AND FISH KILLS

(See Appendix 4)

The Barwon-Darling Water Sharing Plan (*Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012*) (B-D WSP) covers the towns of Mungindi, Mogil Mogil, Collarenebri, Walgett, Brewarrina, Bourke, Louth, Tilpa and Wilcannia. In 2012, changes were made to the B-D WSP. These have attracted some attention for their likely impact on the environment (Senate Committee 2018) and were seen as a contributing factor by the community members consulted during this inquiry. Issues with the changes include (i) rule changes that allowed increased take of water during low flows and increased pump sizes; (ii) rule changes that permitted the take of water when flows reach certain thresholds (hence harvesting environmental flows); (iii) water theft; and (iv) extreme impacts (Productivity Commission 2018, Senate Committee 2018).

In addition, current proposals to change water resource plans (WRPs) are to include the revision of current long-term diversion limit equivalent (or cap) factors, which are used to convert various different types of entitlements into a long-term average (Slattery and Campbell 2018). Draft cap factors have been significantly changed by NSW (especially for supplementary licences in the northern NSW basin), but South Australia, Victoria and Queensland have not released their cap factor adjustments as yet. The implication of the changing cap factors is that it changes the long-term average annual yield of water entitlements in general, potentially increasing or decreasing the need for water recovery. Currently, a change in northern NSW draft cap factors implies an over-recovery of water entitlements in the Northern Basin (Productivity Commission 2018), which, if corrected, could further reduce flows to the Darling. There is increased need for clarity around what states need to self-report annually in order to show compliance with WRP obligations; the compliance assessment regime relevant to WRP obligations; and processes for updating plans. Otherwise the ability to implement adaptive management will be very difficult.

Issues around governance and management of the Darling river system (and broader Murray Darling basin) that underlie the reduction in low flows, and hence the fish kills, are presented in Section 7 below.

FINDINGS FOR SECTION 4

(See also Appendix 3 and 4)

Water diversions, river flows and rainfall

Most (98.8%) of the Darling River flows are generated from its tributary river catchments.

Growth in diversions from the Darling River and these river catchments has continued, after the Murray-Darling Basin Cap and establishment of the Murray-Darling Basin Plan.

Numbers and size of off-river storages have continued to increase after the Murray-Darling Basin Cap of 1995 and the Water Act and Murray-Darling Basin Plan.

Diversions have now reduced annual flow volume in the Darling River by about half at the following gauges down the river, compared to before water resource development, based on observed data: Brewarrina (49.1%), Bourke (55.8%) and Wilcannia (46.7%).

Numbers of days of cease to flow and low flow days have increased, increasing the risk of blue-green algal blooms and fish kills.

Reductions in overbank flooding in the Darling River and its river catchments are contributing to long term declined of floodplain forests, which will continue to degrade and die, producing more carbon which can be mobilised by large floods (blackwater events) and further contribute to fish kills.

This has continued to reduce river flows in the Darling River at Bourke and Wilcannia across all flow thresholds: cease to flow, very low flow, low flow, small and large freshes and overbank flows.

There is poor accounting of actual diversions across the Barwon-Darling and its contributory catchments, with an over reliance on models for compliance.

Concerns remain about diversions to groundwater systems, particularly those connected to the river, further reducing flows in the Darling River.

Ramsar-listed sites in the Darling River and its catchments (specifically Gwydir wetlands, Macquarie Marshes, Narran Lakes and) are continuing to degrade, inconsistent with the environmental objects of the *Water Act 2007*.

There has been no obvious long-term change in rainfall patterns, driving flows into the river catchments over more than a century.

The current drought (2017–2018) has experienced very low rainfall in the catchment but not the lowest over a century and not as extensive yet as other long droughts (e.g. Federation, World War II and Millennium Droughts).

Increasing diversions are related to pumping of environmental water, increased floodplain harvesting, policy changes in NSW in relation to the Barwon-Darling Water Sharing Plan and access to low flows and theft.

Hydrological models used to assess the environmental and socio-economic impacts of water recovery poorly estimate low or high flows, leading to underestimates of environmental impact.

Management of Menindee Lakes and management response to recent drought and fish kills

Flows to Menindee lakes have progressively declined, resulting in storage which once full is quickly expended because rules for release under the Murray-Darling Basin Agreement, unchanged for decades, assume that inflows continue.

By reducing reserves needed to endure the subsequent (and unforeseen) drought, the releases from Lake Menindee over 2017 and 2018, while well intentioned and within current operating guidelines, have contributed to the current crisis in the lower Darling system. At least 400 GL of accessible water should be kept in storage in the upper Menindee Lakes as drought contingency in support of local needs.

The proposed water efficiency project for the Menindee Lakes is deficient in several respects and should be put on hold pending further, externally assessed review of predicted gains and of ecological and social impacts.

There needs to be a Menindee Lakes restoration project, not an efficiency project, focusing on sustainable environmental management of the lakes system, guided by environment and water agency focusing on restoring wetting and drying regimes for Lakes Menindee and Cawndilla. This would reduce the amount of water saved, requiring adjustment to Sustainable Diversion Limits.

The operation of the Menindee Lakes is governed by a schedule of the Murray-Darling Basin Plan and reflects the period when it was negotiated, more than 50 years ago when there was substantially more water reaching Menindee Lakes. There is a need to renegotiate this agreement, in the context of a Menindee Lakes restoration project and a contingency storage volume of 400 GL.

The Northern Connectivity Event in mid 2018 demonstrated that agencies can work together to respond rapidly to critical events and effectively shepherd environmental water downstream. But even that was insufficient to restore the ecological condition of the Menindee Lakes and lower Darling. This, again, points to there being insufficient environmental water held in the Darling system to respond to acute conditions.

Looking forwards, the MDBA (2019) has outlined some important initiatives for management that the panel supports.

Northern Basin management practices

The NSW Barwon-Darling Water Sharing Plan, and changes to it in 2012, contributed directly to the decline of low flows, independent of rainfall, and hence to the recent fish kills.

Further undesirable reductions in flow in the Darling River are possible with pending changes by states to calculations of long-term diversion limit equivalent (or cap) factors.

The implementation of the NSW Floodplain Harvesting Policy in 2013 will potentially legitimise growth in diversions after the Murray-Darling Basin Cap.

5. WHETHER THERE HAS BEEN A STEP CHANGE IN INFLOWS DUE TO CLIMATE CHANGE OR WHETHER MORE WORK IS REQUIRED IN THIS RESEARCH AREA

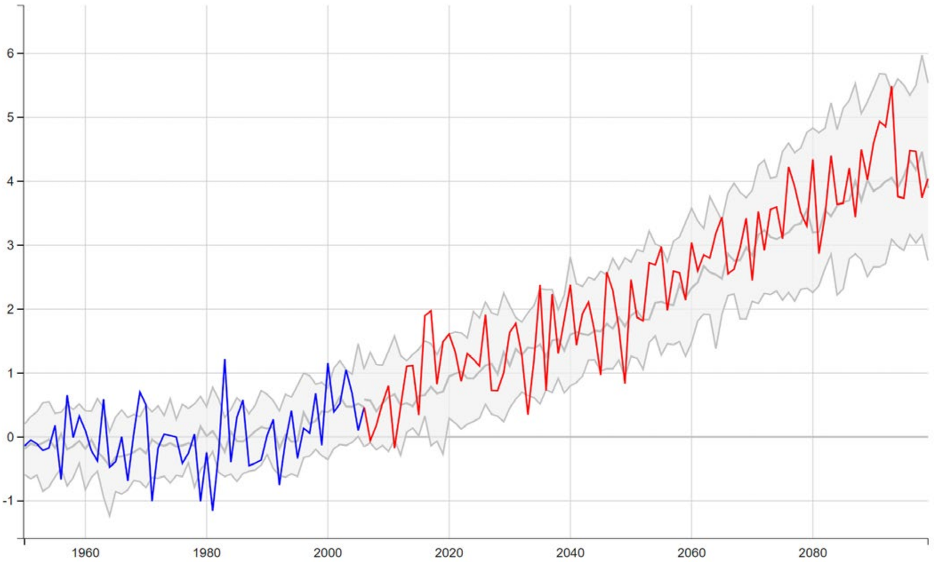
TERMS OF REFERENCE 5

(See also Appendix 5)

The Murray-Darling Basin is particularly sensitive to changes in its water flow characteristics induced by climate change because of its latitude. CSIRO (2012) noted apparent long-term reductions in cool season rainfall and river flow across the system. This was confirmed by Whetton (2017). The changes were at least partly attributable to global warming, pointing towards a possible future climate of below average late-autumn and winter rainfall across south-eastern Australia. These changes were visible in both observational data and models. The models indicate that these trends are likely to continue.

CSIRO estimates that the Murray-Darling Basin area has warmed by around a degree since 1910, and will continue to warm (projected ranges is 0.6–1.5 °C in 2030 relative to 1995, and by 0.9–2.5 °C in 2050 without mitigation), with more hot days and fewer cold days (Figure 18). January was the hottest month on record for Australia and temperatures in both December and January continued the trend towards strong increases in maximum temperature across the Murray-Darling Basin (Figure 20). These data (and see Figure 19) point to increasing temperature and relatively unchanging rainfall patterns over the years prior to the fish kills. While climate change linked to increasing emissions has contributed to hotter conditions, it is unlikely that the observed reductions in flows is attributable to a step change in climate.

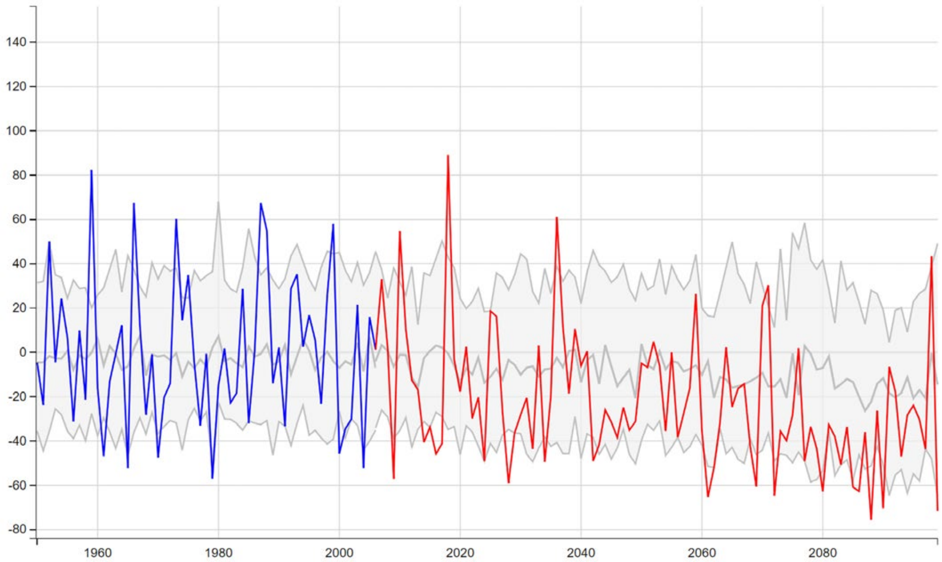
Figure 18



Example of model simulated historical (blue) and projected (red) annual temperature (in °C) for Murray Basin region from a single global climate model (ACCESS-3 model, RCP 8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website[11].

11 https://www.climatechangeinaustralia.gov.au/en/climate-projections/explore-data/time-series-explorer/

Figure 19



Example of model simulated historical (blue) and projected (red) winter precipitation anomaly (in %) for Murray Basin region from a single global climate model (GFDL-ESM2M model, RCP 8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website[11].

Looking to the future, CSIRO (2012) indicates that in the longer term, the larger increases in temperature will affect the Darling's flow in different ways. Higher temperatures may drive changes in the amounts, seasonal patterns and characteristics of rainfall. Projections for potential evapotranspiration indicate increases in all seasons, with largest absolute rates projected in summer. However, despite high model agreement there is some uncertainty in the magnitude of the projected change due to shortcomings in the simulations of observed historical changes. Also, there is some evidence that higher temperatures increased the potential for evaporation, as seen in the increase in potential evaporation during the Millennium Drought.

The most likely scenario based on climate modelling is rainfall will decrease, particularly in the south and in winter, with more time in drought and decreased soil moisture. However, both natural variability and variation between models is high, particularly in the north with some models predicting increased warm season rainfall in the northern tributaries of the Darling.

The dry scenario projects that there will be large reductions in runoff and water availability throughout the basin. The wet scenario projects that there will be significant increases in runoff and water availability in the north, grading towards little change in the south.

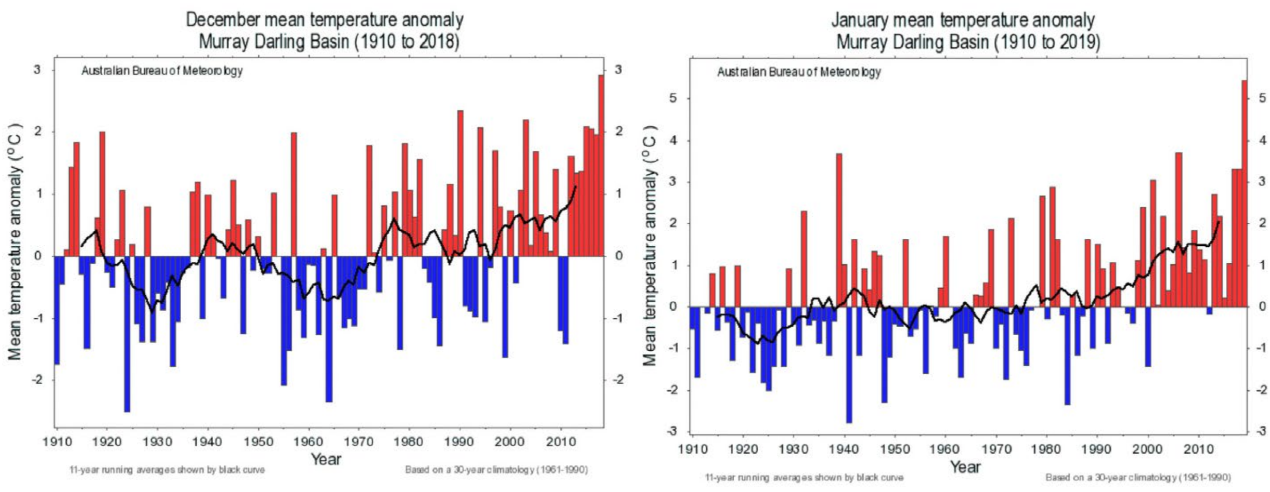
The intensity of heavy rainfall events will increase such that daily extreme rainfall is projected to increase even if average rainfall declines. This will mean that floods will increase in severity. We cannot tell with the variability in natural rainfall patterns exactly when the climate change impacts will be expressed. However, time spent in meteorological drought, and the frequency of extreme drought, will increase over the course of the century.

An enhanced greenhouse effect will have a strong impact on southern Australia's water resources, in addition to any reduction in rainfall. In the south, projections show a long-term decline in water flowing into the Murray-

Darling river system from its tributaries as the greenhouse effect continues. It is unlikely that this decline will be offset by an increase in rainfall, as most climate models are projecting a rainfall reduction. We can expect more occurrences of low inflow, as observed in more recent years.

Understanding how climate change impacts on hydrological behaviour and incorporating these changes will be critical to the work of incorporating climate change into future water management plans for the basin.

Figure 20



Trend in mean monthly temperatures for December and January across the Murray-Darling Basin (data from BOM). Climate change has increased the chance of these monthly records by a factor of 6 (Lewis et al. 2014).

FINDINGS FOR SECTION 5

The Murray-Darling Basin has increased in temperature by ~1 °C since 1910 and there is high confidence that the Northern Basin will continue to warm, towards a further 1–2 °C increase over the coming one to three decades. These large changes cannot be explained without anthropogenic emissions.

There is no detectable long-term change in observed annual precipitation over the historical record (see also Section 4, Figure 15). Rainfall projections for the Northern Basin are uncertain due to substantial differences across models and across simulations within models.

While climate change linked to increasing emissions has contributed to hotter conditions, it is unlikely that the observed reductions in flows is attributable to climate change alone.

Even with the same rainfall, increased temperatures could increase variability of flows, and also reduce flows through increased evaporation. Climate change could also directly affect species and ecosystems. However, there is urgent need for substantial improvement in modelling of changes in average rainfall and its variability, at scales relevant to catchment management, and increased temperature will affect flow regimes.

There is a critical need to include adjustments for potential reductions in river flows explicitly in water resource plans and their operation to ensure costs are equally distributed among users and the environment.

6. WHAT IMMEDIATE STEPS CAN BE TAKEN TO IMPROVE THE RIVER SYSTEM'S HEALTH AND MANAGEMENT WITHIN THE BASIN PLAN FRAMEWORK

TERMS OF REFERENCE 4

(See also Appendix 6)

SHORT-TERM RESPONSES TO RESCUE FISH POPULATIONS

Unless there is substantial rain in the coming weeks, the near-term options to improve the Darling system's health and management within the Basin Plan framework appear to be limited to:

1. finding suitable water in sufficient volumes to refresh the weir pools and river channel in the Menindee section of the Darling
2. attempting to improve oxygen conditions in key refugia in the river channel and weir pools using appropriate aeration technology.

Option 1: Obtaining sufficient water of adequate quality is impractical in the immediate future and involves a level of risk. Overall, there is just not enough water in the right tributary storages, given the instream losses, to rescue the Menindee region fish refuges without rain in catchment that is sufficient to initiate a natural flow through the entire system. Due to the extremely hot conditions prevailing this summer, there is a high risk that any water released will not reach the Menindee area. As conditions cool after April, the chances of a flow reaching the Menindee area will improve. If there is no natural flow in which to piggyback environmental water by that time, the water reserves in both Held Environmental Water and Licensed Entitlement Water, as documented below, should be purchased on the market, and released, with embargo provisions that guarantee that this water for the river environment cannot be extracted for consumption purposes. That embargo provisions can work was demonstrated by the recent 'northern connectivity event' which shepherded an environmental flow from upstream catchments through to Bourke.

It is estimated that, assuming arrangements to access water from the entitlement holders could be achieved, the respective tributary systems would yield about 75 GL and 45 GL of licensed water and environmental water respectively at the confluence with the Barwon-Darling system. This would also require a significant proportion of the 'essential needs' water to be consumed in this delivery. It is expected that under current conditions approximately 20 GL of licensed water and less than 15 GL of environmental water would arrive at Menindee. Acquiring water owned by others and amending statutory plans to liberate the Planned Environmental Water would be highly problematic under current operating governance. It appears from our enquiring that a volume much less than 30 GL is likely to be available to Menindee reaches of the Darling if one were to tap into upstream NSW storages for all but essential (primarily human) water needs.

We also note the following constraints:

- Under current conditions there is a significant risk these flows could de-stratify pools, causing hypoxic conditions and death of native fish. Environmental water holders currently consider that autumn may present more favourable conditions for a coordinated release of these emergency environmental flows
- The small volume of environmental water currently held in Menindee lakes (3608 ML) would not alleviate poor water quality in the Lower Darling. Further, its release could negatively impact the Menindee Lakes.
- There is insufficient water held by the Commonwealth Environmental Water Holder and available in public storages across the Northern Basin to support an environmental flow that would make it to and through the Menindee Lake system, under current temperatures and with no additional in-flow from rainfall in northern catchments.

Clearly this dire situation underpins our finding that there is not enough environmental water held in the Darling system to meet critical environmental and social needs in time of drought.

Option 2: Until temperatures ease, and without sufficient water to flush the system, there is a strong possibility of ongoing fish kills in the remnant and degraded refugial pools. NSW Fisheries field staff have been deploying aerators to improve the condition of selected pools in critical condition. This approach does not scale geographically, but can be applied strategically. Based on expert advice (B. Sherman, pers. comm.), it appears that the following is the best option:

Direct oxygenation. For very shallow systems like weir pools, the approach with the greatest effectiveness is likely to be direct oxygenation using a technique called 'side-stream supersaturation'. The most efficient application would involve pumping water out from close to the bottom in the deeper part(s) of a weir pool and passing it through an O2-transfer device such as a Speece Cone to produce highly supersaturated water that is then reinjected into the pool. Injection is best done through small, highly-turbulent jets to ensure the maximum mixing with the ambient oxygen-depleted water, otherwise the supersaturated oxygen will form bubbles and outgas to the atmosphere. The Water Authority of Western Australia has employed direct oxygenation for a number of years to improve water quality in both the Upper Swan Estuary and Canning Rivers and could advise on the cost and oxygen transfer efficiency of the method.

As an alternative in some circumstances, aeration involving gas transfer between introduced air and surrounding water can be effective; it is usually less expensive and builds on technology derived from the aquaculture and sewage treatment industries (B. Sherman, pers. comm.). Depending on the system, this can provide a similar level of physical flexibility as oxygenation. Shore-based systems are available that are conceptually similar to direct oxygenation in that water flow rates, intakes and outlets can all be controlled to produce more predictable results. Water is pumped out of the waterbody, enters a device that greatly enhances gas transfer with ambient air, and then delivers the highly air-saturated water back to the waterbody. Dissolved nitrogen can be an issue for aquatic fauna because high oxygen transfer occurs along with high nitrogen transfer in such systems. Surface agitation and fountain systems are common in aquaculture and sewage treatment plants. They can be designed to produce an oxygen transfer rate into the surface layer. Some systems are easily transported with a tractor and use the tractor drive to power the mixing device allowing greater flexibility in where the mixers can be deployed at any given time. It is difficult to predict how effectively the oxygen will be transported through the thermocline and into the bottom layer and what effect the physical disturbance of surface agitation or fountains will have on the stratification dynamics.

MANAGEMENT OF HARMFUL BLUE-GREEN ALGAL BLOOMS IN WEIR POOLS

Management of cyanobacterial blooms to reduce biomass may reduce the respiratory demand that contributes to acute weir pool hypoxia. A relatively new and promising approach, the application of hydrogen peroxide, has been used successfully at a number of sites in Europe and has undergone preliminary testing in South Australia (B. Sherman, pers. comm.). When applied to produce the correct concentration in the treated water (nominally 2 mg/L), the results have generally been near complete eradication of algal blooms within a few days without either a subsequent increase in toxin concentration or substantial harm to non-target aquatic organisms. The peroxide breaks down to water and oxygen within a few days and the beneficial effect appears to last for up to seven weeks. SA Water has experience in this intervention and can be consulted for further information on Australian tests of peroxide treatment.

To improve the river system's health and management, within the Basin Plan framework requires governments and managers to address the root cause of the current situation—reduced water and flows in the Darling as attributable to excess extraction upstream. To address this issue (and TOR4), the following section explains the complex system of governance and management of the MDB, the social values pertaining to water in the basin, and how these factors have contributed to the current ecological crisis in the Menindee region (TOR2).

FINDINGS FOR SECTION 6

Without immediate and substantial rainfall, there is insufficient environmental water in holdings by CEWH or State government, either in Menindee Lakes or upstream, to enable immediate flushing of the Darling River. Even if available water could be accessed, through direct purchase of allocation or entitlements, a release to flow downstream would likely result in low quality water by the time it reaches Menindee lakes or Darling river channel ponds and weir pools. This observation supports the panel's summary finding that there is not sufficient water recovered in the system to meet critical environmental (and social) needs during drought.

Increasing oxygen levels to improve remnant pools, refugia, and weirs is a short-term option to reduce ongoing fish kills in some key refugia. Direct oxygenation, as used in the Swan river of Western Australia, is an effective option. The panel supports the intent of NSW DPI and the MBDA to quickly expand surveys and such rescue efforts.

Blooms of blue-green algae, such as contributed to these fish kills, can be ameliorated by hydrogen peroxide treatment. This option should be explored. The is experience and expertise available in South Australia.

7. ISSUES OF GOVERNANCE AND MANAGEMENT THAT CONTRIBUTED TO THE FISH KILLS AND POOR ECOLOGICAL CONDITION OF THE DARLING RIVER

(See Appendices 4 and 7)

GOVERNANCE AND MANAGEMENT OF THE MURRAY-DARLING

The legal and water management context

Water management in the Murray-Darling Basin has rapidly changed during the past 25 years in response to water scarcity, its environmental effects, and contestation over water access, use and values. There is simply not enough water in the Basin to satisfy all needs for water, and so a system of water sharing has progressively developed to allocate and regulate water with the need to ensure greater sustainability becoming increasingly apparent.

Water law and governance is concerned with the interface between people and the national and state institutions and structures (including legal rules) that govern those people and ecological systems. Law operates within the context of political systems and institutions, and civil society that collectively give expression to environmental and other values related to water. This system is also the forum for raising and potentially resolving conflict over water and environmental issues, and for the implementation of law reforms.

As a federation, governance functions in Australia are shared between a federal (Australian Commonwealth) government, and state and territory governments. Various areas of responsibility are divided between the Commonwealth, state, territory and local governments (see Intergovernmental Agreement on the Environment 1992). Internationally, the Australian Government has entered into important treaties (e.g. Ramsar wetlands treaty and UN Convention on Biological Diversity) which means Australia has international obligations to protect these significant areas and ecological communities and species. Such obligations are reflected in the objectives of the *Water Act 2007* and in setting the purpose of the Basin Plan and the formulation of the sustainable diversion limit—although there are contrary interpretations of the priority to be given to international obligations relating to social and economic factors in this calculation (Appendix 4). These responsibilities of the national government also translate into areas such as the environmental watering plan under the Basin Plan and the role of the Commonwealth Environmental Water Holder in making environmental water available to support river health and ecological functions.

The division of legislative powers between the levels of government in Australia is a complex and divisive issue. It has resulted in fragmented but at times overlapping responsibility for water and environmental matters between the spheres of government (Godden et al. 2018). Historically, it was the state governments under their constitutions that had the powers to hold and regulate water resources and not the Commonwealth. Progressively, over time the Commonwealth Government has assumed a larger role in managing water, especially in the Murray-Darling Basin. That process in response to the Millennium Drought culminated in the *Water Act 2007* and the Murray-Darling Basin Plan 2012—together with the establishment of the Murray-Darling Basin Authority and a little later the Commonwealth Environmental Water Holder (Appendix 4). However, even now the division of powers to manage water remains a shared and often conflicted one—in managing a transboundary water resource with competing demands such as the Murray-Darling Basin (Godden 2016). Legally, states are the ones that have 'vested' water resources, which is the legal basis for why state governments can grant entitlements (e.g. water access licence) and then make allocations of water to people and companies that hold such entitlements (Gardner et al. 2018). State governments also have the major legal powers in respect of monitoring and compliance, and indeed in stopping and punishing illegal uses of water that have been identified as contributing to reduced instream water and groundwater.

The Commonwealth has no direct constitutional powers to legislate for and manage water but does so under a range of legal mechanisms, some of which rely on the international obligations (Appendix 4) and some on states 'giving' them the necessary powers. Federalism plays a large role in the overarching management of the Murray-Darling Basin as reflected in governing bodies for the Basin such as the Ministerial Council (Appendix 4). Since the 1990s, the policy setting has been one of 'cooperative federalism' (Godden et al. 2018) with the Council of Australian Governments (CoAG) playing a significant role in making policy decisions, for example in guiding the water law reform process from 1994. Although the term is cooperative federalism, given the different and sometimes competing interests of governments, there are inevitable tensions and trade-offs when it comes to federal policies and laws for managing water in the Basin. In recent years the limits of cooperative federalism have been tested, with water laws in the Basin being prominent.

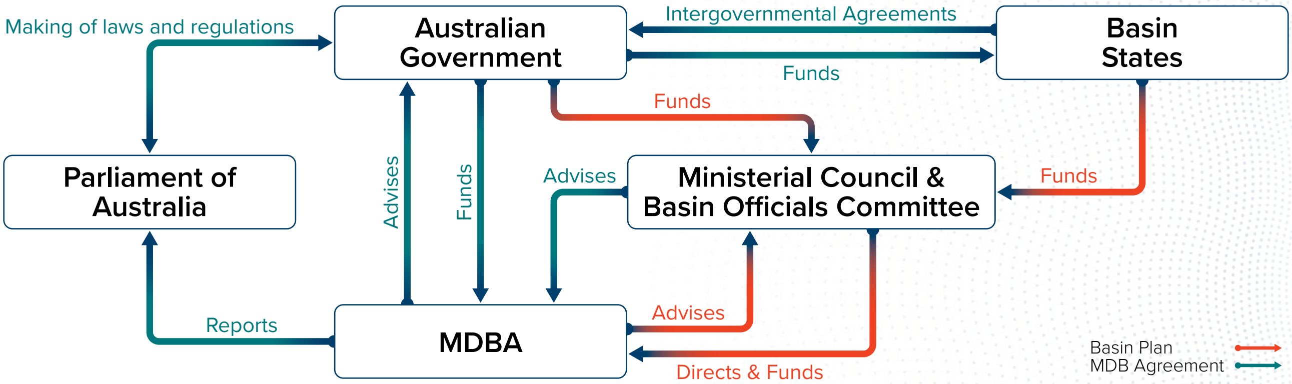
There is also a wide range of intergovernmental agreements that have been negotiated since 1914 (Appendix 4) that assist in managing the operations of the rivers (including the delivery of water) and for the 'sharing' of waters between the states. Since before Federation there have been conflicts between upstream and downstream states, especially South Australia (Appendix 4). South Australia is heavily dependent on water coming down the rivers, including from the Darling River and its tributaries. Similarly, there are 'shared' Commonwealth and state legal powers with respect to the water market (Horne and O' Donnell 2014) that developed from the earlier water reform process that unbundled water rights from land title; for example, a Commonwealth agency sets the market rules, but states 'manage' the entitlement and trading system.

While we focus on the frameworks that govern water management practices, it is important to note that the law itself is influenced by economic and cultural framings. Society receives many direct (e.g. fishing, tourism, irrigation use) and indirect benefits (e.g. broader community benefits such as wellbeing) from water resources (as for Menindee - see Appendix 8). There are also a range of other non-use values (e.g. values associated with future use of a resource, leaving resources/healthy environment to future generations and values associated with knowing a species continues to exist). Economic valuation studies conducted in the Barwon-Darling area have suggested that Australians attach a significant value to an improved riverine environment, and these use and non-use values are easily in the tens of millions of dollars (Appendix 7). However, such valuation techniques take poor account of cultural values including Indigenous perspectives.

Throughout much of white settlement of the Darling region, water has been regarded through a cultural lens that separates it from society in an effort to maximise its potential as a resource available for exploitation. That lens has ignored the customary rights to and relationships with water of Indigenous nations including the native title rights that have recently been recognised in the Darling region (Appendix 4 and Box 2).

The laws and organisations that manage water and the various policy instruments are extremely complex. They are summarised in Figure 21, which is explained in detail in Appendix 4. New Commonwealth legislation, namely the *Water Act 2007*, set in place water planning around a sustainable diversion limit (SDL) for consumptive water use across the Murray-Darling Basin. Two important new organisations were established to help manage water: the Murray-Darling Basin Authority (MDBA), and the Commonwealth Environmental Water Holder (CEWH). In 2012, a Murray-Darling Basin Plan was adopted with an explicit commitment to implement a SDL, and the Northern Basin Review led to an amendment in the SDLs in 2018. The SDL and water policy process are explained further below and in Appendix 4.

Figure 21



Overview of current administration of the Murray-Darling Basin (Productivity Commission 2018; 9).

How federalism can exacerbate MDB water management problems

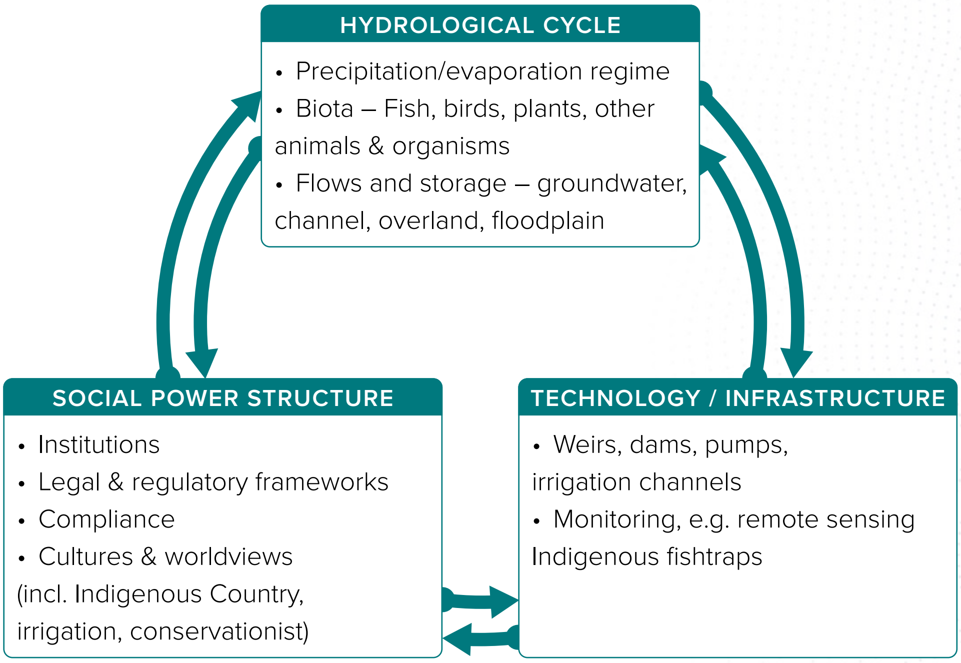
The complex legal and political federal interactions shape Basin water management (see above and Appendix 4). This complexity with its inherent tensions is a factor which has exacerbated the long-term management problems that surface as algal blooms and fish kills in the Darling River. Federalism is also an influence in terms of shaping the extent, but also the constraints on the powers of Commonwealth statutory agencies such as the MDBA and CEWH—both in long-term Basin planning contexts and when ecological crises, such as the fish kills, occur. These statutory agencies must act in the cooperative federalism governance model alongside state and territory governments, but also have key responsibilities under the *Water Act 2007* and Basin Plan to ensure that the legal objectives around environmental water, amongst other objectives, are met (Appendix 4). Importantly, under the Water Act (s 21 (4), the Authority (MDBA) and the (Commonwealth) Minister must, in exercising their powers and performing their functions in respect of the Basin Plan:

a. take into account the principles of ecologically sustainable development
b. act on the basis of the best available scientific knowledge and socio-economic analysis.

RIVERS AS A HYDROSOCIAL SYSTEM

Water management involves interactions between a range of natural and social processes (Wesselink et al. 2017). Rivers such as the Darling bear a human imprint, for example through diversions for agriculture which affect the downstream flow and reduced water quality which affects fish habitat. It is no longer helpful to think of such systems as purely natural and separate from society. The 'hydrosocial cycle'(Figure 22) highlights the entanglements between ecological outcomes such as fish kills and economic and social processes (Linton and Budds 2014). It also emphasises the direct connection between the health of fish populations and the broader river system and the responsibilities and rights of the Indigenous community (Box 2). We cannot do justice to all the contributing influences, and this report focuses on the most important ones. We understand the disaster includes consequences for human communities on the lower Darling as well as the fish, as the town supply and the fish are now competing for the same water.

Figure 22



The Murray-Darling basin as a hydrosocial system, from Linton and Budds (2014).

Box 2 Indigenous rights and interests in the Darling River region

Indigenous people comprise 30% of the population of the NSW region through which the Darling River flows (ABS 2016). Water, rivers and springs are of high significance in studies of Indigenous environmental knowledge of the Darling (Jackson et al. 2015, Muir et al. 2010, Goodall 2012). As the essence of live, water is creative and sustaining, underpinning cultural practices and social structures such as kinship relationships with fish and other beings. The presence and movement of water in rivers throughout the catchment emphasises the interconnectedness of people and country.

Aboriginal peoples have rights and interests under both the NSW Aboriginal Land Rights Act (1983) and the Commonwealth Native Title Act (1993). This report is focused on the Menindee Lakes area of the lower Darling River, where the native title rights of the Barkandji and Malyangapa people were legally recognised in 2015. Badger Bates described to the panel the central role of water in Barkandji traditional narratives:

'Our Barka means everything to us, it is our mother. It is who we are. We take our name from it, Barkandji means people belonging to the Barka. The Barka was created when Kuluwarra (ancestor from the Dreaming) let the Ngatji (Rainbow Serpent) out of his waterbag up near Bourke, and the Ngatji lives in it still.... The Ngatji looks after us and we have to look after it, it is our traditional job to look after the Ngatji and the river and the other waters of the Barka and its floodplains.'

The native title claim took 18 years to resolve, becoming the first successful determination within the NSW portion of the Murray-Darling Basin. Under the Native Title Act, claimants must establish an ongoing connection to traditional lands and waters since before white settlement. 'Waters' includes freshwater sources, such as rivers, lakes, and groundwater supplies.

The native title holders have rights as determined by the court to particular areas, including a 400 km stretch of the Darling River (from Tilpa to the northern point of the Great Darling Anabranch), and several water courses and lagoons in the south. The native title rights of traditional owners include the taking and use of water for domestic, social and cultural purposes. The Act protects activities such as ceremonies, the preparation of food and bush medicines, the manufacture of artefacts, and the teaching of traditional laws, customs and practices such as fishing. Traditional owners of Menindee told the panel how vital such cultural activities are to their way of life. Under NSW water law, these water requirements are given similar priority to stock and domestic rights and are therefore to be met prior to any other consumptive water uses, even in extreme drought conditions (Tan and Jackson 2013). Native title rights to take and use water do not allow commercial water use, nor confer exclusive ownership of water.

NSW water legislation and national water policy (National Water Initiative 2004, NWI) also provide for Aboriginal water interests, although they are not afforded strong protection in either (Tan and Jackson 2013). Research has identified a gap in how native title decisions are reflected in water plans (Hartwig et al. 2018). The NWI states that water plans should 'account for any water allocated to native title holders for "traditional cultural purposes"'. The Water Sharing Plan for the Murray-Lower Darling regulated river was finalised in 2016, a year after the native title determination. Even so, because the plan considers that there are no native title rights, water requirements for native title use are 0 ML/year.' The *Water Act 2007* is also weak, as while there are requirements under the Basin Plan for water managers to consult with Indigenous communities when they prepare water resource plans (they must describe Indigenous water uses, and have regard to Indigenous objectives for water), there are no mandatory requirements for stronger participation in water management. There have been calls to strengthen these consultation and engagement provisions and for Aboriginal nations to have greater access to water.

The UN Declaration on the Rights of Indigenous Peoples 2007 (UNDRIP) is the leading international instrument elaborating principles to guide nations in respect of their obligations to Indigenous peoples (Davis 2016). It offers a valuable pathway forward for building relationships around water between Indigenous and non-Indigenous Australians. International environmental instruments, such as the Biodiversity Convention 1999 also recognise Indigenous peoples' relationships to land and waters.

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COMMUNITY KNOWLEDGE AND EXPERIENCES OF ECOLOGICAL IMPACTS AND MANAGEMENT PRACTICES

(See Appendix 8)

Panel members met with a diverse cross-section of the community of the Menindee area over two days. The perspectives and knowledge presented is consistent with well-documented research on human relationships with rivers, including the Darling: sense of place and belonging in changing environments, and the importance of custodianship and community engagement in effective and equitable management practices (Appendix 8).

For those we met, fish kills are a symptom of severe ecological degradation brought about by the systematic de-watering of the Lower Darling. Over the last 15 years especially, the simultaneous depletion of inflows due to upstream extraction and rapid drawdowns from Menindee Lakes have eroded the capacity of this region to sustain aquatic life and human livelihoods. Changes to the flow regime and water quality have disrupted highly valued relationships with the river (Appendix 7) and are threatening the community's very existence. Panel members were told Menindee residents are depending on donated bottled water for drinking.

> *'If fish are dying, people can't swim in it, bathe in it or drink it'*
> — RACHEL STRACHAN, HORTICULTURALIST AND GRAZIER

> *'With no floods, no floodplain water, and pumping town water from the aquifer when the river is dry, we will end up with nothing to drink at all, and our fish, mussels, birds and everything will be gone, and our creator the Ngatji will leave us'*
> — BADGER BATES, MEMBER, BARKANDJI PRESCRIBED BODY CORPORATE

> *'We used to work on the blocks, apricots, oranges, grapes, everyone worked here, now we've got nothing...no water in the lakes, no tourism, no income for this town'*
> — JOY WILLIAMS, MEMBER OF MENINDEE LOCAL ABORIGINAL LAND COUNCIL

Although not raised as an issue during consultations, the effects of drought and the long-term lack of water in the Darling River have been cited as factors in high crime rates in the Central Darling Shire by research conducted during the previous drought (McCausland and Vivian 2010).

Significant environmental changes have occurred within recent times and these are considered to be unprecedented:

> *'This is the first time I've seen it happen in my 60 years in Menindee'*
> — DENNIS SLOANE, MEMBER OF MENINDEE LOCAL ABORIGINAL LAND COUNCIL

> *'We've never had fish kills like this—even in the Murray where they have fish kills it is with black water events'* — ALAN WHYTE, GRAZIER

We were also told that the community is united in its determination to recover, then maintain a healthy and mutually beneficial relationship with the river.

> *'If we're going to develop as all Australians, we're going to have to draw a line. And the biggest line should be for the environment'*
> — BADGER BATES, MEMBER, BARKANDJI PRESCRIBED BODY CORPORATE

The consultation and engagement practices of both NSW and Commonwealth water managers, including the MDBA, were described as completely inadequate. The local community has lost faith and trust in the Basin's systems of water governance—they feel they have insufficient influence over decisions affecting the river and lakes and they continue to witness their decline. From this perspective, efforts to manage river connectivity (the whole of river) are being undermined by insular water sharing processes that do not address the needs of the environment downstream or the communities dependent on the lower Darling.

> *'They have to fix the problem at the top. You cannot fix the problem in the middle'* — PATRICIA DOYLE, MENINDEE LOCAL ABORIGINAL LAND COUNCIL

> *'There is no priority to get first flows that are so critical for the river and communities downstream'* — ALAN WHYTE, GRAZIER

The observations of fish kill events and the formulation of recommendations by community members showed evidence of detailed local ecological knowledge. The panel has taken this knowledge and proposed solutions into account. For example, in dry times, the flow objective should be 300–500 ML per day, in pulsed flows, to the bottom of the Darling. And the top two lakes in the Menindee system (Pamamaroo and Wetherell) are considered especially critical lakes for the ecology, and need 400 GL or more of accessible ('live') water.

THE NORTHERN BASIN REVIEW AND AMENDMENT

The adjustment mechanism in the Basin Plan allows for the recovery target to be amended up or down, prior to 2019, but by no more than 5%, with physical water recovery to be offset by a combination of supply, constraint and efficiency projects. In July 2018, and following a review of the Northern Basin in 2016, the recovery target for the Northern Basin was reduced from 390 GL per year to 320 GL per year (Basin-wide water recovery target was reduced by 605 GL). As Senate Committee (2018) stated: 'The MDBA determined, via the Northern Basin Review, that the same environmental benefits could be achieved without having to use as much water'. One of the reasons for this adjustment downwards was the argument that water recovery was significantly harming Northern Basin communities (the validity of this argument is discussed more in Appendix 4). Given that the adjustment mechanism was only legislated last year, this amendment would have not physically contributed to the current Menindee situation; but by further reducing available environmental water, the reduced recovery targets will likely increase the potential for future drought-related fish kills in the Darling. It is worth noting that water recovery is not yet complete in the Northern Basin (Productivity Commission 2018 reports 291 GL recovery out of target 320 GL), hence if the amendment had not occurred, and full recovery had been achieved by the Commonwealth, then the Commonwealth Environmental Water Holder may have held greater environmental water entitlements to deal with the crisis. However, full water recovery is not required until the middle of 2019 and the difference between acquisition and registration of water entitlements also delays timeframes.

Other issues with the Northern Basin amendment include the implementation of toolkit measures (e.g. includes constraints, protection of environmental water, and supply projects) for the Northern Basin, where the adjustment was made conditional upon commitments from the Commonwealth, NSW and Queensland to implement toolkit measures (although it was recognised that the toolkit measures were not within the MDBA's remit). Toolkit measures will not be finalised until sometime in 2019, and there is current concern regarding their effective implementation (Productivity Commission 2018).

Finally, the original modelling of the Basin Plan (under the reduced water recovery targets from the draft) outcomes were based on assumptions that Basin states would implement pre-requisite policy measures (PPMs). PPMs are meant to enable the efficient use of environmental water (e.g. credit environmental return flows for downstream environmental use and allow the call of held environmental water from storage to piggy-back on unregulated flows). If PPMs are not implemented, SDLs then may be recalculated (Productivity Commission 2018).

ENVIRONMENTAL WATER GOVERNANCE

Total water recovery to achieve the SDL (initially through willing buyback of water entitlements and subsidisation of irrigation infrastructure) was to be achieved by 1 July 1 2019 (Murray-Darling Basin Authority 2012). As of 31 October 2018, environmental water recovery had registered over 2000 GL in water entitlements across the Basin, which is just over two thirds of the Basin Plan environmental water target of 2145 GL (given that the original Basin Plan target of 2750 GL was reduced by 605 GL in 2015). These entitlements are (mostly) held by the Commonwealth Environmental Water Holder and managed in accordance with environmental water plans prepared by the Murray-Darling Basin Authority (Productivity Commission 2018), and most of these entitlements have been achieved through buying water directly back from irrigators (Grafton and Wheeler 2018). The Commonwealth Environmental Water Holder enables the environment itself to be represented within water resource management (O'Donnell 2013), although the Commonwealth Environmental Water Holder remains responsible to the relevant Minister (*Water Act 2007*, ss 105, 107) (O'Donnell 2018). There is a need for stronger independence for and to rebuild legitimacy for the Commonwealth Environmental Water Holder to allow it to effectively fulfil a range of statutory responsibilities (O'Donnell et al. 2019).

LIMITS ON WATER PURCHASE AND ENTITLEMENTS HELD BY THE COMMONWEALTH ENVIRONMENTAL WATER HOLDER

It is vital that there is adequate environmental water in the Basin system to meet problems such as blue-green algal blooms and fish kills. Unfortunately, due to a widespread belief by rural communities that buyback of water entitlements was having serious economic ramifications (which is not justified in any of the peer-reviewed literature so far—see Appendix 4 for more detail), in 2015, the *Water Act 2007* was amended to limit the water entitlements which can be obtained via purchase from willing sellers and held by the Commonwealth Environmental Water Holder to a maximum of 1500 GL (s85C). All future water recovery is to be achieved through irrigation efficiency projects and supply projects (e.g. Menindee Lakes project is one such example), and there is currently around $5 billion left for water recovery purposes. The cap meant that the federal government has to cease purchasing water once it acquires 1500 GL, but that it is also currently prevented from using the water market to acquire further entitlements in future, which remains the cheapest, most effective and fastest way to recover environmental water (Grafton and Wheeler 2018). This compromises the ability of the Commonwealth to provide sufficient environmental water to maintain ecological health, and it is essential that the remaining monies are allocated to where they can achieve the most environmental and social benefits.

The Commonwealth Environmental Water Holder now holds nearly all of the water recovery target water in the Northern Basin (291 GL contracted out of the target 320 GL) (Productivity Commission 2018). These instream flows can be extracted by other users, and under current water laws, the Commonwealth Environmental Water Holder has limited powers to protect this water while it is in transit (Loch et al. 2017). Similarly, the Murray-Darling Basin Authority has few relevant powers, and serious issues around compliance exist (Matthews 2017). Although NSW has put in place legislative changes to address some of these issues, concerns remain, and there is a serious call to implement new satellite measuring capability to track both historical (for water resource plan setting) and current water use (Appendix 4 has more details).

WATER RESOURCE PLANS

We see some areas where there is a need to strengthen the capacity of the MDBA agencies to exercise their powers in a accordance with Basin Plan objectives. Specifically, the water resource plans (WRPs) that are to come into effect in 2019 should address the panel's key findings on the fish kill and algal blooms in the Darling River. Pertinently, there is a need to ensure stronger integration between upstream and downstream water resource plans in the Northern Basin to meet the holistic and interconnected objectives of 'good' water, connectivity, and inclusion of Indigenous values (Appendix 4).

Further, the expert panel's key findings have identified several areas where there is a need for robust consultation and the implementation of Murray-Darling Basin Authority responsibilities in Basin Plan accreditation for WRPs in the Northern Basin. Several recommendations address the need to strengthen the 'on the ground' consultation processes that were identified as deficient. To provide sufficient and good quality water in the Darling River it is the responsibility of the Authority to prepare advice for the Commonwealth Minister who approves the accreditation of state WRPs—which are to be compliant by July 2019 (Appendix 4). There is a window of opportunity to ensure that the lessons learned from the blue-green algal blooms and fish kills in the Darling River that, in part, arose from the changes to earlier water sharing plans in the Northern Basin are addressed (see recommendations). Appendix 4 discusses in detail many of the explicit issues associated with these WRPs.

EPBC ACT AND STATE BIODIVERSITY CONSERVATION LAWS

Alongside the Water Act and Basin Plan, a range of other legislation is relevant to management of a healthy river, even though water is often managed in isolation from other environmental laws. This disconnect can lead to gaps in how we manage aquatic ecosystems such as those in the Darling River. Further, the ongoing and serious ecological problems in the Darling River should prompt rapid consideration for listing as endangered ecological communities under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The biodiversity threats and appropriate management responses also should be reflected in the relevant WRPs. Overall, to address gaps in ecologically sustainable management of the Darling River there is a need for a more precautionary approach and to strengthen the interaction between the Water Act, Basin Plan and EPBC Act, especially project assessment and approval processes under the EPBC Act that impact water management. The Authority's Native Fish Strategy also provides an effective policy lever that would help prevent fish kills.

WATER ACCOUNTING

As well as strong compliance, institutions need to develop robust environmental water accounting. Much information on water use, diversions, return flows, storage, carryover, floodplain harvesting, overland flows and other important processes is not available publicly, or available at all. Especially for water, this needs scientific and economic measurement of all potential negative externalities, such as the measurement of return flows and the catch of floodwater and unregulated water diversions at both catchment and basin scales. This is a particular problem for the Northern Basin. All of the data gaps and irregularities justify calls for more robust water accounting and research to better understand connectivity issues between groundwater and surface water, as well as account for unregulated water diversions and theft. There must be greater use of satellite measuring and monitoring, especially in regards to the estimation of historical floodplain harvesting (Grafton et al. 2018).

FINDINGS FOR SECTION 7

The Northern Basin Adjustment passed by the Australian Government in 2018 removed 70GL of environmental water to be physically recovered from the Northern Basin which, if available and had been purchased in time, would have helped reduce the risk of future fish kills.

Socio-economic analyses underpinning the Northern Basin Adjustment overestimated the costs of reduced irrigation diversions and inadequately assessed the benefits to the broader community and ecosystem services dependent on river flows.

There is a need to rebuild the legitimacy of the Commonwealth Environmental Water Holder by strengthening its independence and allowing it to effectively fulfil a range of statutory responsibilities.

The 2015 Amendment to the *2007 Water Act* that placed a 1500GL limit on purchases of water entitlements from willing sellers by the Commonwealth compromises the ability to provide sufficient future environmental water to maintain ecological health of the Darling system.

The process for accreditation of water resource plans lacks sufficient consultation with affected communities downstream, and there is inadequate reference to other environmental laws, especially the *Environment Protection and Biodiversity Conservation Act 1999*.

8. RECOMMENDATIONS

ACADEMY EXPERT PANEL RECOMMENDATIONS

Headline recommendations

To immediately and in the long term improve the state of the Darling River for its dependent communities, including traditional owners, the environment, and to avoid catastrophic fish kills of native fish species, river flows need to be increased and the Menindee Lakes require improved environmental management.

In the short term (less than 1 year), we recommend:

1. **Within 6 months, take urgent steps to ensure that there is sufficient flow—considering both quality and quantity of water—in the Darling River to prevent stratification and blue-green algal blooms.**
   - At the first substantial natural flow event in the river tributaries, the Commonwealth Environmental Water Holder and states should cooperate to release available environmental water to flush the system, protected by pumping embargos, and lift water levels in upper lakes to above 200 GL.
   - In the absence of sufficient rainfall in upper catchments, the Commonwealth Environmental Water Holder should consider purchasing additional temporary consumptive (allocations and/or long-term leases) water following assessment of risks of low water quality and cost.
   - In the interim, use direct oxygenation of weir pools, which could be an effective in a few key refugia. However, this is only a short-term solution until conditions ameliorate.
   - Implement long-term strategies to increase flows and water quality in the Darling River and its tributary river catchments (recommendations 5 and 6).

2. **Within 6 months, establish a Menindee Lakes restoration project, to determine sustainable management and operation of the lakes system and the Lower Darling and Darling Anabranch**
   - Establish a whole-of-government committee (state, federal and water, environment, fisheries), with a local community advisory committee, which includes Indigenous peoples and which reports regularly to the public.
   - Restore wetting and drying regimes in lakes Menindee and Cawndilla, within Kinchega National Park.
   - Ensure relevant authorities hold and manage at least 400 GL of usable water reserves, using lakes Pamamaroo and Wetherill, with progression towards an environmental restoration program for the lakes and Lower Darling, including the Darling Anabranch.
   - Make the required adjustments to sustainable diversion limit estimates, given implementation of restoration of drying and wetting regimes and rigorous estimation of evaporation savings.
   - Consider any required changes to the interstate Murray-Darling Basin Agreement for operation of Menindee Lakes.

3. **Initiate a community planning process in the Lower Darling to restore river health and sustain local livelihoods**
    - Establish a Lower Darling Communities rescue plan focused on river health, Menindee Lakes management, livelihoods based on water, customary management practices, and critical human needs (drinking water and sanitation).
    - Provide structural adjustment funding to affected communities in relation to water recovery and changes to river management to value add for regional communities (supporting Productivity Commission recommendation).

4. **Improve meaningful engagement with river-based communities, including Indigenous peoples**
    - Implement the Ministerial Council recommendation to amend the Basin Plan to include Indigenous representation on the Murray-Darling Basin Authority
    - Improve governance and transparency in Basin water management, including establishing a Northern Connected Basin Environmental Watering Committee, with representation of traditional owners

In the longer term (1–2 years), we recommend:

5. **Improve the health of the Darling River, through adequate and effective planning which is scientifically informed.**
    - Repeal the Northern Basin Amendment decision (70 GL/ year), given:
        - insufficient scientific evidence for over-recovery of environmental water
        - peer-reviewed scientific evidence of ongoing decline of river ecosystems, including Ramsar-listed wetland sites, and superficial socio-economic analyses not adequately incorporating long-term costs on ecosystem services
        - broad community concern, including from Traditional Owners and lower Darling and Menindee communities.
    - Improve the capability for prediction of critical events, using satellite-based catchment 'real time' water quality monitoring, focused on improved understanding of dynamics of hydrology and microbial and cyanobacterial populations.
    - The Murray-Darling Basin Authority and states should rigorously assess and implement Northern Basin water resource plans to ensure they:
        - **i.** meet needs of downstream catchments
        - **ii.** align with environmental and water quality objectives of the Basin Plan; and assess the water quality requirements in respect of Indigenous cultural and spiritual values, referring to guidance on values contained in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality
        - **iii.** fully protect environmental flows throughout the Darling
        - **iv.** apply event-based management to meet the full range of ecologically-informed flow targets
        - **v.** rigorously report, monitor and audit diversions; these must be metered, not just modelled

- **vi.** incorporate the rights and interests of Aboriginal communities (Indigenous people's values, uses and native title rights), noting that the accreditation process must consider the objectives of Indigenous people in relation to managing the water resources of the water resource plan area and the outcomes for the management of the water resources of the water resource plan area that are desired by Indigenous people, as well as cultural flows.

- Restore funding to the Sustainable Rivers Audit, including native fish, to improve monitoring and understanding of the metapopulation dynamics of priority species, and enable adaptive management.

6. **Return to the intent of the 2012 Murray-Darling Basin Plan to avoid increasing risks of more fish kills and other environmental problems for the Darling River:**
    - Identify and implement legal, policy and operational mechanisms, including 'shepherding arrangements' which protect environmental water throughout the Darling River systems and its tributary river catchments.
    - Repeal the cap on 1500 GL on water buybacks (Sec 85C of the *Water Act 2007*) from willing irrigators to recover water at the least cost to taxpayers, and fund additional infrastructure, constraint and supply projects, only where independent reviews find with high confidence that they provide required hydrological, ecological, cultural and economic benefits.
    - Audit and assess the take of floodplain harvesting on New South Wales and Queensland floodplains, adjusting for commitments to the Murray-Darling Basin Cap and accounting for long-term groundwater impacts, before licensing and regulation. Regulation should be supported by ongoing monitoring and metering.
    - Reinstate the Murray-Darling Basin Cap of 1995, agreed to by all state and territory governments and the Commonwealth Government. To achieve that outcome an inquiry must be undertaken to specify the levels of take of water at 1993/1994 (NSW, VIC, SA) and 1999/2000 (QLD) levels of water resource development from the river, floodplains and connected groundwater systems, affecting flows into the Darling river.
    - Implement regulation of floodplain harvesting across New South Wales and Queensland, incorporating understanding of assessment of take at Murray-Darling Basin Cap levels and accounting for long-term groundwater impacts.
    - Implement rigorous water accounting across the Northern Basin, applied to all recovery through supply, infrastructure (e.g. increasing volume of off-river storages), purchase projects, and interaction with floodplain take and greater assessment of connectivity issues through groundwater use and return flows issues to determine long-term impacts on declining Darling River flows.
    - Adjust sustainable diversion limits for the Northern Basin, with regards to a future hotter climate change and other effects on Darling River flows, informed by improved modelling and observed data analysis.

7. **Invest to fill high priority knowledge gaps as the MDBP continues to be implemented, and then reviewed in 2026:**
   - Improve capacity for early warning of prolonged cease-to-flow conditions and ecological stress, including water quality and algal status.
   - Better understand the relationship between land management practices and the quantity and quality of water in the Darling River.
   - Re-establish comprehensive monitoring (such as the Sustainable Rivers Audit) of the biota and drivers of rivers and wetlands in the Darling River and its tributary river catchments.
   - Improve prediction of hydrological and ecological responses to climate change. Understanding how climate change impacts on hydrological behaviour and the interaction and responses of vegetation to changing CO2 concentrations and increasing temperature will be critical. This is essential to development of policy and water management strategies that can deliver ecological wellbeing of our basin rivers under the changes in climate and the changing hydrological and ecological process in our rivers and catchments.
   - Noting that the research agenda for the Murray-Darling Basin has in recent years been relatively well served by the biophysical sciences, and that the Southern Basin has been more closely studied than the north, we recommend that government agencies and research organisations increase and re-focus their research efforts to meet the water governance and management challenges outlined here. We also note that there has been an overall decline in funding for water research in the past decade with the loss of key agencies that supported integrated natural resource management (NRM) research and participatory methods (e.g. Land and Water Australia, the National Water Commission). There is a clear need for more research to assist Australian society with the transformations that are required to sustainably manage the Darling River and its wider basin. This will require a better understanding of:
     - models and processes to support adaptation around structural and economic change in the water sector and to climate change
     - collaborative water planning
     - the processes of institutional change in water organisations
     - conflict resolution, transparency and legitimacy in public policy decision-making
     - Indigenous recognition and access to water
     - stewardship in land and water management, as well as innovations in sustainable livelihoods.

8. **Commission within 12 months an independent scientific panel to review progress in implementing the above recommendations.**

ASSOCIATED RECOMMENDATIONS FROM OTHER RECENT REVIEWS

Two major reviews of the Murray-Darling Basin Plan were released just prior or during the Academy's expert panel research. The panel's findings and recommendations were independent of these, but we note some congruent findings here. The Productivity Commission (2018) and the SA Royal Commission (Walker 2019) make a number of specific recommendations that are valuable in the context of the wider water management issues facing the Northern Basin.

Some of the more important and wide-ranging recommendations that we endorse include:

i. new determinations of the ESLTs, and SDLs for both surface water and groundwater, to be made on the 'best available scientific knowledge', including climate change projections and risk (Walker recommendations 1 and 3)

ii. a strengthening of the regulatory powers of the Murray-Darling Basin Authority, as well as a consideration to separate the MDBA's service delivery and regulatory functions into two institutions (Productivity Commission (Rec 14.2))

iii. establishment of an independent, scientifically astute and experienced body responsible for auditing the effectiveness of the implementation of the Basin Plan, akin to the previous National Water Commission (Walker recommendation 3).

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INVESTIGATION OF THE CAUSES OF MASS FISH KILLS IN THE MENINDEE REGION NSW OVER THE SUMMER OF 2018–2019

APPENDICES

AUSTRALIAN ACADEMY OF SCIENCE, FEBRUARY 2019

CONTENTS

APPENDIX 1: FISH KILLS RECORDED FOR THE NSW PART OF THE MURRAY-DARLING BASIN OVER TIME

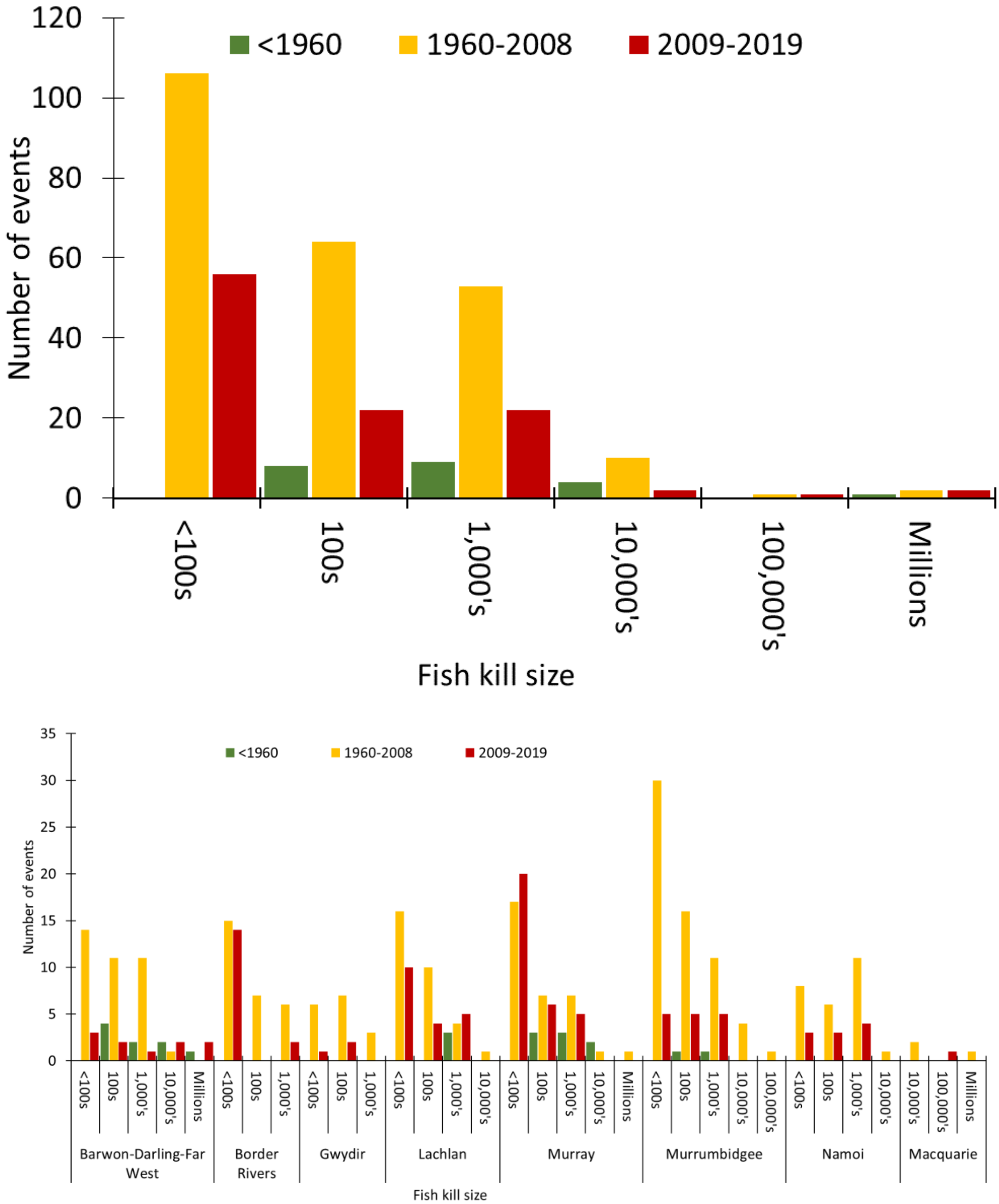

Figure A1.1 Fish kills recorded for the NSW part of the Murray-Darling Basin over time and in each river, sorted by periods including before water resource development (1960), 1960-2008 (main period of water resource development and 2009-2017 (water recovery period). (Data provided by NSW DPI from NSW Fisheries fish-kill database; see Table 1, main report, for details on large fish kills).

APPENDIX 2: WEIR POOL DYNAMICS—CAUSES OF STRATIFICATION, MIXING AND DEOXYGENATION

Prepared by Dr Bradford Sherman, Reservoir Doctors Pty Ltd.

Weir pools, constructed to facilitate water supply, recreation and navigation in the Murrumbidgee, Murray and Darling rivers exhibit similar heating and mixing dynamics.

HEATING

The temperature in weir pools follows the sun and the seasons. It is best to think of the warming process as happening from the top of the water column and moving downwards from there.

The important heat fluxes entering and leaving the water are shortwave radiation, longwave radiation, sensible (conduction), and latent (evaporation). Sensible and latent heat fluxes depend on air temperature near the ground and the latent heat flux depends also on the humidity of the atmosphere. Both sensible and latent heat fluxes increase with increasing wind speed for a given air temperature and humidity.

Shortwave radiation (wavelengths <2.5 µm) is absorbed within the water column after a relatively small portion is reflected back up to the atmosphere. As sunlight enters the water column it is absorbed and scattered. Combined, absorption and scattering are referred to as attenuation and light attenuates exponentially with depth following Beer's Law. The euphotic depth is the depth at which the downwelling light intensity measured in the water is 1% of the intensity measured at the water surface. Photosynthesis typically does not occur below the euphotic depth. Virtually all of the water temperature change imposed by absorption of radiation occurs above the euphotic depth. The euphotic depth is typically <2 m in many inland Australian waterways. A simple rule of thumb is: if you wade into the water up to your neck and you cannot see your feet, then the euphotic depth is <2 m and probably about 1–1.5 m.

Longwave radiation (>2.5 µm) is absorbed from the sky and emitted from the water surface. Longwave radiation varies as the fourth power of temperature; the downwelling component from the sky increases with cloud cover and atmospheric temperature and the upwelling emission from the water surface varies with the water surface temperature. The net longwave radiation is virtually always a net emission to the atmosphere and contributes to surface cooling.

The sensible heat flux is the flow of heat from a higher temperature to a lower temperature; at night conduction will typically be a heat loss whereas during a hot summer day it will typically be a heat gain.

Evaporation always occurs and causes a loss of heat from the water surface.

In summary, heat gain in the water column occurs both at the surface of the water and within the water column down to the euphotic depth. Heat loss occurs *only* at the surface. This is illustrated in Figure A2.1.

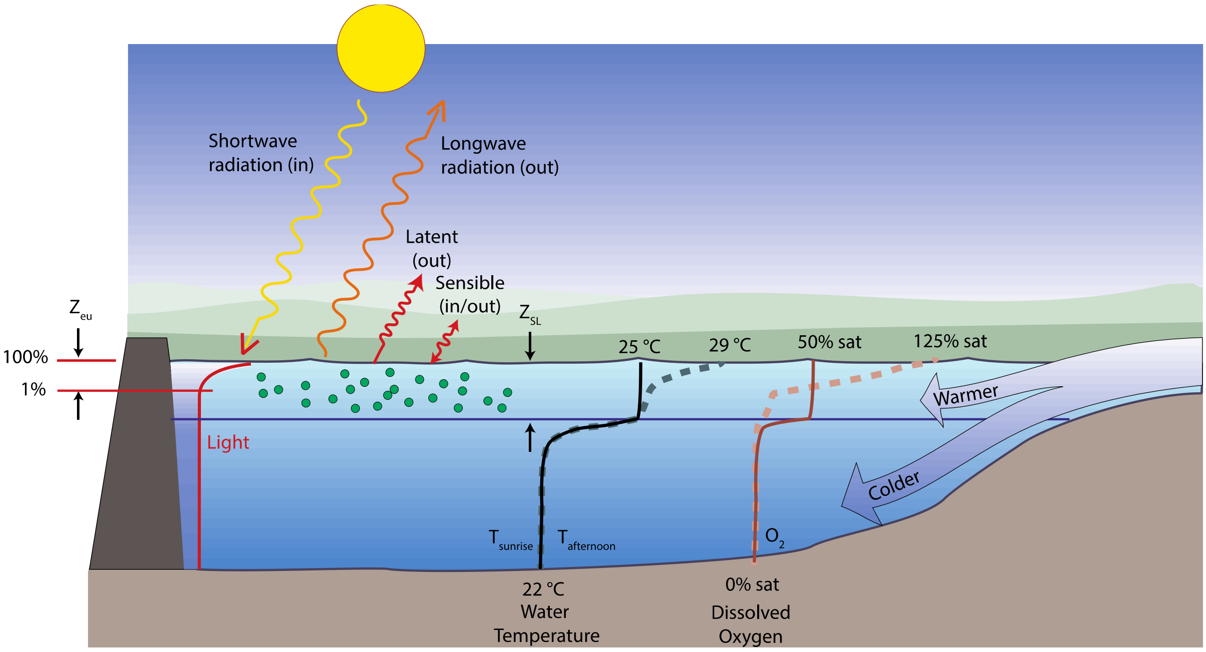

Figure A2.1 Weir pool heat fluxes, light, temperature and dissolved oxygen profiles and inflow scenarios. Representative temperature (black) and dissolved oxygen (brown) profiles are shown for sunrise (solid line) and mid-late afternoon (dashed line). Depending on the inflow temperature, water flowing into a pond or weir pool may enter exclusively into the surface layer (warm inflows), exclusively into the bottom layer (cold inflows), within the thermocline (intermediate temperature). If inflows are large enough, they can mix the entire water column and enter essentially as a plug flow.

Thermal stratification

When there is a net gain of heat, and in the absence of other physical mixing by strong winds or river discharge, the water column becomes stratified. As the water near the surface heats up, it expands and a density gradient results with the colder, denser water at the bottom and the warmer, lighter water near the surface.

As the water column expands more rapidly at the surface than at the bottom (because that's where it is heating up the most), the centre of volume of the water column moves upward relative to the centre of mass of the water column. When the water column is well-mixed, the centres of mass and volume are coincident. Just like a boat, the higher the centre of volume (buoyancy) is above the centre of mass, the more stable (resistant to mixing) the system becomes.

At this point it becomes useful to think of stratification in potential energy terms. As the thermal / density stratification becomes stronger, the centre of volume rises higher above the centre of mass. **The potential energy of the stratification is the amount of energy required to raise the centre of mass of the water column to coincide with its centre of volume.**

Once stratification has been established, it is useful to think of the water column as consisting of three regions: the surface layer (SL), the bottom layer, and the thermocline. The surface layer in many Australian weir pools and reservoirs is typically 1 to 2 times the euphotic depth, a range very conducive to the growth of harmful buoyant cyanobacteria (Sherman et al. 1998).

The thermocline is the region where the temperature decreases relatively rapidly from the surface layer temperature. The top of the thermcline usually has a very abrupt temperature change (anyone who has duck-dived in a lake or gone scuba diving is probably familiar with this change of water temperature).

Once a thermocline has been established, the vertical transport of dissolved compounds, such as dissolved oxygen, slows down dramatically—conceivably by 10 to 1000 times to approach Fickian diffusive rates under very calm conditions. At the same time, particles, e.g. non-floating algal cells or suspended sediment, continue to fall from the surface layer to the bottom layer where they accumulate eventually in the sediment. This typically leads to depletion of dissolved oxygen in the bottom layer because respiration of aquatic fauna and bacteria greatly exceeds the vertical downwards transport of oxygen through the thermocline.

Diurnal cycles

On a daily basis, and in the absence of significant lateral inflows and ouflows, the water column begins to warm as soon as sunlight strikes it. Heating continues until late afternoon at which point heat gain from solar radiation and sensible heat flux is less than heat loss by net longwave radiation, sensible and latent heat fluxes. Typically, the minimum surface water temperature occurs just before sunrise and the maximum temperature occurs around 1500–1600 h.

On a daily basis, in most Australian inland waters, the maximum depth of the surface layer (SL) almost always occurs just before sunrise and is determined primarily by nightime surface heat losses. It is a common misconception that wind stirring determines the SL depth whereas, in fact, in inland Australia the wind speed exhibits a strong diurnal periodicity with little to no wind at night and it is actually surface heat losses that drive SL deepening through a process called penetrative convection. This means the downwards excursions of the SL that entrain deeper waters into the SL are particularly sensitive to strong cooling events.

Mitrovic et al. (2010) measured the water temperature at a range of depths in **Weir 32** between February 2006 and February 2009. On a daily basis, the temperature near the water surface varied characteristically by approximately 4 °C during the daily cycle but daily temperature ranges up to 6 °C were not uncommon. Below the surface mixing layer the diurnal temperature range was generally less than 1 °C. The SL depth was not formally assessed but appeared to be in the range 1–1.5 m typically based on my interpretation of temperature data.

Seasonal cycles

In deeper inland water bodies, the development of persistent seasonal stratification is usually well underway by about the 3rd week of September in Australian inland waters. The water column temperature is generally reset to its coldest value in mid-winter and then commences to warm as the days become longer. Beginning in February, it's common to see a progressive decrease in water temperature as the days become shorter and heat losses exceed heat gains.

Data collect by Mitrovic et al. (2010) in Weir 32 show a seasonal warming pattern commencing with a low temperature of ~16 °C in mid-October 2007 and increasing to ~28 °C by January 2008 (Figure A2.2). This was a period of very low or no discharge from Weir 32. The heating of the weir pool consisted of five periods of 10–14 days duration characterised by strong heating of the upper 1.8 m and a surface layer between 1 and 1.8 m deep typically followed by short periods of 2–5 days leading to complete mixing of the water column which demonstrates the important role of periods of strong cooling with regards to the seasonal temperature.

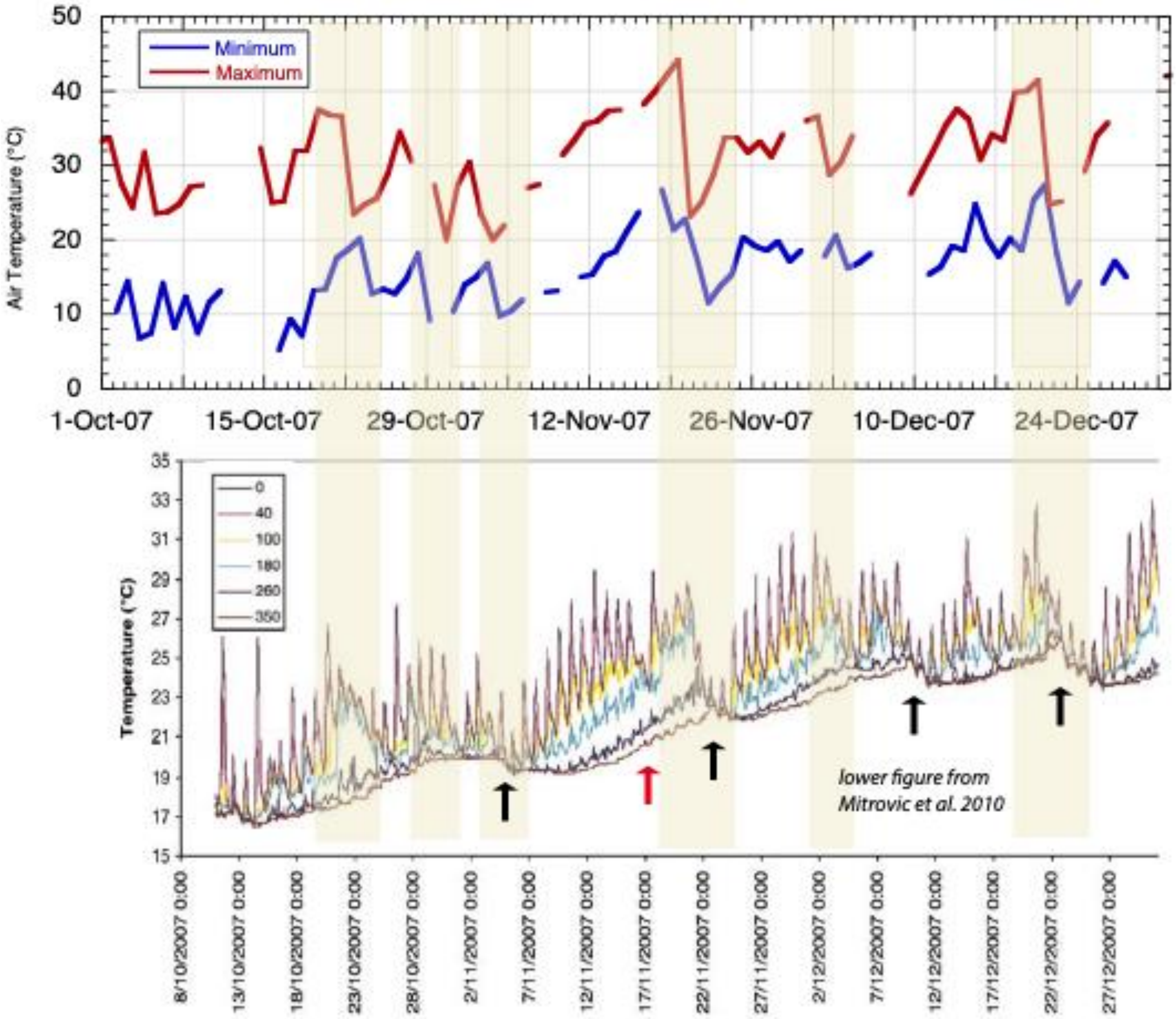

Figure A2.2 Upper panel shows daily minimum and maximum air temperatures from BoM Menindee Post Office station. Lower panel reproduces thermistor chain data from Figure 5 from Mitrovic et al. 2010. Shaded bands denote passage of cold fronts. When thermistor chain traces converge, complete mixing of the water column has occurred to the depth of the deepest trace. Depth of thermistors is in cm below the surface. Bold black arrows denote complete mixing of the water column to a depth of 3.5 m, bold red arrow denotes mixing event to at least 1.8 m but not to 2.6 m.

MIXING PROCESSES

Mixing of the water column occurs mostly from the top and bottom boundaries and then works its way towards the opposite side. Turbulent kinetic energy (TKE) enters at the boundaries of the water column due to penetrative convection caused by cooling of the water surface; wind mixing arising from velocity shear generated at the water surface as the wind blows across it; and velocity shear generated at the bottom of the water column as water flows over the sediment.

At the water surface

In waterbodies with little flow, mixing occurs predominantly downwards from the water surface due to penetrative convection and wind stirring. TKE continuously enters the water column at the air-water interface. During daylight, the water column is also heating up and typically develops a temperature gradient just below the water surface (e.g. the top 25–50 cm) that increases the potential energy of the stratification. The TKE introduced at the surface must overcome the daytime increase in potential energy before it can cause deepening of the surface layer which, by midday, may be only 10s of cm thick reflecting the balance of potential energy by heating and TKE introduced by cooling and wind stirring.

Generally, solar heating adds more potential energy than penetrative convection and wind stirring can mix out until about 1600 h. By late afternoon, the contribution of potential energy by solar heating diminishes sufficiently that the TKE introduced by penetrative convection and wind stirring are able to cool and start deepening the surface layer.

In general, in inland Australia, wind speed is a maximum during the daytime and decreases to close to zero at night. This means that wind stirring is constantly working against solar heating and, often, is insufficient to maintain the surface layer depth at the level encountered at sunrise. It is quite common for the surface layer (the region below the water surface that is actively mixing and cannot support gradients of salinity or other dissolved constituents) to become shallower (only 10s of cm thick) during the middle of a relatively calm day.

Eventually the balance between potential energy gain by heating and TKE introduced by cooling and wind stirring shifts in favor of TKE and the surface layer cools and deepens until sunrise the following day.

The passage of cold fronts and/or particularly windy conditions (especially at night) increases the supply of TKE and allows the surface layer to deepen beyond the level at which it started the day. This causes the entrainment of deeper water into the surface layer and a homogenisation of the dissolved constituents within the surface layer. For example, assuming a 1 m thick surface layer with 15,000 cells/mL of algae and 100% dissolved oxygen saturation deepened to 2 m into a bottom layer with no algae or dissolved oxygen, then the surface layer would have an algal concentration of 7500 cells/mL and dissolved oxygen of 50% (neglecting photosynthesis and respiration for the moment). A simple mass balance view of the system is appropriate.

At the bottom of the water column

In much the same way that wind produces a velocity gradient at the air–water interface (the surface of the water drifts relative to the water below it), river discharge can produce a velocity gradient varying from zero at the bottom boundary of a weir pool to a characteristic velocity in the flow above. The change in velocity from the boundary is referred to as velocity shear. Velocity shear introduces TKE at the boundary. Wind-induced velocity mixes the water column down from above and flow-induced velocity mixes the water column up from the bottom.

Flow can produce a relatively well-mixed boundary layer along the bottom whose thickness grows upwards as the velocity increases until eventually sufficient TKE is generated at the bottom to mix the entire water column. In this case, water from above is entrained into a well-mixed bottom layer.

Flow-induced mixing of weir pool water columns was thoroughly investigated by (Bormans and Webster 1997; Sherman et al. 1998) and the learnings from the Maude Weir pool study informed the subsequent development of many flow-based weir pool management guidelines for the suppression of cyanobacterial growth.

Mitrovic et al. (2010) empirically determined the relationship between discharge and full water column mixing in Weir 32 and found that discharge of approximately 350 ML/day was sufficient to suppress the development of persistent stratification during January 2009. Of course, all sources of TKE are important and the actual flow required to complete mixing of the water column will depend on weather conditions at the time, i.e. hotter, calmer conditions are likely to require larger discharges to completely mix the water column.

Upwelling

If persistent strong winds blow from a direction aligned with a weir pool, upwelling may result at the upwind end of the weir pool. Under such circumstances, the sustained wind pushes the warmer surface layer water to the downwind boundary and it is common to observe consipcuously warmer water temperatures and often an apparently deeper surface layer at the downwind end. Here, the water accumulates and there is a slope in the air water interface, i.e. at the upwind end the water surface is lower than at the downwind end. The change in elevation of the water surface creates a pressure gradient within the water that can be balanced by a tilting of the thermocline such that the pressure change arising from the horizontal temperature gradient (which produces a horizontal density gradient) balances the pressure change caused by the tilting of the water surface. Circulation patterns are set up within the surface and bottom layers.

If the wind is strong enough and persistent enough, the thermocline can tilt so far that it intersects the air–water interface near the upwind end of the weir pool in which case the water column at this end is effectively all bottom layer water. Continued winds then sees this upwelled water blown downwind and mixed laterally to some extent along the surface of the weir pool.

DISSOLVED OXYGEN DYNAMICS

The dissolved oxygen concentration in a waterbody reflects a balance between production by photosynthesis, respiration by all aquatic biota, air–water exchange of oxygen across the water surface, and gain/loss of dissolved oxygen as a result of inflows and outflows in the weir pool.

For most practical purposes, production of dissolved oxygen within a waterbody only occurs at depths less than the euphotic depth, Z_{eu} (Figure A2.1), below which less than 1% of light incident at the water surface penetrates. In most inland Australian river weir pools, Z_{eu} is between 1 and 2 m. During the daytime, dissolved oxygen concentrations in the surface layer typically exceed 100% saturation. This produces a concentration gradient causing a flux of oxygen from the water to the atmosphere so not all of the oxygen produced during the daily photosynthetic cycle is retained within the water column. The degree of supersaturation depends on the amount of phytoplankton growing in the water.

Below the surface layer, dissolved oxygen concentrations can drop very rapidly to less than 1 mg/L.

Consumption

All aquatic organisms, plants, animals, bacteria consume oxygen as they respire. The rate of respiration increases rapidly with increasing temperature. The combination of photosynthesis and respiration produces a characteristic daily cycle of dissolved oxygen concentration in the surface layer. Data for Burtundy Weir during Jan 2019 presented in NSWDPI (2019) investigation into the recent Menindee fish deaths illustrates this cycle well. Dissolved oxygen concentrations varied typically from 50% saturation at night to 250% saturation during the day (Figure A2.3). Note that no information was provided regarding the depth of measurement of dissolved oxygen, the depth of the weir pool or the location of the measurement within Burtundy weir pool.

Below the euphotic depth, in the bottom layer, respiration in the sediment and water column can rapidly deplete the available oxygen. Depending on the water chemistry, a range of reduced compounds may accumulate as oxygen, nitrate, sulphate are depleted. This can lead to a very large 'oxygen debt' developing which may rapidly consume oxygen as it becomes available.

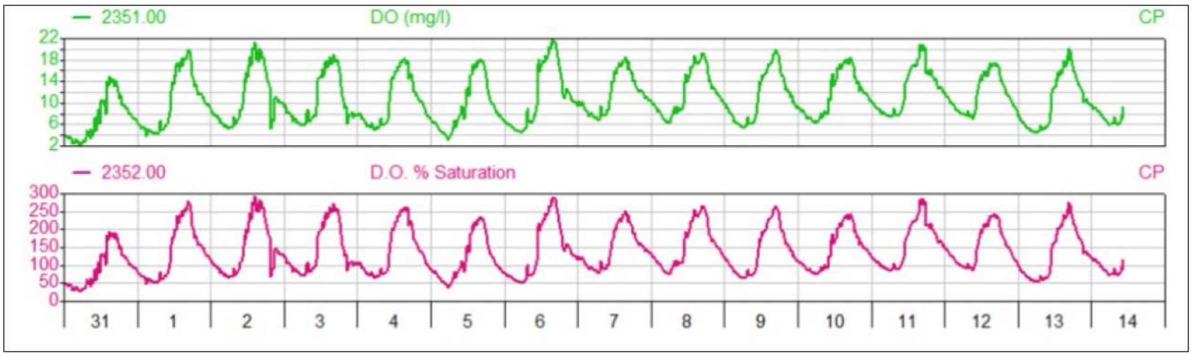

Figure A2.3 Dissolved oxygen concentrations (top panel) and level of saturation (bottom panel) at Burtundy on the Darling River from 21/12/2018 to 14/1/2019. From NSWDPI (2019) based on WaterNSW data.

Dissolved oxygen response to mixing events

When a weir pool is characterised by such a dynamic dissolved oxygen content in the surface layer as suggested by Figure A2.3 and a potentially large oxygen debt in the bottom layer, the timing of mixing events can be very important. For example, consider a weir pool with a surface layer of 1 m and a bottom layer of 2 m thickness with a surface layer dissolved oxygen concentration similar to that shown in Figure A2.3. If complete mixing happened instantly during midday, the dissolved oxygen concentration would, by simple mass balance, become 85% of saturation throughout the water column and would then fall as the oxygen debt from the bottom layer is 'paid off'. Whether or not there is enough oxygen available to pay the debt and support the local ecology will depend on how big the debt is.

If this same mixing event occurred at 05:00 when surface layer dissolved oxygen concentration is 50% then the resultant instantaneous concentration becomes 17% before any of the accrued oxygen debt is paid off. At a temperature of 25 °C, the saturation concentration of oxygen in water is about 8 mg/L so everywhere in the weir pool will experience roughly 1.5 mg/L before considering the demand from the bottom layer debt. When mixing is forced by weather, it occurs effectively over the entire weir pool so the impact of hypoxia could be quite widespread.

WHAT HAPPENED AT WEIR 32?

Data are scarce for the Menindee system during the fish kills in December 2018 and January 2019. In Figure A2.4, I've tried to lay out what I could discern from the available data and placing it in the context of the basic physical and chemical principles described above.

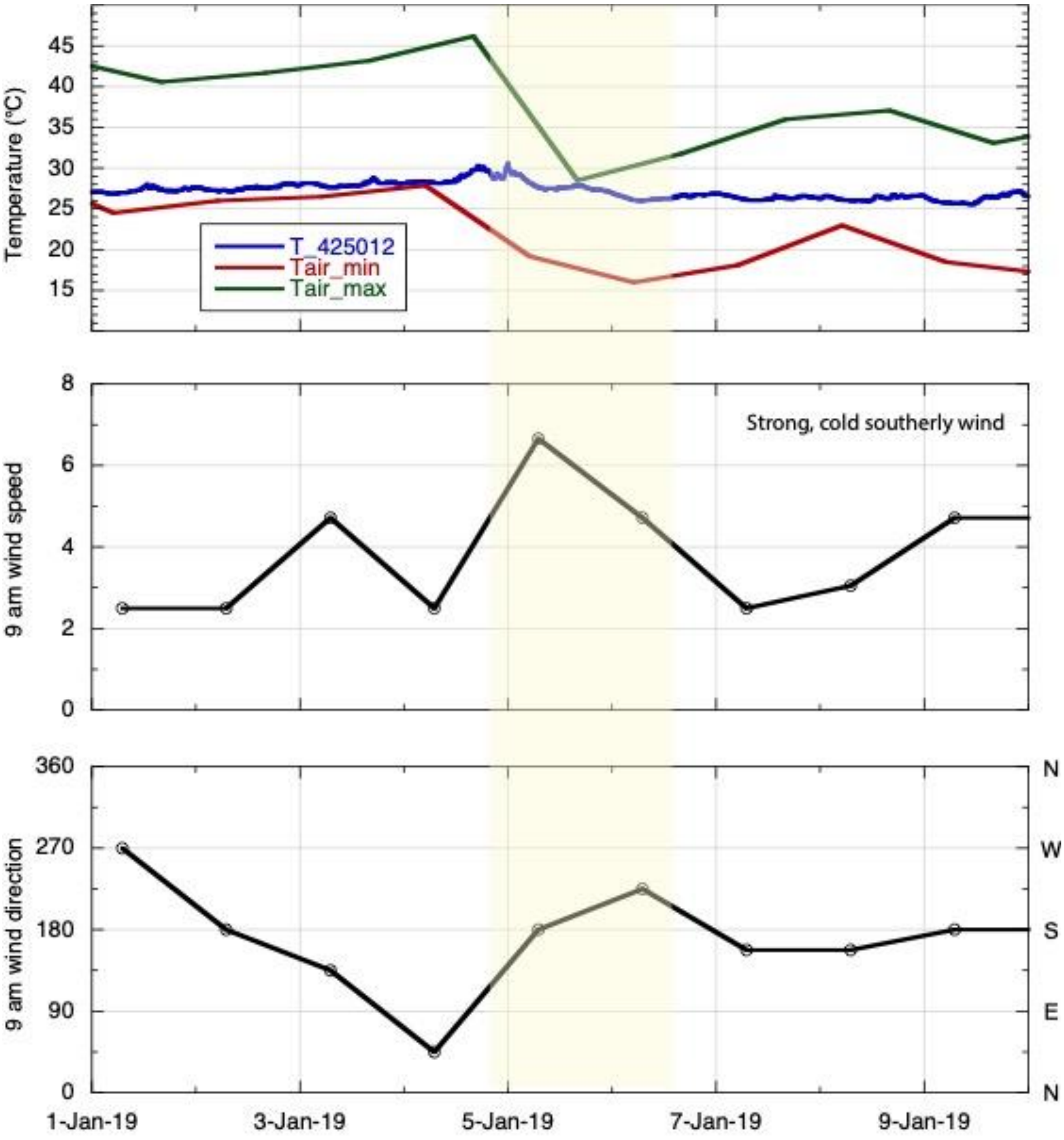

Figure A2.4 Maximum and minimum daily air temperature, 9 am wind speed and direction measured at Menindee Post Office and water temperature upstream of Weir 32 (site 425012). Times of minimum and maximum temperature are assumed to be 0500 and 1600, respectively.

The passage of the cold front on 5 and 6 January are clearly evident in Figure A2.4 and have been commented on by many others previously. A very interesting feature of the figure is the very strong southerly wind that accompanied the cold front. The 09:00 wind speed increased from 2.5 to 6.5 m/s. If sustained (these are point measurements) over time, this represents a 6-fold increase in wind mixing energy and nearly a tripling of the sensible and latent heat fluxes. Such an event would be expected to cause significant deepening of the surface layer.

Figure A2.5 shows water quality profiles measured at three locations along Weir 32 by WaterNSW on 7 Jan 2019. The temperature. All sites clearly show surface layer deepening to 3 m in the temperature profile data and no indication of mixing below 3 m at the Town Gauge or N1095 (further upstream). All profiles were measured between 12:50 and 13:33. The much colder (by 2.5 °C) surface temperature and very low dissolved oxygen concentration observed at u/s Weir 32 is consistent with the surface drift and associated upwelling that would have accompanied the strong southerly wind as this site is at the upwind end of a N-S-aligned reach whereas the other two sites are along an E-W-aligned reach and would not experience as much wind-induced transport.

There is clearly a pronounced horizontal gradient in dissolved oxygen with concentration decreasing at a given depth in the downstream direction. Discharge was sustained at >300 ML/day from mid-December 2018 through 5 January 2019. From 5 to 7 January there was a mostly steady decrease in discharge from 300 to 200 ML/day. The dissolved oxygen profiles may indicate progressive consumption of dissolved oxygen at 1 m depth and below as water moved along the weir. Without information regarding the inflow conditions, i.e. inflow temperature, flow rate, and dissolved oxygen concentration, it is not possible to speculate any further.

Because the Main Weir upstream of Weir 32 can be quite deep for a weir pool (12 m maximum depth) and photos of the weir from the WaterNSW web site show that water can be discharged from the bottom of the Main Weir, some consideration should be given to the potential role of discharge from the Main Weir directly into the Darling River. Water discharged directly from the weir could be expected to be relatively colder and with less dissolved oxygen than water that is routed through the overflow regulators via Lake Pamamaroo.

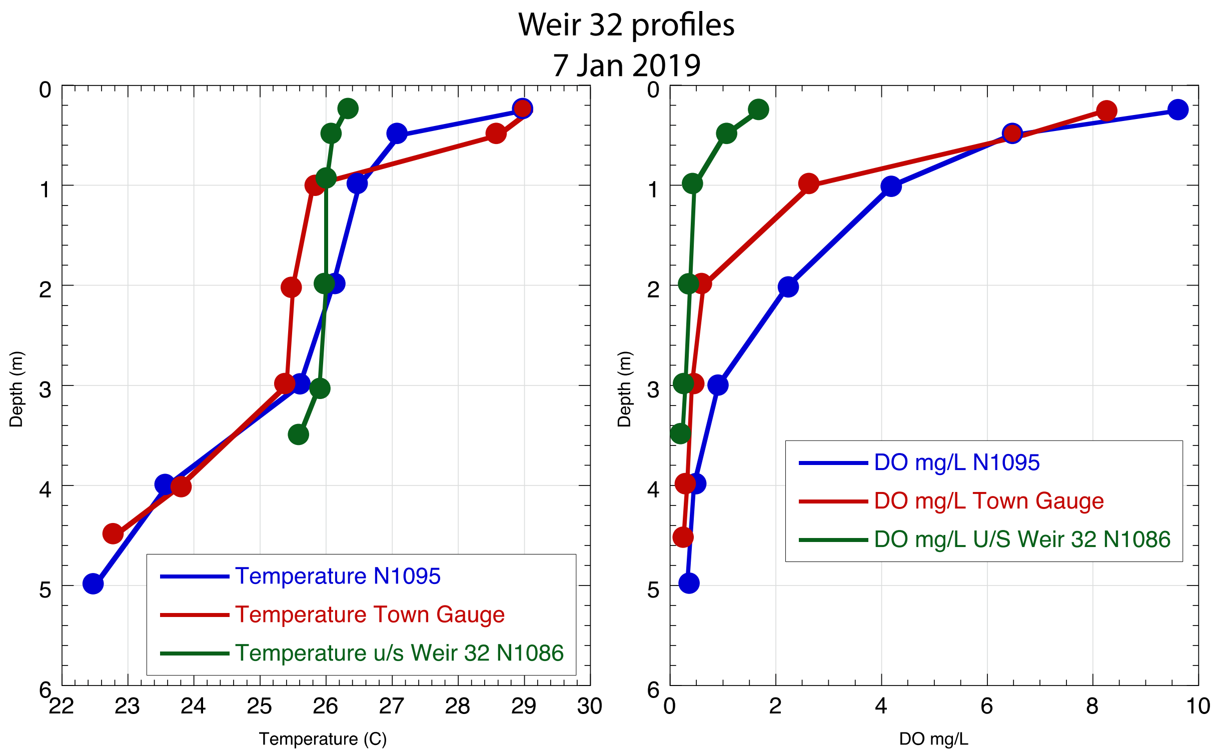

Figure A2.5 Water quality profiles measured by WaterNSW at Weir 32 on 7 Jan 2019.

It seems likely that the fish kills at Weir 32 are a direct consequence of low dissolved oxygen concentrations throughout the water column such that the fish were unable to find suitable oxic refugia following the onset of hypoxic stress.

It is conceivable that maintaining the weir pool water level with diminished flows because of the drought will create a system that oscillates between the accrual of substantial oxygen demand in the bottom layer during the 10–14 day warming periods punctuated by 2–5 day mixing events driven by cold fronts and stronger winds which lead to hypoxic conditions throughout the water column.

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APPENDIX 3: WATER RESOURCE DEVELOPMENT, FLOW ANALYSIS AND RAINFALL INDICES FOR THE DARLING RIVER AND ITS TRIBUTARY CATCHMENT

WATER RESOURCE DEVELOPMENTS

Table A3.1 Tributary rivers and their catchment areas (numbered in Figure 7, main report), wetland area, average diversions and storage capacity (public and private) in major river systems of the Darling River System.

River system	Catchment area (km^2)	Wetland area (ha)[a]	Average annual diversion from river valley in 2014-2015 and 2015-2016[b]	Public storage capacity (ML)	Private storages capacity (ML), (date of available assessment)[c]
1. Border River and Moonie Rivers	65,300	118,852	189,045	642,200	512,290 (NSW 2018, QLD 1998)
2. Condamine-Balonne	158,770	1,284,284	309,625	233,700	1,582,000 (QLD) (2007)
3. Darling River	174,680	580,179	78,870	2,312,500	298,000 (2007)
4. Gwydir	25,930	56,688	130,590	1,361,000	614,000 (2018)
5. Macquarie-Bogan/ Castlereagh	109,900	438,758	122,980	1,543,000	94,000 (2007)
6. Namoi/ Peel	43,050	52,237	176,325	925,000	209,000 (2007)
7. Paroo	76,200	1,000,044	10	0	0
8. Warrego	72,800	1,007,041	5,095	4,800	19(QLD,2007)
Total	726,330	4,538,083	1,013,275	7,022,,200	3,309,309

[a] (Kingsford et al. 2004)

[b]Calculated using data from (Murray-Darling Basin Authority, 2017)

[c]data from (CSIRO, 2007a, Webb, 2007, Kingsford, 2000a, NSW Department of Industry, 2018, CSIRO, 2007b, CSIRO, 2007c).

SATELLITE IMAGERY OF THE DARLING RIVER CATCHMENTS IN 2016 AND 2018

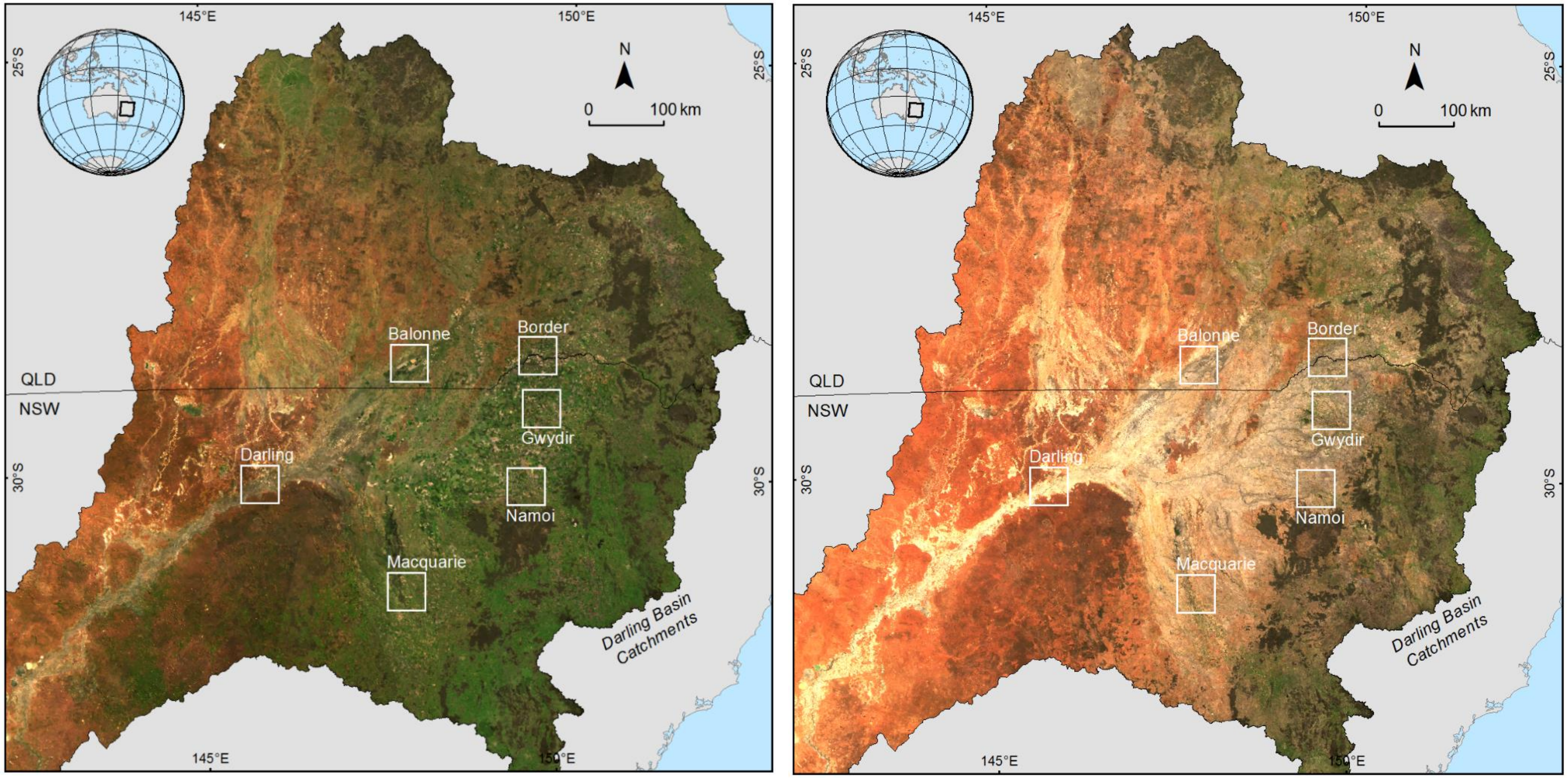

Figure A3.1 Darling River basin catchments in 8 day composite images on 29 Sept. 2016 (wet year) and 24 Oc. 2018 (dry) from MODIS sensor on the Terra/Aqua satellites at 500 m spatial resolution, processed to 8 day cloud free composites of surface reflectance, corrected for atmospheric conditions such as gasses, aerosols, and Rayleigh scattering (Vermote 2015) and downloaded from the United States Geological Survey (USGS) AppEEARS website. Squares identify some of the main areas of off-river storage concentration in each of the rivers (see Figure A3.2).

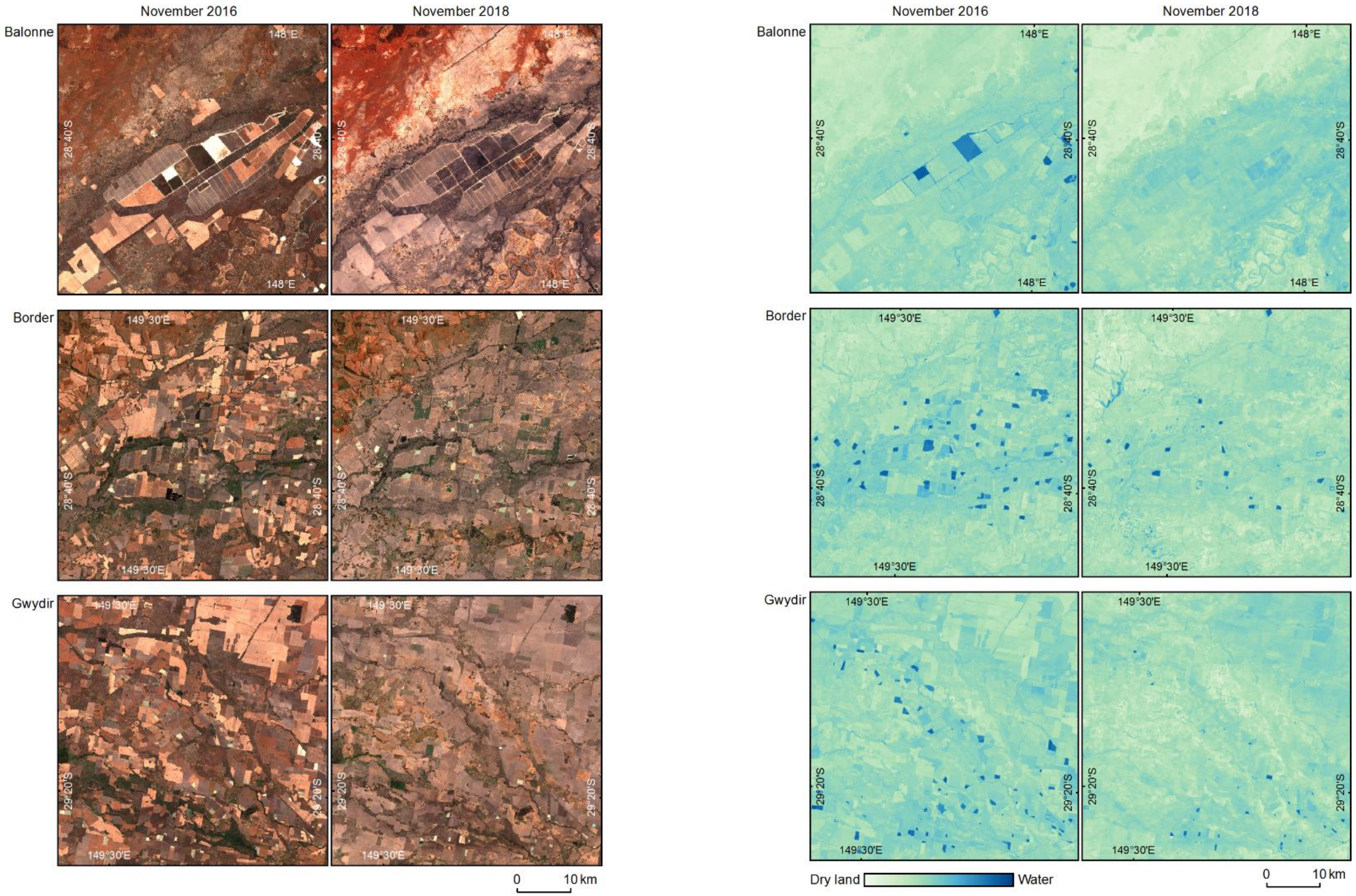

Figure A3.2 Images from the MSI sensor on the Sentinel2-A/B satellites, at 10 m spatial resolution of some major irrigation areas (see Figure A3.1), processed to surface reflectance, corrected for atmospheric conditions, adjusted to standard set of sun and view angles, and with topography adjusted to a horizontal surface (Flood et al. 2013, Flood 2017). The water index images (right) were created using an algorithm developed for Landsat satellite images (Fisher et al. 2016), applied to the corresponding Sentinel-2 image bands. The same scaling was applied to all images, so colour changes between images are due to changes in land cover.

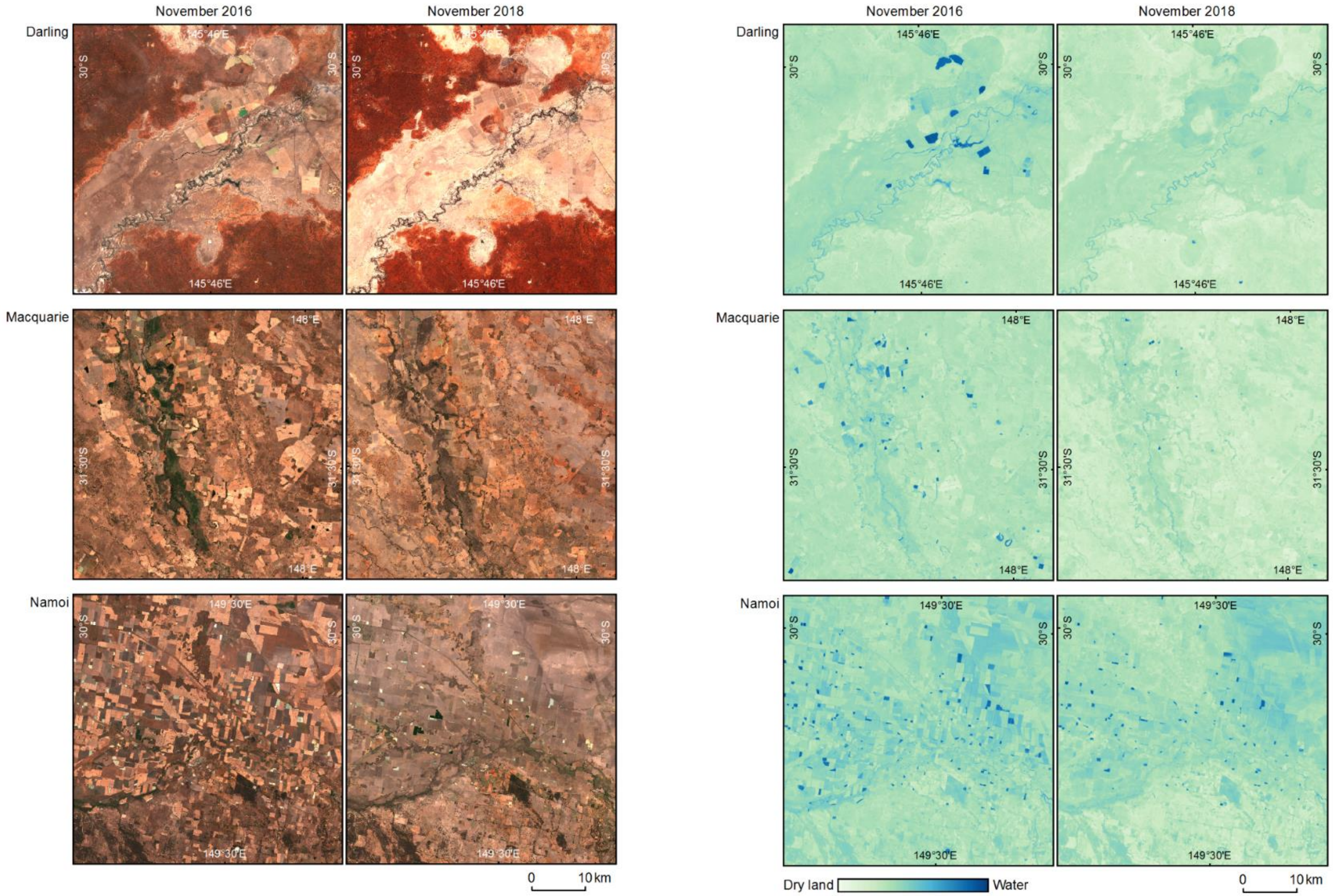

Figure A3.2 continued. Images from the MSI sensor on the Sentinel2-A/B satellites, at 10 m spatial resolution of some major irrigation areas (see Figure A3.1), processed to surface reflectance, corrected for atmospheric conditions, adjusted to standard set of sun and view angles, and with topography adjusted to a horizontal surface (Flood et al. 2013, Flood 2017). The water index images (right) were created using an algorithm developed for Landsat satellite images (Fisher et al. 2016), applied to the corresponding Sentinel-2 image bands. The same scaling was applied to all images, so colour changes between images are due to changes in land cover.

Table A3.2 Areas of off-river storages calculated in each of the different subset areas during 2016 and 2018, classified using the optimum threshold (Fisher et al. 2016), and all water pixels within each subset area were counted.

	2016		2018	
Subset	**Date**	**Water area (km²)**	**Date**	**Water area (km²)**
Balonne	22/11/16	36.21	12/11/18	0.51
Border Rivers	19/11/16	45.57	24/11/18	15.83
Gwydir	19/11/16	36.16	24/11/18	7.41
Namoi	9/12/16	33.47	24/11/18	17.42
Macquarie	9/12/16	15.88	24/11/18	1.99
Darling	22/11/16	28.58	12/11/18	3.32
Total		195.87		46.48

CHANGES IN FLOW IN THE DARLING RIVER

Data for Darling River flows are available for long periods of time, before water resource development (pre 1960) and afterwards (up to present), although availability varies among flow gauges on the river (Figure A3.3). In particular, there are limited data for Menindee flow gauge, after the 1960s, coinciding with the development of the Menindee Lakes Scheme. Data for Wilcannia provide a useful surrogate for flows into Menindee Lakes, given there was a high positive correlation (97% variation explained) between annual flows at Wilcannia and Menindee before water resource development in the Darling River. At any particularly time and place, the river flows and the distribution of water (e.g. in lakes, waterholes and floodplains) in the Darling River are a complex reflection of the relative contribution of river flows from the tributary catchments, temperature and the past flooding and drying. More particularly, the current state of the flows in the Darling River is a result of flow and flooding regimes over at least the past five years, not just 2018. The Darling River flows fluctuate considerably between periods of high and low to no flow, indicative of high variability (Thoms and Sheldon 2000; Figure A3.4). Generally, large floods (overbank flows) occur about every decade but there are a range of small, medium and large floods (freshes) which connect the river, its waterholes, floodplains and other wetlands.

Flows progress down the Darling River eventually to where the Darling meets the River Murray at Wentworth. Importantly, particularly for the Darling River, much of the flow in the Darling River and its tributaries exceeds the channel capacity of the main river channels and flows out onto the floodplain, including swamps and lakes (Kingsford et al. 2004). Naturally, flows inundate large areas of wetlands in each of the tributary catchments and the Barwon-Darling River (Figure 7 main report; Table A3.1), as well as flowing into aquifers. Most wetlands, apart from those relatively few that fill from groundwater or local rainfall, rely on water delivered by rivers or creeks (Kingsford 2001, Kingsford 2004a, Kingsford 2004b, Murray-Darling Basin Authority 2012).

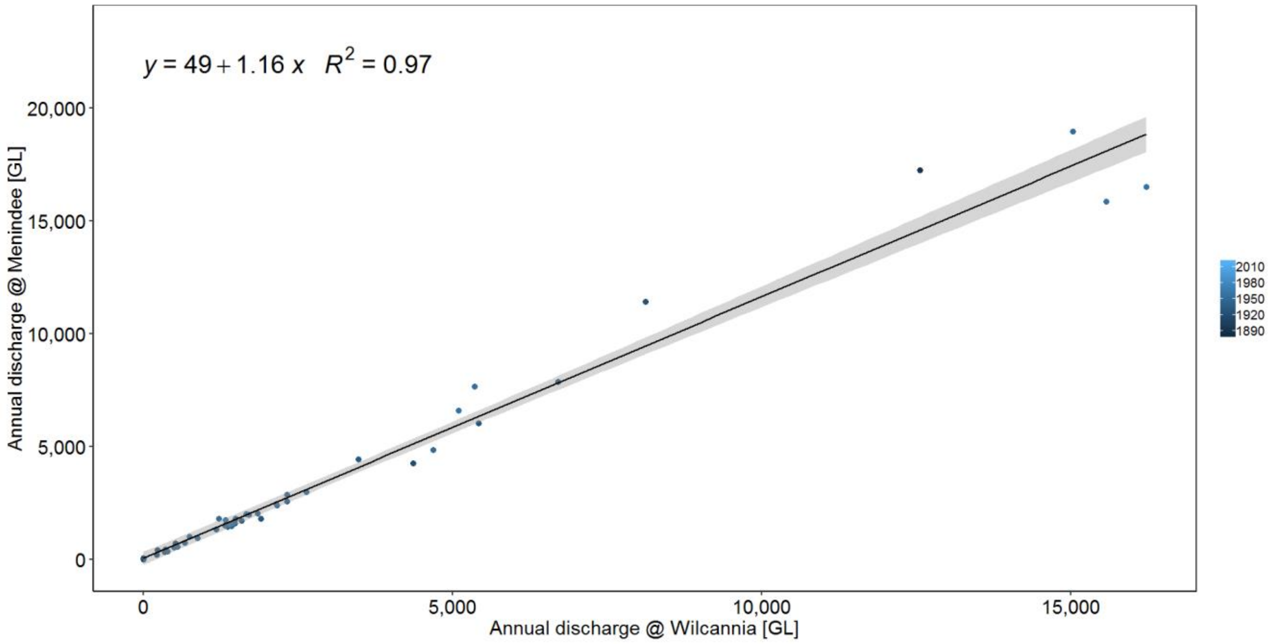

Figure A3.3 Relationship between annual flows at Menindee and Wilcannia.

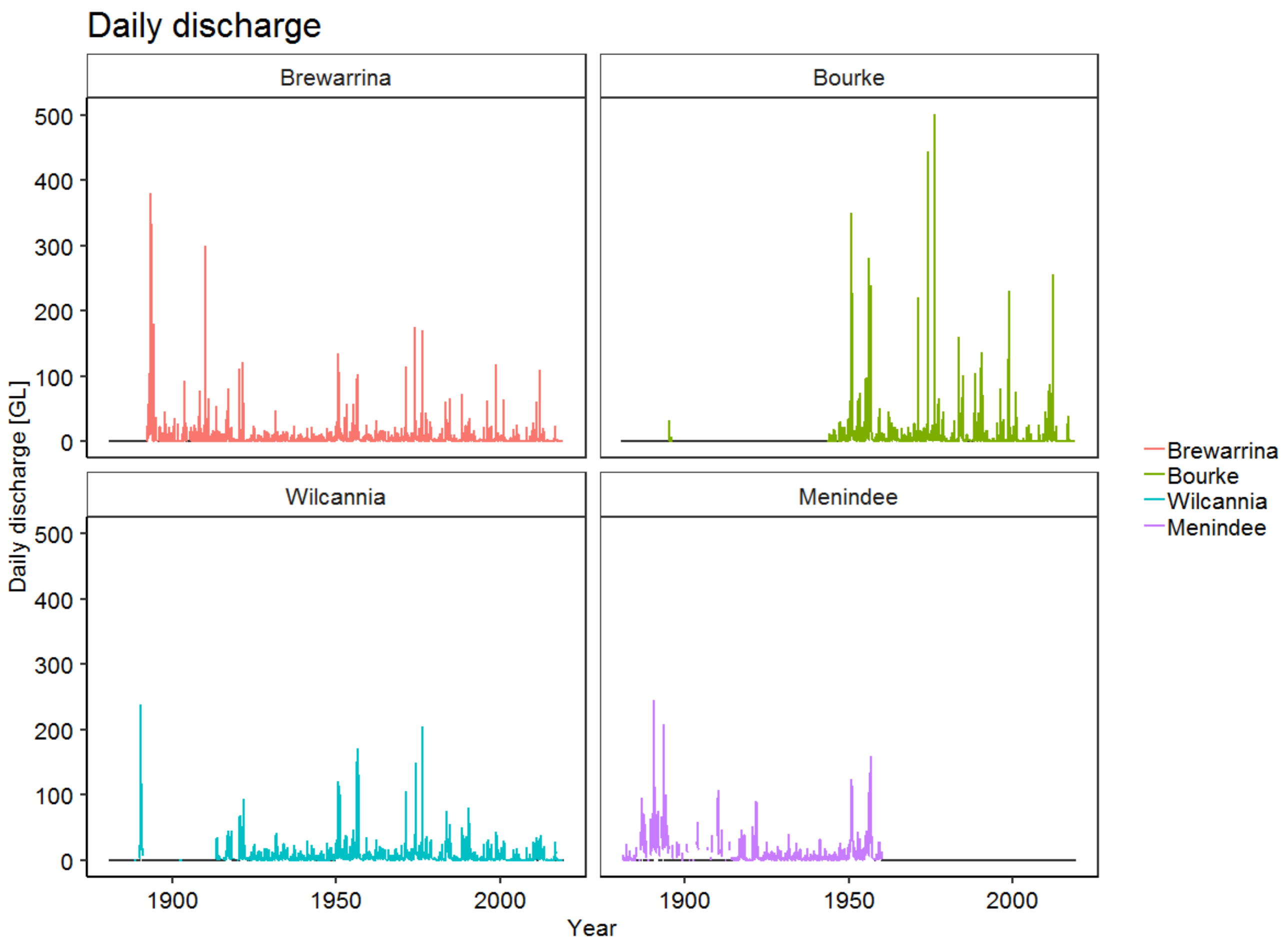

Figure A3.4 Long-term annual flow or discharge (GL) in the Darling River, measured at Brewarrina, Bourke, Wilcannia and Menindee, illustrating availability (colours) and gaps in observed data (black lines).

Table A3.3 Mean proportion of annual flow volume reaching the three flow gauges on the Darling River (Figure 7, main report), as a proportion of annual flow without development (modelled data, Murray-Darling Basin Authority, Figure 6).

Gauge	Water decade	Mean	Median	SD	LQ	UQ
Brewarrina	1890-1899	1.05	1.16	0.34	0.72	1.28
	1900-1909	1.13	1.09	0.59	0.60	1.94
	1910-1919	1.27	1.23	0.51	0.71	1.94
	1920-1929	0.74	0.72	0.17	0.55	0.86
	1930-1939	0.76	0.78	0.15	0.62	0.97
	1940-1949	0.65	0.60	0.16	0.46	0.86
	1950-1959	0.93	0.94	0.25	0.68	1.22
	1960-1969	0.93	0.94	0.22	0.71	1.12
	1970-1979	0.80	0.83	0.15	0.62	0.97
	1980-1989	0.78	0.74	0.22	0.53	1.02
	1990-1999	0.58	0.59	0.26	0.24	0.91
	2000-2009	0.38	0.38	0.12	0.25	0.52
Bourke	1940-1949	0.58	0.49	0.21	0.41	0.83
	1950-1959	0.84	0.85	0.29	0.55	1.16
	1960-1969	0.71	0.74	0.19	0.49	0.91
	1970-1979	0.76	0.81	0.22	0.53	1.00
	1980-1989	0.69	0.76	0.26	0.38	0.90
	1990-1999	0.55	0.49	0.29	0.18	0.89
	2000-2009	0.30	0.28	0.14	0.15	0.45
Wilcannia	1910-1919	0.73	0.64	0.29	0.48	1.08
	1920-1929	0.69	0.71	0.32	0.31	0.96
	1930-1939	0.77	0.78	0.17	0.57	0.94
	1940-1949	0.62	0.61	0.16	0.47	0.78
	1950-1959	1.12	0.84	0.71	0.66	1.72
	1960-1969	0.76	0.72	0.22	0.54	0.98
	1970-1979	0.93	0.91	0.37	0.55	1.32
	1980-1989	0.72	0.72	0.24	0.39	0.98
	1990-1999	0.60	0.52	0.32	0.23	1.08
	2000-2009	0.29	0.30	0.19	0.11	0.57

Table A3.4 Mean proportion of annual flow volume reaching the three flow gauges on the Darling River (Figure 7, main report), as a proportion of annual flow without development (modelled data, Murray-Darling Basin Authority, Figure 11, main report) for three periods (before 1960, 1961-2009).

Gauge	Periods	Mean	Median	SD	LQ	UQ	N
Brewarrina	pre-1960	0.92	0.80	0.40	0.56	1.45	64
	1960-2008	0.70	0.73	0.27	0.30	0.99	49
	2009-2018	0.34	0.34		0.34	0.34	1
Bourke	pre-1960	0.74	0.74	0.29	0.44	1.01	64
	1960-2008	0.61	0.60	0.28	0.18	0.92	49
	2009-2018	0.27	0.27		0.27	0.27	1
Wilcannia	pre-1960	0.79	0.74	0.42	0.49	1.12	64
	1960-2008	0.67	0.64	0.34	0.22	1.03	49
	2009-2018	0.33	0.33		0.33	0.33	1

Table A3.5 Significance testing of changes, after vs. before development, in the observed annual flow volume reaching the three flow gauges on the Darling River (Figure 10, main report) as a proportion of annual flow without development as modelled by the Murray-Darling Basin Authority.

Gauge	Period	Period	estimate	SE	df	t.ratio	p.value
Bourke	1960-2008	pre-1960	-0.08	0.05	267	-1.53	0.13
Brewarrina	1960-2008	pre-1960	-0.12	0.04	267	-3.24	<0.01
Wilcannia	1960-2008	pre-1960	-0.07	0.04	267	-1.83	0.07

Table 3.6 Descriptive statistics of observed annual discharge by decades 1890-2010 for Brewarrina, Bourke and Wilcannia where data were available (see Figure 7, main report), showing mean, median, SD, LQ (lower quartile), UQ (upper quartile) and mean number of days, matching Figure 10, main report).

Gauge	Water decade	Mean (GL)	Median (GL)	SD (GL)	LQ (GL)	UQ (GL)	Mean N
Brewarrina	1890-1899	4,938	2,144	6,216	629	13,100	320.6
	1900-1909	2,114	1,313	1,920	833	3,409	357.4
	1910-1919	2,771	1,905	2,675	398	6,805	365.2
	1920-1929	1,614	1,093	1,645	281	4,013	365.3
	1930-1939	1,203	978	832	301	2,083	365.1
	1940-1949	988	1,088	457	440	1,440	359.2
	1950-1959	4,341	3,506	3,653	767	8,773	365.2
	1960-1969	1,365	1,277	683	717	2,217	365.3
	1970-1979	3,007	2,535	1,956	1,178	5,531	365.2
	1980-1989	1,661	1,497	1,330	476	2,784	365.3
	1990-1999	1,843	1,184	2,024	191	3,437	365.2
	2000-2009	643	418	783	135	1,111	365.3
	2010-2018	1,376	666	1,814	78	4,390	349.8

(Continued)

Gauge	Water decade	Mean (GL)	Median (GL)	SD (GL)	LQ (GL)	UQ (GL)	Mean N
Bourke	1890-1899	741	741	684	355	1,128	166.5
	1940-1949	1,352	1,601	563	642	1,812	344.8
	1950-1959	7,837	5,748	7,518	1,309	18,139	365.2
	1960-1969	1,679	1,195	1,106	815	2,902	365.3
	1970-1979	5,312	3,478	4,637	1,680	11,335	365.2
	1980-1989	2,912	2,781	2,765	522	4,773	345.0
	1990-1999	3,100	1,516	3,478	180	7,602	365.1
	2000-2009	805	398	1,042	123	1,599	365.3
	2010-2018	2,348	935	3,231	84	7,841	349.8
Wilcannia	1880-1889	0	0	0	0	0	122.5
	1890-1899	7,834	10,945	6,832	2,189	12,234	131.0
	1900-1909	0	0	0	0	0	121.3
	1910-1919	1,979	520	2,573	188	5,295	226.0
	1920-1929	2,370	1,539	2,496	311	5,689	331.6
	1930-1939	1,481	1,392	1,054	387	2,713	365.2
	1940-1949	1,282	1,273	631	544	2,162	337.8
	1950-1959	6,933	4,889	6,205	1,316	15,638	365.2
	1960-1969	1,585	1,183	1,027	740	2,869	365.3
	1970-1979	4,463	3,356	3,384	1,691	9,259	365.2
	1980-1989	2,391	1,395	2,864	411	4,152	365.3
	1990-1999	2,393	1,574	2,294	267	5,500	365.2
	2000-2009	722	315	915	80	1,829	360.6
	2010-2018	1,656	908	2,004	47	4,522	347.3
Menindee	1880-1889	3,152	498	6,269	0	8,266	280.7
	1890-1899	9,954	9,466	8,146	1,146	18,991	209.4
	1900-1909	1,296	879	1,696	0	3,010	126.8
	1910-1919	2,326	751	2,635	164	4,992	250.0
	1920-1929	2,849	1,754	3,427	290	6,577	365.3
	1930-1939	1,706	1,549	1,313	436	3,135	365.2
	1940-1949	1,541	1,608	776	618	2,485	365.3
	1950-1959	7,819	5,731	6,823	1,465	16,768	362.1
	1960-1969	1,371	1,371	NA	1,371	1,371	275.0

Table A3.7 Descriptive statistics of observed annual discharge by three different periods (pre-1960, 1960-2008, post 2008) 1890-2018 for Brewarrina, Bourke and Wilcannia where data were available (see Figure 7, main report), showing mean, median, SD, LQ (lower quartile), UQ (upper quartile) and mean number of days, matching Figure 10, main report).

Gauge	Period	Mean (GL)	Median (GL)	SD (GL)	LQ (GL)	UQ (GL)	N.Years
Brewarrina	pre-1960	2,502.93	1,280.73	3,133.26	441.92	6,309.30	49
	1960-2008	1,733.22	1,348.21	1,609.90	262.44	3,708.26	49
	2009-2018	1,274.90	261.68	1,753.62	85.91	4,333.35	49
Bourke	pre-1960	4,887.07	1,767.52	6,449.69	585.10	13,708.86	18
	1960-2008	2,811.93	1,707.44	3,234.49	218.31	7,559.23	49
	2009-2018	2,161.24	297.12	3,126.92	92.51	7,758.19	11
Wilcannia	pre-1960	2,873.05	1,427.11	4,041.35	0.00	7,548.92	55
	1960-2008	2,352.17	1,665.04	2,557.79	268.33	5,560.15	49
	2009-2018	1,530.32	277.38	1,946.43	51.93	4,409.89	11
Menindee	pre-1960	3,915.26	1,706.62	5,435.33	167.89	11,263.03	73
	1960-2008	1,370.91	1,370.91	NA	1,370.91	1,370.91	1

Table A3.8 Significance testing of annual flow by period (pre-1960, 1961-2008, post 2008), with shading of significant probability values at $p<0.05$,

Gauge	Period 1	Period 2	estimate	SE	df	t.ratio	p.value
Brewarrina	1960-2008	2009-2018	1.14	0.61	383.00	1.87	0.06
	1960-2008	pre-1960	-0.32	0.34	383.00	-0.94	0.35
	2009-2018	pre-1960	-1.46	0.59	383.00	-2.47	0.01
Bourke	1960-2008	2009-2018	1.12	0.61	383.00	1.85	0.06
	1960-2008	pre-1960	-0.51	0.50	383.00	-1.01	0.31
	2009-2018	pre-1960	-1.63	0.70	383.00	-2.34	0.02
Wilcannia	1960-2008	2009-2018	1.25	0.61	383.00	2.05	0.04
	1960-2008	pre-1960	0.61	0.36	383.00	1.69	0.09
	2009-2018	pre-1960	-0.64	0.60	383.00	-1.07	0.29
Menindee	1960-2008	pre-1960	0.17	1.83	383.00	0.09	0.93

DAILY FLOW THRESHOLDS USED FOR ANALYSES OF DARLING RIVER FLOWS

Table A3.9 Flow thresholds used to analyse long-term changes on the Darling River at Bourke and Wilcannia flow gauges (see Figure 7, main report). Flow thresholds relate to different ecological and hydrological responses and adapted from those used by the NSW Government in relation to analysis of the Barwon-Darling Water Resource Plan and presented to the Stakeholder Advisory Panel.

Flow thresholds	Rationale	Bourke	Wilcannia
Cease to flow	Maintenance of all native fish species	<180 ML day^{-1}	<90 ML day^{-1}
Very low flows	Maintenance of all native fish species and and functions through maintenance of water quality	180-450 ML day^{-1}	90-400 ML day^{-1}
Base flow	Maintenance of all native fish species, including local movement opportunities	450-972 ML day^{-1}	400-4000 ML day^{-1}
Small freshes	Spawning of 'generalist' and 'river specialist' fish species; recruitment of 'generalist', 'flow specialist' and 'river specialist' fish species; improved condition of all native fish species, and; movement/dispersal opportunities) and functions	972-5400 ML day^{-1}	4000-10000 ML day^{-1}
Large freshes	Spawning of 'flow specialist' fish species; movement/dispersal opportunities, and; improved pre-spawning condition of all native fish species) and functions	5400-10000 ML day^{-1}	10000-20000 ML day^{-1}
Bankfull	Spawning and recruitment of 'floodplain specialist' native fish species; improved condition of all native fish species, and; movement/dispersal opportunities) and Vegetation and Functions	10000-35,000 ML day^{-1}	20000-29,000 ML day^{-1}
Overbank	Floodplain inundation, including floodplain vegetation communities stimulating flowering, seeding and germination, frog and waterbird habitats promoting breeding and recruitment, breeding and recruitment of native fish species, ecosystem services for grazing	>35,000 ML day^{-1}	>29,000 ML day^{-1}

Table A3.10. Other reported flow thresholds for the Barwon-Darling at Bourke and Wilcannia. – indicates no other thresholds proposed.

Flow thresholds	Bourke	Wilcannia
Cease to flow	–	–
Very low flows	20-450 ML day^{-1}; Small fish movements (MDBA 2018)	–
Base flow	500 ML day^{-1}, maintain native fish populations and spawning (Commonwealth Environmental Water Office); 450 ML day^{-1}, Algal suppression (Mitrovic et al. 2003); 440 ML day^{-1}, (Murray-Darling Basin Authority, 2018)	350 ML day^{-1}, Algal suppression (Mitrovic et al. 2003); 361 ML day^{-1}(Murray-Darling Basin Authority, 2018)
Small freshes	1,500 ML day^{-1}, CEWO enhance native fish spawning and recruitment	Flow pulse >2,000 ML day^{-1}, algal suppression
Large freshes	6,000 ML day^{-1}– small fresh (NSW Department of Primary Industries, 2015)	6,000 ML ML day^{-1} – small fresh (NSW Department of Primary Industries, 2015)
Bankfull	10,000 ML day^{-1}– large fresh (NSW Department of Primary Industries, 2015)	29,000 ML day^{-1} – large fresh (NSW Department of Primary Industries, 2015)
Overbank	30,000 ML day^{-1} – large fresh (NSW Department of Primary Industries, 2015) – mid floodplain (NSW Department of Primary Industries, 2015) – outer floodplain (NSW Department of Primary Industries, 2015)	>30,000 ML day^{-1} – outer floodplain (NSW Department of Primary Industries, 2015)

The main stem of the Darling River includes a river channel, many distributary creeks and watercourses onto the floodplain, and billabongs. The main channel of the river also includes 'in channel benches', essentially small 'steps' on the river bank; these benches accumulate debris (e.g. leaf litter) which builds up and they have a similar function to small floodplains (Thoms and Sheldon, 1997, Thoms et al. 2006, Murray-Darling Basin Authority 2018). Generally, low to medium flows (small and large freshes, bankful flows) remain within the banks of the Barwon-Darling River (Appendix 5), with high flows inundating connected floodplain wetlands. Many of these waterholes and wetlands retain water for long periods of time so when a small flood comes down the river it 'tops up' water levels.

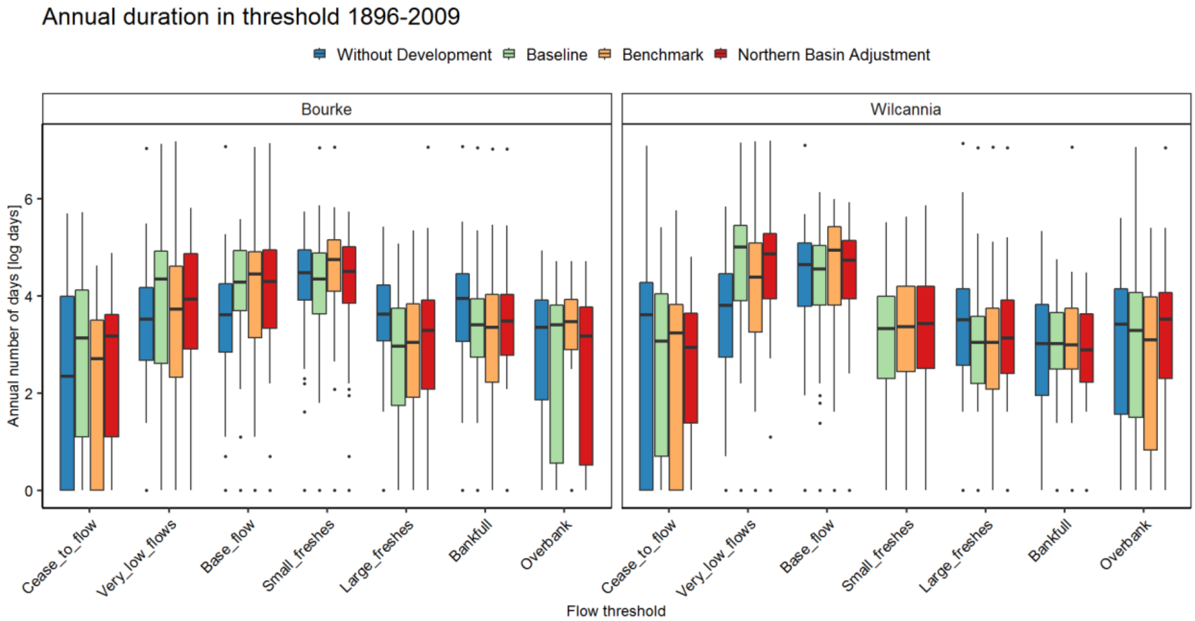

Figure A3.5 Changes to different flow thresholds for daily flow at Bourke and Wilcannia, using modelled data for without development, baseline (2008 level of development), benchmark (Murray-Darling Basin Plan 2012), Northern Basin adjustment (Murray-Darling Basin Plan, with 70GL less flow and other measures), in relation to different mutually exclusive levels of flows, related to fish ecology and floodplain ecology (Tables A3.9 and A3.10).

These changes in observed data at different thresholds were clearly apparent when observed proportions of flows at different thresholds were examined (Figure A3.5). The number of days of cease to flow and low flow days increased with reductions in river flows, following diversions upstream (Figure 12, main report). Similarly, there were reductions in small freshes, large freshes, baseflows and even overbank flows (Figure 12, main report). These differences were not as obvious in the modelled data but still occurred (Figure A3.5).

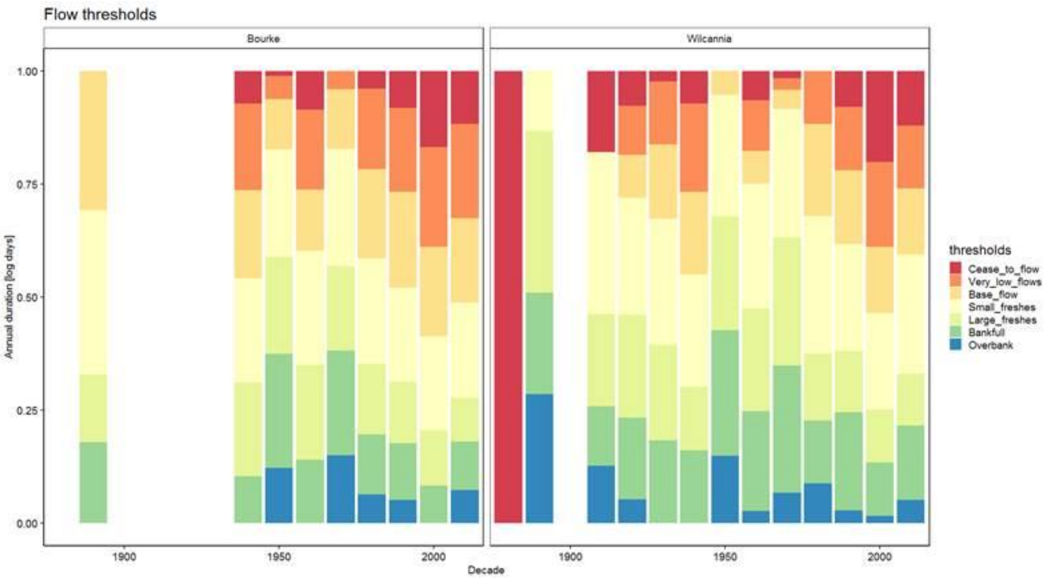

Figure A3.6 Proportional changes to different thresholds of daily flow at Bourke and Wilcannia, using observed, in relation to different mutually exclusive levels of flows, related to fish ecology and floodplain ecology (Tables A3.9 and A3.10).

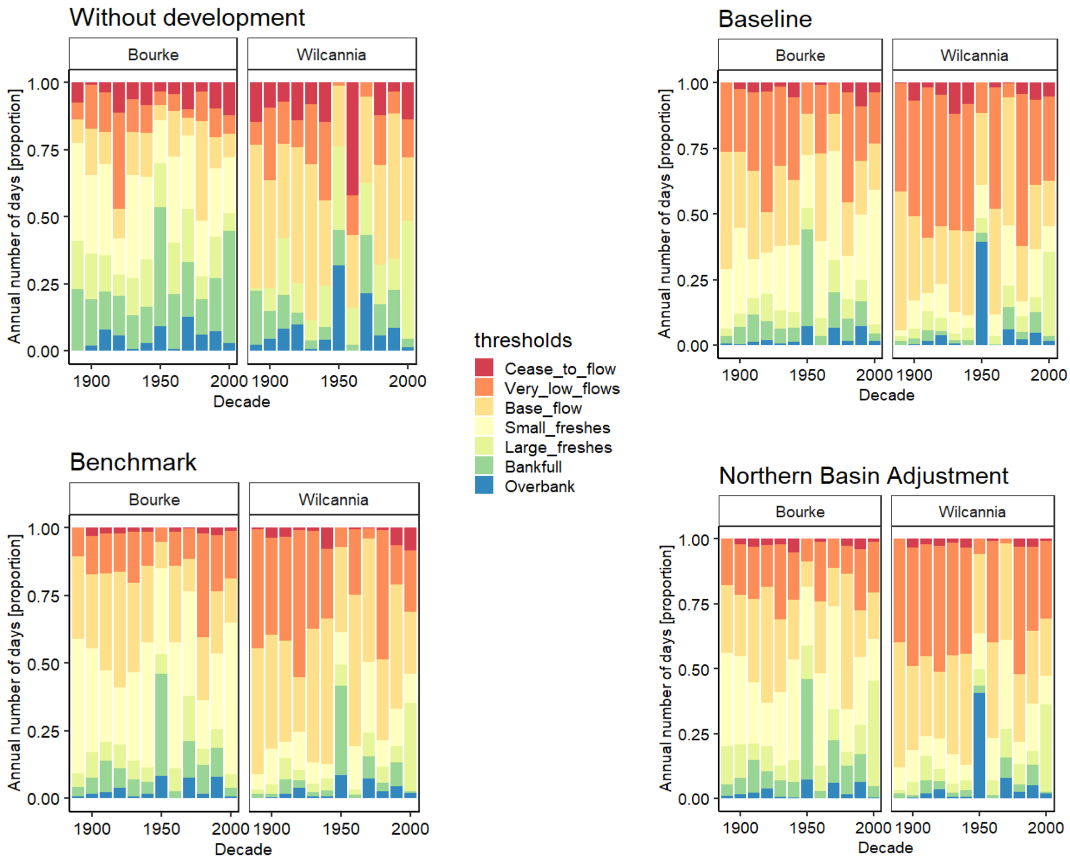

Figure A3.7 Proportional changes to different thresholds of daily flow at Bourke and Wilcannia, using modelled data for without development, baseline (2009 level of development), benchmark (Murray-Darling Basin Plan 2012) and Northern Basin Adjustment, in relation to different mutually exclusive levels of flows, related to fish ecology and floodplain ecology (Tables A3.9 and A3.10).

Table A3.11 Descriptive statistics of Cease to flow for different drought periods on the Barwon-Darling at Bourke and Wilcannia. NA – indicates no other thresholds proposed.

Droughts	Time Period	Bourke	Wilcannia
Federation Drought	1895-1903	NA	43.56±71.56sd
World War I drought	1914-1915	NA	46±21.21sd
World War I drought-5yr	1910-1915	NA	0
World War II Drought	1939-1945	146.5±64.35sd	83.57±58.74sd
Nineteen sixties drought	1965-1968	114.75±59.28sd	87.75±63.68sd
Nineteen sixties drought-5yr	1963-1968	0	0
Nineteen eighties drought	1982-1983	74±104.65sd	70.5±99.7sd
Nineteen eighties drought-5yr	1978-1983	10.5±21sd	22.75±45.5sd
Millennium Drought	2001-2009	166.33±108.84sd	171.33±111.3sd
Menindee fish kill drought	2017-2018	101±110.31sd	121±110.31sd
Menindee fish kill drought-5yr	2013-2018	155.5±96.26sd	142±105.21sd
Other years		26.52±53.18sd	23.23±47.69sd

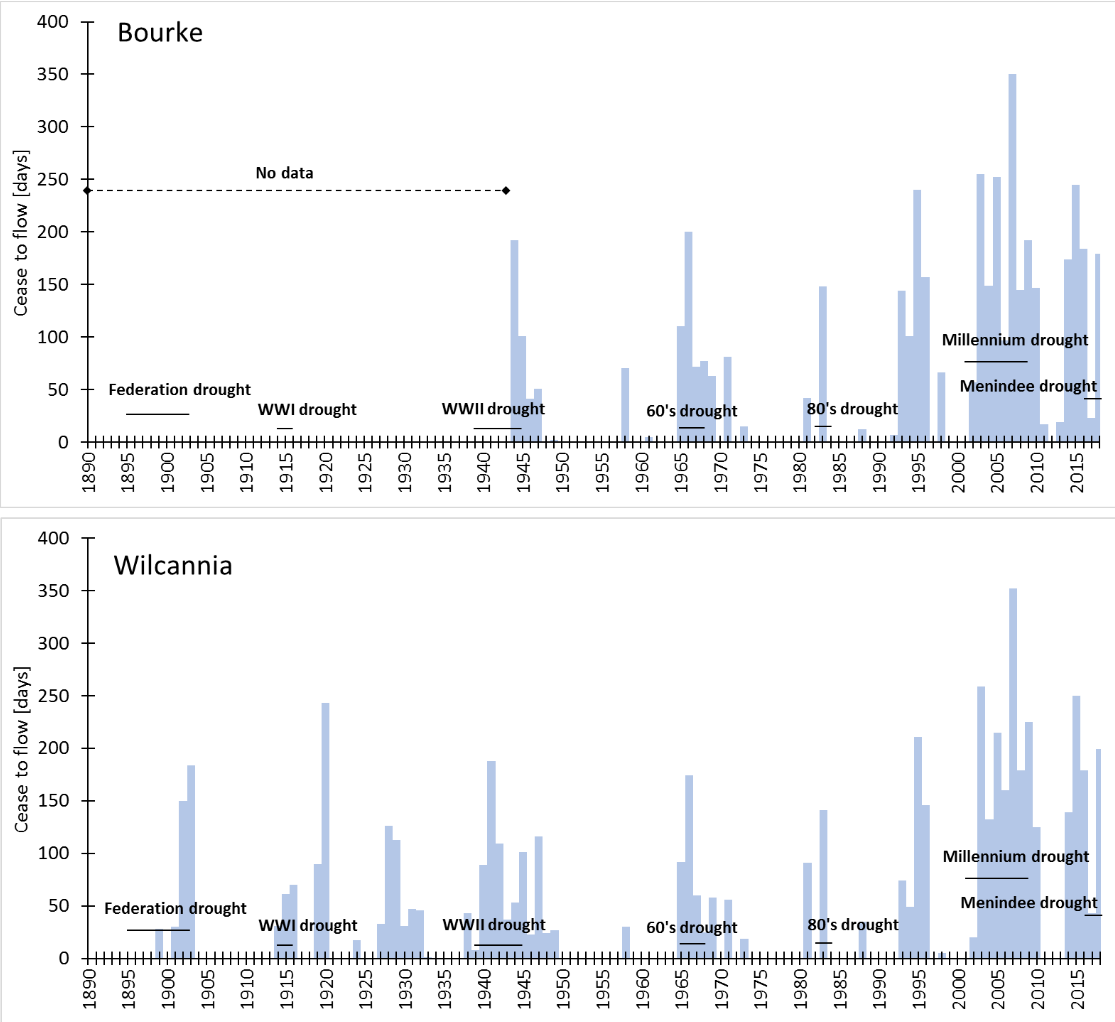

Figure A3.8 Changes in cease to flows in the Darling River at Bourke and Wilcannia, in relation to major drought periods, including current Menindee drought conditions.

ECOLOGICAL EFFECTS OF DIVERSIONS ON RIVER AND FLOODPLAIN ECOSYSTEMS OF THE DARLING RIVER

Wetlands in the Barwon-Darling are key environmental features or 'hotspots' for biodiversity within the system (Kingsford 2004a, Bino et al. 2016, Kingsford et al. 2016). Some wetlands are also connected to the river through distributary creek systems (i.e. downstream of the tributaries). They include billabongs, claypans, flood-outs, floodplains, lakes, lagoons, marshes, overflows, swamps, creeks and river channels. Water flows out from the main Darling River to fill these wetlands, down distributary creek systems. Examples along the Darling River include the Tallywalka and Terrywenyia Creek system and the Darling River Anabranch and its lakes (Figure 7, main report). There are many smaller such wetlands including billabongs and floodplains, dependent on river flows along the Barwon-Darling River system. There are also large areas of floodplain wetlands dependent on overbank flows in each of the tributary river catchments, although concentrated in some systems more than others (Table A3.1; Figure 7a, main report). These wetlands are predominantly defined by floodplain vegetation (e.g. river red gum *Eucalyptus camaldulensis*; black box *E. largiflorens*, coolibah *E. coolabah*). There are three large wetland areas which are not only recognised in the protected area network (i.e. National Parks and Reserves) but are also listed as wetlands of international importance under the Ramsar Convention: Macquarie Marshes, Gwydir wetlands and Narran Lakes (Pittock and Finlayson 2011).

Diversions of water in the Darling River and its tributary catchments has had profound ecological consequences for the rivers and downstream floodplain wetlands (Thoms et al. 1996, Sheldon et al. 2017). There is widespread loss and degradation of wetlands in the Murray-Darling Basin (Kingsford 2000b), considerably more than in the other 11 major river basins in Australia, largely because of the high development of water resources, through the building of dams (private and government) which allow for the diversion of water and the development of floodplains (Bino et al. 2016). Much of this has occurred in the Darling River catchments, where there has been significant development of water resources and widespread and ongoing degradation of wetlands (Kingsford and Thomas 1995, Kingsford 1999, Thoms 2003, Kingsford 2004a, CSIRO 2008). This has also affected water-dependent organisms, including vegetation, invertebrates, fish, amphibians and birds, including waterbirds.

Understanding from large intact floodplains is increasingly showing that many native fish species also require overbank flows and floodplain inundation (Kerezsy et al. 2014, Arthington and Balcombe 2017, Leigh et al. 2010). The removal of each of the flow events (Appendix 6) cumulatively increases the risk of poor water quality, reduces movements, spawning or reproductive events. It is the mismanagement of these flows that goes to the heart of fish kills, because there is a cumulative increase in the risk factors beyond the threshold of these fish. Native fish populations of the Murray-Darling Basin rivers and wetlands have greatly declined and have been estimated to be at about 10% of pre-European levels with the need for a range of recovery actions to be undertaken (Koehn and Lintermans 2012). While there are a range of threats that impact native fishes, the majority of these, and the greatest impacts are associated with water extraction and infrastructure. The provision of environmental water under the Basin Plan is a key component in recovery (Koehn et al. 2014). Its implementation is not about preventing fish kills, but reducing the risk of such catastrophic events, recovering populations and restoring ecological functions (Koehn and Lintermans 2012) so that there is resilience within populations to withstand any occasional but lesser events.

Golden perch is one of the highly mobile species and the Darling River population does not exist in isolation. This fish kill will also result in population reductions in the Murray River, both downstream in SA and upstream in NSW and Victoria. Also for Murray cod, a long-lived species (50+ years), effects on Murray cod populations will only occur over long-time frames (10+ years) (Koehn et al. 2012, King et al. 2009b). Recovery of both species will rely on either recolonization from other areas or increased spawning and subsequent recruitment (Zampatti et al. 2013a, Zampatti et al. 2013b, King et al. 2009a) from remaining or adjoining adult populations, both of which need to be facilitated by the provisions of additional flow pulses (Mallen-Cooper et al. 2003). Other actions to assist fish populations (eg. provision of fish passage (Baumgartner et al. 2014)) should be undertaken in addition to, not instead of the provision of flows. Fish kills are not a symptom of the recent drought. Large Murray cod, at least 20-30 years old which had survived the Millennium Drought (2002-2009) died. The major causes of flow reductions (especially components such as flow pulses) in the Darling River and caused by water extraction has produced a stressful environment for native, with few opportunities for them to escape.

The native fish species affected by the recent fish kills in the Darling River are indicators the state of integrity and resilience of the river ecosystem. Their loss in the kills provide a clear ultimate measure of overall river stress, not just from drought but from long term reductions in river flows. The statement that ‘fish need water’ is a simple truism but it does bely a more nuanced interpretation that includes aspects of flow components and their ecological importance; pulses, amounts, timing, frequency, inundation and duration. It is these components that should be utilised in the determination of environmental flows (Bunn and Arthington 2002, Vorosmarty et al. 2010, Arthington et al. 2010) but are also the ones that are largely removed by water diversion or extraction. It is these flow components that are most important ecologically and it is the magnitude of the loss of these small and medium flows, not average flow volume that should be considered. Understanding from large intact floodplains is increasingly showing that many native species also require overbank flows and floodplain inundation (Kerezsy et al. 2014, Arthington and Balcombe 2017, Leigh et al. 2010). The removal of each of the flow events cumulatively increases the risk of poor water quality, reduces movements, spawning or reproductive events. It is the mismanagement of these flows that goes to the heart of fish kills, because there is a cumulative increase in the risk factors beyond the threshold of these fish. Native fish populations of the Murray-Darling Basin rivers and wetlands have greatly declined and have been estimated to be at about 10% of pre-European levels with the need for a range of recovery actions to be undertaken (Koehn and Lintermans 2012). While there are a range of threats that impact native fishes, the majority of these, and the greatest impacts are associated with water extraction and infrastructure. The provision of environmental water under the Basin Plan is a key component in recovery (Koehn et al. 2014). Its implementation is not about preventing fish kills, but reducing the risk of such catastrophic events, recovering populations and restoring ecological functions (Koehn and Lintermans 2012) so that there is resilience within populations to withstand any occasional but lesser events.

Many other dependent plants, animals and microbe species (the biota) depend on flows of rivers and inundation patterns of wetlands. River flows are also essential for establishing microbial communities (Robertson et al. 2001) and invertebrate populations (Boulton and Lloyd 1991, Boulton et al. 2006, Jenkins and Boulton 2007), which form the basal food webs supporting higher level organisms (e.g. native fish, frogs, turtles, waterbirds). Reductions in low flow periods, or extended no-flow periods, affect the ecology of the river communities which are adapted to a different, pre-water resource development, flow regime (Rolls et al. 2012). Once flow regimes are altered, particularly in relation to reductions in the frequency and duration of flooding, many aquatic organisms decline in abundance and distribution (Boulton and Lloyd 1992, Gehrke et al. 1995, Brock et al. 2006, Kingsford et al. 2006, Jenkins and Boulton 2007, Ocock et al. 2014). There are major negative impacts to invertebrate communities (Boulton and Lloyd, 1991, Sheldon and Walker, 1997, Jenkins and Boulton, 2007), which, in turn, support many high order organisms.

Many different frog species depend on the flooding of wetlands to complete their life cycles (Wassens et al. 2010 Ocock et al. 2014). The ecology of turtle species is also greatly influenced by flooding regimes (Georges and Guarino 2017, Ocock et al. 2017). Waterbirds are highly dependent on wetland water regimes for their diversity, abundance and breeding (Kingsford and Thomas 1995, Kingsford 2004a). The Barwon-Darling River system and floodplain provides habitats for all of these groups of organisms and their interactions.

Perennial aquatic vegetation delineates the boundaries of wetlands and floodplains in the Darling River catchments. Common species includes lignum, river cooba (*Acacia stenophylla*), canegrass and the floodplain eucalypts (*Eucalyptus camaldulensis*), black box (*E. largiflorens*) and coolibah (*E. coolabah*). Reductions in the frequency of flows and inundation have caused high mortality of river red gums, with floodplain dependent vegetation increasingly replaced by terrestrial plants or agricultural crops (Catelotti et al. 2015). There are large areas of flood dependent vegetation on either side of the main channel of the Darling River, illustrated by the distribution of floodplain vegetation along the Darling River between Bourke and Wilcannia. In more frequently inundated wetlands, such as billabongs, sedges (*Cyperus* spp., *Eleocharis* spp.) also usually occur around the margins. Common Reed (*Phragmites australis*) and cumbungi (*Typha domingensis*) are also often present. During floods, a wide variety of wetland plants can become established, including water couch (*Paspalum paspaloides*), nardoo (*Marsiliea drummondii*) and red water-milfoil (*Myriophyllum verrucosum*) (Brock et al. 2006, Roberts and Marston 2011). There is now less 'overbank' flooding of floodplains and as a result less inundation of floodplain eucalypts that had initially established under natural flooding regimes (Murray-Darling Basin Authority 2018, Murray-Darling Basin Authority 2012).

There is also increasing evidence that many other animals not usually considered dependent on aquatic ecosystems, are also affected by the presence of floodplains and the habitats they provide. Woodland birds are more diverse and dependent on floodplain areas during dry periods when resources are scarcer in adjacent terrestrial habitats (Selwood et al. 2018, Selwood et al. 2017). With increasing mortality of floodplain forests as a result of reductions in flow regimes, these floodplain habitats have reduced productivity, effectiveness and importance for woodland birds.

Some threatened ecological communities are dependent on flows in the Darling River. This includes the *Coolibah - Black Box Woodland of the northern riverine plains in the Darling Riverine Plains and Brigalow Belt South bioregions*. In 2014, the independent Scientific Committee in NSW listed this community as endangered. The plant community included an overstorey of coolibah, black box, belah (*Casuarina cristata*), river cooba and eurah (*Eremophila bignoniiflora*) with mid-storey, including flood dependent, species such as lignum and Warrego summer grass (*Paspalidium jubiflorum*) http://www.environment.nsw.gov.au/threatenedspecies/CoolibahBlackBoxWoodland.htm This community occurs within the local government areas of Brewarrina, Central Darling and Walgett (locations that include the sites of the alleged unlawful diversions). The community is threatened by clearing and alteration of flow regimes exacerbated by '…*widespread modification of the floodplain by the construction of diversion banks, channels, levees, drains and upstream extraction of water for irrigation…*' which has considerably changed '*seasonality, periodicity, duration, frequency, depth and pattern of flood regimes*.'

There is also a significant amount of evidence about the impacts of degraded wetlands and reductions in environmental flows on waterbird communities across the Murray-Darling Basin (Kingsford 2004a, Kingsford and Thomas 2004, Paton et al. 2009, Kingsford et al. 2017), including decreasing the amount of breeding (Kingsford and Johnson 1998, Brandis et al. 2018, Brandis et al. 2011, Leslie 2001, Arthur et al. 2012). There are a 28 migratory waterbird species which use the major and minor wetlands. In addition, 19 waterbird species, listed as threatened under national and state legislation, are affected by upstream changes in river flows, including diversions. These include four Critically Endangered Species (curlew sandpiper, double-banded plover, Eastern curlew, great knot) and three Endangered Species (Australasian bittern, lesser sand plover, red knot), listed under national legislation (*Environment Protection and Biodiversity Conservation Act 1999*). There are also 18 waterbird species listed in different categories of risk of extinction (endangered, vulnerable, rare) of state legislation.

RAINFALL IN THE DARLING RIVER AND ITS TRIBUTARY RIVER CATCHMENTS

Rainfall in the tributary catchments, which drives flows into the Darling River, is highly spatially and temporally variable (Figure A3.9). Over more than a century, there are no clear trends in total annual rainfall contributing to flows into the Darling River and this does not vary before (pre 1960) or after the start of significant water resource development (post 1960, Tables A3.13 and A3.14). This absence in trends is generally supported by analyses of trends in the contributory catchments, with few significant trends (Figure 15, main report). Specifically, there were only three significant differences among 26 pairwise comparisons (1900-1959 compared to 1960-2008) in the Gwydir, Macquarie-Bogan/ Castlereagh and the Namoi (Table A3.14). Importantly, there was an indication of a significant positive trend in rainfall overall from all tributary catchments into the Darling River (Total cumulative, $p=0.06$, Table A3.14).

Table A3.12 Rainfall stations in each river catchment and their number (Bureau of Meteorology) used to develop a cumulative rainfall index for inflows into the Darling River.

River	Rainfall station	Rainfall Station Number
Border	Deepwater	056008
Condamine-Balonne	Mitchell	063076
	Dulacca	042010
Darling	Ivanhoe	049019
	Ivanhoe.AD	049000
Gwydir	Guyra.PO	056016
	Guyra.Hospital	056229
	Uralla	056034
	Bundara	056006
Macquarie_Bogan_Castlereagh	Binnaway	064013
	Blackville	055006
	Oberon	063063
	Gulgong	062013
	Sofala	063076
Namoi	Nundle	055041
	Weabonga	055172
	Quirindi	055049
Paroo	Hungerford	044181
Warrego	Nive	044057
	Morven	044050
	Minnie.Downs	035190

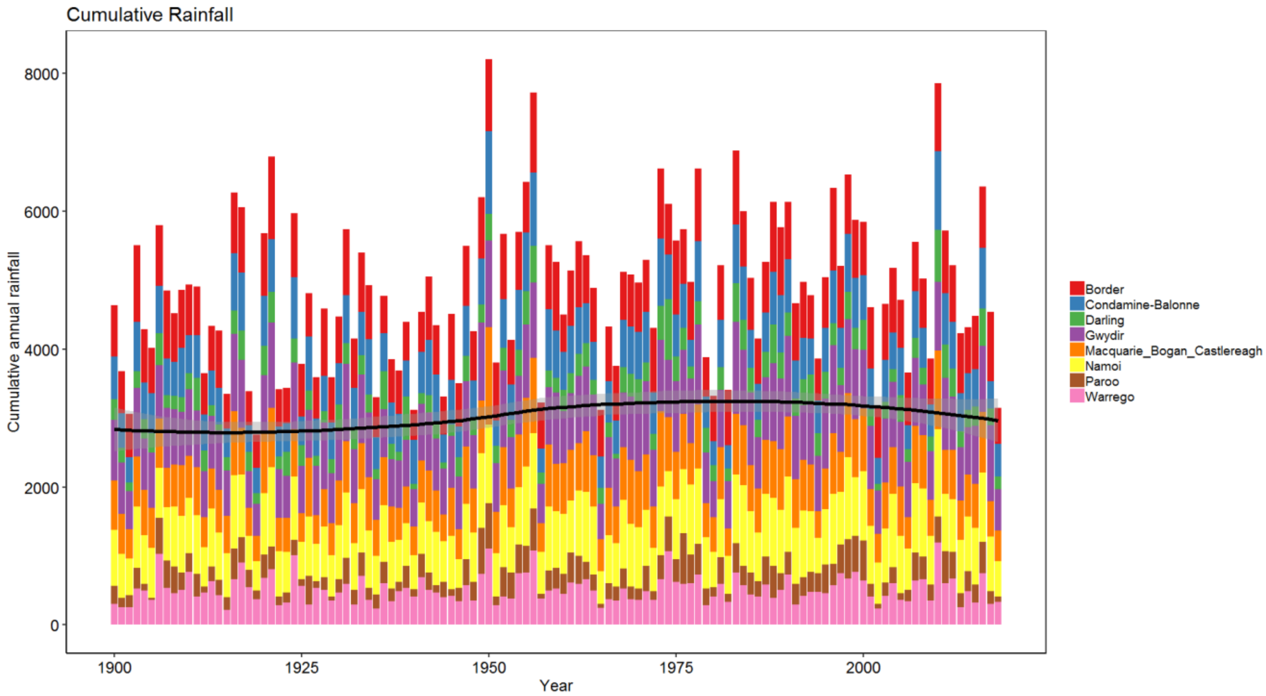

Figure A3.9 Cumulative annual rainfall in the upper catchments of all the major river catchments flowing into the Darling River, with long-term trend line (black).

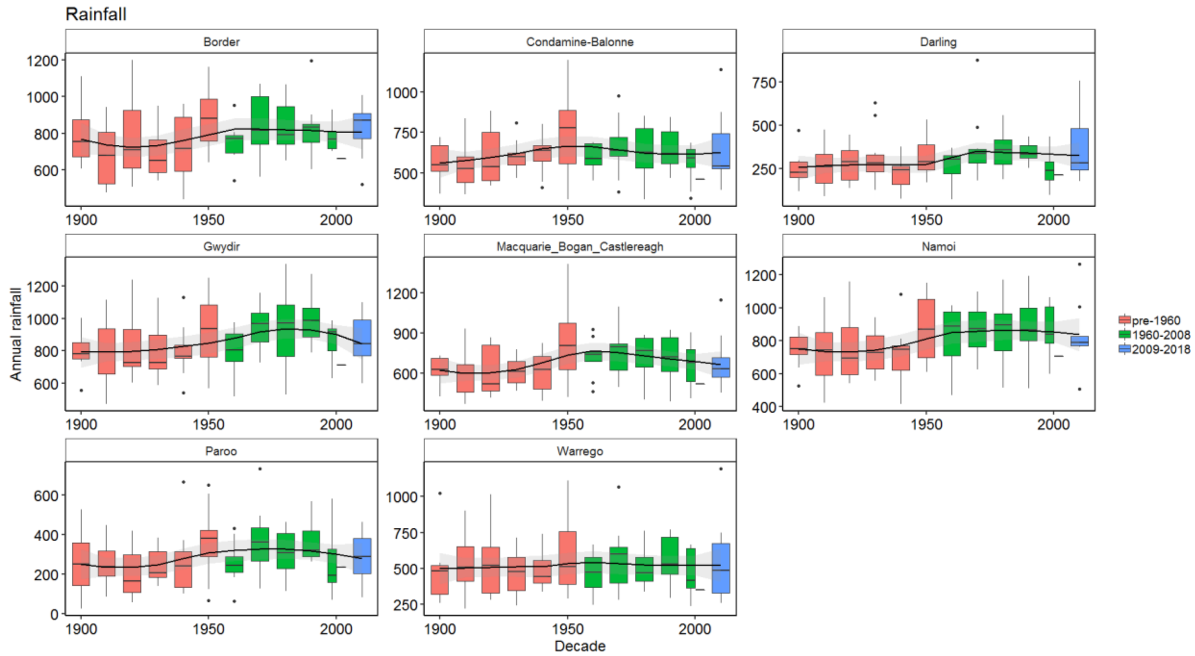

Figure A3.10 Catchment rainfall boxplots (median, the 25th and 75th percentiles, 95% CI) for upper reaches of all the major river catchments into the Darling River (see Figure 15, main report; Table A3.13), by periods of river development (pre-1960 (before river development), 1960-2008 (main period of river development), 2009-2018 (water recovery phase)). Lines depict a Local Polynomial Regression Fitting (loess) to illustrate trends.

Table A3.13 Mean, standard deviation, and range of annual rainfall measured in rainfall gauges in the upper reaches of each river catchment flowing into the Darling River by periods of river development (pre-1960 (before river development), 1960-2008 (main period of river development), 2009-2018 (water recovery phase).

River	Period	Mean	SD	Min	Max
Border Rivers and Moonie	pre-1960	758.08	180.67	440.50	1199.60
	1960-2008	806.96	137.25	543.20	1196.50
	2009-2018	810.11	154.96	522.40	1007.80
Condamine-Balonne	pre-1960	616.99	174.11	339.50	1197.40
	1960-2008	619.43	142.89	336.95	975.45
	2009-2018	638.44	227.58	396.60	1139.85
Darling	pre-1960	274.40	120.51	72.00	630.00
	1960-2008	321.37	128.90	69.00	879.70
	2009-2018	360.47	186.80	176.40	759.20
Gwydir	pre-1960	818.37	178.47	472.07	1250.85
	1960-2008	908.68	170.56	518.50	1335.02
	2009-2018	847.27	166.93	600.88	1101.68
Macquarie-Bogan/ Castlereagh	pre-1960	646.26	190.51	368.16	1413.69
	1960-2008	717.51	160.18	387.98	1096.76
	2009-2018	669.28	206.51	450.78	1147.63
Namoi	pre-1960	760.48	177.06	416.45	1157.35
	1960-2008	855.86	175.27	467.87	1193.27
	2009-2018	824.14	197.03	506.35	1262.85
Paroo	pre-1960	262.93	144.59	26.60	667.10

River	Period	Mean	SD	Min	Max
	1960-2008	310.43	141.06	62.40	734.80
	2009-2018	293.24	125.22	81.80	466.00
Warrego	pre-1960	519.70	212.83	219.48	1110.65
	1960-2008	518.24	164.82	233.82	1069.40
	2009-2018	527.00	289.68	257.23	1194.32
Total cumulative[1]	pre-1960	4657.20	1153.36	2757.11	8204.34
	1960-2008	5058.48	936.76	3121.02	6876.03
	2009-2018	4969.94	1367.10	3146.65	7849.91

[1]Total cumulative rainfall from upper catchments of tributary rivers, weighted by contribution to discharge annual discharge in the Darling River (Paroo: 0.01%, Warrego: 0.01%, Condamine-Balonne: 15.4%, Border:23.2%, Gwydir: 14.2%, Namoi: 23.4%, Castlereagh: 0.01%, Macquarie-Bogan-Castlereagh: 22.6%, Darling: 1.2%)

Table A3.14 Statistical testing of differences annual rainfall measured in rainfall gauges at the upper reaches of each river catchment flowing into the Darling River by periods of river development (pre-1960 (before river development), 1960-2008 (main period of river development), 2009-2018 (water recovery phase)). Three comparisons were significant (bold).

River	Period	Period	Estimate	SE	df	t.ratio	p.value
Border Rivers and Moonie	pre-1960	1960-2008	-48.89	32.39	928	-1.51	0.13
	pre-1960	2009-2018	-52.04	57.47	928	-0.91	0.37
	1960-2008	2009-2018	-3.15	58.38	928	-0.05	0.96
Condamine-Balonne	pre-1960	1960-2008	-2.44	32.39	928	-0.08	0.94
	pre-1960	2009-2018	-21.45	57.47	928	-0.37	0.71
	1960-2008	2009-2018	-19.01	58.38	928	-0.33	0.74
Darling	pre-1960	1960-2008	-46.98	32.39	928	-1.45	0.15
	pre-1960	2009-2018	-86.07	57.47	928	-1.50	0.13
	1960-2008	2009-2018	-39.10	58.38	928	-0.67	0.50
Gwydir	pre-1960	1960-2008	-90.31	32.39	928	-2.79	0.01
	pre-1960	2009-2018	-28.90	57.47	928	-0.50	0.62
	1960-2008	2009-2018	61.40	58.38	928	1.05	0.29
Macquarie-Bogan-Castlereagh	pre-1960	1960-2008	-71.25	32.39	928	-2.20	0.03

River	Period	Period	Estimate	SE	df	t.ratio	p.value
	pre-1960	2009-2018	-23.01	57.47	928	-0.40	0.69
	1960-2008	2009-2018	48.24	58.38	928	0.83	0.41
Namoi	pre-1960	1960-2008	-95.38	32.39	928	-2.94	<0.01
	pre-1960	2009-2018	-63.66	57.47	928	-1.11	0.27
	1960-2008	2009-2018	31.72	58.38	928	0.54	0.59
Paroo	pre-1960	1960-2008	-47.50	32.39	928	-1.47	0.14
	pre-1960	2009-2018	-30.31	57.47	928	-0.53	0.60
	1960-2008	2009-2018	17.19	58.38	928	0.29	0.77
Warrego	pre-1960	1960-2008	1.46	32.39	928	0.05	0.96
	pre-1960	2009-2018	-7.30	57.47	928	-0.13	0.90
	1960-2008	2009-2018	-8.76	58.38	928	-0.15	0.88
Total cumulative[1]	pre-1960	1960-2008	401.3	210	116	1.915	0.06
	pre-1960	2009-2018	312.7	372	116	0.841	0.40
	1960-2008	2009-2018	88.5	378	116	0.234	0.82

[1]Total cumulative rainfall from upper catchments of tributary rivers, weighted by contribution to discharge annual discharge in the Darling River (Paroo: 0.01%, Warrego: 0.01%, Condamine-Balonne: 15.4%, Border:23.2%, Gwydir: 14.2%, Namoi: 23.4%, Castlereagh: 0.01%, Macquarie-Bogan-Castlereagh: 22.6%, Darling: 1.2%).

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APPENDIX 4: MURRAY-DARLING BASIN WATER MANAGEMENT—LAW, POLICY, ORGANISATIONS AND PRACTICES

INDIGENOUS WATER GOVERNANCE AND MANAGEMENT

The Murray-Darling River basin encompasses territories of more than 40 autonomous Indigenous nations that number approximately 15% of Australia's Indigenous population (Taylor and Biddle 2004: see Appendix 4.1, MDBA map of Indigenous nations. Land tenures imposed since colonisation have left Indigenous nations in possession of less than 0.2% of the basin (Morgan 2012), signalling a higher level of dispossession than many other Australian regions (Robison et al. 2018).

Prior to colonisation, Indigenous peoples of the Murray-Darling Basin were organised into clans, local landowning groups whose membership was based on descent from a common ancestor, and broader language groups whose members spoke similar dialects (Clarke 2009). Group, or joint, property rights over land and water regulated access to territory, including rivers and waterholes, and natural resources. Over successive generations, the basin's land and water systems were vested with religious and cultural significance. According to traditional narratives, ancestral beings constructed complex mythical landscapes around spiritually powerful water bodies like rock-holes and billabongs. Each language group maintained their own origin stories describing actions of creator beings, tying people's identity to the river 'in a potent, spiritual way' (Weir 2009 p. 77). Shared languages enabled communication up and down the river, which served as a conduit for common ceremonial practices (Clarke 2009). The Murray-Darling River was also a ribbon of life, especially for those peoples whose territories spanned the dry and harsh hinterland.

The Brewarrina fish traps (Baiame's Ngunnhu) on the Barwon River and others in Barkandji country near Wilcannia, exemplify the ingenuity of Aboriginal societies who have existed in this region for extraordinarily long time scales. The Brewarrina fish traps are possibly the oldest continuously used human water construction in the world (Bark et al. 2015; Taylor et al. 2017; Grafton and Wheeler 2018). They demonstrate the methods employed to control surface water systems and manage the landscape, as well as the maintenance of water sharing practices and other customary institutions capable of sustaining a vast and enduring regional economy.

Colonial legislators ignored Indigenous water rights throughout the early period in which Australian water law developed. Navigation and irrigation then preoccupied political leaders' deliberations, with no thought given to the implications for Aboriginal peoples of altering flow regimes or intensifying water resource development (Robison et al. 2018). Indigenous rights or interests in land or water were not referred to in policy debates underpinning the restructuring of water rights during the late 1800s, or in changes brought about during the 1990s (Jackson 2017). During such moments, Indigenous representatives were prevented from influencing the rules governing access to water (Robison et al. 2018). The marginalisation of Indigenous peoples' rights to and relationships with water has been referred to as 'aqua nullius' (Sheehan and Small 2007; Marshall 2017; Taylor et al. 2017).

It was not until 2004 that Australian water policy acknowledged the need to take account of Indigenous interests in water management, a full ten years after the passage of the *Native Title Act 1993* (Jackson and Morrison 2007). Under the National Water Initiative (NWI), government parties agreed that water entitlement and planning frameworks should recognise Indigenous needs in relation to access and management. To that end, Indigenous peoples are to be included in water planning processes, and water plans are to incorporate their objectives. Although the NWI contains clauses designed to improve Indigenous access, these provisions are discretionary and rely on interpretations of native title constraining the commercial scope of this newly recognised property right (Tan and Jackson 2013).

In the 2000s, some state water laws were amended to improve consultation and protect Aboriginal heritage and, in NSW, to improve access to water for communities (Tan and Jackson 2013; Jackson and Langton 2012). The shortcomings of the legislative provisions and attendant policies are detailed in the literature. Many commentators agree that the water management practices of Indigenous nations and the rights and interests that stem from customary law and ongoing connection deserve greater recognition in Australia's water governance frameworks and its institutions (O'Donnell 2013; Jackson and Langton 2012; Hartwig et al. 2018; Godden and Gunther 2010; Taylor et al. 2017; Marshall 2017; McAvoy 2002; Morgan et al. 2004).

During the last ten years especially, Indigenous representative organisations have testified in many governmental review processes to the immense significance of water in Indigenous societies and the urgent need for reform (see Taylor et al. 2017; MLDRIN https://www.mldrin.org.au/). The latest report of the Productivity Commission also urges reform (2018). In a submission to the review of the *Water Act 2007*, the Northern Basin Aboriginal Nations (NBAN) called for the Basin Plan and subsidiary Water Resource Plans to '[f]acilitate Aboriginal Peoples' ownership of a fair and equitable proportion of commercial and environmental water licenses[,]' proposing measures aimed at remedying the injustice felt by Aboriginal people.

The internationalisation of law and norms relating to Indigenous peoples is an important dynamic for protection and/or restoration of Indigenous communities' connections to water. International legal instruments, based on human rights have proved to be significant to achieving Indigenous aspirations in land, waters, and resources. The UN Declaration on the Rights of Indigenous Peoples (UNDRIP) is the leading international instrument elaborating principles to guide nations in respect of their obligations to Indigenous peoples. UNDRIP was adopted by the UN General Assembly in 2007. It establishes a framework for Indigenous rights globally, functioning akin to a comprehensive charter of the rights of Indigenous peoples. As a 'soft law' instrument, UNDRIP will only formally bind governments when it is passed into law in Australia, but it does offer a valuable pathway forward for building relationships between Indigenous and non-Indigenous Australians (Davis 2016). Its value is interpretive and norm-setting, both in the international domain and in domestic setting. International environmental instruments, such as the Biodiversity Convention, also recognise First Nations' relationships to land and waters.

Efforts by Indigenous peoples to redress the crisis facing the basin have shown remarkable consistency in their position that 'the primary policy objective must be to restore natural flows and cycles to the river system.' (Morgan 2012, 458). There has been substantial investment by the MDBA through its Aboriginal Partnerships such as the Aboriginal Waterways Assessment, Use and Occupancy Mapping project (which has included the Barkandji), and an Aboriginal Socio-Cultural survey of the Northern Basin and in collaboration with the National Native Title Council—the National Cultural Flows Research project. It important that these initiatives are adopted and implemented by state governments and effectively reflected at a local level in water resource plans (WRPs).

A FEDERAL RIVER AND ITS CATCHMENT

The history of state efforts to manage co-operatively the MDB begins before Australian federation (driven by the Federation Drought of 1895–1902) (O'Connell 2007, 2014). The River Murray Waters Agreement of 1915 established a management framework between the states and the Commonwealth government. The Agreement is a Schedule to the Water Act and remains in force. It is relevant to the algal bloom and fish kill in a broad way as it sets out water sharing arrangements between the states and thus for example how much water and of what quality is required to flow to South Australia. Governments may renegotiate these agreements in the longer term, but as a short-term measure to address the Lower Darling low flows/fish kill problem it is unlikely that these longstanding arrangements would be altered.

Intergovernmental MDB water management arrangements are currently governed by the following policy and legal institutions, which include Commonwealth, Basin states, Ministerial Council and Basin Officials Committee (shown in Figure A4.1).

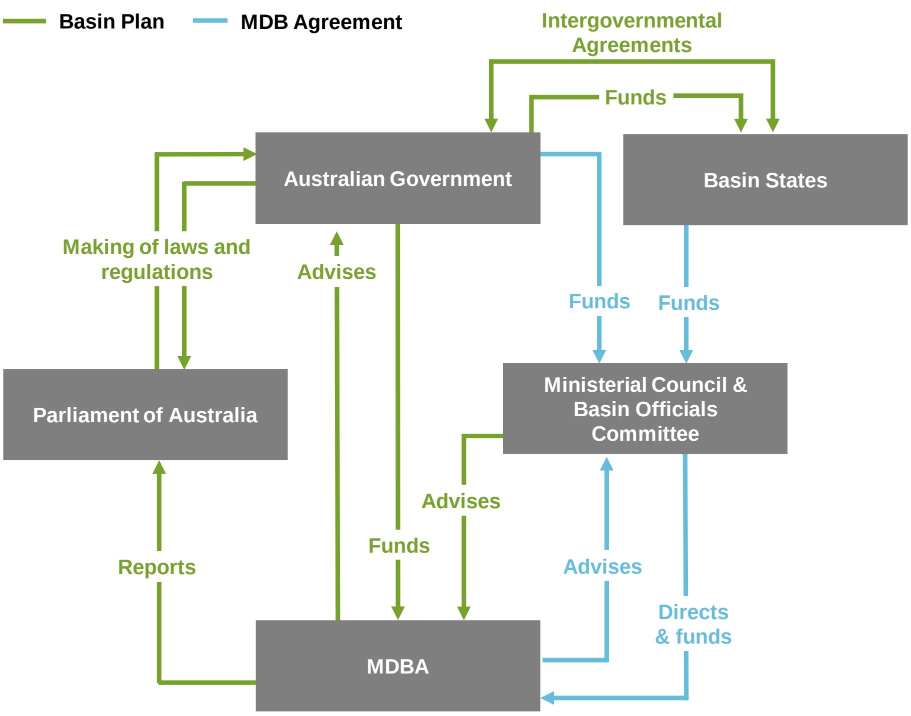

Figure A4.1 Schematic diagram of intergovernmental water management arrangements. Source: Productivity Commission (2018; 9)

Water management responsibilities go across the Australian Government, state governments, Murray-Darling Basin Authority (MDBA), Productivity Commission and the Australian Competition and Consumer Commission (whose role is to enforce and monitor water market and charge rules). Table A4.1 highlights some of these roles.

Table A4.1 Water Resource Management and Basin Plan Roles in the MDB

	Australian Government[a]	*Basin States*	*Joint Basin Governments*[b]	*MDBA*	*Productivity Commission*
Resetting the balance					
Setting and reviewing SDLs				▲	
Recovering water	▲				
Implementing SDL adjustment measures	▲	▲	▲	■	
Reconciling SDL adjustment measures				▲	
Delivering structural adjustment programs	▲				
Funding to improve Indigenous outcomes	▲				
Management arrangements					
Water resource planning	▲	▲ ●		▲	
Environmental water management	▲	▲ ●	■	▲■	
Facilitating water trading	▲	▲■●	■	▲■	
Facilitating Indigenous values and uses	▲	▲■●	■	▲■	
Meeting critical human water needs		▲■●	■	▲■	
Managing water quality and salinity		▲■●	■	▲■	
Ensuring compliance with SDLs and Basin Plan				▲	
Ensuring compliance with water take rules		■●			
Reporting, monitoring and evaluation	▲	▲ ●	■	▲■	▲
River management		■●	■[c]	■[c]	
Asset management and operation		■●	■[c]	■[c]	
Resource manager		■●	■[c]	■[c]	

[a] Includes the roles of the Commonwealth Environmental Water Holder, Department of Agriculture and Water Resources, and Department of Infrastructure, Regional Development and Cities. [b] Consists of Basin States and the Australian Government. [c] River Murray only.

▲ Basin Plan ■ MDB Agreement ● State water resource management laws

Source: Productivity Commission (2018; 345)

THE LEGISLATIVE FRAMEWORK AND CHANGE

Water management legislation is complex due to its need to address numerous interests in water, the input of technical requirements for river and groundwater operations, and the necessity to interact with other laws and to manage water between states and the Commonwealth. Each state developed its own legislation over the 20th century (Gardner et al. 2018).

The 1990s water law reform process (in particular the introduced cap on surface water extractions and agreement to unbundle water from land) was initiated in part due to algal blooms in the Darling River and evidence of environmental degradation across the Murray-Darling Basin. This resulted in water legislation that adopted explicit environmental objectives and measures that reformed the nature of consumptive water rights (introduction of water 'share' not fixed volume extraction); capped water allocations; and introduced a water market (cap and trade) under a set of reform principles for the MDB but which are being progressively applied throughout Australia (Macpherson et al. 2018). The intent at this point in the history of reform was to stop diversions from increasing and the cap was central to this objective. It followed an audit on water use in the basin published by the Ministerial Council. The cap of 1995 limited water use to levels of development in 1993/94 in NSW, VIC, SA and 1999/2000 in Queensland. It was seen at that time 'as an essential first step in establishing management systems to achieve healthy rivers and sustainable consumptive uses' (MDBC pamphlet, https://www.mdba.gov.au/sites/default/files/archived/cap/cap_brochure_0.pdf).

The Millennium Drought in the 2000s exposed the need to respond further to over-allocation of water and consequent environmental problems. It prompted a host of initiatives and institutional responses, including the Living Murray Initiative and National Water Initiative (NWI—an intergovernmental agreement), the formation of the National Water Commission (to support and audit the reform process), the *Water Act 2007*, the National Plan for Water Security (which became Water for the Future with a budget of $12.9 billion), the Murray-Darling Basin Authority (MDBA) to replace the MDB Commission, and the Commonwealth Environmental Water Holder (CEWH) and Commonwealth Environmental Water Office (CEWO) (Grafton and Wheeler 2018; Connell et al. 2005; Crase 2008; Crase and Dollery 2008).

The key objects of the *Water Act 2007* were: '3d(i) to ensure the return to environmentally sustainable levels of extraction for water resources that are overallocated or overused'; and 3d(ii) 'to protect, restore and provide for the ecological values and ecosystem services of the MDB.' Emphasis was placed on giving effect to international agreements (Commonwealth constitutional basis for legislative power relies heavily on the external affairs power where the Australian Government has entered treaties (international obligations)) and referral of nominated state regulatory powers to the Commonwealth (Godden Peel and MacDonald 2018 chs 2,3). However, state governments retained the primary legal basis for developing water resource plans and many aspects of water management, such as granting of water licences and ensuring compliance with them.

Sustainable diversion limit

The sustainable diversion limit (SDL) is a key concept in the water management structure of the MDB. It is the primary legal mechanism designed to address the over-allocation of water resources in the MDB. It might be understood as both a 'cap' on extractions of water and also a target for the overall objective to be reached by the Basin Plan and the respective water resource plans (previously water sharing plans) under the Plan (*Water Act 2007*, s 3, 19, 20, 21, 22, 23).

Under the legislation, the MDBA has a duty to prepare the Basin Plan and to set the SDL which must reflect the environmentally sustainable level of take (ESLT)—*the level at which water can be taken from a water resource, which if exceeded would compromise: a) key environmental assets; or b) key ecosystem functions; or c) productive base of water resource; or d) key environmental outcomes.*

The MDBA released the guide to the Basin Plan in 2010, which called for an average basin-wide reduction in current watercourse consumption diversions between 3,856 GL (that represented a 38% reduction in diversions in the southern MDB) in a high uncertainty scenario in terms of achieving environmental water requirements, and 6,983 GL (that represented a 68% reduction in diversions in the southern MDB) to achieve a low uncertainty scenario (MDBA 2010, pp. 114–15). Using a 20% confidence interval around the high uncertainty estimate, the MDBA recommended in its guide to the proposed Basin Plan a reduction in diversions of between 3,000–4,000 GL annually (MDBA 2010). Due to considerable opposition and community response, the reduction in diversions was correspondingly revised downwards. MDBA stated: 'Taking into account the evidence on benefits and costs, the diminishing capacity to achieve additional benefits as water is recovered above 2800 GL/y in the context of existing system constraints, …the Authority considers that water recovery of 2750 GL/y on a long-term average will result in environmentally sustainable levels of take in the surface water resources, returning enough environmental water to the Basin to achieve most environmental objectives, while also ensuring that social and economic effects are best managed.' (Basin Plan 2012, Transmittal Letter from MDBA to Minister, 21 Nov 2012).

The Australian Parliament passed the Basin Plan into law in 2012, setting a sustainable diversion limit of 10,873 GL/year for the MDB—representing an overall reduction in diversions of 2750 GL/year based on a long-term average annual yield (LTAAY, which takes the security and reliability of water entitlements into consideration). The Basin-wide SDL for groundwater was set at 3334 GL/year. To meet potential future water use requirements, groundwater SDLs were set much higher overall than historical use in the Basin, with only a few areas capped at current levels or reduced.

Total water recovery (through willing buyback of water entitlements and subsidization of irrigation infrastructure and through implementation of ELST in water resource plans in all Basin states) was to be achieved by 1 July 2019 (MDBA 2012). To ensure a high court challenge by the South Australian government did not proceed, 450 GL/year of additional water for the environment was to be secured through efficiency/supply and constraint infrastructure expenditures ($1.77 billion committed for this from 2014–2024), bringing total water recovery to 3200 GL/year. In 2015, the *Water Act 2007* was amended to cap the purchase of water entitlements at 1500 GL in the MDB. All remaining water had to be sourced through either supply or infrastructure projects, which have been heavily criticised. In addition, it has been argued there are substantial problems associated with irrigation infrastructure subsidies, namely: a) infrastructure is at least 2.5 times more expensive per $/ML than buyback; b) return flow issues (reduction of seepage into groundwater/rivers) and the rebound effect (where more irrigation land or higher water using crops are adopted) are ignored; c) surplus/buffer water (farmers now utilise more of their seasonal allocations on average) and the conjunctive use or substitutability of groundwater for surface water are ignored; and d) rural communities resilience is hampered due to path dependency impacts (increased switching to permanent crops places them at higher risk in drought times plus increasing electricity costs from modernized irrigation infrastructure) (Grafton and Wheeler 2018). This reinforces the need for robust water accounting (see final section in this appendix).

In implementing the Basin Plan, governments have provided assistance to rural communities to adjust to reductions in water access. The Productivity Commission (2018) found that assistance has not been provided to those areas considered most vulnerable to the Basin Plan. It recommended such funding should have clear objectives and selection criteria and be subject to monitoring and evaluation. The water entitlement of the major cotton producer in the lower Darling has been acquired (with some criticism of the process from the Productivity Commission), however, there are other water users in the Menindee area and downstream who may be affected by the Menindee Lakes water saving project and reductions in the quantity and quality of river flows.

Northern Basin Review and SDL adjustment mechanism

The MDBA carried out the Northern Basin Review (NBR) from 2012 to 2016, conducting research into the hydrology, ecology and socio-economic impacts of water recovery in the Northern Basin. (Further comment on the socio-economic impacts are covered in the last part of this appendix.) The review was directed by the Northern Basin Advisory Committee who, in their findings, recommended that water recovery alone was insufficient to ensure ecological outcomes are achieved, and hence recommended that 'toolkit measures' be implemented in addition to water recovery. Toolkit measures are defined as 'a collection of measures in addition to water recovery under the Basin Plan that can contribute to the environmental objectives of the Plan while minimising negative economic and social impacts' (MDBA FAQs https://www.mdba.gov.au/basin-plan-roll-out/basin-plan-amendments/faqs-northern-basin-basin-plan-amendments).

In 2016, the MDBA published the Northern Basin Review and recommended an amendment to the Basin Plan to increase the SDL in the basin and reduce the water recovery target from 390 GL to 320 GL.[1] The Basin Plan included a mechanism to adjust sustainable diversion limits, where the total could be adjusted up or down by a maximum of 5% (implemented as supply and efficiency projects in the Southern Basin). In the Northern Basin, the adjustment was made conditional upon commitments from the Commonwealth, NSW and Queensland to implement toolkit measures (although it was recognised that the toolkit measures were not within the MDBA's remit).

Toolkit measures will not be finalized until sometime in 2019. The MDBA reports toolkit 'options' as: 'protection of environmental flows, coordinated delivery of environmental water, active management of environmental water entitlements, construction of new fishways and addressing cold water pollution issues through improved dam operations, and a new package of constraints

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[1] The recovery target for the whole MDB of 2750 GL/year was to be reduced by 605 GL/year, offset by environmental gains in 36 water supply and two efficiency projects (rather than buy-back). Groundwater SDL also increased in the amendment in the MDB from 3334 GL/year to 3494 GL/year.

measures in the Gwydir Valley, among with other potential measures'.[2] Figure A4.2 illustrates how the toolkit measures are portrayed by the NSW Department of Industry (2018).

Better management of environmental water proposed measure	Relevant northern Basin 'toolkit measure'
Actively manage held environmental water in-stream	Protecting held environmental water so that it can be used to enhance low flows and fresh flows. Improved coordination and management of environmental water flows to maximise the environmental outcomes of this water moving from upper catchments downstream to the Barwon-Darling.
Limit daily water take Implementing individual daily extraction limits (IDELs) and enabling trade of IDELs provides additional mechanisms for environmental water holders to achieve outcomes.	Event-based mechanisms in unregulated rivers that can be used by environmental water holders to meet important flow targets.

Figure A4.2 Toolkit measures as presented by the NSW Department of Industry. Source: NSW Dept Industry (2018; 3)

As noted by the Productivity Commission (2018), there are no formal checks and balances on the toolkit measures in the Northern Basin (unlike the oversight of supply projects in the Southern Basin). The Productivity Commission advised that Northern Basin governments should implement transparent and accountable governance arrangements for the Northern Basin Toolkit within reasonable timeframes, and that the MDBA should independently assess states. It also recommended establishing a Northern Connected Basin Environmental Watering Committee to allow for intergovernmental coordination for planning and coordinating connected environmental watering events.

In addition, the original modelling of Basin Plan (under the reduced water recovery targets from the draft) outcomes were based on assumptions that Basin states would implement pre-requisite policy measures (PPMs). PPMs are meant to enable the efficient use of environmental water (e.g. credit environmental return flows for downstream environmental use and allow the call of held environmental water from storage to piggy-back on unregulated flows). If PPMs are not implemented, SDL then may be recalculated (Productivity Commission 2018).

One of the most important measures of these PPMs are whether it can include shepherding or not. Walker (2019) provides considerable discussion on this, and states that he believes it is clear that the measures in the Basin Plan that 'credit environmental return flows for downstream environmental use' are what is often described as 'water shepherding', albeit citing the MDBA as stating that the PPMs defined in the Basin Plan do not include shepherding.

[2] https://www.mdba.gov.au/basin-plan-roll-out/basin-plan-amendments/faqs-northern-basin-basin-plan-amendments

Figure A4.3 summarises the overall process of the implementation of the Basin Plan.

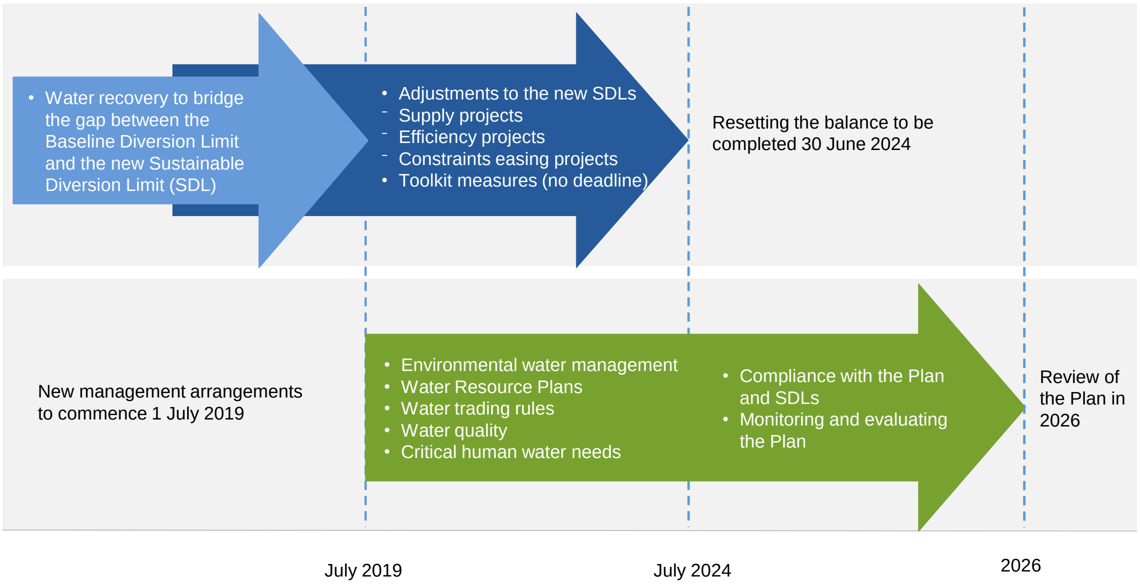

Figure A4.3 Implementation of the Basin Plan. Source: Productivity Commission (2018; 5)

New management arrangements are to be in place by 1 July 2019

Implementing the Basin Plan involves establishing a new and ongoing management framework, with the states needing to embed the Plan and the SDLs into their normal water planning and management processes through water resource plans. Water sharing plans are currently being converted to water resource plans (WRPs) and this process is supposed to be completed by mid-2019. The WRPs must be compliant with the requirements set out in the Basin Plan.

The Barwon-Darling WSP (Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources) covers the towns of Mungindi, Mogil Mogil, Collarenebri, Walgett, Brewarrina, Bourke, Louth, Tilpa and Wilcannia. The unregulated river management system in the Darling River is characterised by different water licence classes, cease to flow thresholds, and number and sizes of pumps allowed. A water sharing plan has a strategic planning function under state water legislation and in relation to the overall Basin Plan and its SDL.

In 2012, changes were made to the Barwon-Darling WSP. These have attracted some attention for their likely impact on the environment, with people worried about: i) rule changes that allowed increased take of water during low flows; ii) rule changes that permitted the take of water when flows reach certain thresholds (hence harvesting environmental flows); iii) water theft and iv) extreme impacts (Productivity Commission 2018, Commonwealth of Australia 2018). The Senate Committee report on water markets (Commonwealth of Australia 2018; 8) noted:

> the new rules were introduced after extensive lobbying by irrigators. It was alleged that the changes allowed irrigators to access more water than prior to the implementation of the Basin Plan in 2012. It was further alleged that the changed rules allowed larger pumps to extract water during periods of low flows.

The MDBA made the following comment on the Barwon-Darling WSP to the Senate Committee inquiry:

> [The WSP]… commenced a month prior to the Basin Plan coming into effect [in 2012]. Significant changes occurred between the draft plan and the final plan being released, including a change to the sharing components that resulted in fewer C Class (high flow) shares, and an increased number of A Class and B Class (low and medium flow) shares. The net effect of this was to allow extraction of water more often at the lower end of the flow regime. These and other changes, such as allowing trade of A class water, removing pump intake size limitations, and allowing storage of A class water, made by NSW to the WSP have the potential to impact on the integrity of environmental flow events and the magnitude of downstream flow. Stakeholders have raised concerns about aspects of the current Barwon-Darling WSP and, in particular, whether it is consistent with the Basin Plan and whether the MDBA has any role in compliance for this WSP. Under the Water Act 2012 [sic] (Cth), the Barwon-Darling WSP is deemed to be an 'interim' water resource plan because it was made under NSW law prior to the Basin Plan being finalised. 'Interim' plans prevail over the Basin Plan to the extent of any inconsistency between the two (Commonwealth of Australia 2018 p. 34).

The Senate Committee report notes that the MDBA was not consulted over late changes made to the draft WSP. That same report refers to the views of the CEWH on the lack of protection for e-flows afforded by the WSP:

> … while Individual Daily Extraction Limits were provided for by the WSP, NSW had not implemented these limits. The CEWH stated that 'some flow events since 2012 have been significantly reduced by water extraction' (Commonwealth of Australia 2018, 34).

The Committee Report also notes comments from a downstream grazier association representative:

> The 2012 Barwon-Darling water sharing plan has failed to meet its own objectives in terms of equitable resource sharing between all stakeholders. Several operating rules were introduced that resulted in significant windfalls for irrigators. The operating rules of particular concern were the removal of pump-size limits, the approval to extract 300 per cent of an entitlement per annum and the failure to implement daily extraction limits (Commonwealth of Australia 2018, 35).

In June 2018, the *NSW Water Management Act 2000* was amended to address some of the above issues in the Barwon-Darling water sharing plan. The changes allow for: i) changes to the Barwon-Darling water sharing plan, including allowing the establishment of Individual Daily Extraction Limits and Total Daily Extraction Limits to better protect environmental water and ii) temporary water restrictions (section 324 notices) to protect environmental water (Productivity Commission 2018).

The Productivity Commission (2018) found that the development and accreditation of water resource plans (WRPs) is well behind schedule and there are key issues still to be finalised, with the risk highest in NSW, and a lack of information about how the MDBA will address the risk of some plans not having accreditation. It also found the process of developing WRPs has been onerous and unnecessarily costly because of inadequate guidance on the requirements of plans and little clarity on the MDBA's expectations for accreditation, although the differences in WRP progresses between states suggests that perhaps other state factors are in play. As suggested by comments in the Senate Committee (2018), these changes are seen to better irrigators after extensive lobbying by irrigators for the changes. The Productivity Commission (2018) recommended that there is a need for clarification around what states need to self-report annually to show compliance with WRP obligations; the compliance assessment regime relevant to WRP obligations; and processes for updating plans, otherwise the ability to implement adaptive management will be very difficult.

The WRPs are to include the revision of current long-term diversion limit equivalent (LTDLE or cap) factors, which are used to convert various different types of (which have varying security levels) into a long-term average. For example, LTDLE convert supplementary, low, general and high security licences into an average long-term percentage. A factor say of .90 indicates that 90 years out of 100, that the entitlement receives its full allocations, and for 5 years it receives reduced allocations. There are currently a number of versions of LTDLE. For example, there was the version used in the Living Murray, which was consequently applied to water recovery in the Water for the Future program. There are different LTDLEs used by the MDBA in the basin plan baseline diversion limits (which give less long-term equivalent yield), and the Commonwealth environment department reverted to the Basin Plan LTDLEs in 2011, which had the impact of reducing the amount of water recovered, causing concern that environmental outcomes would not be met. The Ministerial Council ordered a reversal to the original LTDLEs used, and for the LTDLEs to be finalised (Slattery and Campbell 2018). Cap factors are in part meant to represent long-term average annual yield. Draft cap factors have now been significantly changed by NSW (especially for supplementary licences in the northern NSW basin), but South Australia, Victoria and Queensland have not released their cap factor adjustments yet. The implication of the changing cap factors is that it changes the long-term average annual yield of water entitlements in general, potentially increasing or decreasing the need for water recovery. The LTDLEs proposed by NSW are a product of reliability (namely long-term diversion limit) and utilisation (the actual amount of water used as a proportion of total water available for the period 2004 to 2016). Slattery and Campbell (2018) report that many regard these new estimates as a 'fix' to finalise water recovery targets. Currently, a change in northern NSW draft cap factors implies an over-recovery of water entitlements in the Northern Basin. For example, see the worked example for the changes in the cap factors in the Gwydir by the Productivity Commission. In particular, cap factors for supplementary licence (goes from 2011 estimate of 0.19 to 0.485 in 2018) and general security from 0.36 to 0.38. The PC showed that this meant that the current estimate of CEWH holdings in LTAAY in the Gwydir goes from a holding of 40,623 GL to 47,932 GL (without buying or selling any entitlement). Hence, the CEWH suddenly finds itself holding more water entitlements in some areas (and less in others). The change in cap factors is considerably different to previous estimates of LTAAY by the MDBA, and need urgent reassessment. Because, once WRPs are in place, the Productivity Commission (2018) recommended that the MDBA should assess which (if any) resource units are over recovered against the SDLs, and then the CEWH should develop a process and an appropriate timeframe to return any identified over recovery water to consumptive uses.

One major reform will be the monitoring of floodplain harvesting from 2019 onwards, in previously unregulated systems. The NSW Floodplain Harvesting Policy was introduced in 2013 to bring existing floodplain harvesting extractions into the water entitlement system, first in the Gwydir, Namoi, Border Rivers, Macquarie and Barwon-Darling valleys before being expanded across the state. Although historical estimates of floodplain harvesting extraction were included in the Basin Plan's

Baseline Diversion Limit in 2012, they are widely thought to be inaccurate, and better estimates are being sought. As outlined by the Productivity Commission (2018; 184), 'floodplain harvesting entitlements will be allocated so that the new long-term average level of extractions is equal to the lower value of the new modelling estimates for the extraction levels in the 1993-94 and 1999-00 water years. If the estimated current level of extractions is higher than this, the entitlements of all landholders who had approved works in place as of July 2008 will be allocated so that they face an equal reduction in extraction volumes. Works which were not approved by this time will not be eligible for floodplain harvesting entitlements. The new policy will not change the amount of water that must be recovered to meet the Sustainable Diversion Limits in each Water Resource Plans (WRP) Area.'

Although the new SDL accounting requirements are stricter than the ones that would have applied to unlicensed floodplain harvesting had it remained unlicensed and been listed separately in WRPs as an interception activity, many argue that the extraction should be capped at the same level of extraction as other water resources in the mid-1990s, and that allowing a clause on approved works in mid-2008 will mean a continuation of the over-allocation of consumptive water use. Walker (2019) recommended the NSW Government work towards addressing the shortcomings identified in its floodplain harvesting policy, and Queensland must act to provide further publicly available information as to how it proposes to address floodplain diversions.

Further reforms of water sharing arrangements could also be explored. Young (2019), for example argues that we should change the amounts of water managed within the system, by defining the water sharing pool on a reach by reach (and groundwater by groundwater) basis. Young further supports the concept of 'hands off flow', or conveyance water, built into this. Such a measure would incorporate connectivity issues, and once this threshold is reached, no other allocations by users would be available. The next level of sharing goes from high priority to general, to low priority, of which the environment has a range of different shares in. For example, the environment may have a lower amount of high priority shares in such a system, and correspondingly have a greater proportion of low priority shares.

COMPLIANCE AND MONITORING

For any water entitlement and sharing system to be successful, there needs to be institutions set up to ensure compliance, through monitoring, enforcement and penalties. There have been some quite damning reports in the past few years highlighting that this has not been the case in the MDB, and especially in the Northern Basin. They include:

- MDBA (2017a) found that from 2011–2012 to 2015–2016, in the Southern MDB between 77 and 84% of the surface water take was metered, while in the Northern MDB, between 25 and 51% of surface water take was metered.
- Matthews (2017) found overall standard of NSW compliance and enforcement work was poor, ineffectual and required significant and urgent improvement. He recommended greater transparency, more independence, and improved effectiveness of water monitoring and compliance.
- NSW Ombudsman (2017) revealed that there had been three previous ombudsman investigations in 2009, 2012, and 2013 that had been critical of water regulation and the action was not taken to address this, and serious issues with chronic under-resourcing of compliance and enforcement rules remain.

- A review by MDBA (2017b) found robust water compliance, regulation, and monitoring in South Australia, the Australian Capital Territory, and Victoria, but that NSW did not have a strong governance culture (especially in regard to unregulated water sources and floodplain history). Major weaknesses in Queensland's metering, compliance, floodplain take, and monitoring were also identified.

In response to the above, on 26 November, the South Australian government announced a state royal commission into MDB water theft and other water reform issues. The MDB Royal Commission handed down a report on 29 January 2019, and made 44 recommendations. The top six included:

i) new determinations of the ESLTs, and SDLs for both surface water and groundwater that reflect those ESLTs, should be carried out promptly. Those determinations must be made lawfully—that is, according to the proper construction of the Water Act
ii) in order to achieve a higher recovery amount, additional water will need to be purchased by the government and held by the CEWH. That water should be purchased through buybacks
iii) the MDBA should be required to urgently conduct a review of climate change risks to the whole of the Basin, based on the best available scientific knowledge. This should be incorporated into the determination of the ESLT
iv) a Commonwealth Climate Change Research and Adaptation Authority should be established. This Authority must be independent of government. It should be appropriately funded so that it can properly conduct research into climate change, and formulate plans and give guidance on how the Basin (and other) communities can best adapt to climate change
v) full disclosure in relation to the implementation of supply measures. The MDBA and Basin states should publish all relevant documents in relation to project design, risk assessment and ecological outcomes, and all material relevant to the BOC's oversight of project implementation
vi) a fully resourced, scientific analysis should be conducted to ascertain the causes, effects and available ecological responses to the continued ecological decline of the Menindee Lakes and the Lower Darling (Walker 2019).

The Senate Committee (2018) recommended the development of a uniform schedule of evidentiary requirements, penalties and sanctions be developed in relation to breaches of water legislation and licences, and that is should consider:

- the appropriate burden of evidence for water breaches
- the use of technology (e.g. satellite mapping) in determining breaches
- the suitability of strict liability offences
- the simplification of offences.

In June 2018, the New South Wales Government responded to the issues of water theft and inadequate monitoring of water licence conditions that had been identified by a range of inquiries, with a package of amendments to the *Water Management Act 2000*. NSW noted that under the 2009 National Framework for Non-urban Water Metering, the Northern Basin had until 2020 to install meters. Nonetheless, NSW instituted a range of responses which included provisions for comprehensive water metering for all licence extractions, and proposed metering for all licensed users with pumps, pipes, or offtakes of 100 millimetres or larger for surface water or bores of 200 millimetres or larger for groundwater. Anyone who holds a licence that currently requires a meter will be required to keep and maintain that meter.

The legislative amendments boost water management compliance powers, including the option of accepting enforceable undertakings by holders of water licences (a type of financial assurance or bond) and authorities can direct that a compliance audit be undertaken, as well as authorising the regulator to share intelligence with other authorities, including other jurisdictions. The legislation allows the regulations to prescribe a methodology for estimating the quantity of water illegally taken. The legislation increases maximum penalties for both corporations and individuals. Some measures are yet to come into force.

WATER ACCOUNTING, SOCIO-ECONOMICS AND DATA REQUIREMENTS

As well as strong compliance, institutions need to develop robust environmental water accounting (which indeed was part of the National Water Initiative). Much information on water use, diversions, return flows, storage, carryover, floodplain harvesting, overland flows and other important processes is not available publicly, or available at all. Especially in water, this needs scientific and economic measurement of all potential negative externalities, such as the measurement of return flows and the catch of floodwater and unregulated water diversions at both catchment and basin scales. There is therefore a critical need to measure both diversions and return flows, especially when the stated intent of such expenditures is to generate public benefits. Although it is claimed that some project proponents have assessed the issue of return flows (e.g. NVIRP in Victoria (Productivity Commission 2018), little information is available about the assessments done.

MDBA recently commissioned Wang et al. (2018) to provide an overview on the return flow issue, and they suggested that return flow issues from irrigation efficiency projects reduced return flows by 121 GL/yr (with a range from 90-150 GL/yr). The reduction represents 16% of the recovery transferred to environmental entitlements. The largest reduction is in ground return flow, making up 80% of the total reduction in return flow. Williams and Grafton (2019) reviewed this report, and estimate that in fact the reduction in return flows from irrigation efficiency projects could be up over five times higher than Wang's estimates.

All of the data gaps and irregularities justify calls for more robust water accounting and research to better understand connectivity issues between groundwater and surface water, as well as account for unregulated water diversions and theft. There must be greater use of satellite measuring and monitoring, especially in regards to the estimation of historical floodplain harvesting (Grafton et al. 2018).

There is a further issue that follows on from the concept of the negative externalities associated with reduced return flows in spending money on irrigation infrastructure as a form of recovering water. In addition, there have been serious questions raised in regards to the MDBA's modelling of the full assessment of the socio-economics of water reallocation in the Northern Basin. Walker (2019) discusses many of the issues, as does Wheeler et al. (2018) who highlighted that the costs of reallocating water away from irrigation use were over-estimated, probably by a factor of two, while the benefits of returning water to the environment were either ignored or not estimated. In particular, the criticisms of the socio-economic modelling conducted in the Northern Basin review included:

1. falsely assuming a proportional relationship between Water Use and Farm Production: Failure to recognise the true production relationships between water and agricultural outputs and characterising production changes as directly proportional to water availability. This is not borne out in practice or in tested theoretical contexts

2. ignoring positive economic impacts of water entitlement buyback and the negative impacts of irrigation infrastructure subsidies: There are a number of positive economic impacts of adjustment mechanisms, such as buyback, and the consequent positive impacts of spending within communities, while at the same time there are a number of negative impacts of infrastructure subsidies (such as reflows). Studies often ignore the benefits of buyback while also ignoring the full social costs of irrigation infrastructure
3. key term definitions: Poor definition of rudimentary terms like water use efficiency, water entitlements and allocation such that what is being assessed and measured is indeterminate
4. sample selection biases: Sample selection exists where specific ill-affected (in terms of reduced irrigation use) communities or community members are chosen and then presumed to be representative of a wider population (while not including other communities that may have benefitted from increased environmental water)
5. statistical modelling issues: Less-than-rigorous statistical approaches that confound mis-specified assumptions about hydrological, agricultural and/or economic relationships
6. inadequate documentation: In some cases inadequate citing of information such that the evidence cannot be meaningfully reviewed or tested and must be taken on trust.

All of these faults in the modelling implied that the true socio-economic net benefits of water reallocation were underestimated. In a paid peer review in 2018 funded by the MDBA on their socio-economic modelling, and to consider the validity of the Wheeler et al. (2018) criticisms, Blackwell et al. (2018) supported the substance of the criticisms above and recommended further work must be undertaken by the MDBA (and consultants to the MDBA for socio-economic modelling) to address the concerns.

Overall, there is not strong evidence to suggest that recovering water through irrigation infrastructure or supply projects provides more net social benefits than buying water back. In addition, Grafton and Wheeler (2018) found that the nominal costs of recovering water for the environment via subsidies were at least 2.5 times more expensive per megalitre than buybacks. Thus, a market-based approach to water recovery is a much cheaper option than subsidy and infrastructure alternatives, and also has less negative externalities in general (see Wheeler et al. 2018 for fuller description). Hence, in terms of the future effectiveness of water recovery in the Basin, it is imperative that the cap on further buyback be repealed.

SUMMARY

An interim evaluation of Basin Plan outcomes occurred in 2017. Another major five-year statutory evaluation report is due in 2020 and a ten-year review of the Basin Plan due in 2026. There has been considerable criticism of:

- the toolkit measures
- the reduction in the water recovery targets from the Northern Basin review, and the increase in the surface water SDL
- the increase in groundwater SDL
- the constraints projects (e.g. physical structures/practices limit ability to deliver environmental water)

- the lack of knowledge on connectivity within the basin and the limited socio-economic analysis of the Northern Basin that overestimated impacts on rural communities from reduced irrigation water use (e.g. Wheeler et al. 2018)
- the limited opportunities for Indigenous nations to access water and participate fully in its management.

It is important to understand this background in relation to the ecological crisis of the fish kills as the reform process is an involved one and it is not yet complete. A very important step will be the development of water resource plans in compliance with the Basin Plan in 2019, and government reaction to the MDB Royal Commission and the Productivity Commission report. However, the fish kills crisis is an important signal for assessing the gaps and deficiencies of current water management laws, strategies and problems of regulation, administration and implementation across the MDB. This crisis also can provide a platform and opportunity for developing ways that might better meet local problems that have surfaced in the Lower Darling.

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APPENDIX 5: CLIMATE CHANGE AND ITS POTENTIAL EFFECTS ON RIVER FLOWS

This analysis specifically directed towards the question 'Has there been a step change in inflows due to climate change or whether more work is required in this research area?'

HISTORICAL RECORDS AND CLIMATE CHANGE IN THE MURRAY-DARLING BASIN

South-eastern Australia has historically experienced large variability in climate from year to year and decade to decade, but the climate over the past 15 years has been outside the historical record. Between 1997 and 2009 ('Millennium Drought'), the region had its lowest 13-year rainfall total of the entire instrumental record since 1865. Using rainfall reconstructions based on climate proxy data, Gergis et al. (2012) have shown that there is a 97.1% probability that the decadal rainfall anomaly recorded during 1998–2008 is the worst experienced since the first European settlement of Australia and unusual in the context of the past two centuries. The drought was broken by frequent and widespread heavy rainfall events from spring 2010 to autumn 2011, and again in late 2011, which resulted in Australia's wettest two-year period on record. The historical pattern is set out in Figure A5.1.

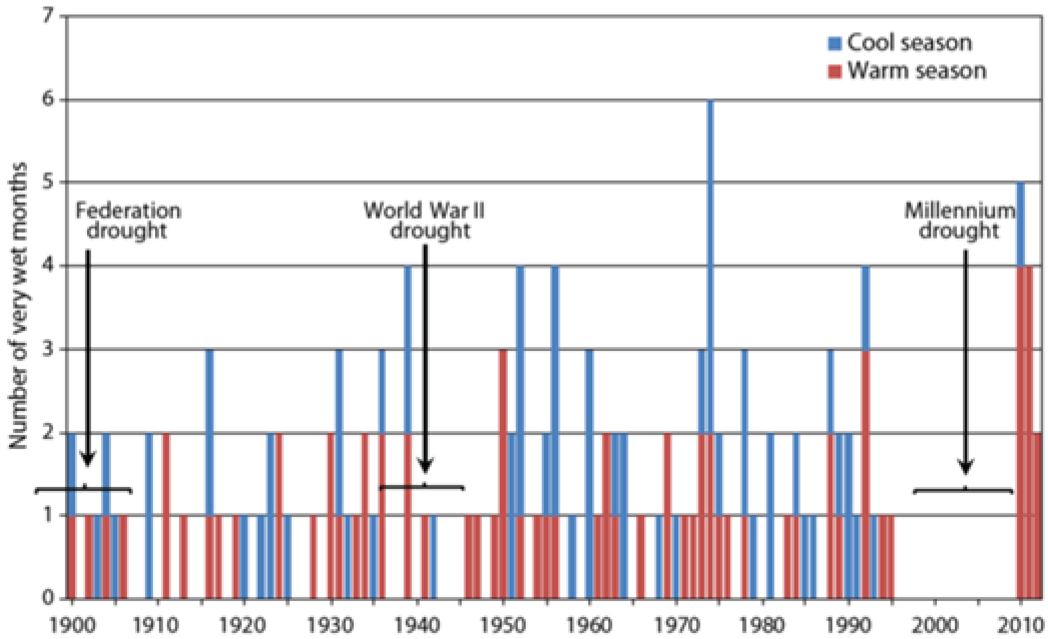

Figure A5.1 The number of very wet months in the Murray-Darling Basin in each year from 1900 to July 2012. Source: CSIRO (2012)

The Millennium Drought stands out as having no very wet months for 180 consecutive months. Additionally, during the breaking of the drought in 2010–12, only one very wet month was recorded during winter as the other 10 were recorded during the summer.

When this Millennium Drought is placed in context of the rainfall anomaly from 1900 to 2018 as set out below (Figure 5.2), it appears that except for a very wet interval in 2011-2013 and a wet winter in 2016 the MDB has been in a drought sequence since 2000.

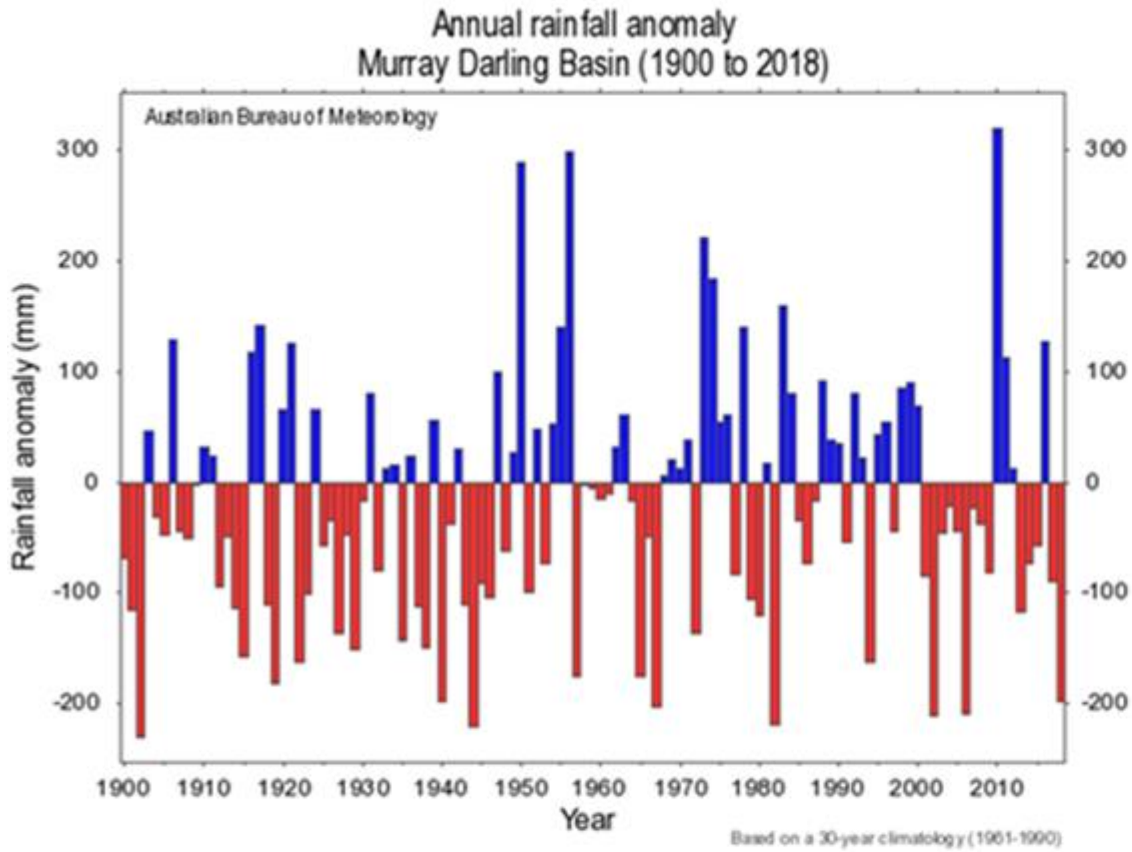

Figure A5.2 Annual rainfall anomaly, Murray Darling Basin (1900 to 2018). Source: http://www.bom.gov.au/climate/.

Timbal and Fawcett (2013) developed these drought depth duration curves computed using annual rainfall for periods from 1 to 21 years for three historical droughts: Federation Drought in green, World War II Drought in blue and Millennium Drought in red (Figure A5.3). The severity of the drought increases up the graph with units on the y-axis showing the rainfall deficiency as a percent reduction compared to 1872–2009. The Millennium Drought was the worst drought in the instrumental record for all durations between 3 and 19 years.

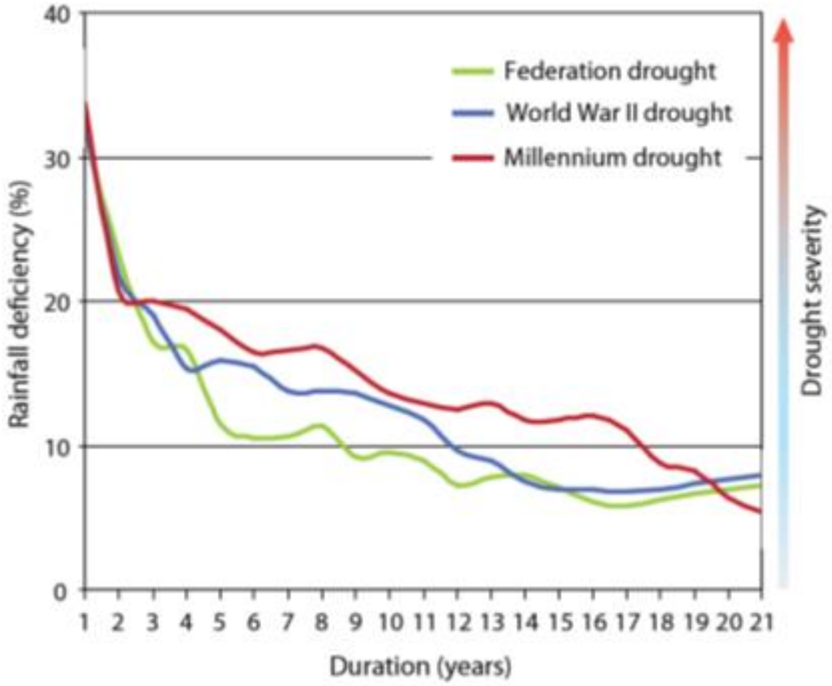

Figure A5.3 Drought depth duration curves (Timbal and Fawcett 2013)

Gallant et al. (2013) show that since 1911, large inter-decadal variations in the characteristics of droughts have overlain trends towards less frequent, shorter and less severe droughts across much of Australia, with the strongest trends in northwest Australia. Regional exceptions include increases in seasonal-scale drought frequency, duration and intensity in areas of southwest and southeast Australia. In parts of the west and southeast of the Murray–Darling Basin, the average duration of seasonal-scale droughts, defined as successive seasons in drought, significantly increased by between 10% and 69% during the second half of the 20th century. Averaged across large-scale regions in southeast and northwest Australia, decades with longer-lasting and more intense soil moisture-based seasonal droughts had statistically significantly higher actual evaporation compared with other decades. These were combined with modest rainfall deficits, suggesting that evaporation may be an important process for regulating drought duration or intensity in these regions. However, other hydroclimatic processes that were not assessed here likely also influence soil moisture, making attribution difficult (Roderick, M. L. and G. D. Farquhar 2011; Sun, Roderick and Farquhar 2018).

Clearly the Millennium Drought was of great hydrological importance to the MDB, particularly the southern MDB. Potter et al. (2010) note that the reductions in runoff were unprecedented in the historical record and estimated their return period as 1/300 years. Notably the runoff was more reduced than may have been expected given the rainfall anomaly, a tendency that has been attributed (Gallant et al. 2013) to increases in potential evapotranspiration and changes to rainfall variability and seasonality. Freund et al. (2017) reveals that the spatial extent and duration of the Millennium Drought (1997–2009) appears either very much below average or unprecedented in southern Australia over at least the last 400 years. Their reconstruction identifies a number of severe droughts over the past several centuries that vary widely in their spatial footprint, highlighting the high degree of diversity in historical droughts across the Australian continent. They document distinct characteristics of major droughts in terms of their spatial extent, duration, intensity, and seasonality. Compared to the three largest droughts in the instrumental period (Federation Drought, 1895–1903; World War II Drought, 1939–1945; and the Millennium Drought, 1997–2005), they find that the historically documented Settlement Drought (1790–1793), Sturt's Drought (1809–1830) and the Goyder Line Drought (1861–1866) actually had more regionalised patterns and reduced spatial extents. To contextualise recent observed trends in regional Australian rainfall Freund et al. (2017) panels show regional rainfall reconstructions since 1600 for the warm (red) and cool season rainfall set down in Figure A5.4.

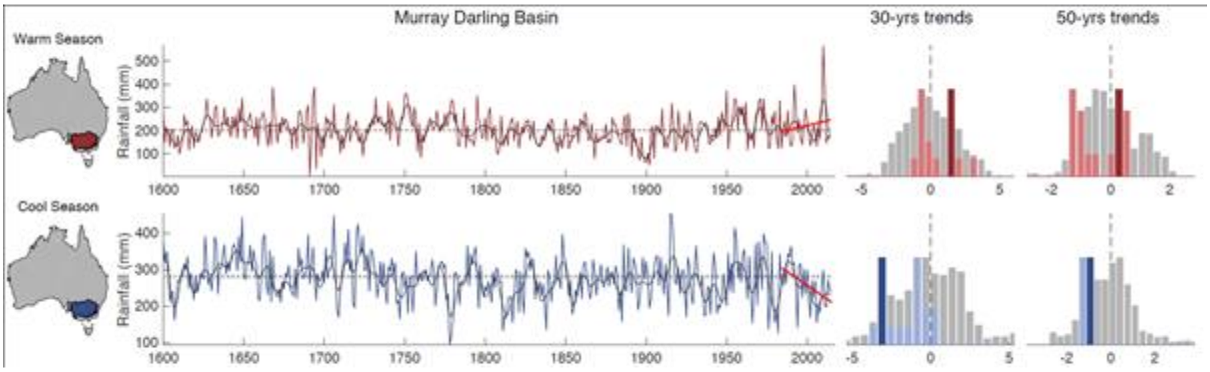

Figure A5.4 Regional rainfall reconstructions (Freund et al. 2017)

In Figure A5.4 the panels show regional rainfall reconstructions since 1600 for the warm (red) and cool season (blue) with the 10-year low-pass filtered series shown as a black line. Grey bars along the x axis denote non-verified periods for each reconstruction. The right-hand panels show histograms of 30- and 50-year regional rainfall trends (mm/yr). Grey shaded bars indicate the full range of the trends prior to 1970 (for 30-year periods) and 1950 for 50-year periods. Light red/blue colouring highlights the trends since 1970 (for 30-year periods) or 1950 for 50-year periods. The dark coloured bars indicate the trend in the most recent period. Bar heights are normalised by the maximum occurrence for each region.

This work shows clearly that cool season rainfall across the basin is declining in recent times and warm season rainfall is trending towards a small increase. Both these observations appear to be consistent with the rainfall projections under climate change as set down in the following sections.

GENERAL OVERVIEW OF CLIMATE CHANGE PROJECTIONS FOR THE MURRAY-DARLING BASIN

The mid-latitude location makes the Basin particularly sensitive to climate-induced hydrological change (Palmer et al. 2008, Gallant et al. 2012, Grafton et al. 2014). In a major work published by CSIRO (2012) the projected changes in climate for the Murray Darling basin was summarised as follows: *'There appear to be long-term reductions occurring in cool season rainfall and streamflow across the region. Evidence indicates that these are associated with changes in the global atmospheric circulation via an expansion of the tropics, with the Hadley circulation expanding at the rate of 0.5° of latitude (approximately 50 km) per decade, pushing mid-latitude storm tracks further south and leading to reduced rainfall across southern Australia. These changes are at least partly* *attributable to global warming, indicating a possible future climate characterised by continued below average late autumn and winter rainfall across south-eastern Australia. These trends are evident in a range of observational data and can be reproduced by global climate models only when human influences (in the form of greenhouse gases, aerosols and stratospheric ozone depletion) are included. The models also indicate that these trends are expected to continue.*

The state of the three oceans surrounding the Australian continent (as expressed by the status of the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM)), will continue to have an important role in influencing the seasonal and inter-annual variability of rainfall. It is expected that the SAM will trend towards more positive values in a warmer world, leading to drier conditions across south-eastern Australia in winter. There may also be an increase in the number of positive IOD events, bringing drier conditions to south-eastern Australia from winter to spring. It is currently not known how ENSO might change in the future or how this may affect the other two variables.

The most reliable estimate of the impact of these changes is for reductions in rainfall and runoff across the southern part of south-eastern Australia (south of 33 S latitude) in particular. For example, with 1 °C of global warming, average annual rainfall is expected to decline by 0 to 9 percent (median of 4 percent), and average annual runoff is expected to decline by 2 to 22 percent (median of 12 percent). For 2 °C of global warming, the reductions in both rainfall and runoff are approximately double these. The situation is less clear in the northern part of the region.'

Whetton (2017) provides an update on this CSIRO (2012) and its earlier work in 2008 and provides more detail analysis of precipitation and temperature for similar wet and dry scenarios using the large CMIP5 ensemble of climate models run under scenarios of increasing levels of greenhouse gases and atmospheric aerosols, known as the Representative Concentration Pathways (RCPs). The CMIP5 ensemble represents the latest round of climate model simulations from the major modelling centres around the world, and are also the simulations assessed by the IPCC (Taylor et al. 2012). Whetton (2017) used the national climate change projections based on CMIP5 prepared by CSIRO and BoM (2015).

The general overview provided by Whetton (2017) based on these studies is that *'The Murray-Darling Basin area has warmed by around a degree since 1910, and will continue to warm (projected ranges is 0.6–1.5 °C in 2030 relative to 1995, and by 0.9–2.5 °C in 2050 without mitigation), with more hot days and fewer cold days. Rainfall is projected to have a tendency to decrease, particularly in the south and in winter, with more time in drought and decreased soil moisture. However, both natural variability and model-to-model differences are large, and both increases and decreases of rainfall are possible, particularly in the north. Daily extreme rainfall is projected to increase even when average rainfall declines, with implications for erosion and flooding. Using a climate analogue approach, sites in the Basin 'move' inland/northwest under the hottest/driest scenario and north/northeast in the coolest/wettest scenario. The analogues may be many hundreds of kilometres away and outside the Basin in 2050 under high emissions.'*

Further, Whetton (2017) following additional analysis concludes that *'Wet and dry extreme climate scenarios used in Sustainable Yields (CSIRO 2008) were assessed as still valid and representative given* *latest science, and thus the consequent hydrological scenarios are similarly still valid and representative (although the latest modelling results suggest that probability of the dry scenario may have declined slightly). For the dry scenario there are large reductions runoff and water availability throughout the basin. For the wet scenario there are significant increases in runoff and water availability in the north grading towards little change in the south.'*

EXAMINATION OF RAINFALL AND RUNOFF PROJECTIONS

Whetton (2017) states *'A tendency for reductions in cool season rainfall under enhanced greenhouse conditions has been a consistent result from climate modelling for many years (CSIRO and BoM 2007). This is most important for the southern MDB where cool season rainfall predominates. The process behind this change appears to be essentially a southward shift of mid-latitude weather systems and an expansion of the tropics (CSIRO 2012; CSIRO and BoM 2015; Hope et al. 2015). Warm season simulated rainfall change in southern Australia is less clear and ranges from an increase to a decrease (CSIRO and BoM 2015). In all seasons, natural variability is high relative to the signal and may obscure the forced change for some decades (CSIRO and BoM 2015, Roderick and Farquar 2011, Sun et al. 2018). Presented below are Coupled Model Intercomparison Project phase 5 (CMIP5) - simulated rainfall changes from Climate Change In Australia (CCIA) technical report (CSIRO and BoM, 2015) for the two regions most relevant to the MDB. It should be noted that dynamically downscaled projected rainfall change over NSW is also available from the NSW Government based on the earlier CMIP3 model ensemble (NSW/ACT Regional Climate Modelling (NARCliM) project http://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW) and that these projections lie closer to the wetter end of the range of rainfall change of CMIP5. Dynamical downscaling using the CCAM model reported in CCIA (CSIRO and BoM 2015) also showed this tendency. Grose et al. (2015) has compared the NARCLiM projections with those of CMIP5 and other downscaling for the Central Slopes, and whilst they noted that the fine resolution technique may more reliably reflect topographical influences in some places, the broad trend for a less drying and a more wetting climate in the NARCLiM projections was not well understood and not necessarily to be preferred.'*

Projected changes in precipitation based on CCIA are tabulated by Whetton (2017) for 2030 and 2050 for southern and northeast portions of the Basin in Table 3 (annual changes) and Table 4 (seasonal changes) (Figure A5.5). *'Annual average precipitation change in 2030 is -11 to +5% in the south and -13 to +8% in the north. By 2050 these ranges are around -17 to +8% and -16% to +11%. Thus the range of change extends from drying to wetting but with a greater tendency for drying, particularly in the south. Indeed, projected drying is stronger still in the Victorian-only component of the Murray Basin region (Timbal et al. 2016). The wetting case is most evident in the north in summer and autumn (around -25 to +25% in 2050), and the drying case is most evident in spring, especially in the south (around -15 to +10% in 2030 and -30 to +10% in 2050). Forced changes are much smaller compared to natural variability (Sun et al. 2018) for rainfall than they were for temperature (see Figure A5.5 for an example of the time evolution of precipitation in a drying model), with the result that the effect of varying emission scenarios is not strongly evident. Natural variability has probably contributed to the observed cool season rainfall decrease since 1995 already being comparable to the dry end of the projected rainfall change for 2030, although this fact also raises the concern that the models may be underestimating the rainfall response.'*

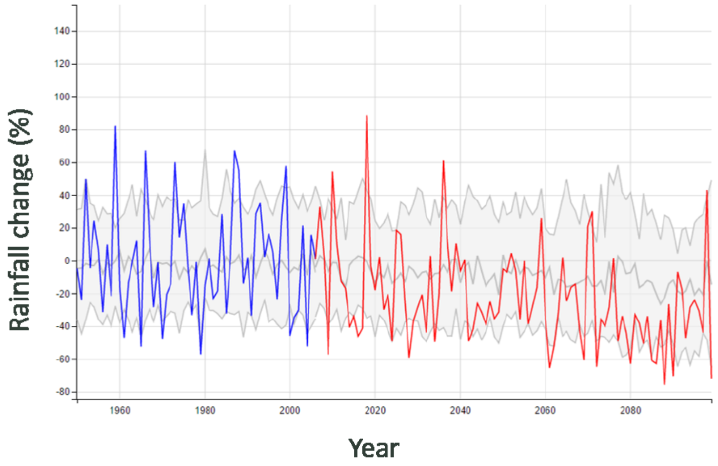

Figure 8. Example of model simulated historical (blue) and projected (red) winter precipitation anomaly (in %) for Murray Basin region from a single global climate model (GFDL-ESM2M model, RCP8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/climate-projections/explore-data/time-series-explorer/

Table 3: Average annual precipitation change (10th to 90th percentiles) in Murray Basin and Central Slopes in 2030 and 2050 and under RCP2.6, RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/)

	Region	RCP2.6	RCP4.5	RCP8.5
2030 (2020-2039)	Murray Basin	-11 to +4	-9 to +5	-11 to +5
	Central Slopes	-11 to +8	-11 to +7	-13 to +8
2050 (2040-2059)	Murray Basin	-17 to +5	-13 to +7	-14 to +8
	Central Slopes	-15 to +9	-13 to +7	-16 to +11

Table 4: Average seasonal precipitation change (10th to 90th percentiles) in Murray Basin and Central Slopes in 2030 (2020-2039) and 2050 (2040-2059) and under RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/)

		Murray Basin		Central Slopes	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
2030	DJF	-15 to +13	-9 to +16	-9 to +16	-12 to +23
	MAM	-24 to +12	-21 to +12	-22 to +19	-17 to +14
	JJA	-15 to +8	-17 to +7	-20 to +11	-27 to +15
	SON	-16 to +12	-17 to +7	-18 to +12	-23 to +12
2050	DJF	-15 to +20	-17 to +14	-9 to +20	-19 to +19
	MAM	-18 to +15	-20 to +20	-21 to +18	-25 to +26
	JJA	-13 to +6	-16 to +9	-21 to +12	-27 to +12
	SON	-24 to +9	-28 to +10	-20 to +13	-31 to +14

Figure A5.5 Tables and figures reproduced from Whetton (2017).

The changes to meteorological drought occurrence (drought occurrence defined in terms of rainfall deficits) largely follow the projected changes to mean rainfall (increase or decrease, but with decrease more likely). Based on its analysis of the CMIP5 models results, CCIA concluded that: 'There is medium confidence that the time spent in meteorological drought will increase over the course of the century under a "High" emission strategy for the Murray Basin and Central Slopes' (Timbal et al. 2015).

The large range in future runoff projections mainly reflects uncertainty in future projections of annual and seasonal rainfall. Nevertheless, the large majority of climate models indicate that the southern Murray–Darling Basin and Victoria will, on average, be drier in the future. This is especially so in winter. Most of the climate models project a rainfall decline in winter, when most of the runoff in this region occurs, translating to a considerable reduction in winter and annual runoff. The projections of rainfall decline in winter are consistent with the expected changes in the large-scale atmospheric and oceanic drivers of rainfall in this region in a warmer world (Whetton 2017).
The projected decline, as well as the range of uncertainty, is larger for higher levels of warming, and although not scaling exactly linearly (Whetton 2017) is roughly twice as large for a 2 °C global warming. This means for the southern Basin with a 2 °C rise in temperature, rainfall median to reduce by approximately 8% while median annual runoff is projected to reduce by approximately 24%. In the Northern Basin however median rainfall is expected to reduce by about 6% and median annual runoff is projected to reduce by approximately 20% (Whetton 2017). These projected changes in seasonal and annual rainfall and runoff informed by each of the 15 global climate models for 1 °C and 2 °C global warming can be downloaded from http://www.seaci.org. The hydrological modelling in SEACI also estimates changes to other streamflow characteristics such as low flows and peak flows that are important for water resources planning and climate change impact assessment and adaptation in water and related sectors. There is an urgent need for new research work to address more fully this important issue.

EXAMINATION OF TEMPERATURE PROJECTIONS

Drawing on the most recent work Whetton (2017) writes that *'Projected mean temperature change for 2030 and 2050 relative to 1995 for the southern and northeast regions are given in Table 1, based on the analysis of CCIA (CSIRO and BoM 2015). Projected warming in 2030 relative to 1995 is around 0.6 to 1.5 °C, with the main source of variation being model differences (variations in the emission scenario have little effect). Projected warming is slightly stronger in the north, than in the south. By 2050 sensitivity to assumed emissions is more noticeable with projected warming of 0.9 to 1.9 °C for 'medium' emission scenario (RCP4.5) and 1.3 to 2.5 °C for 'high' emission scenario (RCP8.5) and with warming a little higher in the north than in the south.'* It is notable that the increase to date in mean temperature, relative to 1995, is already around 0.5 °C (see Figures A5.6 and A5.7), suggesting that the lower bound of 0.6 °C for the projected warming is very likely to be exceeded.

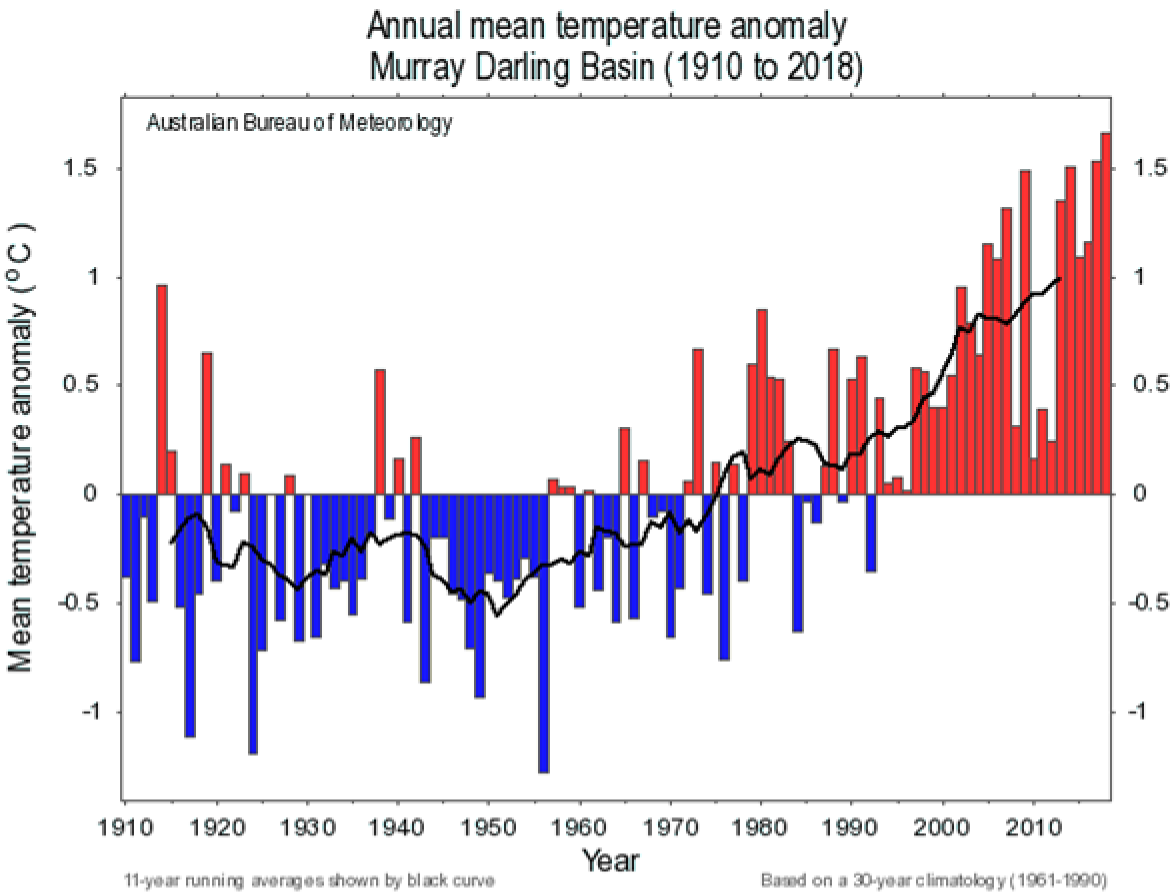

Figure A5.6 Annual mean temperature anomaly, Murray Darling Basin (1910-2018).
Source: http://www.bom.gov.au/climate/.

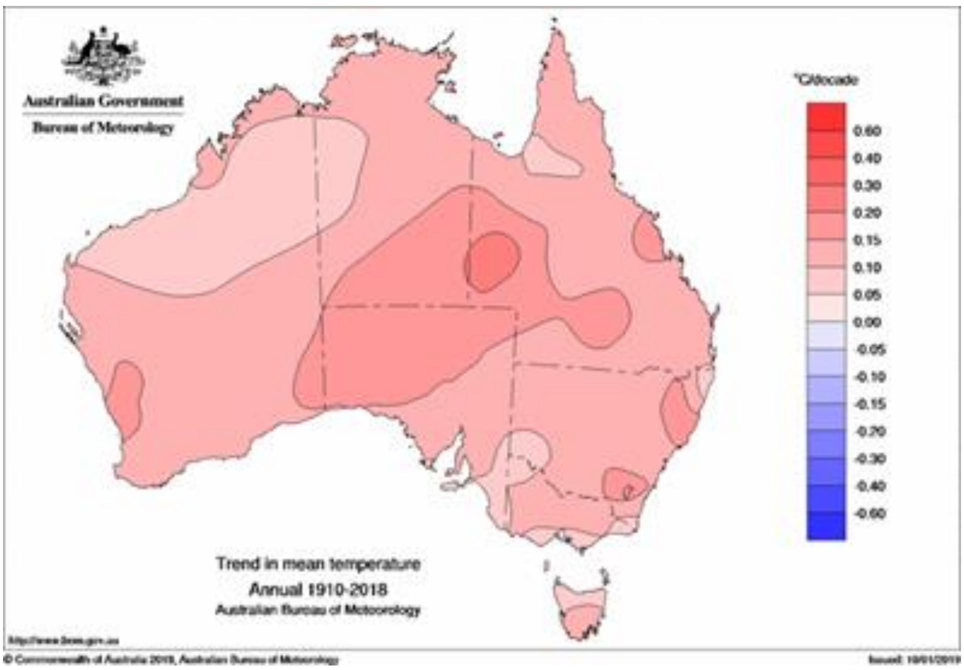

Figure A5.7 Trend in mean temperature, Annual 1910-2018. Source: http://www.bom.gov.au/climate/.

These warmings are large compared to natural variability (see Figure A6.8 for an example of projected warming as a time series using the results from a single climate model under 'high emission scenario' (RCP8.5)). Warming for maximum and minimum temperature are similar to that for mean temperature (CSIRO and BoM 2015).

It important in light of the Fish Kill under examination to consider the observed Temperature Anomaly for December 2018 and January 2019. These are set down in Figure A5.8.

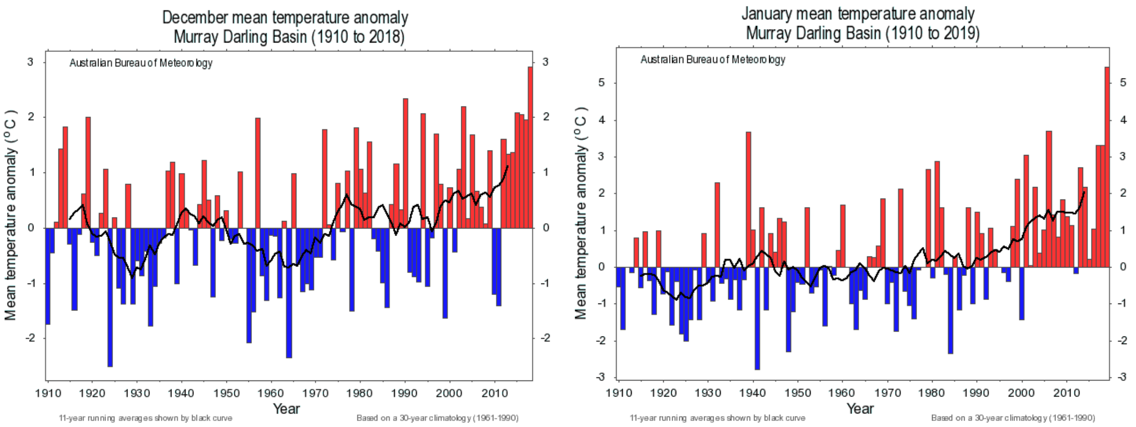

Figure A5.8 Mean temperature anomaly for December 2018 and January 2019. Source: http://www.bom.gov.au/climate/change/

There is increasingly reliable evidence now that human-caused climate change has played a major role in the occurrence of these record temperatures, adding at least 1 °C or more to background temperatures. Natural variability also likely played a role. However, climate change was the dominant factor is increasing the likelihood of these new record temperatures, increased the chances of these new monthly record temperatures in the MDB by at least a factor of 6 compared with a world with no climate change (Lewis, Karoly and Yu 2014).

Whetton (2017) sets down projected temperature increases (see table and figure in Figure A5.9) which can be expected to apply to daily temperature extremes, increasing the temperature of hot days and cold nights, and increasing the frequency of hot nights but reducing the frequency of cold nights. CCIA concluded for Murray Basin based on model results and physical understanding: *'A substantial increase in the temperature reached on the hottest days, the frequency of hot days and the duration of warm spells are projected with very high confidence'* (Timbal et al. 2015).

Table 1: Average warming in °C for the Murray Basin and Central Slopes in 2030 and 2050 and under RCP2.6, RCP4.5 and RCP8.5. Baseline is 1995 (1986-2005). Source: Climate Change in Australia website.

		RCP2.6	RCP4.5	RCP8.5
2030 (2020-2039)	Murray Basin	0.8 (0.6-1.0)	0.8 (0.6-1.1)	0.9 (0.7-1.3)
	Central Slopes	0.9 (0.6-1.2)	1.0 (0.6-1.3)	1.1 (0.7-1.5)
2050 (2040-2059)	Murray Basin	1.0 (0.6-1.3)	1.3 (0.9-1.7)	1.7 (1.3-2.1)
	Central Slopes	1.0 (0.7-1.6)	1.4 (1.0-1.9)	1.9 (1.3-2.5)

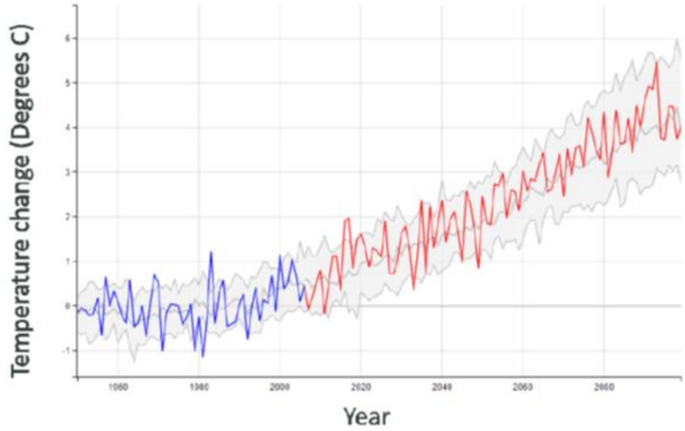

Figure 7: Example of model simulated historical (blue) and projected (red) annual temperature (in C) for Murray Basin region from a single global climate model (ACCESS-3 model, RCP8.5). Grey envelope indicates results from multiple models. Source: Time Series Explorer, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/climate-projections/explore-data/time-series-explorer/)

Figure A5.9 Figure and table reproduced from Whetton (2017).

PROJECTIONS OF RUNOFF, STREAMFLOW, POTENTIAL EVAPOTRANSPIRATION AND INTERACTIONS WITH TEMPERATURE

During the period 1996 to 2010 the southern catchments of the Murray Darling Basin (MDB), responsible for much of Australia's agricultural output, experienced a severe Millennium Drought with record high temperatures and record low inflow. Cai and Cowan (2008) show that a relationship exists between inflow variations and fluctuations of temperature not associated with rainfall in the austral winter and spring. They show that a rise of 1 °C leads to an approximate 15% reduction in the climatological annual inflow. While their correlation is true the physical mechanism cannot be inferred from their approach. Nevertheless their work provides strong evidence that rising temperatures due to the enhanced greenhouse effect will have a strong impact on southern Australia's water resources, in addition to any reduction in rainfall, and they suggest a long-term decline in inflows to this river system as the greenhouse effect continues.

This negative impact of rising temperature is unlikely to be offset by an increase in rainfall, as most climate models are projecting a rainfall reduction. Therefore we can expect more occurrences of low MDB inflow, as observed in more recent years.

Cai et al. (2009) show that a relationship exists between subsurface soil moisture variations and fluctuations of temperature not associated with rainfall over eastern Australia in all seasons, and over south-eastern Australia in spring and summer. On an annual basis, a rise of 1 °C leads to an approximate 9% reduction in subsurface soil moisture in the Southern MDB.

Cai et al. (2009) found that during the Big Dry of the Millennium Drought the sensitivity of soil moisture to rainfall decline is over 80% higher than during the World War II Drought from 1937–1945. In other words during the Big Dry of the Millennium Drought a reduction in rainfall produced 1.8 (2.4/1.33; see Figure A5.10) times the reduction in soil moisture as did a similar reduction in rainfall during the World War ll Drought.

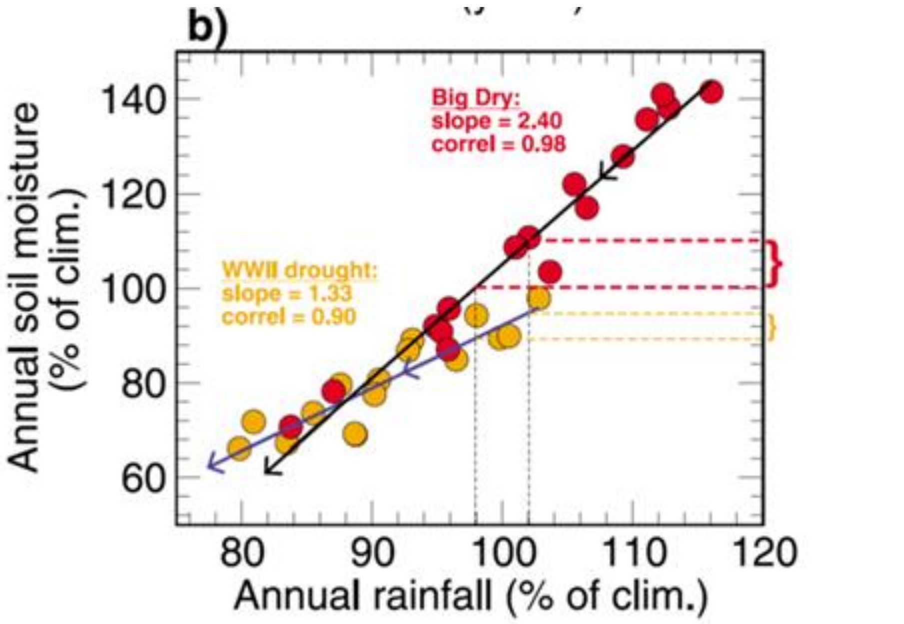

Figure A5.10 Relationships between soil moisture and rainfall decline in the Big Dry (Millennium Drought) and the World War II drought (from Cai et al. 2009).

With the concurrent decline in inflows induced by the same processes dictating soil moisture, the increased irrigation water cannot be provided from rivers without disproportionately curtailing other uses. Further, Cai et al. (2009) show that since 1950, the contribution from rising temperature is comparable to that from declining rainfall. This further strengthens the argument that rising temperatures due to the enhanced greenhouse effect and multi-decadal variability have a strong impact on the future of Australia’s agriculture in the Southern MDB. If the relationship they identify persists into the future, a 2 °C rise by 2060 will lead to a 19% reduction in subsurface soil moisture. This negative effect can only be offset by an increase in rainfall, which appears to be unlikely, as most climate models are projecting a rainfall reduction. Therefore we can expect more occurrences of low soil moisture with concurrent low inflows, as observed in recent years. This work suggests that a comprehensive assessment must be carried out through detailed hydrological modelling. However, our results do highlight a potentially significant impact from rising temperatures.

CSIRO (2012) indicates that in the longer-term, the larger increases in temperature will affect streamflow in different ways. Changes in atmospheric circulation driven by the pattern of global warming may drive changes in the amounts, seasonal patterns and characteristics of rainfall. Higher temperatures are also likely to increase the potential for evaporation, as seen in the increase in evaporation during the Millennium Drought (Roderick and Farquhar 2011). However they noted that potential evaporation does not necessarily increase with increasing temperature, mainly because of the observed reduction in wind speed (McVicar et al. 2008, CSIRO and BOM 2015) can press towards a reduction in potential evapotranspiration. Nevertheless an increase in potential evapotranspiration is consistently projected by CSIRO and BOM (2015) and the increasing trend emerges even in the near future (2030). However the method used did not consider wind speed and more importantly the influence of stomatal conductance reductions commonly induced by increasing atmospheric CO_2 concentrations in climate models (Milly and Dunne 2014; Yang et al. 2019) which can lead to over prediction of evaporation. In preliminary studies reported in CSIRO (2012) which do examine these influences they conclude that *'rising CO_2 levels may also affect runoff due to changes in plant physiology. Initial results indicate an increase in runoff of about 9 percent per 100 parts per million increase in CO_2, due to decreased stomatal conductance and hence decreased transpiration. However, additional feedbacks associated with plant growth and structure are likely to modify this result and further research is necessary to determine the likely net overall consequences of increases in both CO_2 and temperature.'*

Consequently there is a high level of uncertainty placed on the projected evaporation and drying with temperature increase. This is due to there being no clear changes although some evidence of a decline in observed in pan evaporation across Australia in data available since 1970 which on the whole, was attributed to decreasing wind speed (Roderick et al. 2007). This is set down in Figure A5.11 for the Murray-Darling Basin.

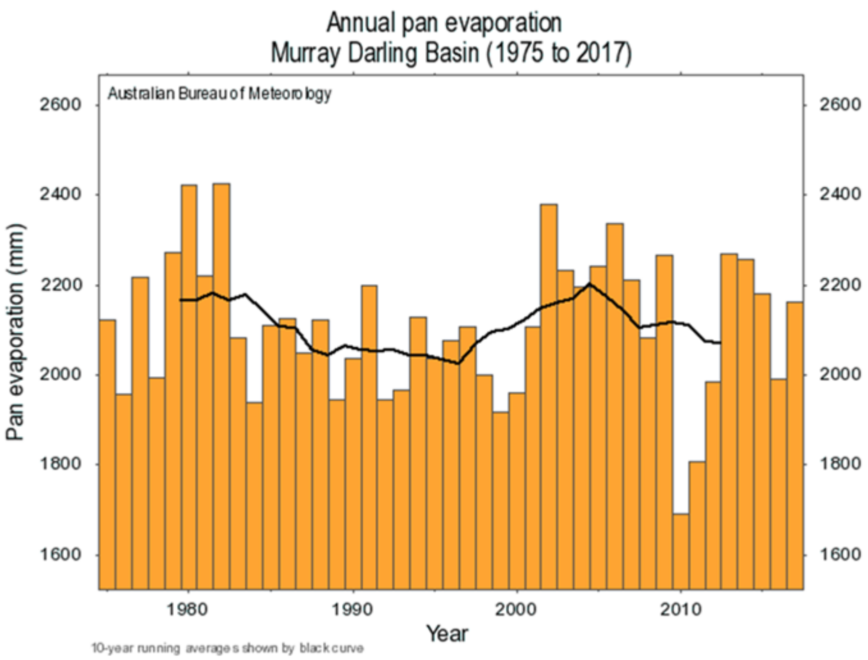

Figure A5.11 Annual pan evaporation, Murray-Darling Basin (1975-2017) Source: http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries&tQ=graph%3Devap%26area%3Dmdb%26season%3D0112%26ave_yr%3D10

Clearly this means that while temperature has been increasing it demonstrates that potential evapotranspiration does not need to follow temperature. Yin et al. (2014) show that during drought where there precipitation during drought reduces the available water thereby decreasing actual evaporation, and in turn the consequent reduction in evaporative cooling causes higher temperature. This is a temperature increase in drought that is not caused by greenhouse warming but a change in the surface energy balance. Both greenhouse warming and changes in the surface energy balance will contribute to the temperature increase in these times of drought.

This work highlights once again a need for much more careful analysis of climate change processes on the hydrological responses in catchments which drive water flows to streams and groundwater. Saft et al. (2015) indicate that most current decadal and longer hydrological predictions implicitly assume that hydrological processes are stationary even under changing climate. However as shown above, changing climatic conditions will affect runoff generation processes and cause changes in the rainfall runoff relationship. Using annual rainfall and runoff records from south-eastern Australia Salt et al. (2015) demonstrate that protracted drought led to a significant shift in the rainfall–runoff relationship in 46% of the catchment-dry periods studied. The shift led to less annual runoff for a given annual rainfall, compared with the historical relationship. They found that long-term drought is more likely to affect transformation of rainfall to runoff in drier, flatter and less forested catchments. Understanding changes in the rainfall–runoff relationship is important for accurate streamflow projections and to help develop adaptation strategies to deal with multiyear droughts.

Understanding how climate change impacts on hydrological behaviour and incorporating these changes will be critical to the work of incorporating climate change into future water management plans for the basin. Milly et al. (2018) show that sensitivity of annual streamflow to inter-annual variability of air temperature can now be quantified and explained theoretically. Temperature affects streamflow mainly because the slope of the saturation-vapour-pressure curve increases with temperature. The theory predicts well the central tendencies of the observed temperature sensitivity of streamflow from 2673 river basins. Although inter-annual streamflow variability is primarily a result of precipitation variability, temperature also plays a role.

CONCLUSIONS

Evidence of climate change in historical climate record has an increasing evidence base. Analysis in the literature show that the Millennium Drought was of great hydrological importance to the MDB, particularly the Southern MDB. The reductions in runoff were unprecedented in the historical record and estimated their return period as at least 1/300 years. Notably the runoff was more reduced than may have been expected given the rainfall anomaly, a tendency that has been attributed to increases in potential evapotranspiration and changes to rainfall variability and seasonality. This work reported here showed clearly that cool season rainfall across the basin is declining in recent times and warm season rainfall is trending towards a small increase. Both these observations appear to be consistent with the rainfall projections under climate change.

Based on the recent updates and detailed re-examination (Whetton 2017) of earlier CSIRO (CSIRO 2008, 2012) work it can be reasonably concluded that the Murray-Darling Basin area has warmed by around a degree since 1910, and will continue to warm (projected ranges is 0.6–1.5 °C in 2030 relative to 1995, and by 0.9–2.5 °C in 2050 without mitigation), with more hot days and fewer cold days. Rainfall is projected to have a tendency to decrease, particularly in the south and in winter, with more time in drought and decreased soil moisture as the rising temperature impacts through changes to the nature of water flow in the soil-plant-atmosphere system. However, both natural variability and model-to-model difference are large, and both increase and decrease rainfall is possible, particularly in the northern tributaries of the Darling. Daily extreme rainfall is projected to increase even when average rainfall declines, with implications for erosion and flooding. Using a climate analogue approach, sites in the Basin 'move' inland/northwest under the hottest/driest scenario and north/northeast in the coolest/wettest scenario. The analogues may be many hundreds of kilometres away and outside the Basin in 2050 under high emission scenarios.

Wet and dry extreme climate scenarios used in Sustainable Yields (CSIRO 2008) were assessed as still valid and representative given latest science, and thus the consequent hydrological scenarios are similarly still valid and representative (although the latest modelling results suggest that probability of the dry scenario may have declined slightly). For the dry scenario there are large reductions of runoff and water availability throughout the basin. For the wet scenario there are significant increases in runoff and water availability in the north grading towards little change in the south.

These projections (CSIRO 2008, 2012) used hydrological models that computed potential evapotranspiration that did not take account of vegetation responses to an elevated atmospheric CO_2 concentration. Recent work (Milly and Dunne 2016 ; Yang et al. 2019) shows that an increase in evapotranspiration caused by a warming-induced vapour pressure deficit increase is almost entirely offset by a decrease in evapotranspiration caused by decreased stomatal conductance driven by rising [CO_2] concentration. When the vegetation response to elevated [CO_2] is taken into account historical and future tendencies towards continental drying, may be considerably weaker and less extensive than previously thought.

Understanding how climate change impacts on hydrological behavior and the interaction and responses of vegetation to changing CO_2 concentrations and increasing temperature will be critical to the work of incorporating climate change into future water management plans for the basin. From this examination it is apparent that there is an urgent need for new knowledge cast at appropriate scales and confidence on the hydrological response of our catchment and rivers to expected rainfall and temperature regimes under climate change. Whilst the work available is significant, progress over the last decade appears to be inadequate for the needs of future policy development and water management strategies that can deliver ecological wellbeing of our basin rivers under the changes in climate and the changing hydrological and ecological process in our rivers and catchments.

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APPENDIX 6: IMMEDIATE STEPS FOR FISH RECOVERY

In the current circumstance the options available to improve river system's health and management within the Basin Plan framework in the immediate term of weeks and months appear to be limited to:

1. finding suitable water in sufficient volumes to refresh the weir pools and river channel in the Menindee section of the Darling
2. attempting to improve oxygen conditions in key refugia in the river channel and weir pools using appropriate aeration technology.

MANAGEMENT OPTION 1: AVAILABILITY OF WATER TO REFRESH THE WEIR POOLS AND RIVER CHANNEL IN THE MENINDEE SECTION OF THE DARLING

There is insufficient water held by the Commonwealth Environmental Water Holder and available in public storages across the Northern Basin to support an environmental flow which would make it to and through the Menindee Lake system, under current temperatures and with no additional in-flow from rainfall in northern catchments. This is because the Barwon-Darling has ceased to flow from Walgett, and below Bourke, for more than 180 days. This means that the actual transmission losses are much greater than expected as any flow would need to travel across very hot and dry river beds with a very high rate of loss to the flow as water is absorbed into dry river beds and banks. High temperatures, shallow flows, increased evaporation and a long distance of travel (2000 km from some northern storages to Menindee) exacerbate these losses.

As at 30 January 2019, the CEWH holds approximately 42 GL that is accessible for use in the Northern Basin catchments, with practically all in NSW and virtually zero (45 ML) in Queensland. Of this, about 8.3 GL is either held within Menindee Lakes themselves (3.6 GL), or part of a current watering event (3.0 GL) in the Gwydir catchment or in small amounts (1.7 GL) in the Macquarie and Namoi and, if delivered, would be unlikely to reach the Barwon River.

The consequence is that CEWH has approximately 33-34 GL of water that could be utilised to generate the flushing and refreshing flows in the Menindee reaches of the Darling. Whilst there is some uncertainty of factors including timing, temperature, natural inflows from rain and broader government agency/community support, it is estimated that a flow of around 46 GL would be required to make it to Bourke.

Clearly the CEWH with just 33-34 GL of water does not have sufficient Held Environmental Water to provide a replenishment flow to connect stranded refuge pools and weir-pools along the reaches of Darling at Menindee.

Therefore an examination was conducted with CEWH and NSW LW OEH of how additional water might be found to provide these replenishment flows.

Current water availability in NSW tributaries of the Darling River

The current total active storage in the Border, Gwydir, Namoi, Peel, Macquarie and Cudgegong river catchments is just 605 GL of which 152 GL is licensed water held by water users. The volume currently assigned to environmental water licences (Held Environmental Water) plus the volume currently assigned to bulk environmental water (Planned Environmental Water) totals around 116 GL. Meanwhile the largest component of some 337 GL is operational water needed to run the rivers to deliver the account water balances. The operational water ('essential needs') is consumed primarily in evaporation and transmission losses although it also includes relatively small volumes of high priority commitments to town water supply entitlements, basic landholder rights, domestic and stock purposes, and cultural water where applicable.

Due to the lack of rainfall and prevailing dry conditions, the actual transmission losses are much greater than expected, with the consequence that much larger amounts of environmental water are required to move the water from the storages to the river channel refugees and weir pools in the Darling from Bourke to Menindee.

It is estimated that, assuming arrangements to access water from the owners could be achieved, the respective tributary storage delivery systems would yield about 75 GL of licensed water and 45 GL of both Planned and Held environmental water at the confluence with the Barwon-Darling system. This would also result in a significant proportion of the 'essential needs' water being consumed in this delivery. It is expected that under current conditions approximately 20 GL of licensed water and less than 15 GL Planned and Held environmental water would arrive at Menindee reaches of the Darling.

Acquiring water owned by others and amending statutory plans to liberate the Planned Environmental Water would be highly problematic under current operating governance. It appears that a volume much less than 30 GL is likely to be available to Menindee reaches of the Darling if one were to tap into upstream NSW storages for all but essential (primarily human) water needs.

An alternative plan for a replenishment flow using only available environmental water to connect stranded refuge pools and weir-pools along the Barwon River is being considered by CEWH. This is a smaller targeted area with outcomes that have environmental priority. These flows could provide benefits for fish habitat, river bank vegetation and river health, as well as social/cultural benefits for communities. There is uncertainty of factors including timing, temperature, natural inflows from rain, and broader government agency/community support—but with the caveat that CEWH estimate that a flow of 46 GL should make it to Bourke. This would comprise: CEWH providing 32 GL (26 from Copeton, 6 from Glenlyon) and NSW OEH providing 14 GL from Copeton Dam utilising the environmental contingency allowance.

This more limited option utilising only currently available environmental water will be restricted to reaches in the Barwon River. There is insufficient environmental water available to deliver replenishment flows to the reaches of the Darling at Menindee.

Current situation in Queensland tributaries of the Darling River

The active storage in dams within the Queensland tributaries of the Darling river is 285 GL, with three major storages: Beardmore Dam near St George with 80 GL, Leslie Dam on the Condamine with 104 GL and Coolmunda dam on the Border River with 69 GL. There are two weir storages on the Condamine with a capacity of 31 GL. In the Condamine and the Balonne rivers there is also a significant storage on private land arising from flood plain harvesting, take from rivers and take from runoff dams (MDBA). This has varied from 1268 GL in 2012-13 to 529 GL in 2015-16. Currently there is 70 GL stored in the dams on the Condamine/Balonne with some 37 GL in Beardmore dam, 13 GL in Coolmunda and only 6 GL in Leslie dam and some 14 GL in the smaller weirs. In Queensland storages the CEWH has only 45 ML of held environmental water which is virtually zero. Thus the only option to access water from Queensland public storages would be purchase from licensed water held by water users. Whilst purchase from licenced water users is perhaps problematic it seems feasible to consider using water in Beardmore dam to service the Menindee reaches of the Darling. With transmission losses of approximately 50% and a travel time of about 30 days, in times of drought, a reserve of 10-15 GL in Beardmore for flushing the Menindee reaches of the Darling River is an option to examine further.

The risks in providing replenishment flows

There are, nevertheless, a number of risks to consider with these replenishment flow options. Under current conditions there is a significant risk that these flows could de-stratify pools causing hypoxic conditions and death of native fish. In essence, if a flow which connects pools with pre-existing poor water quality (low dissolved oxygen) is too small, it can push a front through the pools leading to further fish death. Insufficiently large flows under hot conditions can also spread algal blooms rather than dissipate them. Cold water release from below the thermocline of storages can also lead to fish death. Timing and careful management can mitigate but will not obviate or remove these risks. An additional risk is that the water held by the CEWH in the Gwydir catchment was planned largely to be used to support the environmental watering requirements of floodplain wetlands and Ramsar sites over the next 18-24 months. Therefore a decision to use this volume of water for a refuge replenishment flow downstream in the Menindee reaches of the Darling will increase risks to those sites and reduce flexibility to respond within the Gwydir, particularly if conditions remain dry and there are no further water allocations.

Ways forward

Both NSW and Commonwealth environmental water holders currently consider that autumn may present more favourable conditions for a coordinated release of these emergency environmental flows. The options for replenishment flows for reaches of the Barwon River appear to be feasible using environmental water held by both NSW LW OEH and the CEWH.

While the environmental water is available it is insufficient to deliver replenishment flows to the Menindee reaches of the Darling River. However, success of any refuge flow to the reaches of the Barwon River will depend on a number of factors, including:

- protection of the flow: an embargo under the NSW Water Act (s324) from pumping for irrigation
- agreement to release this volume from storage: authorities will seek to ensure a minimum amount of water within a storage as a basic operational requirement
- temperature: delay until cooler temperatures reduce risk of losses from evaporation
- state agency support: stakeholder engagement, advice to entitlement holders, compliance
- local government, community, Indigenous group support

To direct a replenishment flow to Menindee reaches of the Darling River would require additional water to that which is held by the Commonwealth and NSW environmental water holders. Water is available in both NSW and Queensland to do this but it will require purchase of allocations and or entitlements from licenced water users. This could be problematic but it is technically feasible from either NSW or Queensland tributaries. All things considered, the CEWO preferred option is to piggyback available environmental water on initial unregulated flows (assuming sufficient rain over late summer – early autumn) for a release sometime from April when temperatures have eased. As with the Barwon river option and following from experience gained in the recent and successful northern connectivity event managed by CEWH and NSW DEH, success of any such e-flow would depend on the factors listed above.

Summary for Water Management Option 1

Our examination of the first option of obtaining sufficient water of adequate quality is limited at the moment and involves a level of risk. Overall there is just not enough water in the right tributary storages, given the instream losses, to rescue the fish refuges without substantial rain somewhere in the catchment to initiate natural flow. Due to the extremely hot conditions prevailing this summer, there is a high risk of failure until at least April, when conditions are cool enough to allow a flow to reach the Menindee reaches of the Darling.

At that time, the water reserves held by both Commonwealth and state environment water holders in addition to licensed entitlement water, as documented below, should be marshalled, purchased on the market, or compulsorily acquired and released with embargo provisions that guarantee that this water for the river environment could not be extracted for consumptive purposes.

Clearly this situation underpins our finding that there is not enough environmental water held in the system to meet critical environmental needs in time of drought.

The ideal would be to initiate a flow through to the Menindee reaches of the Darling River to flush stagnating water holes in the main channel and lift the level of the Menindee Lake system. As specified in the plan, this would use environmental water reserves held by Commonwealth and state environmental water holders along with water purchased or acquired in both NSW and Queensland.

MANAGEMENT OPTION 2: MANAGEMENT OF WEIR POOL OXYGEN CONCENTRATIONS

Management of dissolved oxygen is a balancing act between the supply and the consumption of oxygen. Wastewater engineers have done a lot of research on methods to add oxygen to waters receiving sewage effluent, for example, and other organisations such as the Tennessee Valley Authority have a lot of experience with adding oxygen to reservoirs. In order to select an appropriate method, it is important to understand what the rate-limiting processes are. Basically, oxygen is exchanged across the air–water interface, is produced locally during daylight hours within the euphotic zone, is consumed at all times below the euphotic zone and also within the euphotic zone in the absence of daylight.

Approaches for adding oxygen to water typically involve one of: direct oxygen injection; enhanced circulation (e.g. artificial destratification or Solar Bee mixers); or aeration by the injection of compressed air or deployment of vigorous mechanical mixers such as those used in aquaculture ponds. Note that 'aeration' is often used to refer to the use of compressed air to destratify water reservoirs in which case it is more accurately considered an enhanced circulation method.

Some basic principles for increasing dissolved oxygen levels:

- Any system that relies on dissolution of gas from bubbles into the surrounding water will perform best with small bubbles. As soon as the gas (usually compressed air or pure oxygen) is introduced into the open water it will form bubbles and rise to the surface. The goal is to maximise oxygen dissolution into the water before the bubbles reach the air–water interface. The smaller the bubble size, the slower the rise velocity and the larger the bubble surface area to volume ratio, yielding longer contact time and greater transfer efficiency per unit time.
- Oxygen transfer efficiency is proportional to the change in oxygen concentration, i.e. the oxygen transfer efficiency is highest by injecting oxygenated water into receiving water with the lowest dissolved oxygen.
- Systems must be sized sufficiently to match the oxygen transfer rate with the oxygen demand of the water column. Knowledge of the in situ oxygen demand is very helpful.
- For systems that employ compressed air, it is wise to ensure that increased dissolved nitrogen concentrations do not exceed the tolerance levels of the aquatic biota.
- Systems that use porous diffusers (e.g. ceramic diffusers) to produce small bubbles are prone to clogging by particles and by oxidised iron. They are probably not well suited to intermittent operation because of the need to frequently clean the pores.
- Systems that use bubbles or mixers to enhance circulation, e.g. compressed air destratification systems, intrinsically rely on air– water gas transfer to supply most of the oxygen to the water column; typically only a relatively small amount of oxygen is transferred directly from the bubbles to the water. They can sometimes be thought of as imposing a net downwards velocity in the water column away from the bubble plumes. This approach is not suited to shallow systems because the conversion of compressor energy to a reduction in the potential energy of stratification decreases as the water column becomes shallower. Whether or not this approach can supply adequate oxygen will depend on the rate of transfer at the air–water interface, the rate of vertical downwards transport, and the oxygen demand rate in the water column and sediments. Systems that enhance circulation often raise the temperature of the bottom waters thereby increasing the oxygen demand of the sediment and water column (this is not a major concern for systems that completely mix every fortnight or so as they will already tend to approach an equilibrium temperature based on local meteorological conditions).
- The oxygen transfer characteristics of surface agitation and fountain systems are reasonably well understood and the response of surface layer oxygen content can probably be predicted. Less well understood would be the interaction between such systems and the stratification in the weir pool, i.e. how much of the 'enhanced' surface layer oxygen will be transported downwards.

Direct oxygenation

For very shallow systems like weir pools, the approach with the greatest effectiveness is likely to be direct oxygenation using a technique called 'side-stream supersaturation'. The most efficient application would involve pumping water out from close to the bottom in the deeper part(s) of a weir pool and passing it through an O_2-transfer device such as a Speece Cone to produce highly supersaturated water that is then reinjected into the pool. Injection is best done through small, highly-turbulent jets to ensure the maximum mixing with the ambient oxygen-depleted water, otherwise the supersaturated oxygen will form bubbles and outgas to the atmosphere. The Water Authority of Western Australia has employed direct oxygenation for a number of years to improve water quality in both the Upper Swan Estuary and Canning Rivers and could provide relevant advice regarding the cost and oxygen transfer efficiency of the method. Direct oxygenation may be a relatively expensive approach, but provides the most reliable and greatest oxygen transfer rate and better targeting of oxygen delivery.

Artificial destratification (aeration)
Not suitable for shallow systems due to poor mechanical efficiency and sensitivity to air–water gas transfer rate. Unlikely to provide sufficient protection against acute hypoxic events.

Aeration (gas transfer between introduced air and surrounding water)
Depending on the system, this can provide a similar level of physical flexibility as oxygenation. Shore-based systems are available that are conceptually similar to direct oxygenation in that water flow rates, intakes and outlets can all be controlled to produce more predictable results. Water is pumped out of the waterbody, enters a device that greatly enhances gas transfer with ambient air, and then delivers the highly air-saturated water back to the waterbody. Dissolved nitrogen can be an issue for aquatic fauna because high oxygen transfer occurs along with high nitrogen transfer in such systems.

Surface agitation and fountain systems are common in aquaculture and sewage treatment plants. They can be designed to produce an oxygen transfer rate into the surface layer. Some systems are easily transported with a tractor and use the tractor drive to power the mixing device allowing greater flexibility in where the mixers can be deployed at any given time. It is difficult to predict how effectively the oxygen will be transported through the thermocline and into the bottom layer and what effect the physical disturbance of surface agitation or fountains will have on the stratification dynamics.

Management of harmful algal blooms in weir pools

Management of cyanobacterial blooms to reduce biomass may reduce the respiratory demand that contributes to acute weir pool hypoxia. A relatively new and promising approach, the application of hydrogen peroxide has been used successfully at a number of sites in Europe and has undergone preliminary testing in South Australia. When applied in the correct amount (nominally 2 mg/L), the results have generally been near complete eradication of algal blooms within a few days without either a subsequent increase in toxin concentration or substantial harm to non-target aquatic organisms. The peroxide breaks down to water and oxygen within a few days and the beneficial effect appears to last for up to 7 weeks. SA Water can be consulted for further information on Australian tests of peroxide treatment.

Conventional approaches targeting light availability such as artificial destratification and nutrient availability such as Phoslock application are unlikely to be successful over extended periods given the climatic conditions which will likely sustain persistent stratification, and the impact of flow events that would require subsequent reapplication of Phoslock or other sediment amendments.

Summary for Water Management Option 2

Until temperatures ease, and without sufficient water to flush the system, there is a strong possibility of ongoing fish kills in the remnant and degraded 'refugial' pools. NSW Fisheries field staff have been deploying oxygenators to improve the condition of selected pools in critical condition. This approach does not scale geographically, but can be applied strategically. Based on expert advice (B. Sherman, pers. comm.), it appears that the following is the best option:

Direct oxygenation. For very shallow systems like weir pools, the approach with the greatest effectiveness is likely to be direct oxygenation using a technique called 'side-stream supersaturation'. The most efficient application would involve pumping water out from close to the bottom in the deeper part(s) of a weir pool and passing it through an O2-transfer device such as a Speece Cone to produce highly supersaturated water that is then reinjected into the pool. Injection is best done through small, highly-turbulent jets to ensure the maximum mixing with the ambient oxygen-depleted water, otherwise the supersaturated oxygen will form bubbles and outgas to the atmosphere. The Water Authority of Western Australia has employed direct oxygenation for a number of years to improve water quality in both the Upper Swan Estuary and Canning Rivers and could advise on the cost and oxygen transfer efficiency of the method.

As an alternative in some circumstances aeration involving gas transfer between introduced air and surrounding water can be effective; it is usually less expensive and builds on technology derived from the aquaculture and sewage treatment industries (B. Sherman, pers. comm.). Depending on the system, this can provide a similar level of physical flexibility as oxygenation. Shore-based systems are available that are conceptually similar to direct oxygenation in that water flow rates, intakes and outlets can all be controlled to produce more predictable results. Water is pumped out of the waterbody, enters a device that greatly enhances gas transfer with ambient air, and then delivers the highly air-saturated water back to the waterbody. Dissolved nitrogen can be an issue for aquatic fauna because high oxygen transfer occurs along with high nitrogen transfer in such systems. Surface agitation and fountain systems are common in aquaculture and sewage treatment plants. They can be designed to produce an oxygen transfer rate into the surface layer. Some systems are easily transported with a tractor and use the tractor drive to power the mixing device allowing greater flexibility in where the mixers can be deployed at any given time. It is difficult to predict how effectively the oxygen will be transported through the thermocline and into the bottom layer and what effect the physical disturbance of surface agitation or fountains will have on the stratification dynamics.

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APPENDIX 7: WATER VALUES FOR SOCIETY

This appendix outlines very broadly the different values of water in a society, and provides a number of examples and quotes from impacted parties that are relevant to the Menindee fish kill situation.

When considering how to value water to all different areas of society, including irrigation, recreation, tourism, urban use, environmental and cultural value, there are two broad economic frameworks that are often used in the analysis and estimation of water values: the Millennium Ecosystem Assessment (MEA) approach of the value humans receive from a variety of different ecosystem services, and the total economic value (TEV) framework of water that uses the terminology of direct and indirect use values. As Jackson et al. (2011) state, the two frameworks have many overlaps and emphasise that the environment has a far greater value than what is recognised in the marketplace, and that there are many ways people interact with, and benefit from, the environment. Within the TEV, *direct use values* are benefits that directly accrue to individuals who use water, including consumers, rural and urban producers and recreational users. One such example is the value of being close to rivers and lakes, water views and the aesthetics it generates frequently increase property values (Tapsuwan et al. 2015). Another direct use example is the value of recreational fishing and tourism, but also the value of customary and subsistence harvest by Indigenous people (Jackson et al. 2015). For example:

> *The Barka gives us healthy food and medicine, it gives us wood to make our artefacts, reeds to weave, it is where we go as families to swim, boat, camp, picnic, fish, go yabbying, and prepare and cook our traditional food. It is where we relax and enjoy our homeland. When we go fishing we go as a family and we sit and talk and remember and pass stories on about our ancestors and our land and water. If we catch some fish we light a little fire by the river and cook the fish and some johnny cakes and we sit and eat there on the river.*
> William Brian Bates (Badger), Submission to Australian Academy of Science

> *Tourism and recreation make a significant contribution to the life and economy of almost all parts of the Murray-Darling Basin, much more so than is generally appreciated. In recent years, there has been an increasing effort to attract tourists to outback NSW, including the Darling River… Bird watching along the Murray and the Darling rivers is a rapidly growing past time and attracts local and overseas visitors.*
> Discovering the Darling, https://discoveringthedarling.com.au/tourism/

Researchers working with the Ngemba traditional owners from Brewarrina on the Darling undertook a valuation study of the ancient fish traps which are a very popular tourist destination (Bark et al. 2015). The site is registered for its heritage value, being one of the oldest human-made structures in Australia. In that study researchers obtained data from the Brewarrina tourism centre and from the Aboriginal-run cultural centre. Data from qualitative interviews with Indigenous custodians also demonstrated diverse cultural values and associated benefits with respect to the fish traps themselves and to their connectivity with another key water site, an upstream lagoon.

Indirect use values are where there is no direct contact with water, but indirectly people benefit from water bodies and resources. For example, where water in rivers provides important refuges and recreational activity within Aboriginal communities, this can have implications for reduced crime, improved mental health, decreased anti-social behaviour and lower health care costs in communities (Goodall 2012).

> *The river is our memory, we walk along it and remember our history and our ancestors by looking at the marks and places.*
> William Brian Bates (Badger) and Katherine McBride, Submission to Australian Academy of Science, 4 February 2019.
>
> *It's a proven fact in the northern basin that when there was no water in the river up there, the crime rate in town rose quite significantly. The health of people in those basin communities also put pressure on the Medicare system in those towns. The doctors were under pressure because of the amount of people who were in the day surgeries and seeing doctors. When there's water in the river, our people are out there fishing; they're enjoying their knowledge transfer to the younger generation; they're happy to see water in the river. When Mother Earth is healthy, we're healthy*
> Rene Woods, Chair, MLDRIN, Submission cited in Senate Committee Report on Water Markets, 2018, p. 19.

Non-use water values are attributed to people knowing that sufficient water is available; for now and into the future, but direct contact is not required. Non-use values include *option values* (wanting a resource available for potential future use—for example: people may wish to go fishing in the Menindee in the future for Murray cod), *quasi-option values* (wanting a resource available for the future because new knowledge may imply an important new use of it), *existence values* (the resource is valuable in itself and its existence should be continued) and *bequest values* (the resource is valuable for future generations) (Grafton and Wheeler 2018). Some examples of such option, existence and bequest values include:

> *When I was young we lived beside the river in tents, humpies and tin huts, and moved a lot, getting to know every bend in the river, and everything about the river, billabongs, creeks and lakes, the plants and the animals. The river was always fresh enough to drink and we could always get a feed of fish, or yabbies, duck or turtle or something. Our river water should be a slightly milky colour from the clay, settling to a clearer colour after freshes settle down. We used to catch fish with a line, or net, or if the water was still and clear we would use spears we made. Our fish are beautiful to eat, we used to get cod, perch, black bream, catfish and bony bream. We used to get buckets and buckets of yabbies. There were birds everywhere along the river, water birds like pelicans, swans, cormorants, ibis, cranes, herons, and ducks. Often we would see a kite hawk swooping down to catch a fish. There were also lots of birds that would come in for a drink at dusk or hang in the cool of the river red gums, like parrots, finches and cockatoos. There were lots of water rats and river goannas and water dragons, now we only see the odd old goanna. The water had lots of insects such as water boatmen, and lots of wrigglers, that you don't see now. There were lots of water plants in the river and mainly in the billabongs, the fish and other things eat these, but they are disappearing. ……………*
>
> *I know that many of our other smaller shellfish have also gone, the river snail that we used for bait is now officially extinct due to bad water quality and no flows. I remember the first*

carp in the 1970s, we couldn't believe such ugly fish. Now for every 10 carp we catch we might get one decent native fish. Black bream and catfish are nearly extinct in the river now, this has happened only recently because there is no water. So many of our plants and animals have gone or are just disappearing. These are a part of us, it is just the same as losing a family member, or worse because once they are gone that is the end of our cultural life.

We know [about the interconnectivity between water resources] because of the stories handed down to us about the Ngatji or rainbow serpent, we know where Ngatji go and where the water is, both on top of and below the ground. These shallow aquifers are how the Ngatji travel. It is clear to us that we will end up with no water at all, because the aquifer fills from the river and floodplain in the wet, and then it seeps back out into to river in the dry. This is how our river works, it is all connected. But with no floods, no floodplain water, and pumping town water from the aquifer when the river is dry, we will end up with nothing to drink at all, and our fish, mussels, birds and everything will be gone, and our creator the Ngatji will leave us. We try and tell the water people this but they don't listen, they think it is just a blackfella's silly story.
William Brian Bates (Badger) and Katherine McBride, Submission to Australian Academy of Science, 4 February 2019

Figure A7.1 illustrates the different concepts of water values and how they make up total economic value of water.

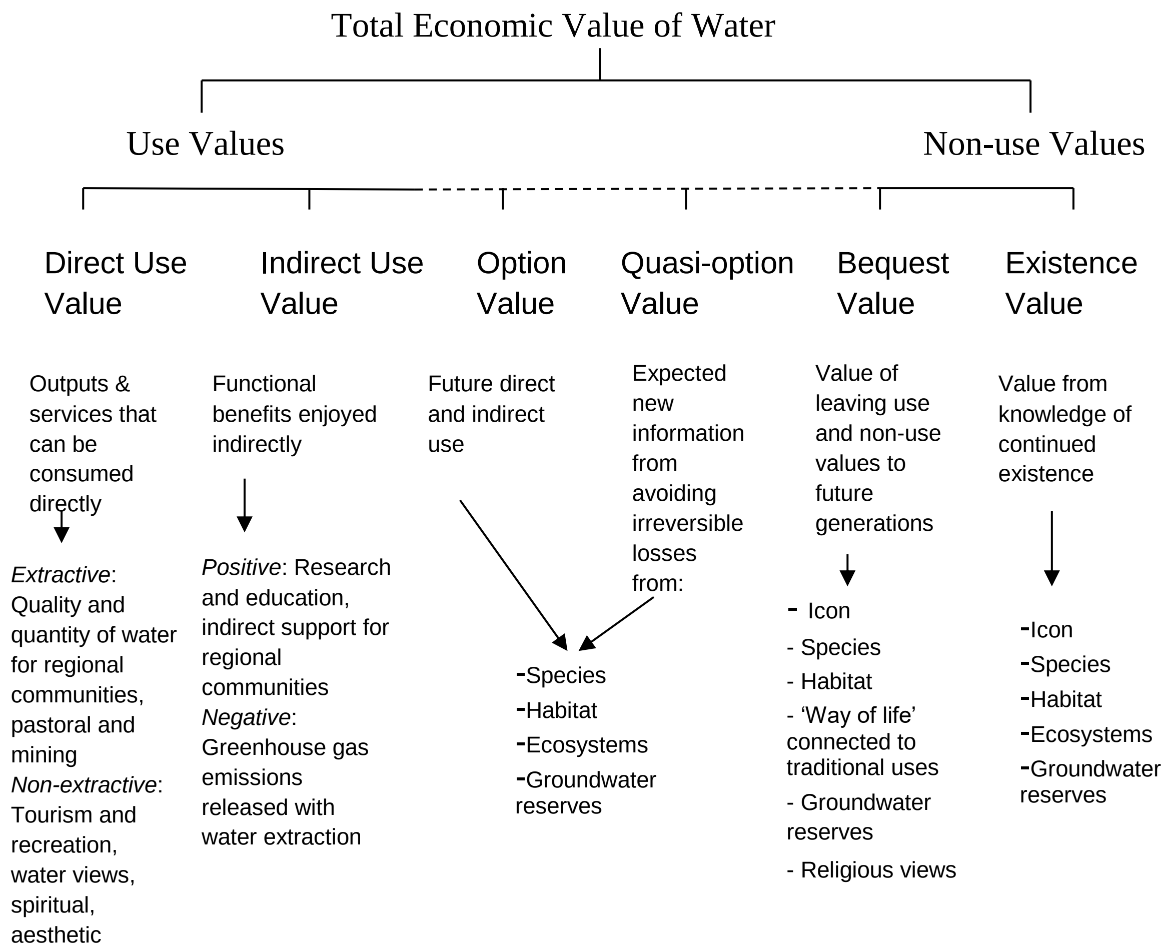

Figure A7.1 Values of Water. Adapted from Grafton and Wheeler (2015) and Rolfe (2008)

Hence, water has many other dimensions beyond its utilitarian purposes, and a range of techniques have been developed to generate intermediate value for water and the in-stream or in situ value of water. Morrison and Hatton-MacDonald (2010) collected a range of Australian studies on the value of improved habitat in native vegetation, native fish, colonial waterbird breeding and waterbirds and other species, and extrapolated values across the 19 regions of the Murray-Darling Basin. They estimated that Australians were willing to pay approximately $13.3 million (2010 $, representing $15.9 million in 2019) to increase fish stocks by 20% over the levels in 2009 in the Barwon-Darling region. People attach a significant value to an improved riverine environment in the Barwon-Darling. Hill and Carter (2009) estimated an economic value for improved water quality in the Darling River after the occurrence of the cyanobacterial bloom in December 1991. They suggested that Sydney households were willing to pay a once-off amount of $26 million (1991 values, representing over $50 million in 2019) to improve water quality in the Darling River. Note, these values do not include the loss that society collectively suffered from the fish kill events because typical loss aversion is such that people would value avoided loss (cost of fish kills) significantly more than gained benefit (improved fishery) of a similar level of change in population. In addition, the scale of the fish kill event in the Lower Darling (which is considered a key nursery for Murray cod) indicates that values across the MDB would be affected if it is shown that the population of Murray cod falls corresponding in the future, and hence only using a measure for improvement in Barwon-Darling is an underestimate. Morrison and Hatton-Macdonald (2010) provide non-market valuation figures for all different areas in the MDB.

However, these techniques can be controversial and there is more certainty over placing values on direct and indirect uses of water resources than trying to determine option, bequest and existence values. In addition, trying to place values on cultural values using standard techniques has significant issues (Stoeckl et al. 2018). In Indigenous societies, cultural affiliations to landscape and waterbody features are expressed through social etiquette, place-based knowledge, narratives, beliefs and daily practices (Jackson et al. 2011). Challenges in traditional valuation methodological issues for application in Indigenous valuation include:

- income disparities: price-based valuation techniques give greater voice to richer people, than to the preferences of the poor
- (in) separability: direct and indirect benefits are frequently interdependent and overlap, hence it is difficult to value them as a body of values
- value and culture: monetary valuation methods are often inappropriate and offensive in the Indigenous context
- community held values: individual values are easier to assess than community held values (Farr et al. 2016).

Hence, alternative approaches, such as the life satisfaction approach, subjective scaling; cognitive mapping; storytelling; and 'benchmarking' are recommended as perhaps more suitable in valuation contexts (see Venn and Quiggin 2007). Overall, what this implies is that any monetary valuation of water resources in the Menindee situation would be significantly underestimated. For example, see the following commentary that emphasises that the river is a living being to many, and fundamental for ongoing survival:

> *I walk along the river and climb down to cut a boomerang out of a bent red gum or black box tree root, then sit on the riverbank and cut it out and shape it. When I do something like this I am looking after my river and my country, I can hear my old people talking to me, I can feel the slight breeze made by them moving around. It is what makes me who I am. Without water in our river the trees will die and there will be no more roots to cut out and make boomerangs. At night on the river I listen to the fish jumping up and I am happy. Or I hear the sound of the swans flying north to meet the fresh water coming down. From this I know when the fresh water is coming and how much, I feel life is right. ……… Our Barka is also very beautiful, the water, the birds and animals and the huge river red gums are famous for their beauty, which gives us pride and happiness. Without these things my people will be buka, they will not live.*
>
> William Brian Bates (Badger) and Katherine McBride, Submission to Australian Academy of Science, 4 February 2019.

Other easier methods of cost calculation for considering the fish kill (that do not include people's values or culture) include looking at the cost of the clean-up, and the replacement cost of the fish. Koehn (2004) estimated the value associated with the loss of Murray cod in four fish kills between Nov 2002 and Feb 2004 (with around 3200 Murray cod fish included—3000 of these occurring in the Darling). To replace 1500 female fish in the Darling it was estimated at $1.9 million (2004 dollars), and take 46-52 years. Management of each fish kill event (e.g. transport, administration, clean-up) was estimated at $50,000 (2004 dollars) each.

Finally, a true evaluation of the local household impacts of poor water quality for stock and domestic in the Lower Darling is likely to have caused considerable losses of value. The infrastructure and or carting costs of replacement (e.g. provision of bottled water) are considerable, similarly so is the loss of farming returns due to some industries affected by poor water quality. There is also likely to be a significant negative values associated with smelling dead fish in a river. Information is not available on the cost of the current clean-up, and further research in this space should be conducted.

All in all, the evidence here suggests that although difficult to quantify, and also subject to considerably undervaluation, the values associated with a healthy river in the Barwon-Darling is at least in the tens of millions of dollars.

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APPENDIX 8: COMMUNITY CONSULTATIONS AND SENSE OF PLACE

COMMUNITY CONSULTATIONS

This appendix provides more detailed notes on the consultations in Menindee on 5 February 2019, summarised in 'Community knowledge and experiences of ecological impacts and management practices', in section 7 of the main report. The key points made by community members are consistent with extensive humanities/social science research and scholarship on place and belonging, particularly in relation to rivers. This research is usually collaborative (sometimes co-authored, e.g. Muir et al. 2010) with community participants, and uses a variety of methods including in-depth interviews, oral history, narrative analysis and cultural mapping (Somerville 2013). After highlighting the issues raised during a visit to Menindee by panel members, we summarise three particular aspects of this research that connect strongly to our terms of reference and provide further context about community perspectives.

Summary of views of community members, Menindee on 5 February 2019

Panel members Craig Moritz and Sue Jackson first met with members of the Lower Darling Horticulture Group, South West Water Users and Murray-Darling Wetlands Working Group. We then went on a tour of the local area, including Weir 32, with Badger Bates (Elder and member of the Barkandji Prescribed Body Corporate), members of the Menindee Aboriginal Land Council, and Graeme McCrab, a local grape grower. A number of other people joined the combined meeting that was held after lunch, including the CEO of the Barkandji PBC, members of the Menindee Water Users Group and local residents.

Key points:

- This community, representing diverse interests (Indigenous or not; irrigators, pastoralists, fishermen, residents) is united in their determination to recover, then maintain a healthy river with all the ecological, social, cultural and economic benefits that flow from that.
- Consultation by state/Commonwealth government and MDBA with this community has been inadequate—either entirely lacking or not listening or responding to community concerns. Quite sceptical of even best efforts by managers—environmental flows are a start—but not enough.
- There has been accelerating degradation of the river and its floodplains from 2000 on, and with tipping point from 2011/12.
- In dry times, goal should be 300-500 ML day, in pulsed flows, to the bottom of the Darling.
- Water volume thresholds are not sufficient—water quality is essential. This is not being measured to the needs of the community.
- Need both 'whole of river' and 'whole-of-values' approaches to manage health of the system. Both are not understood sufficiently by managers.
- WSPs for upper and lower Barwon-Darling need to be articulated so that water need downstream—'shared flows'—can be met. Present process silos WSPs.
- Consensus that there is no single cause or one cure. Fish kills are a symptom of wider, complex problem.

- This group is still questioning why the kills, at this scale and frequency, have happened here and not elsewhere or not in previous big droughts. They have thought about the other hot dry events that have not killed fish, or if they have, not so many native fish.
- The confined space between the Main weir and Weir 32 was 'brewing' algae as far back as September. … 'The fish keep coming in and they can't get out'
- The community members defined this as unprecedented in their region and asked whether the authorities are testing the water for a sufficiently wide range of possible causes, including groundwater discharge. They are not aware of any link between chemicals and fertilisers.
- Texas Downs sandbar appears to be a demarcation point in the fish kills.
- A lot of time was spent discussing the wider governance context and the sense that the lower Darling is being systematically de-watered: simultaneous depletion of inflows (due to upstream extraction) and rapid drawdowns from Menindee Lakes.
- This group have never seen the river dry for so long, as it was in 2016 when it was dry for >6 months.
- Water quality issues have been neglected by all governments, the flow regime is not being managed for this objective any more 'Flow regime has no regard for water quality, it is 100% dictated by flow rate at Burtundy Weir'.
- Low flows are particularly vulnerable, small inflows are no longer delivering water south.
- Efforts to manage river connectivity (whole of river) are being undermined by insular water sharing plans that do not protect the interests of down-stream users and uses, and do not give effect to the long-standing prioritisation system.
- This is threatening the life of the lower Darling and the viability of the human communities, as well as their quality of life and wellbeing.
- The community is dissatisfied with consultation and engagement practices of both state and Commonwealth water managers, including the MDBA. People expressed a loss of faith and trust. People have sought information and been denied access to management assumptions and reasoning, methods etc (e.g evaporation rates).
- Those present feel that governments have adopted an approach to Basin scale management that is harming their region—it is not giving sufficient attention to the local environment (broadly defined). Managing the river system to maximise efficiencies is in tension with ecological needs for water retention and more consistent flows as well as community aspirations for access to water (e.g. BH pipeline, SDL water supply project).
- The community believes that if the Menindee Lakes Water Saving Project were to proceed it would take the draining of Menindee 2 months instead of 9 and leave Menindee with only 80 GL.
- Some see water moving to where the power lies, in the hands of corporations in the Northern Basin.
- Everybody is very distressed by the fish deaths and doing all that they can to prevent more deaths and alert others to the causes and possible solutions.
- This community sees itself united by a shared desire for the healthy and mutually beneficial relationship with the river.

- There are serious concerns about the capacity and willingness of governments to regulate and enforce rules of water access, they are looking to the MDBA to 'take the politics out of it'.
- Robust water accounting processes and regulatory arrangements need to be in place before flood plain harvesting rules are changed.
- Concerns expressed about differences in off-take policy between north and south Basin—the larger annual entitlement draws in north, in comparison to the south.
- The group identified a number of tipping points in a history of cumulative impacts. Until recently and including during the Living Murray, the Menindee Lakes were in good health.
    - Around 2000, water policy and management became more 'political' in NSW, inflows started to decrease (some of this from illegal take) with new developments in BOTH Qld and NSW as contributing to the problem—as well as theft and rule changes in NSW.
    - From 2012, BD WSP rules were introduced and this increased diversions.
    - Plus, at this time, the practice of placing embargoes on use changed (change of Minister). Some of these embargoes had been used to protect Broken Hill's supply.
    - After the Basin Plan, the lakes were drawn down more quickly ('MDBA has pushed us over').
    - 2017, Northern Review and reduction in recovery target.
- For the Barkandji the fish and other river life are kin. As explained by Badger Bates: 'The Barka was created when Kuluwarra (an Ancestor from the Dreaming) let the Ngatji (Rainbow Serpent) out of his waterbag up near Bourke, and the Ngatji lives in it still. Thirri (mud lark) also shaped the channel, bends and islands of the river after the Ngatji went thru with the water. The Ngatji looks after us and we have to look after it, it is our traditional job to look after the Ngatji and the river and the other surface and sub-surface waters of the Barka and its floodplains.'
- Environmental impacts have affected the ability of Barkandji to pursue cultural practices (see statement) and the impacts weigh very heavily: *'There's something in that water. A turtle would walk away, birds would fly away. Fish can't walk. And black people are not going to leave. We should all work out how we are going to fix it.'*
- The concern with the WSP lies in the likely operating rules, rather than the infrastructure. NB Barkandji expressed concerns about the cultural heritage impacts of many of the physical works.
- The two top lakes need to be managed for the benefit of Menindee and downstream; they are especially critical ones for the ecology downstream. They need guaranteed minimum 400+ GL of 'live water' (where 'dead water' is that water trapped in a lake and cannot be used).
- Menindee is a nursery for golden perch—'to breed them with an e-flow in 2017 and then kill them is absolutely criminal'.
- Flow triggers should be deliverable outcomes.
- All agreed that climate change should be accounted for in the Basin Plan and water sharing plans.
- Community members would like to engage with the Academy beyond the life of this inquiry.

On 6 February, panel members Sue Jackson and Lesley Head met with a number of members of Menindee Local Aboriginal Land Council who were not present at the first meeting. At the second meeting participants raised many of the points above. Emphasis was given to the effect of water shortages on cultural practices and on drinking water supplies in the community.

RESEARCH CONTEXT ON PLACE, BELONGING AND TRADITIONAL ECOLOGICAL KNOWLEDGE

Human relationships with rivers, including the Darling

Studies of human relationships with rivers have contributed an important dimension to international research on place and belonging (Weir 2009, Muir et al. 2010). Australian evidence is frequently included in international overviews; for example Gibson's (2012) chapter on the Barkandji ('We are the River') is part of an international collection on *Wellbeing and Place*. Gibson and other researchers have worked collaboratively with Badger Bates (quoted in our report) to document his story and perspectives (Somerville 2013). These works note that the Barkandji take their name and identity from their word for the Darling River (Barka). Similar relationships are documented on the upper Darling; for example Phillip Sullivan of Bourke says,

> *Water to me is the essence of life. And I've got to respect life, and I've got to honour life. If I don't honour it and look after it, then it's going to take my life away from me.* (Muir et al. 2010: 261)

Other work documenting the connections to place and environmental engagements of communities in the Darling and the wider region includes environmental histories of flood (O'Gorman 2012), drought and variability (Muir 2014), and Goodall's extensive work on Indigenous and fishing communities of the Darling (Goodall 2008, Frawley et al. 2011).

Some of this work contrasts Indigenous perspectives and frameworks with the more utilitarian and resource-oriented frameworks of non-Indigenous communities. Others have learned from that work to show how settler Australians also 'have culture' in relation to water (Gibbs 2006, Head et al. 2018). We focus in the report on Indigenous understandings as they are the ones most clearly ignored in water management in the MDB.

Sense of place and belonging in changing environments

As Brierley et al. (2006) argue, sense of place and place-identity are part of a platform for effective adaptive management because local people have detailed knowledge of how their environments are changing. This is particularly relevant in the context of the Darling system being inherently variable, in that traditional ecological knowledge is attuned closely to that variability (Pardoe 2003).

At the same time, neither culture nor ecological knowledge is timeless and unchanging (Muir et al. 2010). Indigenous knowledge is better understood as a process rather than an archive, because 'water and rivers have played a key role in the continuing practice of … cultural processes by Australian Aboriginal peoples' (Goodall 2008: 356). That process and knowledge continues to circulate in the context of passing culture on to children, among other contexts.

Environmental change, whatever the cause, can generate strong community responses. The widespread distress over the fish kills and what they signify about the health of the river system is a manifestation of the widely documented concept of environmental loss and mourning (Brace and Geoghegan 2011, Cunsolo Willox 2012, Head 2016). Although the distress has been manifest around the nation, it is most strongly felt among the local community, those with intimate connections to the places affected. Local connections to the river need water to be ‘in place’, sometimes in tension with the basin-wide perspective of water efficiencies.

The importance of custodianship and community engagement in effective management practices

A feature of Aboriginal environmental relations is ‘the importance that Aboriginal people place on social relationships for good ecological relationships’ (Muir et al 2010 259). Geomorphologists and other natural scientists are starting to utilise the idea that river health is a reflection of societal health (Brierley et al 2006). In this understanding it is not possible to heal the river unless the social relationships are also healed.

Western land management frameworks increasingly recognise the importance of a ‘sense of place’ in management practice (Brierley et al. 2006), including in participatory approaches to address the increasing failure of traditional largely technical planning (Hindmarsh 2012). Brierley et al. (2006: 2) argue that the most effective river rehabilitation projects demonstrate learning opportunities, management flexibility and stakeholder inclusiveness ‘through ownership of place-based information and community participation’.

Goodall (2008: 369) argues that Indigenous knowledge ‘might be thought of more usefully as an approach to land and water management embedded in narrative, rather than as an item of data’. She uses the example of the common Aboriginal awareness that the river system cannot be thought of as being 'naturally' confined within banks, and that rather this flood-dependent ecosystem needs flooding to regenerate.

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APPENDIX 9: EXPERT PANEL MEMBERSHIP AND REVIEWERS

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APPENDIX 10: CONSULTATIONS

In the preparation of this report, panel members consulted with the following organisations and individuals:

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Department of Primary Industries (NSW)
Office of Environment and Heritage (NSW)
WaterNSW

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Dr Maryanne Slattery
Dr Nicola Stern
Dr Martin Thoms
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Dr Penny Whetton
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MENINDEE CONSULTATIONS

Expert panel members met with the following community members in Menindee:

Dick Arnold
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William 'Badger' Bates
Cindy Bates
Howard Jones
Graeme McCrab
Paul Roberts
Wayne Smith
Rachel Strachan
Richard Unsworth
Alan Whyte

The panel members also met with Darriea Turley, Mayor Broken Hill, in Broken Hill.