Assessment of the causes and solutions to the significant 2018–19 fish deaths in the Lower Darling River, New South Wales, Australia

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Abstract. In late 2018 to early 2019, three significant fish death events occurred in the Lower Darling River, Australia, with mortality estimates of millions of fish. We examined the proximate and ultimate causes of these events. We determined that not only were the conditions existing at the time a significant contributing factor, but that antecedent conditions, particularly during the period 2010–17, also contributed. The extreme hot and dry climate during 2018, extending into 2019, shaped the conditions that saw a large fish biomass, which had flourished in the Darling River and Menindee Lakes since favourable spawning conditions in 2016, isolated in weir pools, with no means of escaping upstream or downstream. Strong and persistent weir pool stratification created hypoxic conditions in the hypolimnion. A series of sudden cool changes subsequently initiated rapid and sudden mixing of the stratified waters, causing depletion of oxygen throughout the water column and resulting in the fish deaths. The events were also shaped by broader climatic, hydrological and basin management contexts that placed the Lower Darling River at risk of such fish deaths. Our observations have implications for future river management, and we make several suggestions how policy makers and river operators can minimise fish death risks into the future.

Introduction

Fish death events are defined as any sudden and unexpected mass mortality of wild or cultured fish (Lugg 2000). Fish death events are experienced globally and can range from localised events with the deaths of only a small number of fish to large events resulting in millions of deaths (Hoyer *et al.* 2009; La and Cooke 2011). Such events are often highly visible, generating significant public interest and concern. Natural causes of large fish death events include old age, climatic conditions, hypoxia, starvation and disease outbreaks (Hoyer *et al.* 2009), whereas human-induced factors of fish death events include toxic substances (Koutrakis *et al.* 2016), water infrastructure and water management (Brown *et al.* 2014) or biocontrol measures, such as the removal of invasive species (Bonvechio *et al.* 2011).

Attempts to report and understand fish deaths across the globe have been extensive, particularly as the frequency and severity of events appears to have increased in recent years (La and Cooke 2011). Common themes among many reported events include upwelling of hypoxic bottom waters and sudden extreme changes in weather. For example, hypoxia induced the death of over 10 000 Gulf menhaden (*Brevoortia patronus*) in Lake Madeline in Texas in the US (McInnes and Quigg 2010), whereas the upwelling of hypoxic water was the primary cause of more than 14 mortality events involving over 200 000 fish in the Salton Sea in the Sonoran Desert (CA, USA; Marti-Cardona *et al.* 2008). Extreme changes in weather conditions have also been noted to cause mass fish death events. Marsh *et al.* (1999) described a massive fish death event involving more than a billion tilefish (*Lopholatilus chamaeleonticeps*) and armoured searobin (*Peristedion miniatum*) caused by a sudden reduction in water temperature. Similarly, the death of two billion round herring (*Etrumeus sadina*) and chub mackerel (*Pneumatophorus colias*) was attributed to a sudden decline in water temperature at Pamlico Sound in the US (Wells *et al.* 1961). Although sudden changes in water quality likely account for most observed mass fish death events, the increased anthropogenic pressure on
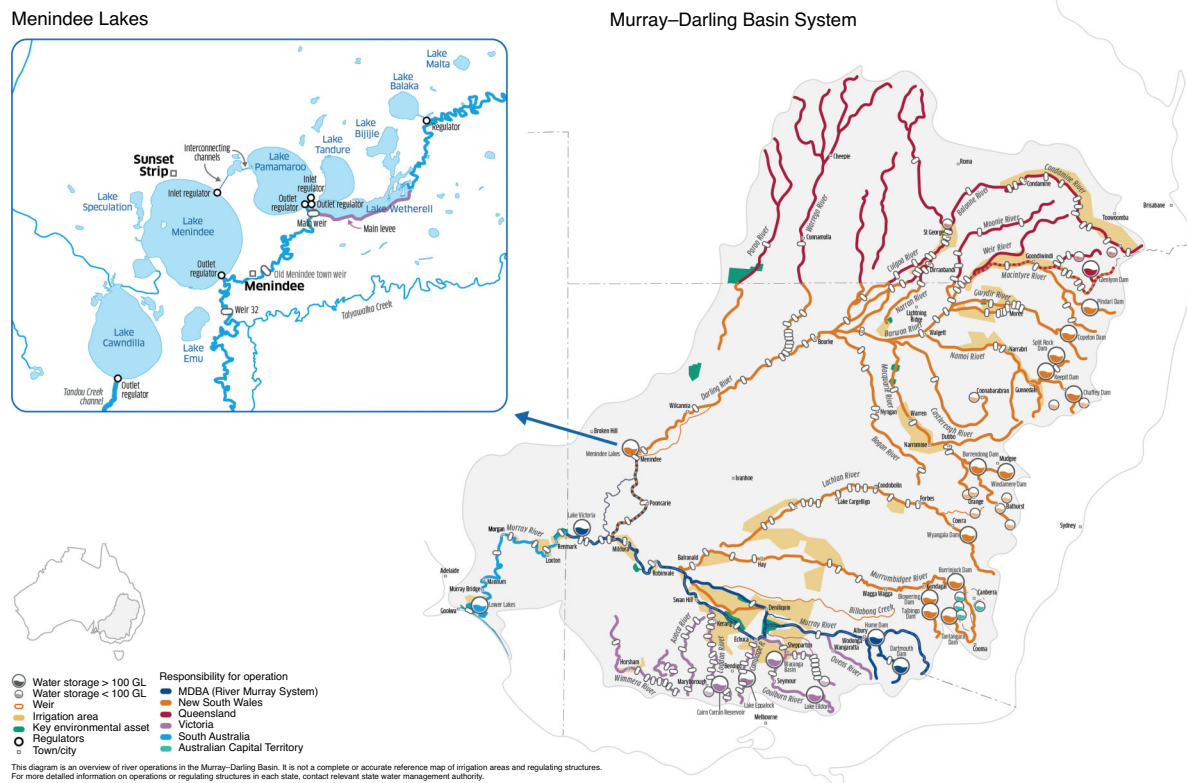
Fig. 1.   The Murray–Darling Basin and Menindee Lakes. MDBA, Murray–Darling Basin Authority. Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

aquatic systems has likely contributed to the increased frequency and severity of these events (Fey *et al.* 2015).

Fish death events in the rivers of the Murray–Darling Basin (MDB), Australia, are not unusual, with over 1600 incidents recorded since the 1980s (Lugg 2000) across several river systems, including the Goulburn River, Campaspe River, Broken Creek and Ovens River (Ellis and Meredith 2004). More recently, on the Darling River, in the northern MDB (Fig. 1), deaths were recorded from Bourke (in 2011) and Tilpa (in 2012; Fisheries NSW, unpubl. data). These events affected tens of thousands of fish and were caused by a range of factors, including hypoxia, toxins and high temperatures. In the Lower Darling River at Menindee Lakes in western New South Wales (NSW), Australia, three significant fish death events occurred between late 2018 and early 2019 within a 30-km reach between Texas Downs Station and Weir 32 (New South Wales Department of Primary Industries 2019; Fig. 1). The main native fish species involved included the Murray cod (*Maccullochella peelii*), silver perch (*Bidyanus bidyanus*), golden perch (*Macquaria ambigua*) and bony herring (*Nematalosa erebi*), with mortality estimates in the range of hundreds of thousands to millions of fish (www.dpi.nsw.gov. au/fishing/habitat/threats/fish-kills).

In 2019, there were two independent investigations into the fish deaths at Menindee, one conducted by the Australian Academy of Science (2019) and the other by the authors of this paper (Vertessy *et al.* 2019). This paper draws on the work of

Vertessy *et al.* (2019) to explore the local and regional conditions leading up to the significant fish death events in the Lower Darling River at Menindee in late 2018 and early 2019. It also outlines recommendations for the future management of rivers to mitigate the risk of fish deaths.

Barwon–Darling river system

The MDB covers approximately one-seventh of the land area of Australia and is divided by climate and geomorphology into the northern MDB (Barwon–Darling River system) and southern MDB (River Murray system; Hart 2016). The northern MDB covers an area of 699 000 km^2 and makes up 70% of the total area of the MDB (Fig. 1). The main trunk of the Barwon–Darling river system rises in the Great Dividing Range, close to the border between NSW and Queensland, and travels south-west for 2700 km before it empties into the River Murray at Wentworth (Fig. 1). The northern MDB is characterised by low relief, with ~60% being <300 m above sea level, resulting in the Barwon–Darling River and its major tributaries being, for the most part, low-energy rivers, with lower reaches comprising a series of branching channels and wetland lakes that distribute their flows across large areas, especially during flood times.

The Barwon–Darling River is a dryland river system and one of Australia's most hydrologically variable rivers (Puckridge *et al.* 1998). The system is divided at Menindee by the large Menindee Lakes water storage complex, upstream of which the
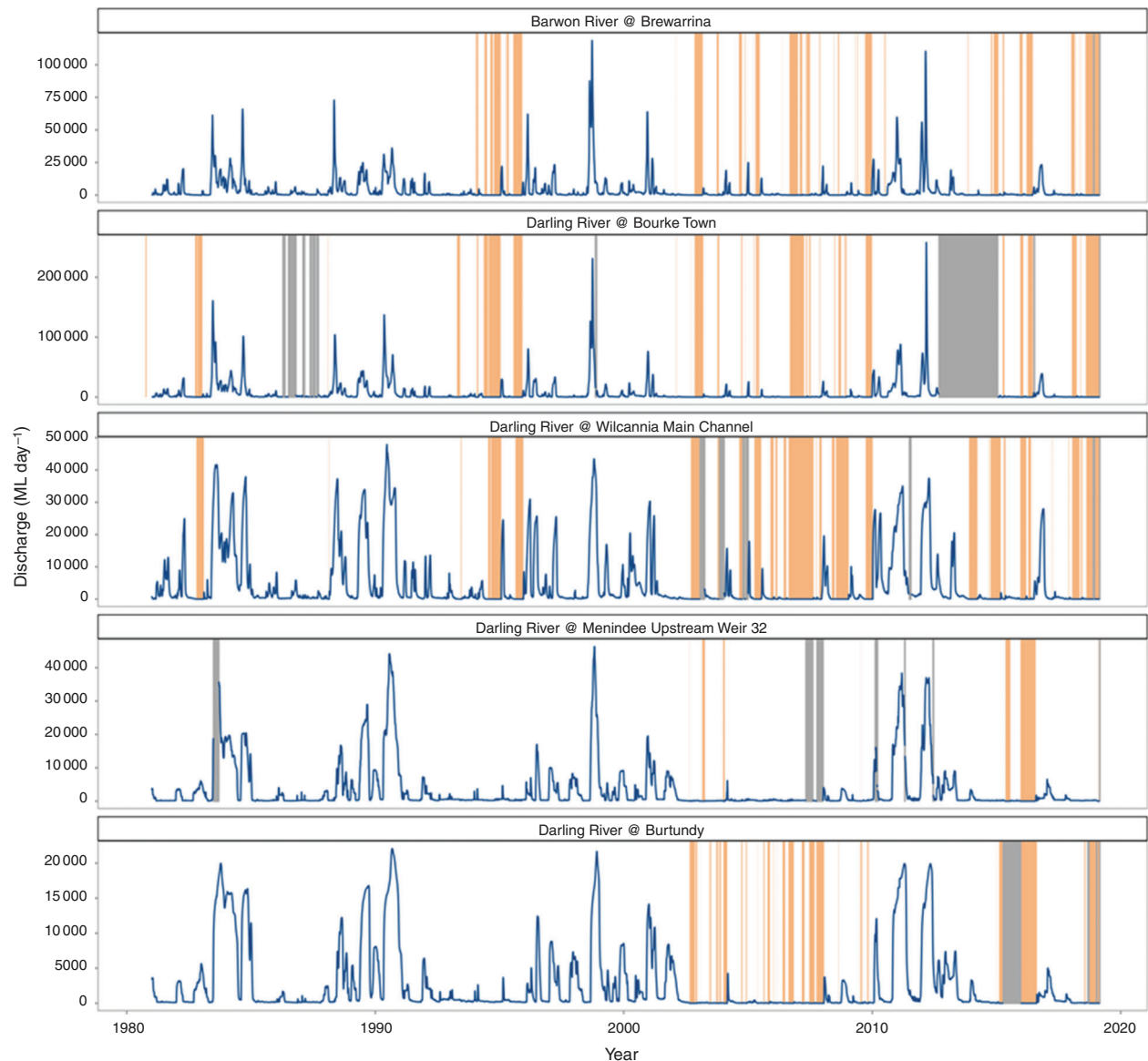
Fig. 2. Hydrological time series for streamflow gauges in the Barwon–Darling system from 1980 to 2019. Periods of cease to flow are identified with orange lines, and missing data are indicated by the grey bars. (Data from the Bureau of Meteorology, Water Data Online). Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

river is characterised by periods of low flow with small pulses, or freshes, punctuated by high-flow events that connect the entire river system and large overbank flows that fuel large-scale riverine productivity (Puckridge *et al.* 1998). Historically, despite protracted low flows, periods without flow were relatively uncommon, with recent hydrological analysis suggesting that the Barwon–Darling River used to flow more than 90% of the time (Mallen-Cooper and Zampatti 2020). However, cease-to-flow periods have occurred regularly since the early 2000s, particularly at Wilcannia, midway down the Barwon–Darling River system (Fig. 2). There has also been a more general reduction in flows evident in the periods 2000–12 and 2012–18 relative to 1980–99 (Fig. 2). These flow reductions reflect the combined effects of upstream consumptive water use and

reductions in catchment inflows during recent droughts (Mallen-Cooper and Zampatti 2020).

The Menindee Lakes system comprises a series of nine natural floodplain lakes that were converted into a water storage scheme during the 1950s and 1960s through artificial connection by a series of weirs, regulators and interconnecting channels (Mitrovic *et al.* 2011; Harriss 2012). The Main Weir on the Darling River raises the upstream water level by 14 m, creating Lake Wetherall, which can feed water into the floodplain lakes Menindee, Cawndilla and Pamamaroo (Harriss 2012; Vertessy *et al.* 2019). Downstream from Main Weir is another weir, Weir 32, which holds water in the channel for the Menindee township. Since the construction of the storage complex in 1968, flows immediately downstream of Weir 32 on the Lower Darling

River have ceased less frequently because of the buffering effect of the storages.

Menindee fish deaths of 2018–19

Three significant fish death events occurred in the Lower Darling River near Menindee between December 2018 and January 2019 and have since been studied in detail (Australian Academy of Science 2019; New South Wales Department of Primary Industries 2019; Vertessy *et al.* 2019). The first event occurred on 15 December 2018, affecting a 30-km stretch of river upstream from Weir 32 (Fig. 1). NSW DPI Fisheries staff who inspected the site reported tens of thousands of dead fish, with high numbers of dead fish observed near the Old Menindee Weir and Menindee Pump Station (New South Wales Department of Primary Industries 2019). The second event occurred on 6–7 January 2019, in the same stretch of river, and was a much larger event, affecting ∼45 km of the river below the Menindee Main Weir, including the stretch of river adjacent to the Menindee Township down to Weir 32 (Fig. 1). During this event, NSW DPI Fisheries staff estimated hundreds of thousands of dead fish, whereas local residents suggested that there were between one million and three million fish deaths (New South Wales Department of Primary Industries 2019). The third event occurred on 28 January 2019, again affecting ∼30 km of the Lower Darling River between Weir 32 and the Menindee Main Weir and involved millions of bony herring, along with many thousands of golden perch and silver perch (Ellis *et al.* 2021). There is also evidence of fish deaths occurring more broadly in the Lower Darling River during 2019 as the system contracted into smaller and smaller refugia, with consequent declining water quality, with NSW DPI Fisheries estimating hundreds to thousands of Murray cod perishing throughout 2019 into 2020;

many of the instances of fish deaths below Menindee possibly went unnoticed because of the remoteness and scale of the region (500 river km; Ellis *et al.* 2021).

Proximate and ultimate causes of the 2018–19 Menindee fish death events

As part of our examination into the causes of the fish deaths (Vertessy *et al.* 2019), we concluded that the three fish death events in the Lower Darling at Menindee between December 2018 and January 2019 reflected not only the conditions existing at the time of the deaths, but also the antecedent conditions in the Menindee Lakes leading up to the fish deaths, particularly the period 2010–17. The sequence of events has been outlined in a conceptual model (Fig. 3) incorporating both long-term (years) and short-term (months–days) contexts. The Millennium Drought (van Dijk *et al.* 2013) ended in the northern MDB in 2009, with two high-flow sequences occurring in the Barwon–Darling River between 2010 and 2019. The first sequence of high flows spanned 2010–12 and filled Menindee Lakes (Fig. 2). After a series of low-flow years (2013–15) there was another significant high-flow sequence during 2016 that connected the rivers and tributaries of the northern MDB and again filled the Menindee Lakes complex (Fig. 2). When full, these lakes become significant nursery habitats for native fish. The high-flow sequences in both 2012 and 2016 facilitated significant fish spawning and recruitment within the Menindee Lakes and Lower Darling region, leading to a significant regional increase in fish biomass (Sharpe and Stuart 2018). The high biomass of fish in the weir pools around Menindee at the time of the fish death events likely reflected a combination of movement from the surrounding lakes as their
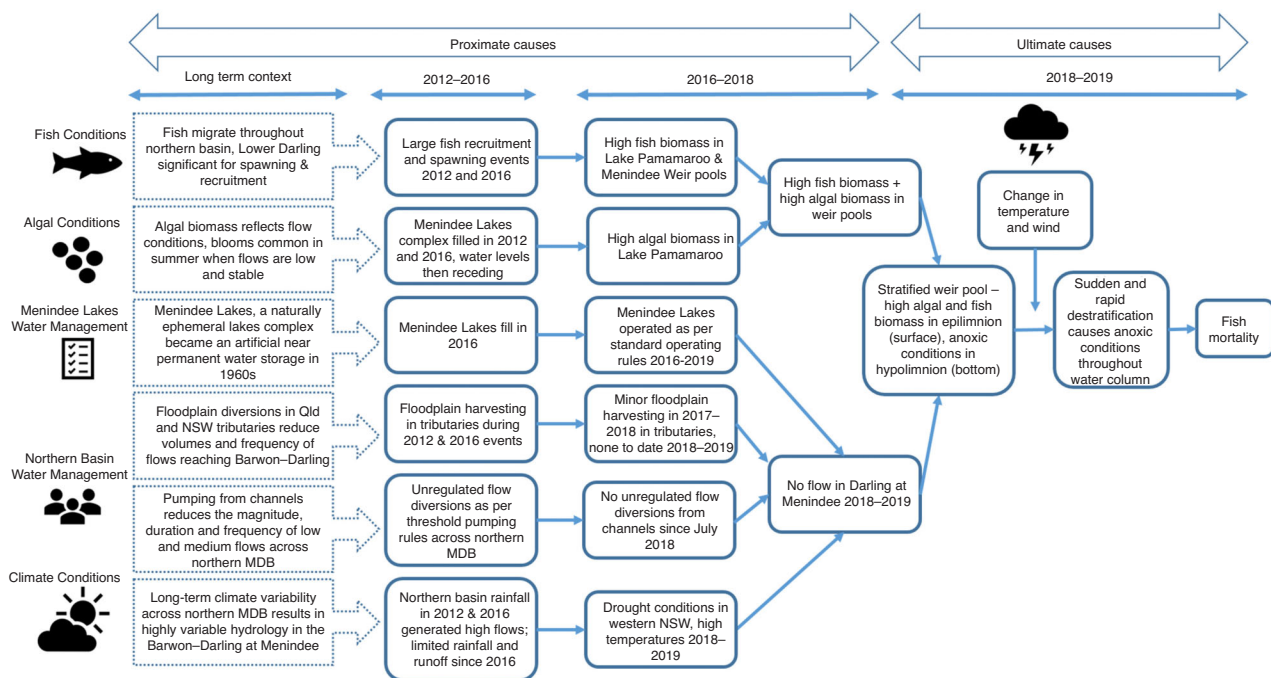

Fig. 3.   Conceptual diagram of the multiple causes of the 2018–19 fish death events in the Lower Darling. NSW, New South Wales; Qld, Queensland. Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

Table 1. January mean maximum and minimum air temperatures, and rainfall for the previous year, for the Menindee Lakes area in 2019 and selected previous years

Numbers in parentheses are anomalies relative to the 1961–90 long-term mean. Area average temperatures are from gridded ACORN-SAT v2 temperature anomalies renormalised as outlined in the Australian Water Availability Project (AWAP), and area average rainfall is from AWAP gridded rainfall analyses (Evans *et al.* 2020). Reproduced under CC-BY with written permission from Vertessy *et al.* (2019)

Date	Air temperature (°C)		Rainfall (mm) in the previous year (percentage of average)
	Mean maximum (anomaly)	Mean minimum (anomaly)	
January 2019	39.7 (+6.0)	23.3 (+5.4)	133.4 (48)
January 2003	36.0 (+2.3)	19.8 (+1.9)	129.9 (47)
January 1966	34.2 (+0.5)	19.2 (+1.3)	172.3 (62)
January 1939	39.3 (+5.6)	22.4 (+4.5)	145.6 (52)

water levels declined and migration upstream from the Murray River and Lower Darling River.

Evidence of persistent thermal stratification: 2016–late 2018

In lakes, river pools and reaches without flow, increasing air temperature will heat surface waters; this less-dense surface water will eventually separate from the denser, cooler deeper waters, causing a physical phenomenon known as 'thermal stratification' (see Boulton *et al.* 2014). Persistent thermal stratification will lead to the complete separation of the surface waters (epilimnion) from the bottom waters (hypolimnion) with a thermocline or area of rapid temperature change between the layers. The epilimnion tends to be warm, well lit and an area of significant primary production, and therefore often well oxygenated during the day but susceptible to declines in dissolved oxygen during night when respiration dominates (see Boulton *et al.* 2014). In comparison, the cooler hypolimnion is dark and a zone of decomposition, with much of the organic matter produced in the epilimnion sinking into the hypolimnion. The hypolimnion is also characterised by sustained reduced dissolved oxygen levels (see Boulton *et al.* 2014). Under persistent thermal stratification, oxygen levels in the bottom water drop with time; if stratification persists for days to weeks, oxygen levels can become very low and decline to critical levels (<2 mg L^{-1}). These critically low levels have been observed previously in the Lower Darling River (Ellis and Meredith 2004). Persistent thermal stratification without mixing can occur for weeks or even months in rivers like the Darling River under extremely low- or no-flow conditions (Mitrovic *et al.* 2003, 2011). Strong winds, lower air temperatures and inflows from rain events or increases in flow are all factors that can work to break down persistent thermal stratification.

After the 2016 high-flow sequence, there were no further inflows into the Menindee Lakes and low flows dominated in the Darling River at Weir 32 from July 2018, increasing from $\sim$150 ML day^{-1} in July 2018 to between 200 and 250 ML day^{-1} from August 2018 to November 2018 due to regulated releases from the storages (Fig. 2). At these flow levels in previous years, thermal stratification that can persist for more than a few weeks has been known to form from mid-October, leading to a separation of surface and bottom water layers in the Lower Darling River (Mitrovic *et al.* 2011). Although there was limited monitoring of water quality conditions in the Menindee Lakes region of the Lower Darling River and along the Barwon–Darling River

between 2016 and 2019, temperature profile measurements and algal monitoring taken before and after the fish death events (Baldwin 2019) indicate that strong stratification likely developed in the weir pools from late 2018. Flow data and water temperature profile data measured after the fish death events (Baldwin 2019) suggest that thermal stratification developed and persisted in the weir pools of the Lower Darling River around Menindee from approximately mid-October 2018. Local air temperature data from December 2018 through to January 2019, the time of the fish death events, also suggests conditions conducive to persistent strong thermal stratification of local standing waterbodies. Maximum temperatures at Menindee in 2018 were the second hottest on record, with the anomaly of +1.77°C being just behind the record +1.80°C anomaly observed in 2013 (Table 1). Minimum temperatures in 2018 were the fourth hottest on record and 1.18°C above the long-term average.

Algal data available for the period around the fish death events (WaterNSW, unpubl. data) suggest a significant algal bloom in the weir pools that may have itself contributed to poor water quality conditions. The increased biological matter associated with the algal bloom, including an increase in dead algal cells, would have contributed to low oxygen levels because the decomposition of dead algal cells uses oxygen. Algal samples collected between July and September 2018 showed no detectable biomass of potentially toxic cyanobacteria (WaterNSW, unpubl. data). However, algal biovolumes increased to $\sim$0.12 mm^3 L^{-1} (amber alert level) during October and, by the next sampling on 24 November 2018, the biovolume had increased to >8 mm^3 L^{-1} (red alert level) and, in some samples, was >60 mm^3 L^{-1} (WaterNSW, unpubl. data). The dominant algal species sampled was *Dolichospermum circinale*, previously called *Anabaena circinalis*, which is a known producer of saxitoxin, a potent neurotoxin. Previous research suggests blooms of *Dolichospermum* spp. occur in the Weir 32 pool during low-flow conditions (< 300 ML day^{-1}) conducive to the formation of thermal stratification (Mitrovic *et al.* 2011). When thermal stratification is persistent, this species has an ecological advantage because it can change buoyancy to access surface waters under reduced mixing conditions (Mitrovic *et al.* 2001). This same species (*A. circinalis*) was the dominant contributor to the extensive algal bloom along the majority of the Barwon–Darling River in late 1991, with low-flow conditions and high nutrient loads being the reported driving factors behind the bloom (Bowling and Baker 1996).

The high biomass of algae observed in the river at the time of the fish death events likely partly originated in Lake Pamamaroo and was concentrated in the weir pools as water moved from the lakes back into the river channel (Fig. 3). Algae photosynthesise during daylight hours and, through this process, produce oxygen in the water. Because photosynthesis does not occur at night, respiratory losses of oxygen lead to reduced levels at night (Fellows *et al.* 2006). This leads to a diel (or daily) cycle of increasing and decreasing oxygen levels. This fluctuation can be minor if algal concentrations and rates of photosynthesis and respiration are low and there is a small biological biomass (of non-algal taxa) in the water. However, during algal blooms, diurnal variations can be very high, leading to large fluctuations in oxygen levels (Fellows *et al.* 2009). The fluctuations themselves, combined with low oxygen saturation at night, can cause physiological stress for all resident biota, including fish, because they are also consuming oxygen (Abdel-Tawwab *et al.* 2019). Significant diurnal fluctuations in oxygen levels were evident at the Burtundy gauging station ~200 km downstream of

Menindee during December 2018 (Fig. 4), suggesting this would also be occurring at Menindee.

Local conditions at the time of the fish death events

Although limited data were collected for the period before and during the fish death events, it is apparent from local reports and the extent of the fish deaths that the physical conditions in the weir pools around Menindee in late 2018 had all the ingredients to cause such events: a high biomass of fish, strong thermal stratification with hot surface waters, significant oxygen fluctuations and high levels of primary production. The factor that would ultimately give rise to the fatal deoxygenation events that killed the fish was the turnover of the water column, whereby the deep hypoxic waters mixed suddenly with the shallow oxygenated layers where the large biomass of stressed fish was concentrated. All three fish death events around Menindee appeared to have been triggered by a series of 'cool changes' in the weather, where ambient temperatures dropped rapidly (Fig. 5). The first fish death event occurred *c.* 13 and 14
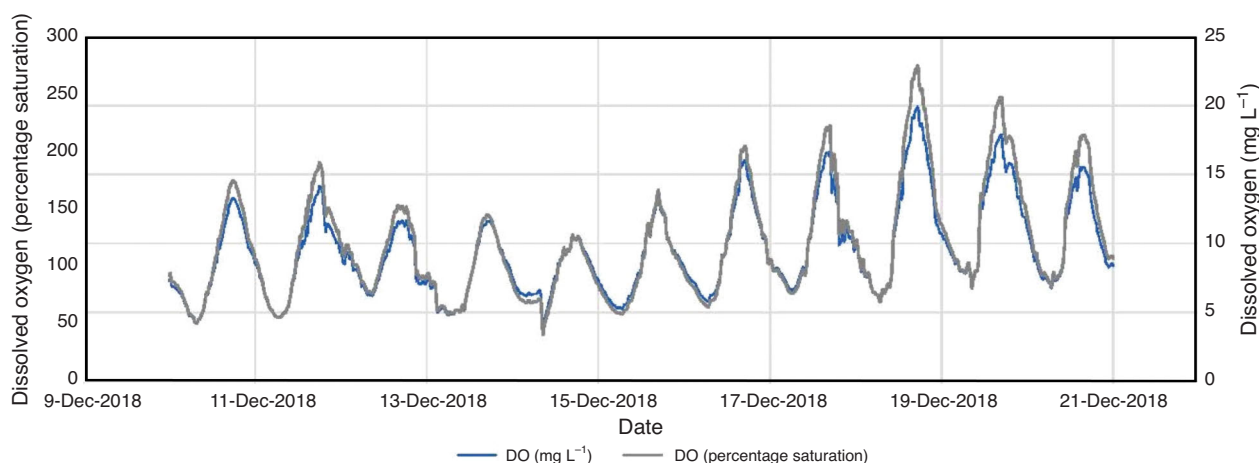

Fig. 4. Changes in dissolved oxygen (DO) concentrations and percentage saturation in surface waters in the Darling River at the Burtundy gauging site around the time of the first fish death event in Weir 32. This is a surface water plot only and therefore does not provide information on stratification (data sourced from WaterNSW real-time data). Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).
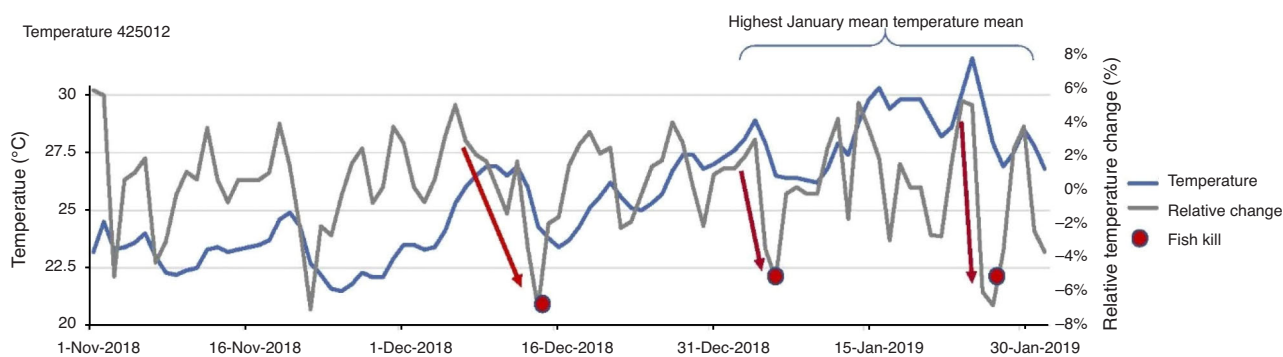

Fig. 5. Changes in mean daily water temperature recorded at the Darling River upstream of Weir 32 gauging station (Station number 425012) over the period November 2018–February 2019. Red dots indicate the timing of fish death events, which coincide with sharp drops in mean water temperature, as shown by the relative change per day (data from the Bureau of Meteorology). Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

December 2018; the first cool change occurred on 13 December 2018, with the maximum air temperature at Menindee Post Office dropping from 39.0°C on 12 December 2018 to 24.5 and 19.3°C on 13 and 14 December 2018 respectively. Coinciding with these air temperature changes, water temperatures measured at a depth of ~60 cm decreased from 27.5°C on 12 December 2018 to 23.1°C on 16 December 2018 (Fig. 5). This cool change was accompanied by increased winds and rain: a wind gust of 43 km h^{-1} was recorded at Broken Hill, 100 km west-north-west of Menindee on 13 December 2018 and 19 mm of rain was recorded at Menindee Post Office between 14 and 15 December 2018.

The second fish death event occurred upstream of Weir 32 (see Fig. 1) and coincided with another cool change. Again, air temperatures at Menindee Post Office fell from a maximum of 46.2°C on 4 January 2019 to 28.5°C on 5 January 2019, with a wind gust of 32 km h^{-1} recorded at Broken Hill on 5 January 2019. The change in air temperature was reflected by a substantial fall in water temperature from >30°C on 4 January 2019 to 26°C on 6 January 2019 (Fig. 5). The third major fish death event occurred in late January 2019 and, again, was accompanied by a rapid change in temperatures (Fig. 5).

These rapid changes in air and water temperatures combined with an increase in wind likely triggered mixing events whereby bottom waters, with very low oxygen, were mixed suddenly with the surface waters where the fish were located. The impact of the weather events and associated rainfall are suggested by the changes in water conductivity *c.* 16 December 2018, coinciding with the first fish death event, and again *c.* 6 January 2019, coinciding with the second fish death event (Fig. 6).

The observed fish death events were also likely influenced by positive feedback loops. Following the first fish death event, a significant proportion of dead fish would have sunk to the bottom. This increase in carbon load would have increased bacterial production in the bottom waters and further contributed to persistent hypoxic conditions in the hypolimnion. Given high organic loads in the bottom waters, and the consequent high biological oxygen demand, there would have also been considerable facultative anaerobic bacterial respiration occurring; a 'sulfur' smell reported by the community at the time of the fish deaths suggests this. As soon as the water column mixed, this bacterial community would have rapidly switched to aerobic respiration and consumed any remaining oxygen. Following the turnover and mixing event triggered by the initial cool change, the water column would have quickly restratified under the hotter and more stable weather conditions, thereby setting up the system for the subsequent turnover and resultant fish death events. The nutrients released from decaying fish would have also contributed to supporting the algal blooms that were present.

Broader flow context

The hydrology of the northern MDB needs to be considered at a landscape scale because the upland tributaries, which are a significant distance from the fish death zone, play a very important role in providing in-channel flows along the Barwon–Darling River (Fig. 1; Table 2). Small in-channel flow pulses can be delivered to the Barwon–Darling River from tributaries with direct connections to the channel (no terminal wetlands); however, for those tributary rivers whose terminus includes complex floodplain wetlands (e.g. Gwydir, Macintyre), the capacity for low flows to build to larger flow events depends on landscape-scale hydrological factors. The terminal floodplain wetlands are important components of this hydrological landscape (Leigh *et al.* 2010). Under natural conditions, these wetlands would have acted as 'sponges', absorbing smaller pulses passing from the tributary rivers and then 'spilling' into the main channel of the Barwon–Darling River when full. Water abstraction, to supply water to irrigators and regional
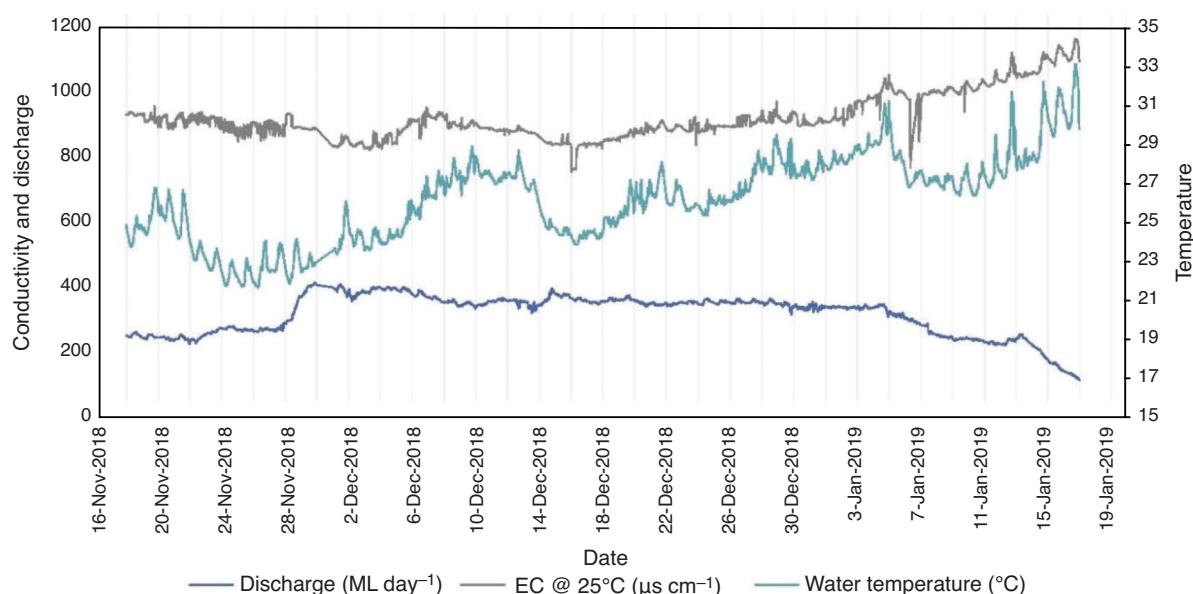

Fig. 6.   Conductivity, river discharge and water temperature as measured at the Weir 32 gauge (data sourced from WaterNSW real-time data). EC, electrical conductivity. Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

Table 2. **Historic annual averages for the 20-year period from 1 January 1999 to 31 December 2018 compared with the modelled long-term average 1900–2012 (in parentheses)**

Data sourced from WaterNSW real-time data. Reproduced under CC-BY with written permission from Vertessy *et al.* (2019)

	Mid-river flow (GL year^{-1})	Mean inflow to Barwon–Darling (GL year^{-1})	Inflows as a percentage of mid-system flow	Inflows as a percentage of total inflows from Barwon–Darling Tributaries
Border rivers	637.9 (829.5)	313.0 (539.6)	49 (65)	20 (24)
Gwydir System	501.4 (732.9)	127.6 (151.2)	25 (21)	8 (7)
Namoi	421.8 (729.6)	321.6 (602.2)	76 (83)	20 (27)
Macquarie–Bogan	763.7 (1192.4)	281.6 (498.4)	37 (42)	18 (23)
Moonie	137.5 (82.7)	132.7 (84.8)	97 (103)	8 (4)
Condamine–Balonne	1045.9 (1035.0)	342.4 (257.9)	33 (25)	22 (12)
Warrego	695.1 (480.8)	70.4 (69.4)	10 (14)	4 (3)
Paroo	415.5 (467.0)	0 (0)	0 (0)	0 (0)
Total flow	4618.9 (5550.0)	1589.4 (2203.5)	34 (40)	100

communities, has changed the way in which most of these terminal wetlands function, with only the western Paroo and Warrego flood plains remaining hydrologically intact. Fewer flow pulses now make their way through the eastern and northern wetlands and into the main channel of the Barwon–Darling River, with effects on the overall flow regime and particularly on lower flows with recurrence intervals of <2 years (Thoms and Sheldon 2000).

The water resource management challenges for the MDB are similar to those for other arid and semi-arid (dryland) river basins globally, and especially those that are environmentally stressed by high levels of water extraction (Vörösmarty *et al.* 2010). Dryland systems are characterised by highly variable hydrology, with unpredictable and episodic high-flow events often dominating the long-term averages (Puckridge *et al.* 1998). This is true for the rivers of the northern MDB, which, under natural flow regimes, were a mix between systems driven by a high degree of flow variability and an associated 'boom' and 'bust' ecology, reflecting periods of extreme flooding and drought (Puckridge *et al.* 1998), and systems with relatively frequent, small and often seasonal freshes (small and large; Thoms and Sheldon 2000). However, modern land use practices often require a more consistent supply of water. Increased water extraction from dryland rivers, coupled with extended periods of low flow and drought, place increasing pressure on both water supply for agriculture, societal needs and the environment. In the northern MDB, large-scale irrigation diverts water from upstream tributaries into off-stream storage, reducing, and often eliminating, the low- to medium-flow events from the tributary rivers that would once have played a role in maintaining water levels in the long riverine pools of the Lower Darling River (Thoms and Sheldon 2000). The large volumes of water diverted into shallow off-stream storages or captured in dams of the tributary catchments are subject to high levels of evaporation, which also contributes to reduced flows downstream (Peirson and Laut 2016). Climate change has reduced rainfall, increased temperatures and increased evaporative losses, thereby exacerbating these stresses (Chiew *et al.* 2009). These cumulative effects present significant challenges for water managers and policy makers in balancing future supply and demand in the MDB. As in many dryland river basins in

mid-latitude regions, supply and demand are trending in different directions, making it increasingly more difficult to maintain water security for consumptive and environmental needs.

Water extractions within the northern MDB can be classified into three different types: (1) 'regulated extractions' from water captured and stored in government-owned water storages; (2) 'unregulated extractions' from tributaries upstream and downstream of public storages, which are opportunistic in nature and can occur from in-stream flows or overbank events that break out of the river and flow across the flood plain (floodplain harvesting); and (3) 'extraction of rainfall run-off', where rainfall falling directly onto the flood plain is intercepted before it reaches a watercourse (rainfall harvesting). The effects of all types of extractions on flows at Menindee over the long term can be assessed by comparing modelled predevelopment flows with modelled flows based on current development. Such a comparison using modelled data for the period 1895–2009 (Fig. 7) suggests that significant additional flows would have occurred during low-flow years at Menindee under a predevelopment scenario. Although the river system models used in these analyses tend to overpredict low flows, it is reasonable to argue that under current levels of water resource development there has been a significant increase in the frequency, magnitude and duration of low-flow conditions and cease-to-flow events in the Barwon–Darling River system (Mallen-Cooper and Zampatti 2020). This tendency has reduced river system connectivity through time and enhanced the probability of occurrence of the hydrobiogeochemical set-up that caused the fish death events near Menindee in 2018–19 (Baldwin 2021).

Conclusions

The combination of a drying climate with water resource development has placed the Lower Darling River at greater risk of fish death events. The fish death events in late 2018–early 2019 were caused by a combination of local hydrological and regional climatic conditions (Fig. 3). The extreme hot and dry climate during 2018, extending into 2019, shaped the conditions that saw a large fish biomass, which had flourished since favourable spawning conditions in 2016, isolated in the weir pools around Menindee with no means of escaping upstream or downstream because the weir pool(s) in which the fish were
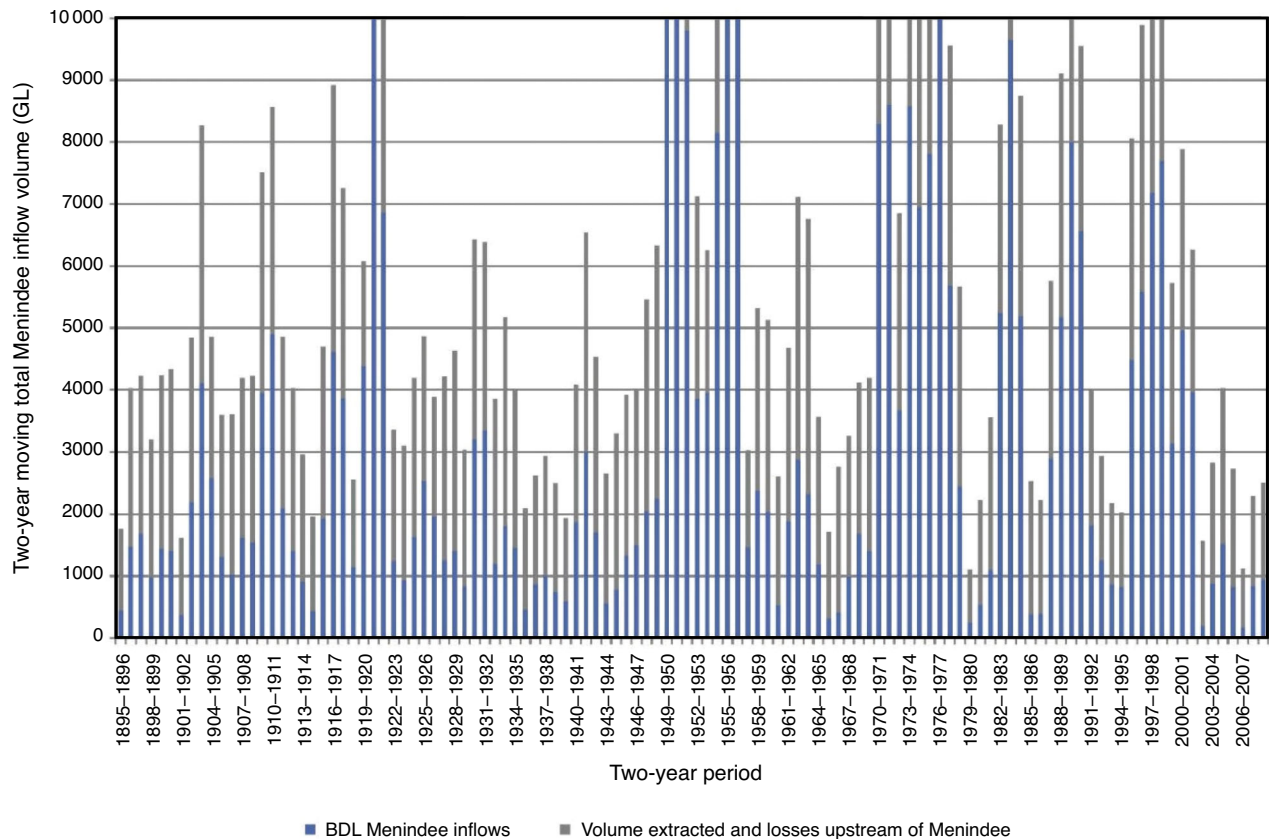
Fig. 7. Predevelopment and baseline diversion limit (BDL) 2-year total modelled Menindee inflows (data sourced from the Murray–Darling Basin Authority). Reproduced under CC-BY with written permission from Vertessy *et al.* (2019).

trapped were bordered downstream by impenetrable barriers (weirs) and upstream by dry channels. The hot, dry climatic conditions contributed to the development of a substantial algal bloom and strong and persistent thermal stratification of the weir pools, creating hypoxic conditions in the bottom waters. A series of sudden cool changes in the weather initiated the mixing of the stratified weir pool waters, resulting in a sudden depletion of oxygen and no escape for the large biomass of stressed fish.

The effects of water resource development on the environment are most severe when they intersect with adverse climate conditions, such as the drying effect of El Niño (Chiew *et al.* 1998). In 2018–19, the northern MDB was experiencing a hydrological drought with meteorological drought conditions (reduced rainfall) occurring over the previous 3 years. The onset of hydrological drought (extremely reduced flows in rivers and streams) generally lags the onset of meteorological drought (a sustained reduction in rainfall) and the lag time reflects the size and responsiveness of the associated catchment (Lake 2011; Yang *et al.* 2017). A large river basin, such as the Barwon–Darling, will, in the absence of abstraction for irrigation and other human uses, retain base flows for an extended period downstream even after the onset of meteorological drought in the upstream catchments. Water resource development that allows extraction from these base flows amplifies the effects of drying, and it does so commencing from the lower sections of the river system and extending upstream. Such legacies of

overextraction have been noted in many other large river basins, including the Colorado River (Pitt 2001), the Ili River delta (Starodubtsev and Truskavetskiy 2011) and the Tarim River (Huang *et al.* 2015).

Prognosis for recovery

Although drought and low flows are a natural part of the Barwon–Darling River system and the fish are adapted to 'boom' (during flooding cycles) and 'bust' (during drought cycles), they cannot be in continual 'bust'. As it currently stands, existing levels of water resource development coupled with a drying climate present a significant risk to the long-term health of native fish populations in rivers of the northern MDB. It is notable that the dry conditions from 2017 to 2019 have occurred against a backdrop of rising temperatures due to global warming, with droughts in the MDB likely to become more frequent and severe as the atmosphere continues to warm (CSIRO and Australian Bureau of Meteorology 2020). Harris *et al.* (2018) emphasised the likely interaction of gradual climate trends with extreme weather events as the trigger for catastrophic ecological responses to global warming, which is entirely consistent with the causes of the fish kills observed in 2018–19 in the Lower Darling River. The mortalities associated with the 2018–2019 fish death events will affect fish populations in the Lower Darling River, and perhaps beyond, for many years to come. Further work is required to understand

the resilience of native fish populations to an increased frequency of such shocks (e.g. see Tonkin *et al.* 2019), but long-term projections paint a bleak picture for native fish diversity in the northern MDB unless more can be done to offset the recent drying trend (Oliveira *et al.* 2019).

In our report to government, we made a series of 27 recommendations to be implemented over a 1- to 3-year period (Vertessy *et al.* 2019). Broadly, these recommendations addressed the following key points:

- To reduce the risk of an increasing frequency of fish deaths in the future, water management arrangements should be modified to protect and restore low and medium flows to the Barwon–Darling River system, including the Lower Darling River, with a focus on protecting first flushes and environmental water releases, sustaining critical refuges, enhancing system connectivity and improving water quality.
- Monitoring of population recovery will be critical and should be undertaken alongside a risk assessment to identify areas at risk of future fish kills, and how populations may be affected by repeated shocks.
- Additional investment is required in water quality monitoring and the use of real-time data to enhance early warning and forecasting abilities. This should occur concurrently with further work on strategies for mitigating or avoiding weir pool stratification and turnover, acknowledging some mitigation options may be a 'last resort'.
- Operating procedures for the regulated Menindee Lakes storages must give consideration to increasing drought resilience of the Lower Darling River system (including the lakes themselves and the Lower Darling anabranch).
- Advances are required in the river system models of the Barwon–Darling River system and other dryland rivers in the northern MDB so that the effects of consumptive use (extractions, floodplain harvesting) can be more easily disentangled from the effects of climate as a driver of changing streamflow patterns (especially changes in low flows). We note that dryland rivers are difficult to model, and the necessary improvements in modelling fidelity will require considerable effort.
- To that end, a significant investment in research and development is required to address long-standing gaps in our knowledge of riverine hydrology and ecology. A priority focus for such investment should be addressing the emerging risks of climate change to achieving environmental outcomes under the MDB Plan (see Hart 2016).
- Additional works and measures may also be required to facilitate fish movements into recovery zones, and these should be scaffolded into an integrated package of solutions to ensure fish have the maximum opportunity to recover (Baumgartner *et al.* 2020).
- Finally, implementation of the Native Fish Recovery Strategy (Murray–Darling Basin Authority 2020) provides an opportunity to bring together government water scientists, academics, consultants, local communities and Aboriginal stakeholders to effectively collaborate in restoring native fish populations. Wherever possible, such efforts should build on existing work, such as the Murray Cod National Recovery Plan (National Murray Cod Recovery Team 2010).

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