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Lower Darling-Baaka River Drought Response and short-term recovery outcomes

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More information

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Original maps and spatial imagery analysis conducted by Karen Danaher, NSW DPI Fisheries, unless otherwise referenced.

Contents

Acronyms

Acronym	Meaning
AE	Aquatic Environment
DO	Dissolved Oxygen
LDBR	Lower Darling Baaka-River
LLS	Local Lands Services
MDBA	Murray-Darling Basin Authority
MDB	Murray-Darling Basin
NDWI	Normalised Difference Water Index
NFDRCC	Native Fish Drought Response Coordination Committee
NFDR	Native Fish Drought Response
NFRS	Native Fish Recovery Strategy
VTAG	Valley Based Technical Advisory Group

Executive Summary

Between 2017 and 2021, the Murray-Darling Basin experienced a record drought, culminating in record low river flows and extended cease-to-flow conditions throughout large sections of the Northern Basin and Lower Darling-Baaka River (LDBR). The impacts of water management and extended drought on native fish communities were highlighted during a series of three mass fish kills at Menindee in the summer of 2018/19, where the death of millions of native fish due to declining water quality and reduced connectivity between refugia, captured world-wide attention.

Following the mass fish kills at Menindee in the summer of 2018/19, NSW DPI Fisheries in collaboration with other state and federal agencies initiated a range of actions to preserve as many native fish as possible across NSW rivers of the Murray-Darling Basin (MDB) during the unprecedented low flow conditions. Here, we report on activities implemented in the LDBR, which encompasses the Menindee Lakes and the river downstream to Wentworth.

Activities undertaken as part of the LDBR Drought Response program included:

- The collection of images, samples and measurements assisted by local volunteers to investigate the scale of the fish kills, environmental conditions during and after each fish kill event, and the age of fish affected for three large bodied native fish species (Golden Perch, Murray Cod and Silver Perch). Large Murray Cod killed during the events had an estimated age of at least 26 years, indicating recovery will take many years.
- Providing assistance to the local council in sourcing a service provider to clean up dead fish from the river adjacent to the Menindee township following the third fish kill event. Approximately four tonnes of dead fish were removed.
- A rapid appraisal to estimate surviving fish densities in the Menindee weir pool following the third fish kill event using boat-mounted sonar. Results suggested tens of thousands of smaller fish (predominantly Bony Herring) persisted in the Menindee weir pool.
- Mapping of refuge habitats in the LDBR to inform subsequent drought actions. As few as 51 large disconnected pools offering suitable fish habitat persisted in the LDBR downstream of Menindee through the extended cease to flow period from February 2019 to March 2020. An additional 199 moderate sized pools may have supported small and large bodied individuals, with another 319 small/shallow pools that were most likely unsuitable habitat except for several tolerant small-bodied species of fish.
- Funding support for local volunteer efforts trialling water aeration techniques in the LDBR during summer 2018/19 following the second Menindee fish kill event. Water quality assessments through early 2019 indicated these preliminary community led efforts to create aerated refuge undoubtedly saved native fish.
- Large pump-driven venturi mechanical aeration trials in early 2019 to determine efficacy at aerating long stretches of connected river channel. These trials indicated the potential to create and maintain aerated refuge over at least 300m of connected river channel.
- Water quality monitoring and associated assessment of the effectiveness of various aeration techniques to inform subsequent fish protection activities.
- Coordinating the deployment of ten (10) large mechanical aeration devices at key refugia locations along the LDBR during summer 2019/20 (including within the Weir 32 and Lake Wetherell weir pools) to create localised priority refuges. A fishing ban was put in place

within 100m upstream and downstream of aerators that were providing much needed oxygen to native fish seeking refuge in these locations.

- Planning and coordination of water quality monitoring efforts funded by the Murray-Darling Basin Authority (MDBA) to provide early warning of high-risk events, and to assess effectiveness of various aeration techniques to inform subsequent fish protection activities (summer 2018/19 and summer 2019/20). See Baldwin 2019 and 2020.
- Fish community monitoring to assess the impact of the 2018/19 Menindee fish kills and subsequent changes in the fish community condition throughout the LDBR through 2019 to 2021. Results illustrated the dramatic impact of the fish kills (at Menindee, and subsequently throughout 2019 in the river downstream) on the LDBR fish community. Limited recovery in key native species was detected until late 2020, six months after flow returned to the system. Ongoing recovery will be dependent primarily on provision of suitable flowing conditions. Annual monitoring of the fish community in the LDBR will be critical in assessing recovery of the fish community in coming years.
- Over 1,600 stranded or at-risk native fish (916 Murray Cod, 616 Golden Perch and 86 Silver Perch) were rescued by DPI Fisheries staff and DPI approved volunteer groups from drying pools downstream of Menindee. While 145 native fish were retained in DPI Fisheries and affiliated hatchery facilities as brood stock (a contingency to preserve LDBR genetics), most fish were relocated to more secure reaches with suitable water quality located in the LDBR upstream of Wentworth (in the Lock 10 weir pool), and adjacent to large aeration units near Menindee.
- Approximately 136,000 Murray Cod and 49,000 Silver Perch fingerlings were harvested and stocked across the Southern MDB in 2019/20 (prior to flow resumption in the LDBR). Following the resumption of flow in March 2020, the release of 60,000 captive bred progeny back in the LDBR occurred in December 2020. Subsequent breeding successes at hatchery facilities will allow for ongoing restocking efforts in the LDBR in coming months/years before the brood stock themselves are returned to the Baaka. Barkandji representation will be sought for release efforts to welcome fish back to country.
- In early 2020, as the water availability outlook in the Northern Basin improved, DPI Fisheries provided expert advice towards the implementation of water use restrictions in the Northern Basin to ensure sufficient flow reached the LDBR.
- DPI Fisheries then informed the active management of Menindee Lakes inflows and releases to the LDBR south of Menindee to minimise the risk of fish deaths associated with flow resumption.
- DPI Fisheries contributed to planning of environmental water releases into the LDBR from mid-September 2020 until mid-January 2021, to help boost the health of the river and support recovery of native fish. Freshwater shrimp, mussels, and smaller native fish were also expected to benefit from the enhanced flows. Monitoring in the LDBR in June 2021 suggests the environmental flows have been successful in supporting spawning by Murray Cod in spring 2020 and subsequent development through 2021, as well as dispersal of juvenile Golden Perch from the Menindee Lakes into the LDBR.

Introduction

The Lower Darling-Baaka River (LDBR) consists of the Menindee Lakes, approximately 500 km of the river downstream to the junction with the Murray River at Wentworth, and the ephemeral Great Darling Anabranch to its west (Figure 1). Aside from the Menindee Lakes regulatory infrastructure, weirs exist at Weir 32 (just downstream of the Menindee Lakes), Pooncarie and Burtundy. The Murray River lock and weir at Wentworth (Murray Lock 10) creates a weir pool that extends up the lower reach of the LDBR to near Ashvale Station.

Over three (3) separate events in December 2018 and January 2019, millions of native fish died along approximately 30km reach of the LDBR in the pool created by Weir 32 (adjacent to Menindee, NSW). After the Menindee fish kill events, NSW DPI Fisheries received reports through 2019 and early 2020 of fish dying in disconnected pools at multiple locations along approximately 500 km of the LDBR throughout 2019 and early 2020.

In response, DPI Fisheries worked with local communities in implementing response actions to protect native fish in the LDBR. Response actions focused on maximising the survival of native fish through the extended dry period (beginning in 2018, which ultimately extended through to early 2020). This report documents those response actions, and the events and conditions that proceeded them.

Rainfall events in the Northern MDB during February-March 2020 provided inflows to the Menindee Lakes system, allowing for a resumption of flow in the LDBR downstream and ultimately the re-connection with the Murray River system in April 2020. Subsequent flow events in early 2021 resulted in additional inflows to the Menindee Lakes and the LDBR.

During both the 2020 and 2021 Northern MDB flow events, the protection of flows in northern inland NSW rivers was prioritised to meet critical human and environmental needs in northern valleys, including those within the Menindee Lakes system and the LDBR.

In this report we also refer to broader initiatives such as the Native Fish Recovery Strategy, that are addressing strategic priorities for the long-term recovery and health of native fish populations across the Basin, including in the LDBR following the return of flow to the system.

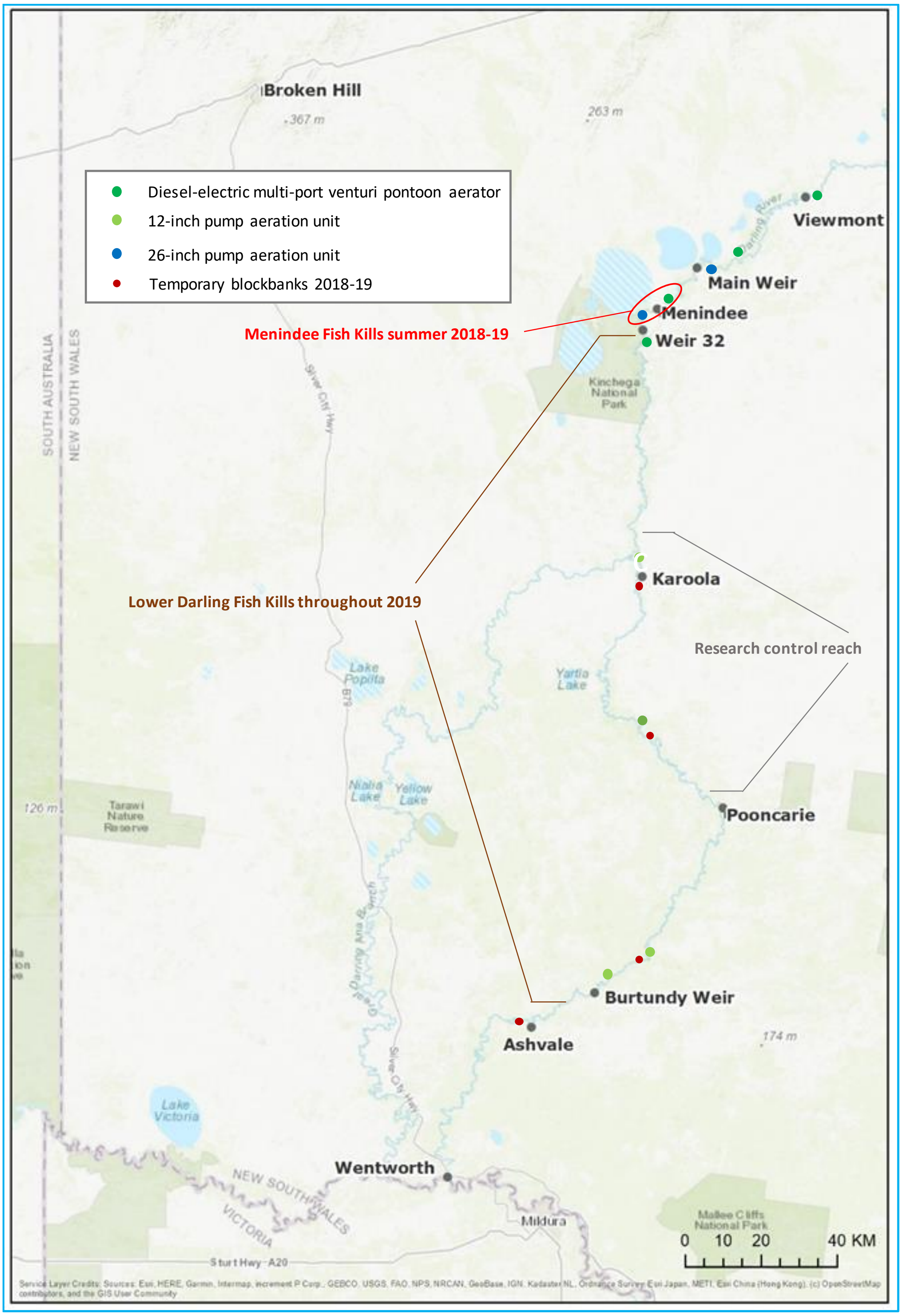


Figure 1. The Lower Darling region in far west NSW showing locations of key stations, towns and weirs, as well as aeration systems deployed through summer 2019/20. The mass fish kill events of summer 2018/19 occurred throughout approximately 30 river kilometres from Menindee Main Weir downstream to Weir 32.

Fish in the Lower Darling-Baaka River

The LDBR is significant for native fish species in the MDB including iconic species such as Golden Perch (*Macquaria ambigua*) and Murray Cod (*Maccullochella peelii*), as well as other threatened species including Silver Perch (*Bidyanus bidyanus*) and Freshwater Catfish (*Tandanus tandanus*). It also supports a suite of small and medium-bodied fish species and is home to the threatened Darling River Snail (*Notopala sublineata)* (critically endangered). The LDBR is also part of the Darling River Endangered Ecological Community.

Prior to the Millennium Drought, the fish community of the LDBR region was in good condition, with robust populations of Murray Cod, Golden Perch and other native fish. The LDBR Murray Cod population is traditionally considered a robust population, which generally exhibited large numbers of juveniles as well as a range of adult size classes (Wallace et al. 2008). This population is also important in relation to recovery of adjacent populations in the mid and lower Murray River system following the 2011 and 2016 blackwater related fish kills which impacted thousands of river kilometres along the Murray and Murrumbidgee Rivers, in which the LDBR was largely spared.

In a whole of Basin context, the LDBR region is important for the breeding and recruitment (growth and survival) of Golden Perch (Sharpe 2011). Adults are known to spawn in response to flow events upstream in the Barwon-Darling catchment, with larvae and young fish drifting downstream, developing in nutrient rich water as they do so. Many reach the Menindee Lakes where they exhibit strong growth and survival in warm, food-rich waters (Sharpe 2011; Stuart and Sharpe 2017). On subsequent flow events that reconnect the Menindee Lakes with the LDBR, juvenile and adult fish return to the river channel and disperse both upstream and downstream (i.e., north to the Barwon-Darling system and its tributaries, or south to the Murray River system). Recent science demonstrates that Golden Perch in the lower and mid-Murray system contain strong representation of fish that began life in the Darling River (Zampatti et al. 2018).

Hydrology and risk to native fish

Although historically the Darling River experienced occasional cease to flow events, they occurred within a broader flow regime that included regular in-channel flow pulses and overbank floods. This differs substantially from the prevailing flow regime in the last two decades, which has been characterised by protracted periods of low flow punctuated by in-channel flow pulses and fewer overbank flow events (aligned with natural system scale floods in 2011, 2012 and 2016) (Figure 2).

Whilst the modification of the Menindee Lakes in the 1960s resulted in suppression of flow variability during low and medium flow periods, impacts of drought and historic patterns of extractions in the Northern Basin over the last two decades has led to higher risk of conditions that can lead to fish deaths during droughts (Vertessy et al., 2019). Linked to droughts and altered hydrology, numerous fish kill events occurred in the LDBR and Menindee Lakes between 2002-2016 (Table 1).

Table 1. Recorded fish kills in the Menindee and Lower Darling region in the last two decades.

Date	Locations
December 2002	Lake Pamamaroo as the lake dried out (thousands of Carp)
August 2003	Three (3) separate events involving thousands of fish dying in the Darling River upstream and downstream of Wilcannia (each involving thousands of fish, mainly Bony Herring)
November 2003	Lake Pamamaroo inlet regulator
February 2004	Thousands of Murray Cod dying along approximately 200 km of the Darling River downstream of Menindee (Ellis and Meredith 2004)
February 2016	Deaths of approximately 19 Murray Cod in disconnected refuge pools at Bono Station on the LDBR approximately 20 km south of Menindee
March 2016	Death of 17 Murray Cod and five (5) Golden Perch early in a disconnected refuge pool at Bald Hill on the LDBR approximately 80 km south of Menindee.

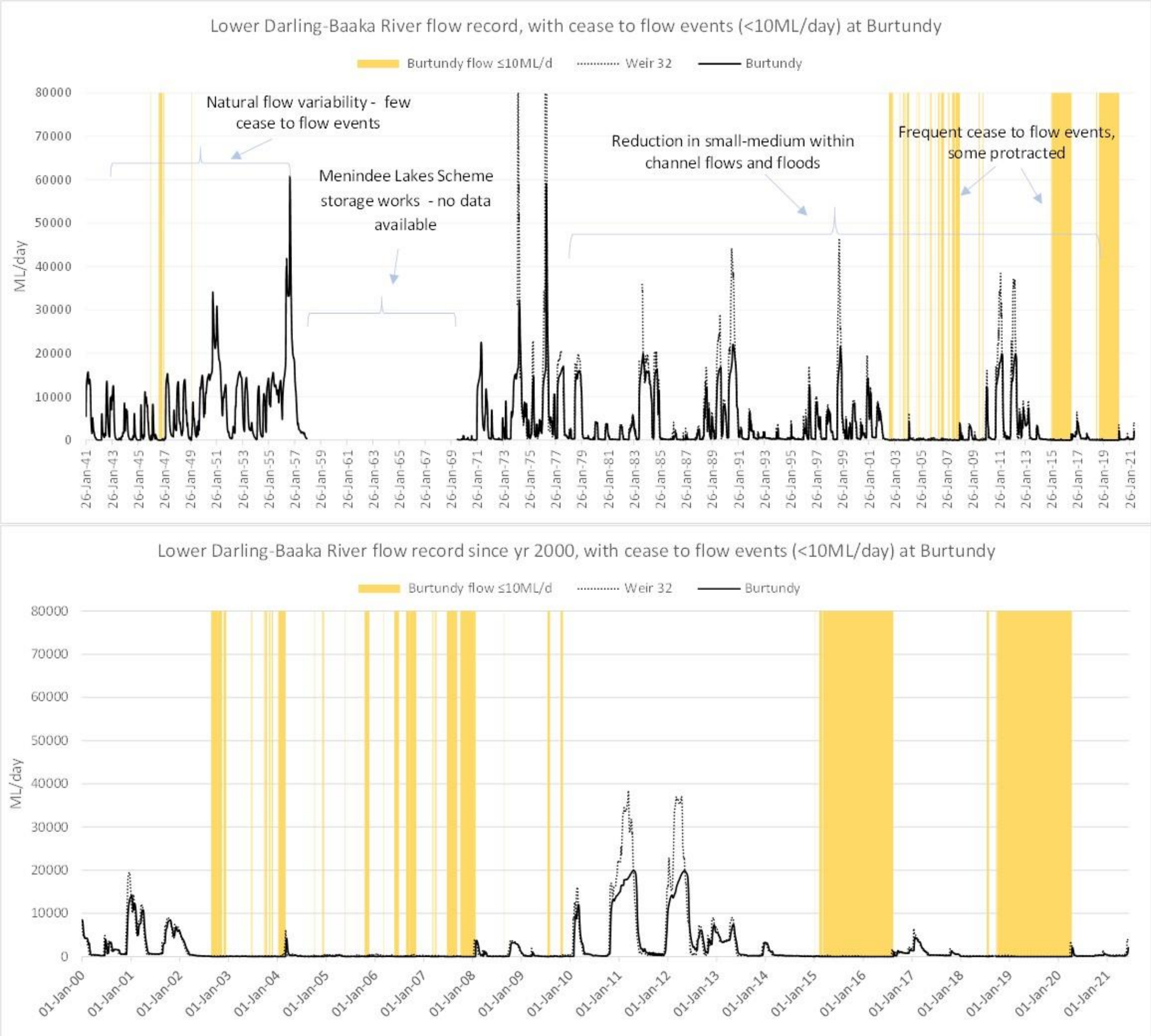


Figure 2. (Top) Historic flow records in the LDBR recorded just downstream of the Menindee Lakes (Weir 32) and at Burtundy in the southern reaches of the LDBR. (Bottom) flow records from 2000 to 2021 (note that y-axis differ between plots). Cease to flow at Burtundy consisting of flow records (of 10 ML/day or less) are shown in yellow. Overbank flows in the LDBR begin at flow rates in the order of 10,000-14,000 ML/day gauged at Weir 32. Data sourced from WaterNSW.

The Menindee fish kills, summer 2018/19

Flow from Menindee to the LDBR was very low through 2018, and absent through most of 2019 (see Figure 2). Over three (3) separate events (15-16 December 2018, 6-7 January 2019 and 28-29 January 2019), millions of native fish died along a 30-40 km reach of the LDBR in the pool created by Weir 32 (Menindee Weir Pool) adjacent to the town of Menindee in far west NSW (Figure 3). These fish kill events are referred to in this document as the "Menindee fish kills, 2018/19".

Figure 3. The reach of the LDBR near Menindee affected by the first Menindee fish kill (yellow) and the second and third fish kills events (yellow and green) in summer 2018/19 (background image source: Google Earth).

The first of the Menindee Fish Kill events occurred on 15-16 December 2018 with the highest numbers of dead fish observed in the vicinity of the Old Menindee Weir. In the lead up to this fish kill event, the Menindee region experienced very hot and still conditions with daytime maximum air temperatures regularly over 35^{0}C, and overnight minimums exceeding 20^{0}C in the week prior to the fish kill (Figure 4). A sudden decrease in temperature associated with a cold weather front coincided with early reports of a fish kill in the Weir 32 pool adjacent to Menindee. Blue-green algae were prevalent throughout the region during the hot, still conditions, with 'red alert' notifications (or blooms) issued by WaterNSW for the LDBR at Menindee and the Menindee Lakes throughout December 2018.

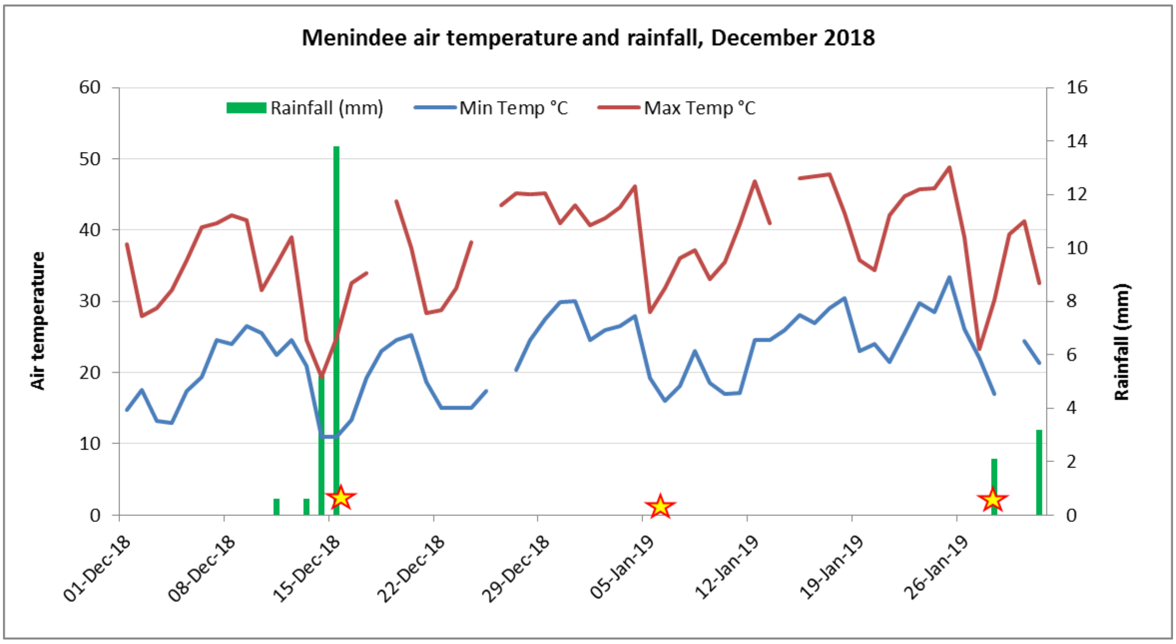


Figure 4. Recorded daily maximum and minimum air temperature and rainfall at Menindee from 1 December 2018 to 31 January 2019 (Source: Bureau of Meteorology). Observed fish kill events are indicated by stars. Growth of blue-green algae occurred during the hot conditions, with 'red alerts' issued by WaterNSW.

Managed flow releases to the Menindee Weir pool (and through to the LDBR) had remained below 250 megalitres per day (ML/day) for nearly 12 months leading into the summer of 2018/19. Two (2) weeks prior to the first fish kill event flows through the weir pool increased to 300-350 ML/day (gauged at Weir 32) to maintain supply for stock and domestic users downstream of Weir 32 (Figure 5). The flow releases were intended to fill the pools created by four (4) block banks that had been constructed in the river downstream of Menindee in late 2018 (see Figure 1).

After the first fish kill event, temperatures increased in Menindee and remained high from 24 December 2018 through to 4 January 2019 (Figure 4). Blue-green algal red alert notifications were still in place for the Menindee region. A cold front moved through the region on 5 January 2019, and an associated rapid decrease in temperature preceded reports of a second major fish kill in the LDBR adjacent to Menindee reported at 9:30am on 6 January 2019. This series of weather conditions also preceded the third fish kill reported on 28 January 2019 (Figure 4).

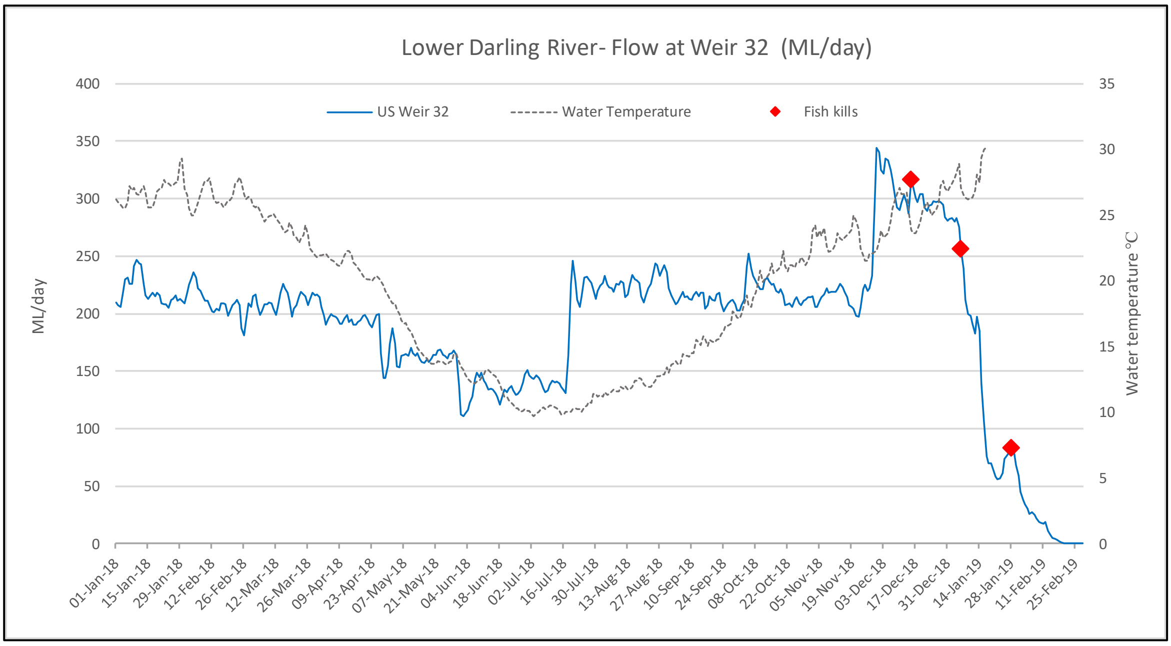


Figure 5. Recorded discharge flow (blue line) and temperature (black line) upstream of Weir 32 (i.e. in the affected weir pool) from 15 November 2021 to 5 February 2019 (Source: WaterNSW. The three (3) observed fish kill events are indicated by red stars.

An initial interim investigation report by DPI Fisheries after the second fish kill event found that the likely principal cause of the three (3) major fish kills at Menindee during summer 2018/19 was de-oxygenation of the water (hypoxia) caused by exceptional local hydrological and climatic conditions (NSW DPI, 2019). This conclusion was based on available environmental data, evidence associated with water quality dynamics in the LDBR, evaluation of historical fish kills in the LDBR and expert opinion (Fisheries Scientists, Fisheries Managers, and independent water quality experts).

The hypoxia was considered linked to several related and compounding factors, including:

- Protracted periods of high temperatures in conjunction with low/no flow conditions in the weeks leading up to each event contributed to extensive thermal stratification in the Menindee Weir Pool.
- Rapid drops in air temperatures associated with cold weather fronts which resulted in mixing of stratified water layers (‘de-stratification’), creating temporary hypoxia. For example, maximum daily temperature dropped from 39°C to 19°C between December 12 and 14, 2018.
- Although not the proximate cause of the fish kills, high algae concentrations in flow releases from Lake Pamamaroo and Lake Wetherell would likely have contributed to thermal stratification, and hence diel oxygen production and consumption, and thus further reduced dissolved oxygen available to fish during the destratification event.

A series of subsequent independent investigations (Vertessy et al., 2019; Moritz et al., 2019; Baldwin, 2019) generally supported these findings. These independent reviews also considered a range of factors that may have contributed to the low oxygen conditions, including climate, hydrology and water management, lake operations and other anthropogenic changes (Vertessy et al., 2019, Moritz et al., 2019, Baldwin, 2019).

Other hypotheses on the cause(s) of the fish kills in the LDBR were put forward in the media. These hypotheses were considered in detail in the Interim Investigation Fisheries Report and are not repeated here (see: https://www.dpi.nsw.gov.au/fishing/habitat/threats/fish-kills/Fish-death-interim-investigation-report.pdf).

Estimating the number of dead fish was problematic given the large area over which the event occurred (30-40 km of remote river), removal of smaller individuals by scavengers/predators (raptors, cormorants, foxes etc.), and sinking of carcasses which decay rapidly in the extreme summer heat experienced on the LDBR (while fish carcasses may initially float, they sink during decomposition when the body cavity is eviscerated). Nevertheless, based on DPI Fisheries fish kill assessments and local eye-witness accounts (Figure 6), we estimate that affected fish were predominantly Bony Herring (in the order of millions dying across the three (3) events), Golden Perch (thousands to tens of thousands), Silver Perch (thousands), and Murray Cod (more than 300), with Common Carp also affected in relatively low numbers (hundreds to a thousand). A range of size classes were affected from each species, albeit with larger individuals dominating observations for Murray Cod, Golden Perch and Silver Perch due to either a higher susceptibility to hypoxia among larger fish (greater oxygen requirements), or removal from view via sinking or scavenging of smaller fish.

Figure 6. Silver Perch (top left), Murray Cod (top right), and Bony Herring (bottom four) that died in the Menindee fish kills, in summer 2018/19 (Photo credits: DPI Fisheries staff, G. McCrabb and R. Gregory).

Ages and natal origins of Golden Perch, Murray Cod and Silver Perch that died in the Menindee fish kills

A detailed description of this work has been published in Thiem J D., Baumgartner L J., Fanson B, Sadekov A, Tonkin Z, Zampatti B P. (2021) *Contrasting natal origin and movement history informs recovery pathways for three lowland river species following a mass fish kill*. Marine and Freshwater Research, (https://doi.org/10.1071/MF20349)

DPI Fisheries staff recorded biological information and sampled otoliths from dead fish (assisted by local recreational anglers) of three (3) long-lived, large bodied native species (Golden Perch, Murray Cod and Silver Perch). Otoliths are tiny ear bones the head of a fish that help with balance. They grow as the fish grows, meaning we can determine a fish age by counting annual "growth rings" in the otolith (like the growth rings in trees). The age can then be used to establish age and length relationships, birth year. DPI Fisheries determined ages for otoliths collected from fish that died in the Menindee fish kills these are presented in Table 2 and Figure 8.

Figure 7. Extracted otoliths from fish that died in the LDBR near Menindee during the 2018/19 fish kills (Photo credit: DPI Fisheries staff).

Ages determined for Murray Cod collected from the Menindee fish kills ranged from two (2) to 26 years. Golden Perch collected ranged in age from two (2) to 16 years, while Silver Perch collected were between six (6) and 11 years old.

While these samples provide an indication of the size and age range of fish that died in the affected reach of the Menindee Weir Pool, the results may not necessarily represent the full size and age structure of the local population. The absence of small Murray Cod in this sample does not indicate that this size/age-class fish were not killed during these events. Smaller individuals may have been harder to locate or may have been removed by birds. Nevertheless, the results demonstrate that this section of the LDBR contained populations of large-bodied native species spanning a range of size and age classes, including mature fish.

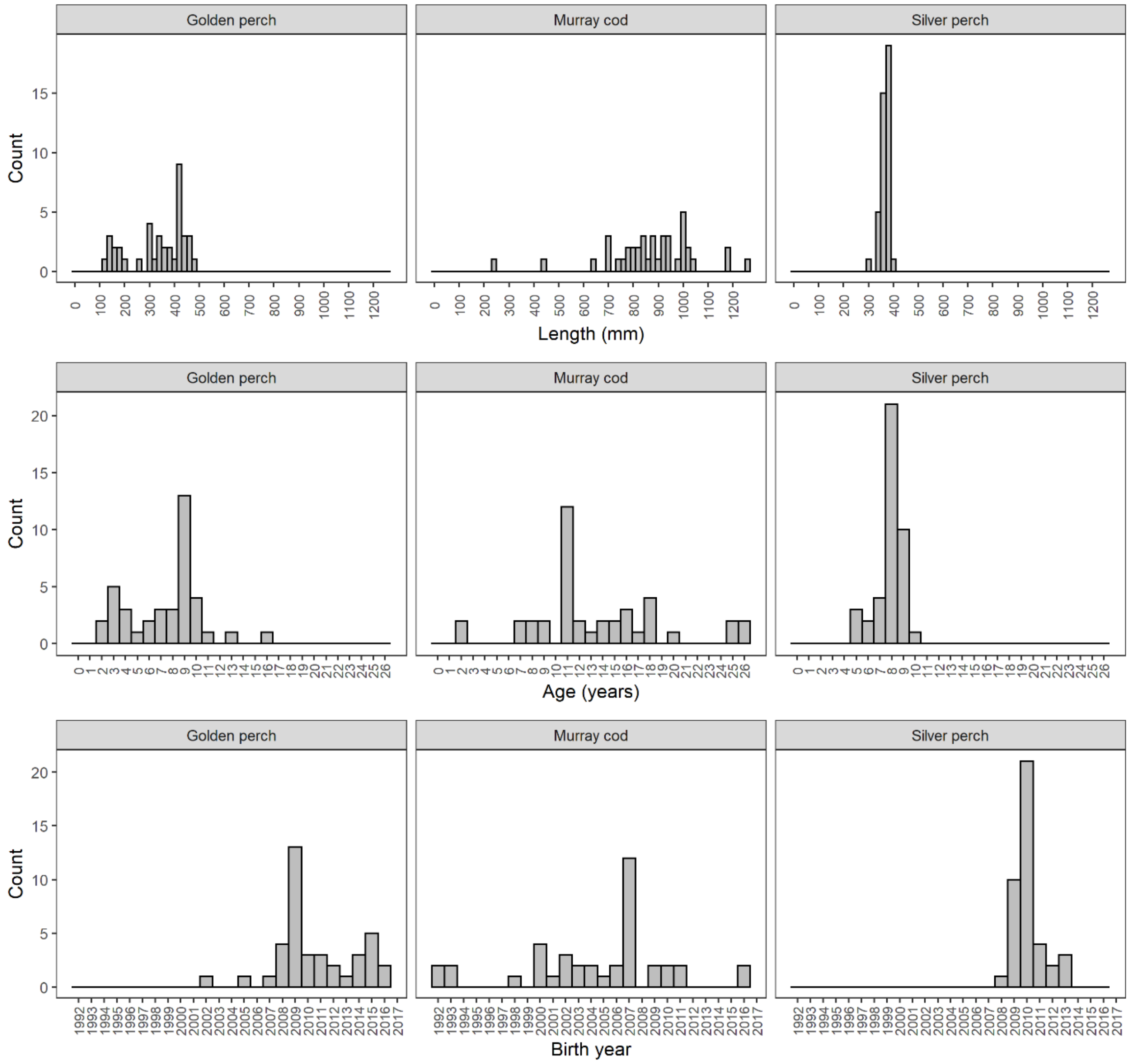


Figure 8. Distribution of length (top), estimated age (middle) and estimated birth year (bottom) of Golden Perch, Murray Cod and Silver Perch collected following fish kills in the LDBR near Menindee in 2018/19. Sample sizes are presented in Table 3.

Table 2. Summary statistics of three (3) large-bodied fish species collected following fish kills in the LDBR near Menindee in 2018/19. Data is presented as a range (min-max).

	Golden Perch	Murray Cod	Silver Perch
Number	39	40	41
Length (mm)	130-480	246-1270	302-402
Age (years)	2+ - 16+	2+ - 26+	5+ - 10+
Nominal birth year	2002-2016	1992-2016	2008-2013

The chemical structure of an otolith can also help us determine when a fish moved between waters of differing chemistry throughout its lifetime. Using this information we were able to tell that the oldest fish that died in the fish kill was a Murray Cod that was 26 years old (born in 1992) and that it was born in the Darling River and spent the rest of its life there (see Thiem *et al*. 2021) This pattern was repeated for most Murray Cod, whether they were two (2) or 22; they were generally born and raised in the Darling River and stayed there until they died.

Golden Perch that were analysed were similarly born in the Darling River, although many moved to the Murray River early in life and later returned to the Darling River, a round trip of more than 1,000 km (Thiem *et al*. 2021). In contrast, most analysed Silver Perch that died in the fish kills were born in the Murray River and moved into the Darling River as juveniles or adults (Thiem *et al*. 2021).

Applying this information to restore native fish populations in the Darling River, we now know that local recovery efforts for Murray Cod should focus on breeding and recruitment from the surviving adult population which can be supported through appropriate river flows and habitat rehabilitation in the LDBR. For Golden Perch and Silver Perch, local river flows are also important, but restoration of these species needs to also consider safe upstream and downstream passage of eggs, larvae, juveniles and adults past weirs and 'end-of-system' flows that attract fish from the Murray River so that they can recolonise the Darling River. Stocking should be considered a complementary measure in addition to an optimised flow regime and not a replacement for wild breeding.

January 2019 rapid appraisal of fish numbers immediately following the third Menindee fish kill event

Following the third Menindee Fish kill on 28 January 2019, a team of DPI Fisheries and WaterNSW staff undertook a rapid appraisal of fish numbers in a small stretch of river in the Menindee Weir Pool adjacent to the Menindee Creek Inlet (where the river channel is approximately 50 m wide). Large numbers of dead fish had been observed in this area during the second and third Menindee Fish kill events.

Fish swimming in the water column were observed using a boat-mounted dual-frequency identification sonar (DIDSON). This technology sends a fan of sonar beams into the water column which produces real-time video or echograms of anything in the water (e.g. fish, fallen timber, sunken boats), up to a range of 16 m. DIDSONs strength is in its ability to record footage in zero visibility water. It also allows researchers to observe fish behaviour and undertake accurate counts (and some species identification) without using other invasive measures like trapping, angling or electrofishing. Given the stressed nature of the fish at the time, it was important to be able to survey fish numbers without handling or affecting the fish in any way.

The surveys were conducted over two (2) mornings from 31 January- 2 February 2019 (Figure 9). Four (4) 60 m transects were run along the channel on each morning in both the upstream and downstream direction. Surveys were conducted pre-dawn (between 5:30am and 6:30am) to coincide with the time when surface water hypoxia is believed to be the most extreme (i.e. lower dissolved oxygen (DO) concentration) due to overnight respiration aquatic organisms (including bloom levels of algae and cyanobacteria at the time) in the absence of daylight driven production of DO (via photosynthesis). On both mornings there was very little change in the temperature through the water column (i.e. no evidence of a thermocline) nor along the reach (i.e. consistent readings of 27-28°C). Surface DO in the survey area was 4-5.5 mg/L, which is considered sub-optimal for fish. A small solar-powered bubble-aerator was present at the survey site. On the first morning the aerator was operating and on the second morning the aerator was switched off due to power failure.

Figure 9. DPI Fisheries and WaterNSW staff undertaking transects with a boat-mounted sonar to count fish near Menindee following the 28 January 2019 fish kill event (Photo credit DPI Fisheries staff).

The DIDSON footage was visualised and analysed in Sound Metrics Software (V5.26) (Figure 10). Each DIDSON transect file was divided up into 2.5 m sections based on geo-time referencing. A snapshot of footage was taken at the centre point of each 2.5 m section and two (2) technicians independently recorded the number of fish and measured the field of view over which the count was taken. An average of the two counts at each 2.5 m section was calculated and then pooled (summed) at the 10 m scale and converted into number of fish observed per metre in that 10 m section. The average and standard error was then calculated for these counts across the four (4) replicate transects.

On average, three (3) fish per metre were observed on the transects, with counts being as high as ten (10) fish per metre in some areas. Although it was not the intention to identify these fish to species, given size, mode of swimming and schooling behaviour DPI Fisheries researchers were reasonably confident that these fish were primarily Bony Herring, with a small number of Carp also being identified. Although millions of native fish perished during the three (3) mass fish kill events at Menindee, this research estimated that there were tens of thousands to hundreds of thousands of live fish surviving in the Menindee Weir Pool.

These results do not detract from the devastating impacts of the fish kills. However, they demonstrate that not all fish were killed during these events, which provides justification for ongoing protection and recovery efforts in the affected reach.

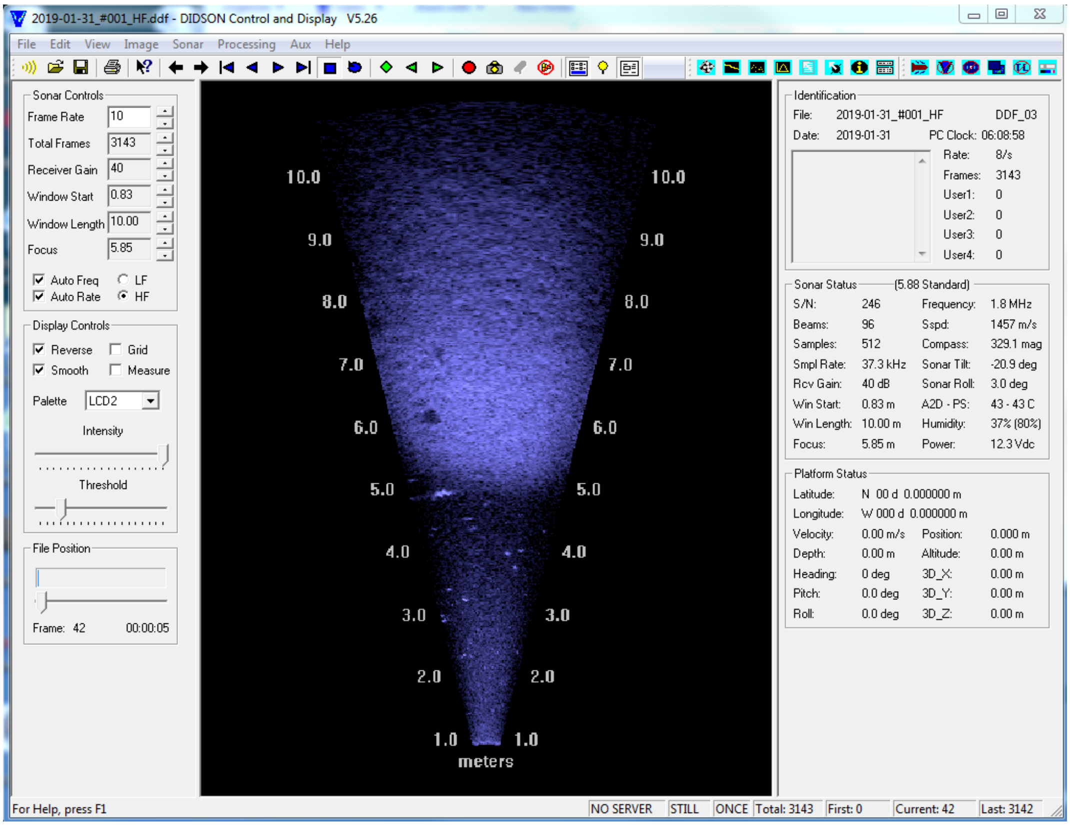


Figure 10. Sound Metrics software used to count fish from DIDSON footage.

Subsequent Lower Darling-Baaka River fish kills 2019/20

The LDBR ceased to flow in January 2019 and flows resumed 14 months later in March 2020. DPI Fisheries refuge mapping estimated that prior to flow resumption in March 2020, fish habitat was limited to approximately 570 pools of surface water that remained as of March 2020, along with approximately 400 km of river between Weir 32 and Ashvale Station. Of these, 51 were deemed large pools, 199 were moderate sized and 319 were small/shallow pools.

DPI Fisheries received first-hand or second-hand reports of fish dying in isolated pools at various locations on the LDBR throughout 2019 and early 2020 (Figure 11). Most reports were of large dead Murray cod, with several reports of large common carp dying in summer 2019/20. A single confirmed report of approximately 15 Golden Perch dying was received (at Bono Station) in February 2020. Thousands of freshwater mussels (consisting potentially of *Alathyria condola*, *Alathyria jacksoni* and *Velesunio ambiguus*) also perished during the extended dry period. These deaths of fish and other aquatic fauna were primarily due to contraction of suitable habitat and poor water quality in progressively drying pools.

Figure 11. Example pictures from fish kills reported to DPI Fisheries throughout 2019 and early 2020 (photos courtesy of station owners W. Smith, R. McBride, R. Strachan and B. Arnold).

A list of reported fish kills, and numbers of each species observed each occasion are included in Table 3. Most of these fish kills were reported in warmer months (February/March 2019, and November 2019-March 2020) as habitat contracted and deteriorated, but some occurred in winter (June – August 2019) suggesting exposure to cold may have contributed to fish kills when the condition of individuals is already likely to be poor (Figure 12). As per the previous fish kills, the most likely cause of death in each of these reports was prolonged exposure to poor water quality due to declining habitat quantity and quality in drying refuge pools. This either killed fish directly (hypoxia, heat stress, hunger) or indirectly through reducing the animal's capacity to withstand extremes in temperature.

Table 3. Observations of dead fish along the LDBR that were reported to DPI Fisheries throughout 2019 and early 2020.

Date	Station	Murray Cod	Carp	Golden Perch
19 January 2019	Bootingee	20	0	0
14 February 2019	Appin – Little Camp	5	0	0
9 March 2019	Appin – Below Weir 32	7	0	0
9 March 2019	Appin – Big Camp	8	0	0
27 June 2019	Karoola	4	0	0
19 July 2019	Aston	1	0	0
21 July 2019	Karoola	12	0	0
8 August 2019	Karoola	10	0	0
9 August 2019	Harcourt	4	0	0
21 August 2019	Jamesville	2	0	0
22 August 2019	Karoola	2	0	0
28 August 2019	Wyarama	25	0	0

Date	Station	Murray Cod	Carp	Golden Perch
5 September 2019	Wyarama	2	0	0
19 September 2019	Tolarno	2	0	0
26 November 2019	Tolarno	15	0	0
27 November 2019	Karoola	20	40	0
27 November 2019	Marara	55	0	0
23 December 2019	Bindara	16	0	0
24 December 2019	Tulney Point	5	0	0
30 December 2019	Pooncarie	4	1	0
19 January 2020	Ellerslie	6	0	0
2 February 2020	Wyarama	25	0	0
2 February 2020	Polia	5	0	0
2 February 2020	Polia	4	60	0
2 February 2020	Court Nareen	20	2	0
2 February 2020	Court Nareen	9	0	0

Date	Station	Murray Cod	Carp	Golden Perch
6 February 2020	Karoola	8	0	0
6 February 2020	Bono	15	40	15
25 February 2020	Menincourt	18	0	0
25 February 2020	Malara	8	0	0
11 March 2020	Pooncarie	0	18	0
12 March 2020	Karoola	8	0	0
	Total	**345**	**161**	**15**
Average dead per report		10.8	5.0	0.5

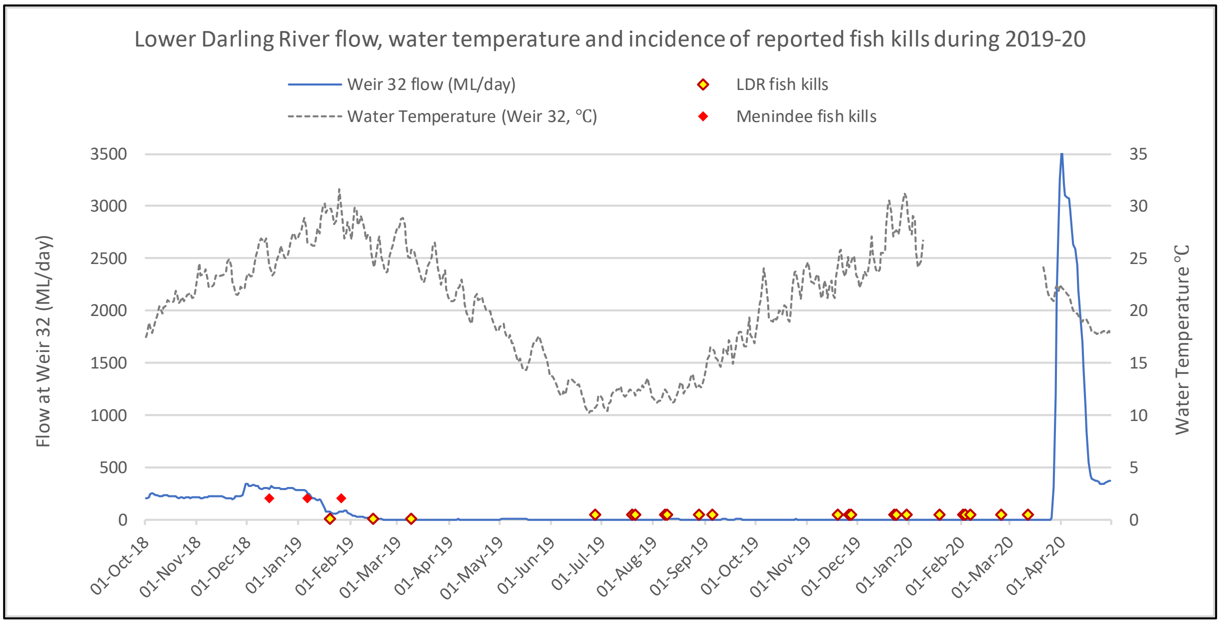


Figure 12. Recorded flow and water temperature upstream of Weir 32 from 1 October 2018 to April 2020 (Data source: WaterNSW). Reported fish kill events during the Menindee fish kills as well as in the river downstream of Menindee are indicated by dots.

DPI Fisheries assume many instances of fish deaths in isolated pools were unnoticed due to remoteness and poor access to much of the reach, and removal of mortalities by scavengers/predators. In particular, the moderate and small pools offered poor refuge habitat as conditions worsened through spring and summer 2019 and therefore native fish mortalities in most small/moderate pools were likely.

By extrapolating from the 32 fish kill reports received by DPI Fisheries in 2019/20 to the number of refuge pools identified in the LDBR refuge mapping, DPI Fisheries estimate that in total 1,000 to 6,000 Murray Cod are likely to have died across approximately 570 drying refuge pools during the extensive drought. Fewer Golden Perch or Silver Perch mortalities were reported (likely a consequence of sinking carcasses or removal by predators), so we are unable to estimate the scale of deaths for these species. Hundreds to thousands of common carp were also likely to have perished. There is some caution with these numbers given the caveats mentioned above, these estimates represent a significant impact on local fish populations.

DPI Fisheries is unable to estimate mortality for counts smaller species or smaller size classes of large-bodied fish. Small-bodied species were either not killed during these events, or if they were killed were not observed/identified because they sank or were removed by predators/scavengers. Small-bodied species are more likely to survive hypoxic events via respiration in a thin layer of oxygenated water at the surface (Figure 13).

Figure 13. Small-bodied fish (including Australian Smelt and Bony Herring) observed at the surface of the Menindee Weir pool (left) and directly below Weir 32 (right) following fish kills in the region (photos I. Ellis, February 2019).

DPI Fisheries response activities

Following the Menindee fish kills in 2018/19 and with conditions worsening across NSW, the NSW Native Fish Drought Response Framework was established to provide a strategic response that outlined policies, procedures, roles and responsibilities for the emergency management of native fish.

The program complemented similar response actions from other MDB governments and agencies, including the Commonwealth (e.g. MDBA), to ensure efforts were consistent, coordinated, efficient and effective. This included assessing all potential response options, such as policy, on-ground actions, research, compliance, and communication to guide drought responses regarding native fish protection and ultimately recovery.

NSW DPI developed internal frameworks and a comprehensive range of activities to help with proactive management of drought conditions for the 2019/20 spring/summer period to minimise risks of fish deaths and establish appropriate response protocols (Table 4). These activities covered the emergency management stages of mitigation, preparedness, response, and recovery.

Mitigation

- Mitigation activities take place before and after emergencies, and include any activities that prevent an emergency, reduce the chance of an emergency happening, or reduce the damaging effects of unavoidable emergencies.
- This includes activities such as identifying and prioritising sites across the NSW MDB that are key to the long-term maintenance of fish populations both locally, regionally and across the entire Basin, and their associated risks of fish deaths.

Preparedness

- Preparedness activities take place before an emergency occurs, and include plans or preparations made to help response and rescue operations.
- This includes activities such as developing agreed policy statements, identifying the range of technological interventions available to reduce the risk of fish deaths, monitoring at key sites to inform any response actions and early warnings, and developing a communication strategy.

Response

- Response activities take place during an emergency, and include actions taken to prevent further damage in an emergency situation, essentially putting your preparedness plans into action.
- This includes on-ground activities, continued monitoring, and implementation of the communications strategy.

Recovery

- Recovery activities take place after the emergency and include actions taken when more favourable weather and rainfall conditions prevail.
- This includes activities such as assessment of the impacts of the drought and responses at priority sites, monitoring at key sites, and continued development and implementation of appropriate native fish recovery actions to support depleted populations.

These stages were largely in line with recommendations from the investigation into the 2018/19 fish kills on the LDBR (Vertessy et al., 2019), however it should be noted the report recommendations suggest a Basin-wide, cross-jurisdictional response. Whilst the planning architecture outlined below focused on a NSW-specific framework, it did not preclude NSW contributing to a broader cross-jurisdictional "emergency response group" or programs coordinated by the Commonwealth or MDBA (in fact it enhanced our ability to contribute to such a framework).

The NSW DPI Fish Drought Response Framework (Figure 14; Table 4) proposed two tiers of management to manage actions and responsibilities:

1. A state-wide **Native Fish Drought Response Coordination Committee (NFDRCC)** consisting of Executive representatives from across NSW DPI Fisheries and Communications branches (Aquatic Environment (AE); Research; Compliance; Recreational and Aboriginal Fisheries, and; Communications and Stakeholder Engagement branches), led by a dedicated Drought Response Coordinator role to consider the broader policy, planning and communication issues common to drought preparedness, and
2. A series of **valley (or regionally) based technical advisory groups (VTAGs)** that provided advice on the planning, development and implementation of priority management and research actions related to drought preparedness and fish kills at the valley scale.

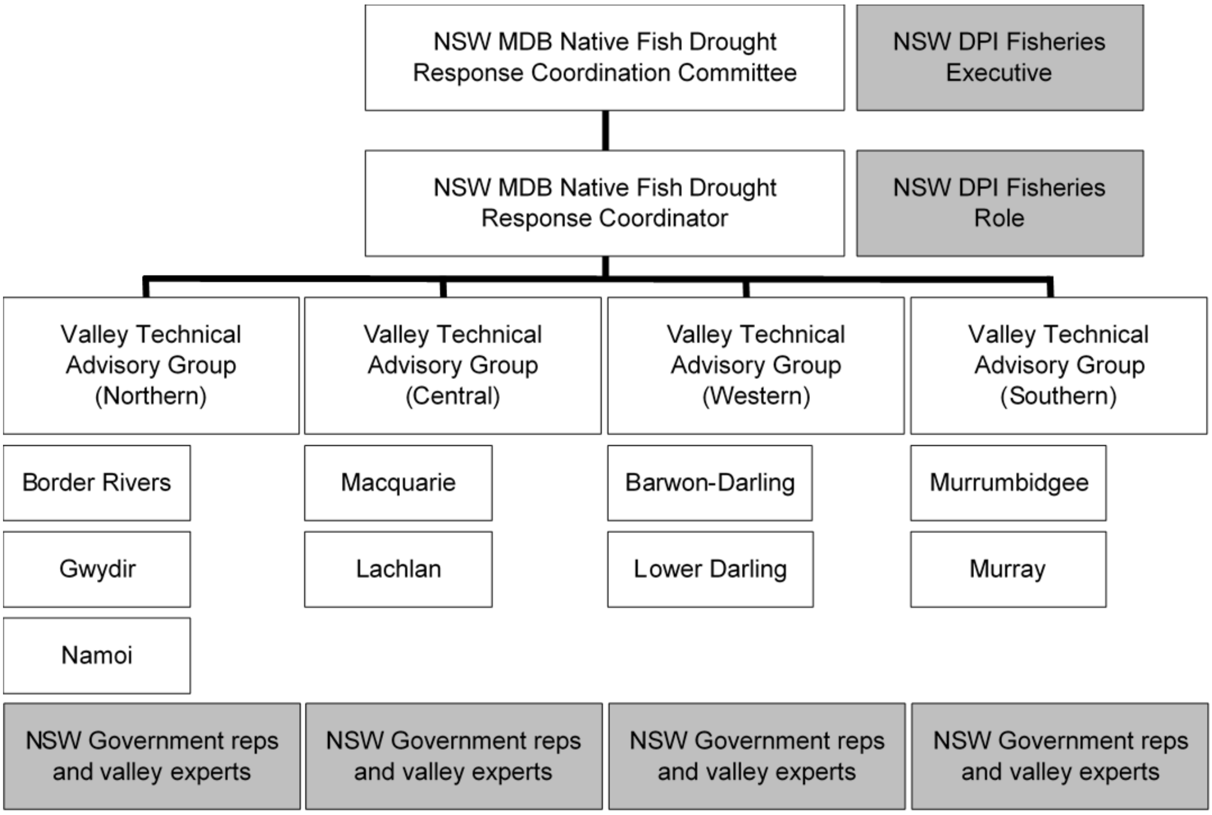


Figure 14. NSW MDB Native Fish Drought Response framework (grey boxes highlight membership of each level).

In the LDBR, DPI Fisheries explored response options and worked with local communities to protect native fish in the region. Management interventions focused on maximising the amount and diversity of native fish that persisted through the extended dry period (2017-20). These response activities and actions are outlined in the following sections.

Broader initiatives such as the Native Fish Recovery Strategy will build on these activities and resulting outcomes, to address strategic priorities for the long-term recovery and health of native fish populations across the LDBR and broader MDB (see: https://www.mdba.gov.au/issues-murray-darling-basin/fish-deaths/native-fish-recovery-strategy).

Table 4. Proposed actions, roles, and responsibilities of the NSW DPI Response Framework.

Stage	Action Summary	Responsibility
Mitigation	Identify sites across the NSW MDB that are key to the long-term maintenance of fish populations, and their associated risks of fish deaths using the latest monitoring, habitat and spatial data	DPI Fisheries Aquatic Environment Branch to inform NFDRCC
	identify specific threats, locations and challenges for managing native fish outcomes at these sites and prioritise, where possible, intervention actions for these sites	NFDRCC
Preparedness	develop agreed policy statements that address key issues in drought preparedness and fish kill response, including, but not limited to: • watering strategies (including use of environmental water, temporary restrictions/relaxation triggers for flows); • range of technological interventions to reduce risks of fish deaths (e.g. de-stratification, oxygenation); • compliance actions and management; • fish rescues and relocations; • threatened species management interventions (rescue/relocation); • monitoring activities for critical elements, including water quality, fish communities • clean-up operations (including key contacts, and procurement assistance)	NFDRCC
	monitor key sites to inform any response actions and early warnings	VTAGS NFDRCC
	develop a communication strategy that informs and involves communities across the Basin and details: • proactive measures to inform the community and stakeholders of the likelihood of mass fish kills in the coming season. • agreed framework for disseminating information on high-risk conditions and specific fish kills to the stakeholders and the wider community, and; • agreed protocol for responding to individual/site-based requests for information.	VTAGS NFDRCC/ DPI Workplace Health and Safety Committee

Stage	Action Summary	Responsibility
	develop a valley-based 'Drought Response Template' for completion by relevant operational teams	
	develop a staff well-being strategy to manage staff throughout the response process.	
Response	implementing appropriate on-ground action at priority sites	VTAGs
	continued monitoring at key sites to assess impact of any deployed intervention	
	continued implementation of communication strategy, including production of periodic (daily/weekly/monthly depending on severity of conditions and circumstances) updates on current conditions, risk ratings and management initiatives to be published on the NSW DPI website, community drop-in stands, social media etc.	NFDRCC
Recovery	Assessment of impacts at priority sites	VTAGS
	Monitoring of key sites to inform any recovery actions	
	Continued development and implementation of appropriate native fish recovery actions, habitat rehabilitation, fish passage, translocation and restocking where relevant, and water management programs.	NFDRCC

LDBR refuge pool identification

In the LDBR throughout 2019, the reported fish kills occurred in isolated pools due to lack of water or poor water quality. To inform the 2019/20 NFDR actions, DPI Fisheries identified larger refuge pools to focus fish protection activities (i.e. artificial aeration), or pools in which fish were at risk of becoming stranded, and hence were candidates for rescue efforts.

The process of identifying refuges utilised satellite imagery (publicly available interfaces from SENTINAL, PLANET and Google Earth) as well as aerial imagery of the LDBR collected by DPI Fisheries and the Western Local Lands Services (LLS) in 2016 (during a previous cease to flow event). Some examples of the imagery used in this process are included in Figure 15. Where possible, ground-truthing of refuge pool characteristics was conducted by site visits (DPI Fisheries staff), and through active consultation with landowners, agency staff, researchers, and recreational anglers.

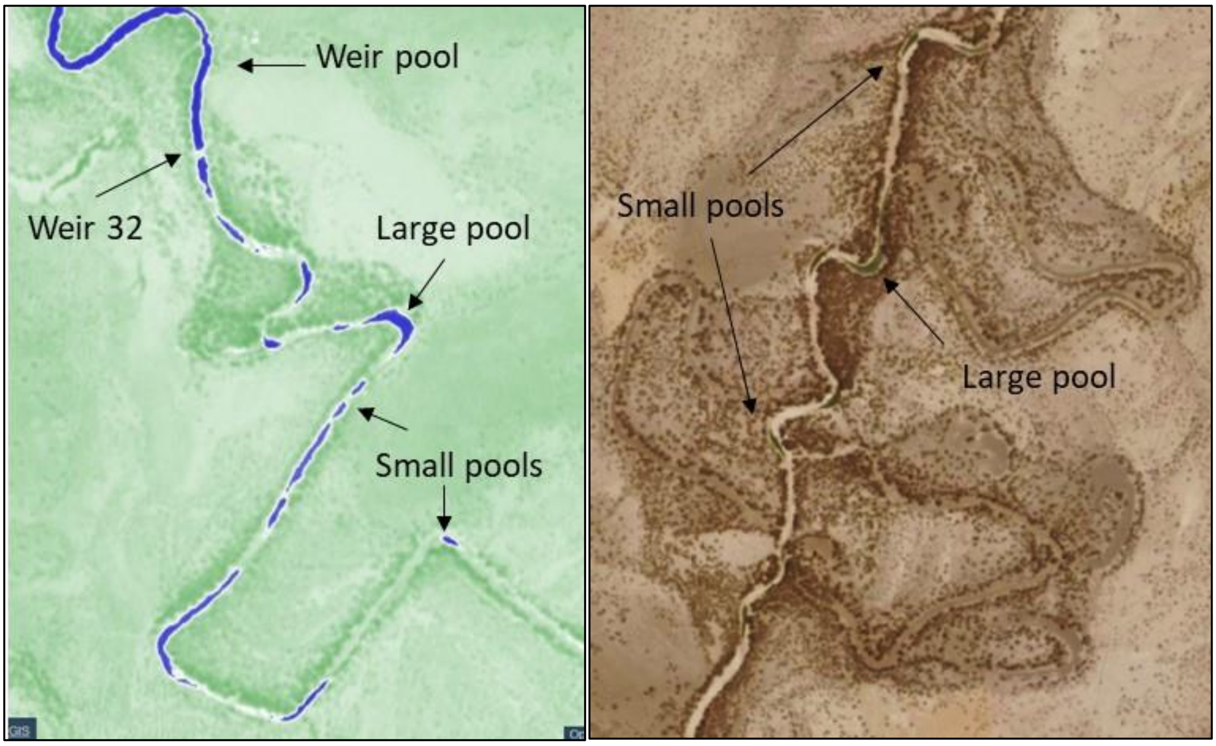


Figure 15. Example images collected during the identification process for refuge pools in the LDBR. The image on the left shows surface water upstream and downstream of Weir 32 in August 2019 and was accessed from the SENTINAL hub playground web application satellite using NDWI rendering tool over Sentinel-2 imagery. The image on the right shows a section of the river downstream of Pooncarie and was accessed from the Planet Explorer web application.

Pools were not distinguished between those located within the zone of influence of permanent weir-pools (i.e. by Pooncarie or Burtundy weirs) or temporary weir pools created by the four (4) block banks installed by WaterNSW in late 2018, and those that were not within a weir pool influence. The refuge pool identification process allowed the development of maps showing the locations of different sized pools (see examples in Figure 16) categorised as:

- **large** pools deemed likely to provide enough liveable fish habitat for the period after the LDBR ceased to flow (February 2019) until flow returned in March/April 2020. These were typically 50 x 100m in size (length x breadth) and held 1-3m of water during summer 2019/20.
- **moderate** sized pools in which some fish were likely to have survived prior to the return of flow in March/April2020, although some mortalities were likely. We estimate these pools retained less than 1.5m of depth through summer 2019/20.
- **small** or shallow pools in which very little surface water remained by March 2020, in which mortalities were likely and few larger bodied fish other than Carp were likely to have persisted when flow returned. Whilst some may have been 20-100m in length, they were very shallow during summer 2019/20. Any larger fish which had been isolated in these smaller pools as the system disconnected throughout 2019, were at a high risk of death.

The refuge pool identification process identified 569 pools of surface water that remained as of March 2020 along the approximately 500 kilometres of river between Weir 32 and Ashvale Station. Of these, 51 were large pools, 199 were moderate sized and 319 were small/shallow pools.

Figure 16. Examples of 'large', 'moderate' and 'small' refuge pools in the LDBR during summer 2019/20 (top to bottom respectively).

The results of these analyses were amalgamated into maps of the LDBR showing locations of refuge pools that represented priority fish habitat, including areas influence by weirs (weir pools) or temporary block banks. Persistence was monitored through 2019 as conditions in the LDBR worsened to allow maps to be updated. Figure 17 shows remaining fish habitat in the LDBR in February 2020, 12 months after flows to the LDBR ceased, with analysis undertaken to estimate reaches that were dry or had water, and if this water was habitable for fish based on spatial imagery.

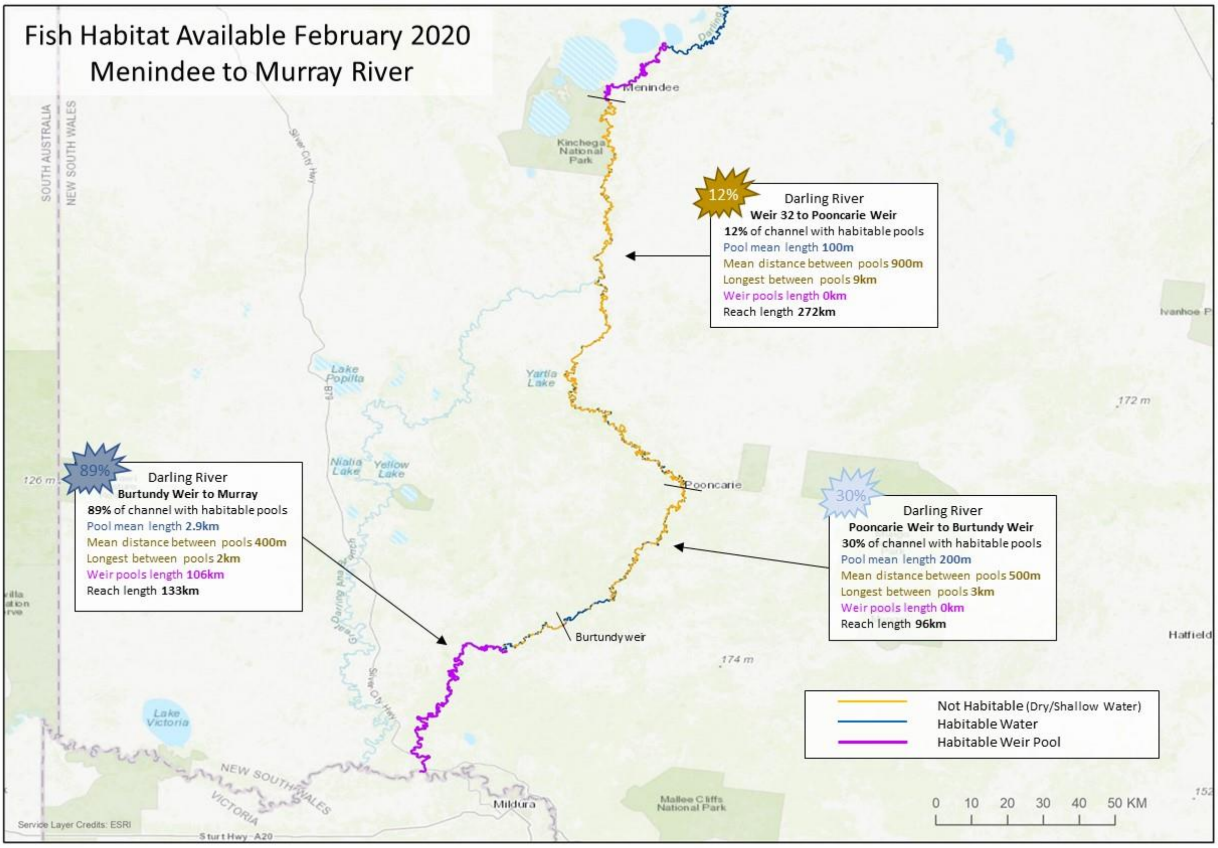
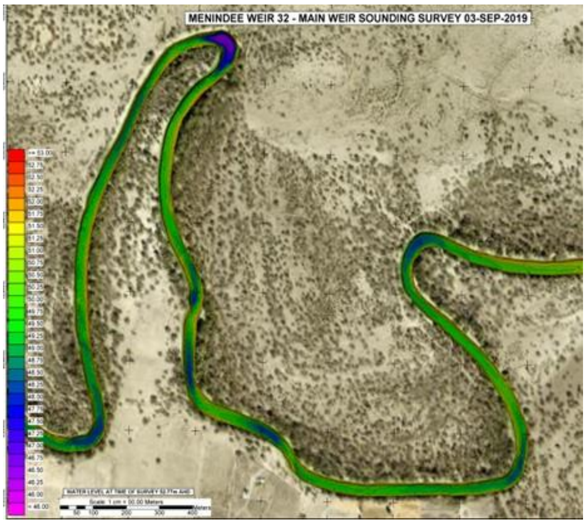


Figure 17. Map of the LDBR showing location of refuge habitat in February 2021. Please note that this analysis is preliminary and only based on best available desktop information - the statistics calculated are only the length dimension of the river channel. The width and depth dimensions are also likely be greatly reduced.

Weir pool bathymetry

In addition to refuge pool identification downstream of Weir 32, the MDBA contracted SA Water to map the bathymetry of key sections of the LDBR in the Menindee Weir Pool, and upstream of Menindee Main Weir (i.e. Lake Wetherell) in September/October 2019. This assisted DPI Fisheries in identifying deeper sections with the extensive weir pool habitats that were likely to persist as connected areas of deeper water through summer 2019/20. Also assisted in identifying which habitat could support large mechanical aeration units to maintain large areas of refuge through the approaching summer. Example outputs from this mapping are shown in Figure 18.



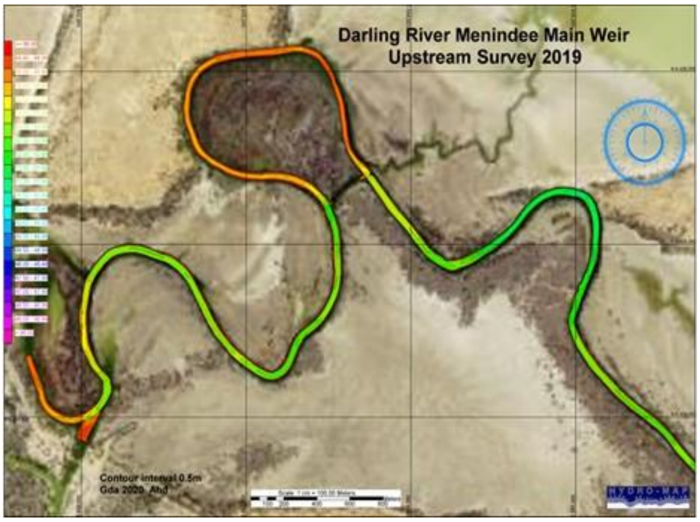


Figure 18. Outputs of the Bathymetry surveys commissioned by the MDBA in the Menindee (Weir 32) and Lake Wetherell (Menindee Main Weir) Weir Pool. Deeper water is indicated by green and blue colours (Source: MDBA).

Preliminary evaluation of the effectiveness of different technologies in mixing, aeration and algal treatment

A detailed description of this work has been published in Boys C, Baldwin D, Ellis I, Pera J, Cheshire KJM (2021) Review *of options for creating and maintaining oxygen refuges for fish during destratification-driven hypoxia in rivers. Marine and Freshwater Research Special Edition – Fish Kills*" (https://www.publish.csiro.au/MF/justaccepted/MF20364)

A list of various options (technologies or general approaches) was evaluated by DPI Fisheries in collaboration with WaterNSW, based on their suitability for achieving one or more of the following three (3) objectives regarding improving refugia condition: mixing, aeration or algal treatment.

To determine the most effective way of creating oxygen refuge for fish during drought conditions, it was prudent to first describe the direct causes of hypoxia so that techniques that mitigate these could be identified and evaluated. The five (5) primary causes of hypoxia are:

1. A lack of flow which results in still (*lentic* as opposed to naturally flowing or *lotic* habitat), disconnected pools, and reduces mixing of water layers.
2. Extended periods of extreme heat (including high overnight temperatures) that strengthens thermal stratification, prevents vertical mixing and leads to hypoxic or

anoxic deeper layers, thus restricting fish to the surface layer where limited DO may prevail.

3. Low wind activity during heat waves, which further reduces the likelihood of mixing within the water column.
4. Blooms of algae or cyanobacteria that establish diel overnight periods of hypoxia in the surface layers (in the absence of photosynthetic oxygen production) thus subjecting fish to chronic and repeated stress over extended periods of time. Blooms also reduce light penetration which can exacerbate the bias of respiration over photosynthesis in the water column, thus enhancing low DO in the deeper layers.
5. Periodic turning-over or mixing of stratified pools, referred to as de-stratification which mixes hypoxic or anoxic deep water with surface waters thus dropping the level of DO throughout the entire water column. In some situations, fish will have nowhere to go to find oxygen refuge.

Given these five (5) primary causes of hypoxia during drought, the best way to maintain oxygen refuges for fish during extended drought conditions is to mitigate these by:

- **Maintaining river flow** to generate thermal mixing, allowing fish to access a greater area of refuges and reduce the risk of algal blooms. Higher flow or discharge increase in-channel flow velocities and turbidity which in turn suppress formation of problematic algal or cyanobacteria blooms. Flow rates (discharge and flow velocities) sufficient to ensure sufficient mixing at key locations throughout the Barwon-Darling River have been recommended (see Mitrovic et al. 2003; 2011). For example, Mitrovic et al. (2003) identified that persistent stratification (>5 days) and growth of *Anabaena circinalis* occurred in the Darling River during periods of low discharge, usually less than 500 ML/day in the hotter periods of the year. Specifically, for the LDBR, Mitrovic et al. (2011) recommended discharge of >300 ML/day would help prevent long periods of thermal stratification and thus suppress the development of algal or Cyanobacteria blooms.

  However, once blooms had formed, much higher discharge is required to disrupt them through mixing, translocation downstream and dilution (potentially in the range of 1,000 to 3,000 ML/day). Unfortunately, during extended drought there is often insufficient inflows or water in storage to achieve these higher flow rates. During 2019, flow management was not an available option for creating oxygen refuges in most NSW catchments (excluding the Murray and Murrumbidgee) over the 2019/20 summer period.
- **Help facilitate water mixing to avoid stratification**, then maintain frequent, regular mixing. This is referred here as pre-emptive mixing and it should be attempted prior to the onset of extreme heat and maintained throughout summer. Pre-emptive mixing can ensure oxygen absorbed from the atmosphere is sufficiently dispersed throughout more of the water column, creating more suitable habitat for fish.
- **Avoid rapid de-stratification (mixing) in waterbodies that have been thermally stratified for long periods** (>4 days) and therefore pose a high likelihood of hypoxia through the water column once mixing occurs. In waterbodies that have been thermally stratified for extended periods (>4 days) it may be possible to **use aeration to artificially boost DO levels** to create 'pockets' of suitable refuge within the waterbody where fish can congregate.

- Since algae can generate daily cycles of oxygen depletion, **reducing the likelihood of algal bloom formation** could assist in reducing the likelihood of hypoxic events, although blooms are not the primary cause of stratification and hypoxia.

Aeration through addition of chemicals

Two (2) chemical aeration options were explored as part of investigations, including calcium peroxide and sodium percarbonate.

Calcium peroxide

Calcium peroxide (CaO_2) is a sparingly soluble calcium salt that breaks down slowly (potentially over months) to produce oxygen through the decomposition of peroxide. It has been effectively used in aquaculture to maintain oxygen levels, mostly through mitigating sediment oxygen demand rather than directly adding oxygen to the water column (because it reacts slowly and is sparingly soluble, tending to accumulate on the sediment surface rather than be dispersed through the water column). However, because its efficacy in rivers of this scale required in the MDB is unknown, pilot tests would be required to determine whether it is a viable solution for large-scale dosing of rivers.

Use of calcium peroxide is likely to be considered low risk to the environment, although some small-scale controlled experiments will still be required to ensure it can be safely used over larger scales. Calcium peroxide has been shown to inhibit algal growth either through direct peroxide toxicity (e.g. Bauza et al, 2014) or indirectly through the coordination and precipitation of phosphorus by calcium (Lee and Cho, 2002). This may pose a risk if used in areas of strong algal blooms, as it could cause an algal crash which would drop dissolved oxygen levels. However, because most of the calcium peroxide will accumulate at the sediment surface, and not in the photic zone, the risk of such an algal bloom crash is relatively low.

If trials proceed and indicate it is safe and effective across a large scale, it could be deployed in remote areas relatively efficiently (e.g. via air drop). If the affected LDBR area is used as a future example to test the application, conservatively, it would require about 1,600 tonnes[1] to raise the total DO concentration of the water by 4 mg/L. However, there is a chance that more may be required, as most of the calcium peroxide may preferentially oxidise the sediments. It was estimated that treating a 40 km stretch of the LDBR may cost approximately

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[1] Assumes that 22 % by weight is converted to dioxygen (i.e. 100 % efficiency), 8000 ML of water to be treated and O_2 levels are raised overall by 4 mg/L. Assuming the top 1 m has 6 mg/L O_2, the bottom 3 m has no oxygen, this would raise O_2 levels in the water column to 5.5 mg/L.

$400,000. Use of any chemicals will require regulatory approval, the chemical needs to be sourced and a deployment plan developed.

Sodium percarbonate

Sodium percarbonate ($2(Na_2CO_3).3H_2O_2$) is a water-soluble compound that rapidly breaks down (minutes to hours) to produce peroxide and carbonate/bicarbonate, which then decomposes to form oxygen. It is found in a number of commercial bleaches and is used as a water sanitiser in aquaculture. It shows promise as a rapid generator of dissolved oxygen. However, because it breaks down so quickly, it is likely to be less effective in longer-term maintenance of dissolved oxygen in refuges. Like calcium peroxide, it would have the ability to be deployed across large scales in remote areas efficiently (e.g. via air drop). It would require about 2,250 tonnes of sodium percarbonate to raise the DO concentration in a reach like the LDBR by 4 mg/L[2]. The cost of doing this has not been investigated and the requirement for repeated dosing would need to be considered in any evaluation of cost. As with calcium peroxide, the use of sodium percarbonate would likely require regulatory approval.

Sodium percarbonate may be of greater ecological risk than calcium peroxide as it would increase the alkalinity of the water in reaches where pH levels can already be quite high due to algal blooms. In reaches where fish are decomposing (like those that occurred in the LDBR), if pH becomes too high, ammonium can be converted to ammonia, which is toxic to fish. Furthermore, as mentioned previously, peroxide can kill algal blooms. As the production of peroxide would occur rapidly, it is likely that peroxide formation would occur in the surface layer and therefore, potentially cause the algal bloom in the surface water to crash, depleting DO.

Fine-bubble injection

This technology injects air into the water column as fine bubbles and is anticipated to be the most effective of the aeration devices. There is an industry standard that is used to describe the size of bubble generated, and they can range in size from fine (<100 micron), to ultra-fine (<1 micron) to nano (<0.1 micron). Regardless of size the mechanism is the same. The small size of the bubble means they are far more stable in fluids than normal bubbles, so they will remain in the water column for longer and therefore have greater opportunity to release oxygen. This differs substantially to the macro-bubbles released from airlift systems which rapidly float to the surface and release most of the air into the atmosphere. Fine-bubble injection often uses pure oxygen, either from compressed liquid gas or generated by a condenser, which further improves the efficiency with which oxygen is added to the water.

[2] Assumes that 15 % by weight is converted to dioxygen (100% efficiency) - the rest of the assumptions as per calcium peroxide.

The injection of nano-bubble oxygen from a liquid oxygen supply has been employed to great effect in the Swan River, Western Australia, where a 14 km stretch of river is permanently aerated to prevent fish kills (Joe Pera, WaterNSW pers. comm.). Whilst this installation is a permanent one, the proprietors of that technology report that smaller, more mobile systems are also available. The cost of these systems has not been evaluated but is likely to be substantially higher than other lower-tech approaches such as Venturi water pumps (but this will need to be tested by approaching the market). The biggest uncertainty is whether this technology can be deployed at a large scale (such as at the Menindee Weir pool) in a cost-effective manner.

There are also concerns that injecting fine bubbles into the water may cause supersaturation of the water column. When total dissolved gas pressures exceed 110%, fish restricted to shallow water can develop gas bubble trauma where emboli form in organs and gills. This can disrupt oxygen absorption and eventually kill fish. Fish kills from gas bubble trauma are frequently reported in the wild as a result of supersaturation resulting from dam spill and algal blooms, or in aquaculture when pumps entrain air into the water stream. Gas bubble trauma is exacerbated in warmer and shallower water (which is to be expected in drought refuges), as warm water can hold more dissolved gas and fish cannot dive deep to mitigate the release of gas from internal body fluids or organs.

The risk of supersaturation and dangerous levels of total dissolved gas pressure following fine-bubble injection was tested in a pilot by DPI Fisheries in hatchery ponds at DPI's Narrandera Fisheries Centre. Results from this trial on a proprietary ultra-fine (< 1-micron bubble diameter) oxygen condenser returned promising results (Custom Fluids™). The data indicated the system raised DO significantly over the untreated control pond without raising total gas pressure above the 110% level reported by the United States Environmental Protection Authority (US EPA) as the lower limit for causing gas bubble trauma (**Error! Reference source not found.** 30). Further experiments, whether in ponds or the wild, are required to ascertain the retention of gas bubbles in the water column following cessation of pump operation.

Algal treatments

Algal blooms can exacerbate hypoxia in certain circumstances by increasing night-time respiration and by reducing light penetration in the water column during the day, therefore reducing the extent of blooms may assist in maintaining refuges for fish. There are many different proprietary products available for treating algae in lakes, ponds and small waterbodies, some of which have extensive research and development to present their efficacy. Some products aim to manipulate the microbial community to favour bacteria, diatoms and green algae over blue-green algae.

At the time, WaterNSW were evaluating a number of algal treatment options that could potentially be used in future events as needed, and hence they were considered for use in summer 2019/20. It is also important to note that algal treatment alone will not prevent stratification and hypoxia. There is also a risk that 'crashing' algal blooms will only exacerbate oxygen depletion in already depleted reaches.

Creating oxygenated refuge

Following the Menindee fish kill events, several approaches were explored and trialled to mix and/or aerate refuge habitat in the LDBR to protect remnant native fish communities. Some of these efforts represent the first such attempts at creating artificially aerated refuge in rivers of the MDB.

The MDBA in collaboration with DPI Fisheries commissioned a comprehensive monitoring program to examine stratification, mixing and dissolved oxygen concentrations in the LDBR. Dr. Darren Baldwin from Rivers and Wetlands (environmental consultancy) was contracted to assess collected data, with key objectives being to:

- Explore available data to identify risk factors that may lead to fish deaths.
- Determine the effectiveness of management interventions, particularly the use of aerators, in ameliorating water quality issues in the LDBR.
- Identify knowledge gaps that could help inform future management of the LDBR especially with respect to managed flows, and during cease-to-flow periods.
- Use the results from the current monitoring program to inform the optimal design of future monitoring programs (including governance arrangements).

Here we summarise the actions initiated in attempts to provide temporary artificially oxygenated refuge for native fish in the LDBR, and include discussion on the effectiveness of different methodologies drawing on the results of the assessments by Rivers and Wetlands (Baldwin 20198; 2020).

Water pumps

Water pumps work by agitating the water surface to encourage mixing with the atmosphere above the water (with the intention of creating refuge), and/or establishing water currents in non-flowing waterbodies. In doing so the intention is to promote mixing and/or de-stratification, and the exchange of oxygen throughout the water column. The effectiveness will depend on the size and depth of the waterbody they are deployed in, the prevalence of stratification and hypoxia prior to installation, and the amount of water they displace. Water can be drawn and released at any depth and potentially released a substantial distance from the inlet. Therefore, the potential to displace water and encourage currents is greater than with other mixing technologies such as water paddles (see next section) or airlift bubble diffusers.

There is however the potential for traditional pumps to draw hypoxic water (given offtakes are often located low in the water column) and release it at the surface of a waterbody and mixing it through the water column, thus increasing risk of hypoxia at the air-surface interface.

Solar-electric powered small bubble injection units

Following the first Menindee fish kill event in December 2018, DPI Fisheries and local OzFish Unlimited recreational angler groups collaborated in the installation of six (6) solar powered small-bubble injection aerators throughout the LDBR. Two (2) were deployed in the Menindee Weir pool where the fish kill had occurred, and four (4) in deeper sections of the river between Weir 32 and Ashvale Station). In bubble injection systems, air is pumped from the surface to diffusers (up to three (3) diffusers in the units used along the LDBR) placed either on the bottom of the water body, or at a specified depth (see Figure 19). Air bubbles then rise to the surface, with some of the air diffusing from the bubble into the water column.

Figure 19. Solar powered airlift bubble systems were deployed at four (4) sites in the LDBR and two (2) sites in the Menindee Weir pool during the recent fish kill events (Photo credit: DPI Fisheries staff).

Initial assessments of the efficacy of these units suggested the solar aerators were not strong enough to prevent hypoxia or improve DO levels for fish in large, deep, LDBR pools (including weir pools) during summer 2018/19 (Baldwin 2019), and unfortunately, the units experienced maintenance issues related to programming complications, positioning of the solar panels (i.e. shading), and position of the diffusers. In assessing these units, it was important to note that prevailing weather conditions and local bathymetry were likely to impart substantial influence on water quality in the vicinity of the aerators.

The effectiveness of the small aerators was likely to be greater in smaller isolated volumes of water (given their design for use in aquaculture ponds or dams) where they may improve DO in the water column immediately adjacent to the bubble plume, dependant on variables such as diffuser location, pool morphology/depth, algal load and the extent of thermal stratification. They remained in operation throughout 2019 as refuge pools contracted and were also subsequently utilised in refuge pools in other NSW rivers (such as the Macquarie and Peel) as the drought worsened in 2018/19.

Diesel electric multi-port venturi pontoon aerators

In January 2019, and in response to observations of stressed fish (including large Murray Cod) aggregating at the surface of pools downstream of the weir (Figure 20), concerned community members installed two diesel-electric powered multi-port venturi aerators in refuge pools directly downstream of Weir 32. In these systems, water enters small venturi (the spraying mechanism) at high pressure, creating a vacuum (Figure 21). The vacuum draws in air and oxygen from the atmosphere where it is mixed into the water stream. In venturi systems, water can be drawn from any level in the water column and released at any level.

The two (2) units were loaned by their manufacturers, with contribution from OzFish Unlimited in delivery to Menindee. Fuel and maintenance costs were provided by Central Darling Shire Council, DPI Fisheries and the MDBA to ensure the units were able to operate during the day and night through the 2018-19 summer to support fish in the refuge pools. Each unit circulated between 2-8 ML/day of water (depending on power and running speed).

Being more powerful, the multi-port venturi aerators performed better than the solar-electric aerators in the river channel environment.

Although the diesel-powered aerators were also more expensive to run and maintain, and deployment was more problematic, sufficient mixing and oxygenation of small pools of 50-100m length/width, and depth of generally <3m depth was maintained through extended heat waves (Baldwin 2019). Thus, the efforts by the local community in deploying and maintaining the two (2) units prevented fish deaths in the targeted pools. Notably, these pools contained high density of aggregated fish given Weir 32 became a barrier to upstream movement of fish in January 2019 when flow to the LDBR ceased.

Figure 20. Murray Cod aggregating at the water surface downstream of Weir 32 in February 2019 (photo: G. McCrabb, February 2019).

Figure 21. Diesel-electric powered multi-port venturi aerators in refuge pools downstream of Weir 32 (photos: G. McCrabb).

Following on from the successful use of diesel-electric multi-port venturi aerators in 2018/19, DPI Fisheries and the MDBA collaborated in the funding and deployment of aeration units at key locations in the Menindee region during the spring and summer of 2019/20. These units were operated day and night until March 2020 when flow returned to the LDBR. These units were in a pool directly downstream of Weir 32, adjacent to the Menindee town pump station, and two (2) deep sections of the Lake Wetherell river channel at Wyndalle and Viewmont stations (see Figure 1). No dead fish were reported in these habitats during the deployment and operation of these units, and water quality monitoring assessments suggested they maintained suitable refuge for fish throughout summer 2019/20 (Baldwin 2020).

Pump-driven venturi aerators

In February 2019, DPI Fisheries conducted a trial of larger 12-inch diesel pump-powered Venturi system aerators to mix and aerate a section of connected river channel in the LDBR in a long pool upstream of a temporary block bank at Karoola Station. The trial involved pumping water from the river with a 12-inch diameter pump, back into the river (at 10-15 ML/day) upstream via a custom-made steel venturi unit, with the hope of circulating aerated water through a loop of river several kilometres long (Figure 22). The venturi unit was designed and constructed by Millewa Pumping on behalf of DPI Fisheries and was installed on 21 January 2019 and operated until 28 March 2019.

Figure 22. A 12-inch pump-driven venturi system trialled at Karoola Station in February 2019.

Monitoring data and analysis by Baldwin (2019) indicated the pump was unable to circulate the entire loop of river. However, it successfully suppressed thermal stratification and created oxygenated refuge for at least 60m (and potentially up to 150m) upstream and downstream of the outlet in water that was 5-6 m deep during its operation, which was likely to attract fish from adjacent reaches (Figure 23 and Figure 24). During the trial period there were at least five (5) instances of de-stratification induced hypoxia at a control sites in the region.

Thus, it was concluded that the Karoola venturi aerator prevented multiple fish kills in the Karoola reach (Baldwin 2019).

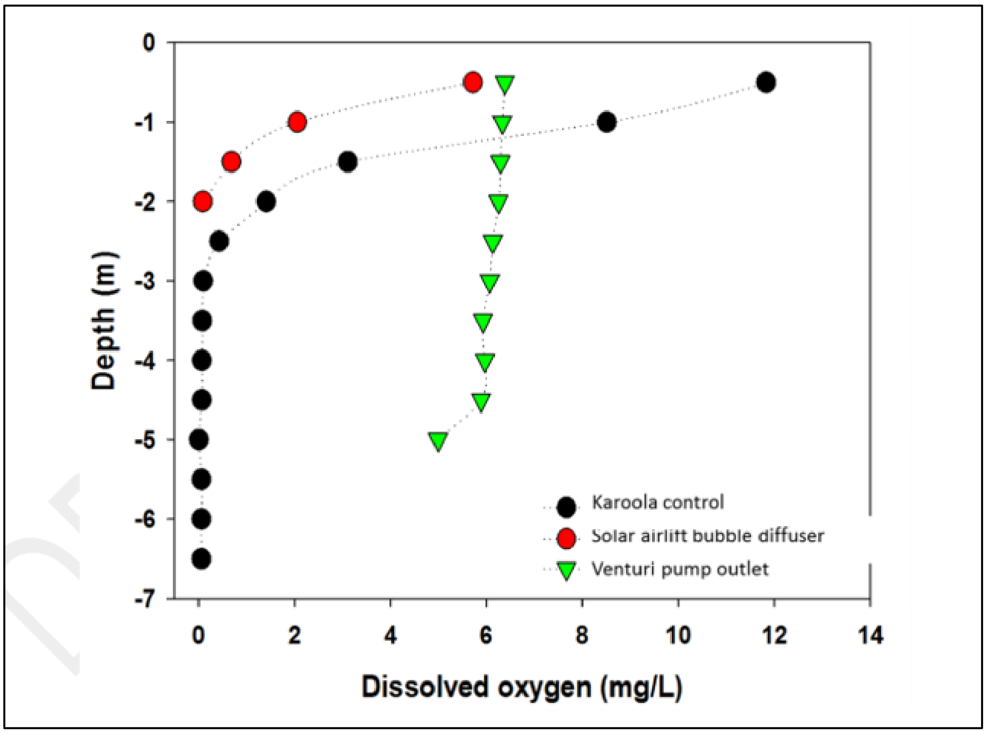

Figure 23. Plot showing a comparison of dissolved oxygen levels at varying depths at an untreated control section (black), near the outlet of the Venturi pump (green) and at the solar-powered airlift bubble diffuser (red) (adapted from Baldwin, 2019).

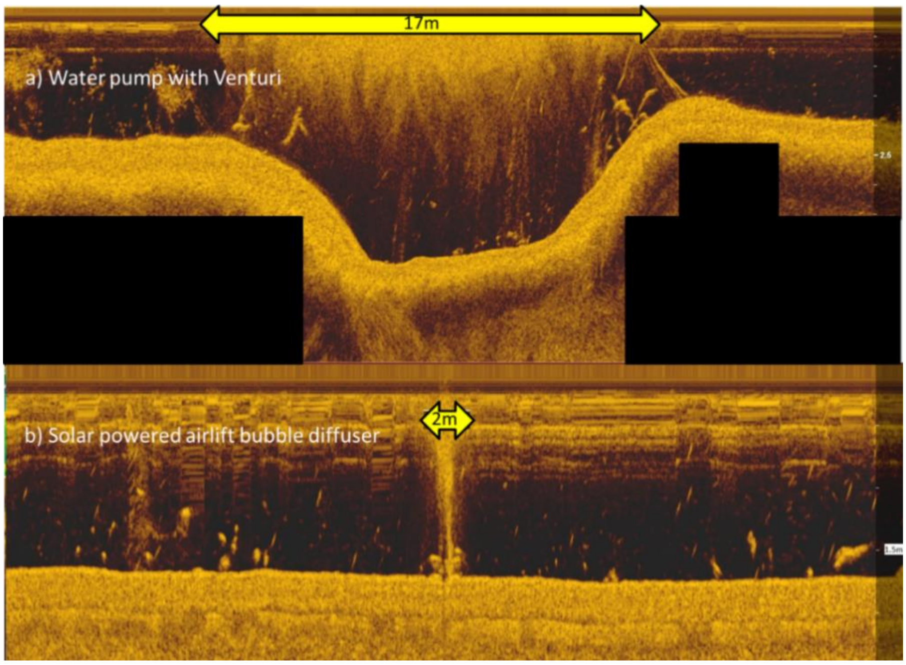

Figure 24. Side scan images of a reach of the Lower Darling at Karoola (south of Menindee) in the vicinity of the outlet of a water pump with a Venturi (a) and at a nearby solar-powered airlift bubble diffuser (b). The yellow arrow highlights the width of entrained air created by both technologies (seen in the side scan as clouding of the water column).

As the drought conditions extended, and based on findings from the field, DPI Fisheries funded the deployment of four (4) similar 12-inch pump driven venturi systems in the spring of 2019 in large disconnected deep pool refugia identified through the refuge identification process described above (see Figure 1). The locations of the units were at Karoola and Moorara Stations between Pooncarie and Menindee, and Kapana and Jamesville Stations between Pooncarie and Burtundy.

Figure 25. A 12-inch pump-driven venturi system operating in a disconnected LDBR refuge pool in February 2020.

Two (2) substantially larger 26-inch pump venturi units were also deployed to aerate connected sections of weir pool habitat in the Menindee weir pool and in Lake Wetherell (upstream of Menindee Main Weir). These were designed to aerate a larger area, and potentially circulate aerated water through a loop of river several kilometres long (Figure 26).

Figure 26. 26-inch pump-driven venturi system located in Lake Wetherell through summer 2019/20.

The large pump-driven aerators were kept running day and night until March 2020, and effectively prevented stratification and hypoxia throughout refuge pools (for 12-inch systems) and in sections of weir pool at least 150 m upstream and downstream of the outlets of the 26-inch systems. Whilst the units were unable to circulate aerated water throughout the entire loop of river, they nevertheless provided a substantial refuge area that would have supported many native fish.

Water paddles

These systems consist of a series of powered rotating paddles mounted on a floating pontoon. As they rotate, the paddles agitate surface waters, entraining some oxygen and mixing air into the water column. This process can create localised pockets of (partially) oxygenated water. The paddle-type aerators also create localised currents that can serve to stop the formation of thermoclines in small shallow water bodies. Therefore, they have proven quite effective in aquaculture ponds (especially in stopping stratification).

Water paddles will likely be most effective in smaller and shallower (<2 m deep) refuges. In these smaller refuges it would be quite feasible to pre-emptively mix the water column and maintain the mixing. The technology is likely to be far less effective at mixing in deeper (>2 m deep) refuges. There are examples of the use of water paddles in response to fish kills. During the 2010 blackwater event on the Murray River, a paddle steamer was used as a large-scale paddle aerator. The oxygen levels in the small marina where the paddle steamer was berthed maintained oxygen concentration levels at reasonable levels but had no effect outside the marina confines (Whitworth et al., 2013).

Commercial water paddles will be quite quick and easy to procure and deploy, making them a convenient and cost-effective option in some instances. But they will require a source of power, which will limit their use in more remote areas. When used as a pre-emptive and sustained mixing technology, paddle wheels would not be expected to cause any risk to the environment.

Downward facing propellers

Downward facing propellers work by drawing oxygenated surface water and pushing it down below the thermocline. This disrupts the thermocline, eventually oxygenating the bottom water, which in turn reduces the availability of iron and phosphorus, and hence algal blooms. The technology was designed for reservoirs where it has been shown to be effective. The feasibility of using this technology in shallow refuges has not been evaluated. The propeller units are not easily deployed like water paddles or airlift bubble diffusers and would cost significantly more to obtain and maintain. They would require constant power which may limit sites where it would be effective, as well as its ongoing operational cost. As these create down currents, there is a risk that it would disturb bottom sediments, placing additional pressure on oxygen levels in the river. Until further evaluation can prove otherwise, other more practical and cost-effective solutions outlined in this report should be considered.

Water fountains or jets

In this approach, water is pumped from the water body and then sprayed through the air, to land back onto the surface of the water. As the small water droplets pass through the air, they are partially aerated. Water fountains are often used to promote mixing and aeration in small residential or public parks to prevent stagnation of water.

Water jets can also be created using hoses. The main benefit of a water jet is associated with the conditions of surface agitation and current generation that are obtained by water pumps (outlined previously). For example, during a blackwater event in the Edwards River in 2000 (Baldwin et al, 2001), local yabby farmers used their fire-fighting pumps and hoses to create improvised water curtains to re-aerate their ponds. Some interest was shown by locals around Menindee during the recent fish kills in using stock and domestic pumps to create water jets. This works on the same principle.

The shooting of a jet of water onto the surface of the river can assist in improving DO levels and may provide some relief to fish in extreme hypoxic conditions. However, this is largely an inefficient way to oxygenate water and therefore the benefits are only likely to extend to the very surface layer and within tens of metres of the jet of water. Little is gained by using energy to eject water into the air than would be gained by agitating surface waters or creating water currents.

Any improvements in oxygen will also only last if the pump is running. The most beneficial time to undertake this activity would be in the early hours of the morning (e.g. between midnight and 10 am), when algae are consuming and depleting surface oxygen levels. At other times of the day, water jets will make little difference to DO levels because the surface DO levels are probably going to be sufficient to support surface ventilation by fish.

Under certain circumstances there is a risk that water jets can make the problem worse for fish. If the pool is heavily stratified, care must be taken to elevate the intake (preferably into the top 1-2 m of water) to minimise the risk of entraining hypoxic deeper waters or nutrient rich sediments that could further deplete surface oxygen level. In some instances, hypoxic water or nutrient rich sediments may be evident as discoloured or stagnant smelling water. However, in many instances it may not be possible to determine the oxygen levels of the water without appropriate monitoring equipment. Therefore, it is best to be conservative and avoid deeper water. As fish will likely accumulate around the water jet, the jet must be sufficient distance away from the pump intake to reduce the likelihood that fish may be sucked into the pump.

The biggest benefit of this approach is that it is highly practical and could be rapidly deployed and used by individuals with no prior training (e.g. landholders, graziers and irrigators). Before endorsing this approach, consideration would need to be given to regulatory implications of allowing landholders to extract water from rivers outside of their licence arrangements and care needs to be taken not to entrain hypoxic water and therefore exacerbate fish kills in areas that are already strongly stratified.

Native fish relocations and brood stock collection

Throughout 2019, DPI Fisheries coordinated the rescue and relocation of native fish stranded in diminishing pools along the LDBR. In total 1,663 native fish were relocated or collected as brood stock. Rescue efforts targeted shallow pools identified in the refuge identification process described above. Larger pools were to be excluded from rescue efforts unless distressed fish in need of assistance were observed. A summary of rescue and relocation efforts is included in Table 5.

Assistance with the relocation efforts was provided by the Arthur Rylah Institute for Environmental Research (Victoria), and by three (3) groups of volunteer recreational fishers that were permitted to undertake native fish relocation efforts in late 2019 and early 2020 (under guidance from DPI Fisheries) (Figure 27). Rescued fish were either transferred to professional hatchery facilities to be temporarily maintained as brood stock or relocated to more permanent reaches (with suitable water quality) in the LDBR upstream of Wentworth (in the Lock 10 Weir pool) and in refugia adjacent to large pump-driven venturi aeration units in the Menindee weir pool. Assessments of water quality at these locations had determined that oxygenated refuge was provided by the aerators (DPI Fisheries unpublished data; Baldwin 2019, 2020).

Initially 20 Murray Cod, 20 Golden Perch, and 20 Silver Perch were collected downstream of Weir 32 in February 2019 and taken to the Narrandera Fisheries Centre breeding facility as brood stock to ensure a sample of local LDBR genetics was preserved in case of subsequent catastrophic losses within the LDBR native fish community. A further 18 Murray Cod collected from drying pools near Pooncarie later in October 2019 were also transported to DPI's Narrandera Fisheries Centre as brood stock. Following health checks and quarantine, these fish were released to holding ponds at the hatchery facilities, attended by Barkandji representatives as an aspiration to maintain cultural connections to these fish. An additional 67 Murray Cod brood were transferred to DPI affiliated native fish breeding facilities in Victoria and NSW to provide additional contingency and breeding capability. These fish also underwent health checks and quarantine before being released into holding ponds and dams. Fish collected for brood stock will be maintained in breeding facilities for four-five (4-5) years before they are returned to the LDBR.

Table 5. LDBR native fish relocation and brood stock collection.

Rescue and relocation	Murray Cod	Golden Perch	Silver Perch
DPI Fisheries brood stock collection	105	20	20
DPI Fisheries	518	467	57
Volunteer relocations	338	129	9
Total	**916**	**616**	**86**

Figure 27. Recreational fishers from Broken Hill and Mildura using prescribed techniques to capture stressed native fish in shallow isolated pools for relocation to more secure habitat in collaboration and under permit from DPI Fisheries (photos courtesy of volunteer anglers).

Native fish restocking

Breeding by brood stock has since been successful, with approximately 136,000 Murray Cod and 49,000 Silver perch fingerlings harvested and stocked across the Southern MDB in 2019 and early 2020. Unfortunately, these fish could not be released in the LDBR because the region was still experiencing cease to flow conditions.

However, following resumption of flow in 2020, DPI Fisheries were able to restock 80,000 Murray Cod fingerlings at six (6) sites throughout the LDBR in December 2020 (Figure 28). Also, 60,000 Golden Perch fingerlings were restocked (again at six (6) sites in the LDBRR) in March 2021. All fingerlings released in these restocking efforts were bred from adult brood stock that were rescued from drying pools along the LDBR in 2019. Silver Perch fingerlings are expected to be restocked back in to the LDBR later in 2021. Barkandji representatives were consulted during the brood stock collection, release to the hatchery ponds, and then at the releases of fingerlings at Menindee brood stock rescues in efforts to retain cultural connections between these bred fish and Barkandji Country.

Figure 28. School students, landowners, recreational fishing contacts and local community representatives assisting with re-stocking events at Pooncarie.

Post-drought recovery

Monitoring by DPI Fisheries in the LDBR post the fish kills as part of the Lower Darling-Baaka Recovery Reach project has highlighted a fish community in continued stress. However, rainfall events in the Northern MDB in early 2020 provided inflows to the Menindee Lakes system, allowing for a resumption of flow in the LDBR downstream and ultimately the re-connection with the Murray River system in April 2020. Subsequent flow events in early 2021 resulted in additional inflows to the Menindee Lakes and the LDBR. The protection of flows in the Northern NSW MDB under a section 324 order, to meet critical human and environmental needs in northern valleys, including those within the Menindee Lakes System and the LDBR was prioritised as part of managing the rainfall events and subsequent flows.

Early signs of recovery were detected in fish community monitoring in early 2021 following the return of flow to the LDBR through 2020 and 2021. Continued monitoring will be important to track the effectiveness of future management interventions to assist recovery of the fish community within the LDBR. While this represents only the first steps towards recovery of native fish populations, the improved outlook provides optimism if the return of flow is supported by investment in broader recovery measures as part of the Lower Darling-Baaka Recovery Reach project (funded as part of the Native Fish Recovery Strategy).

Fish community monitoring in the LDBR following the Menindee fish kills

A detailed description of this work has been published in Stocks JR, Ellis I, van der Meulen DE, Doyle J, Cheshire KJM (2021) *Kills in the Darling: Assessing the impact of the 2018-2020 mass fish kills on the fish communities of the Barwon-Darling River, a large lowland river of south-eastern Australia.* Marine and Freshwater Research Special Edition – Fish Kills. https://www.publish.csiro.au/MF/justaccepted/MF20340

Following the Menindee fish kills in 2018/19, a monitoring program was initiated to investigate the impacts of these fish kills, and document subsequent changes in the fish community in the LDBR over time. This monitoring was funded by the MDBA through the Native Fish Recovery Strategy (NFRS), a commitment from the Commonwealth and NSW Government to rebuild healthy and resilient native fish populations.

The key to this monitoring program is the establishment of a baseline fish community condition dataset including river downstream of Weir 32 and the Menindee weir pool, to which improvements or deterioration can be compared. Prior to this program there was little data pertaining to the fish community in the Menindee weir pool.

Monitoring is conducted by standardised electrofishing at seven sites within each of two ‘reaches’, these being the Menindee weir pool (where mass deaths occurred in summer 2018/19) and the LDBR between Weir 32 and Pooncarie (Pooncarie Reach) (Figure 29). Differences in species abundance, diversity and size composition between the two reaches was assessed in June 2019, six months after the Menindee fish kills (Round 1). The Menindee weir pool was again sampled in October 2019 (nine months post the Menindee fish kills, Round 2), however sampling in the Pooncarie Reach could not be conducted because the river had contracted to a series of pools and electrofishing access was precluded.

Monitoring in both reaches was repeated in June 2020 (Round 3) following a return of flow to the system in early 2020, and again in June 2021 (Round 4) after a second Barwon-Darling flow event in two years delivered inflows to Menindee that facilitated filling of Lakes Menindee and Cawndilla (which had been dry since 2017-18). These inflows also provided an opportunity to deliver environmental flows targeting native fish outcomes in the LDBR the spring and summer of 2020-21. The monitoring program has now collected three consecutive years of repeat annual (June) sampling in both reaches.

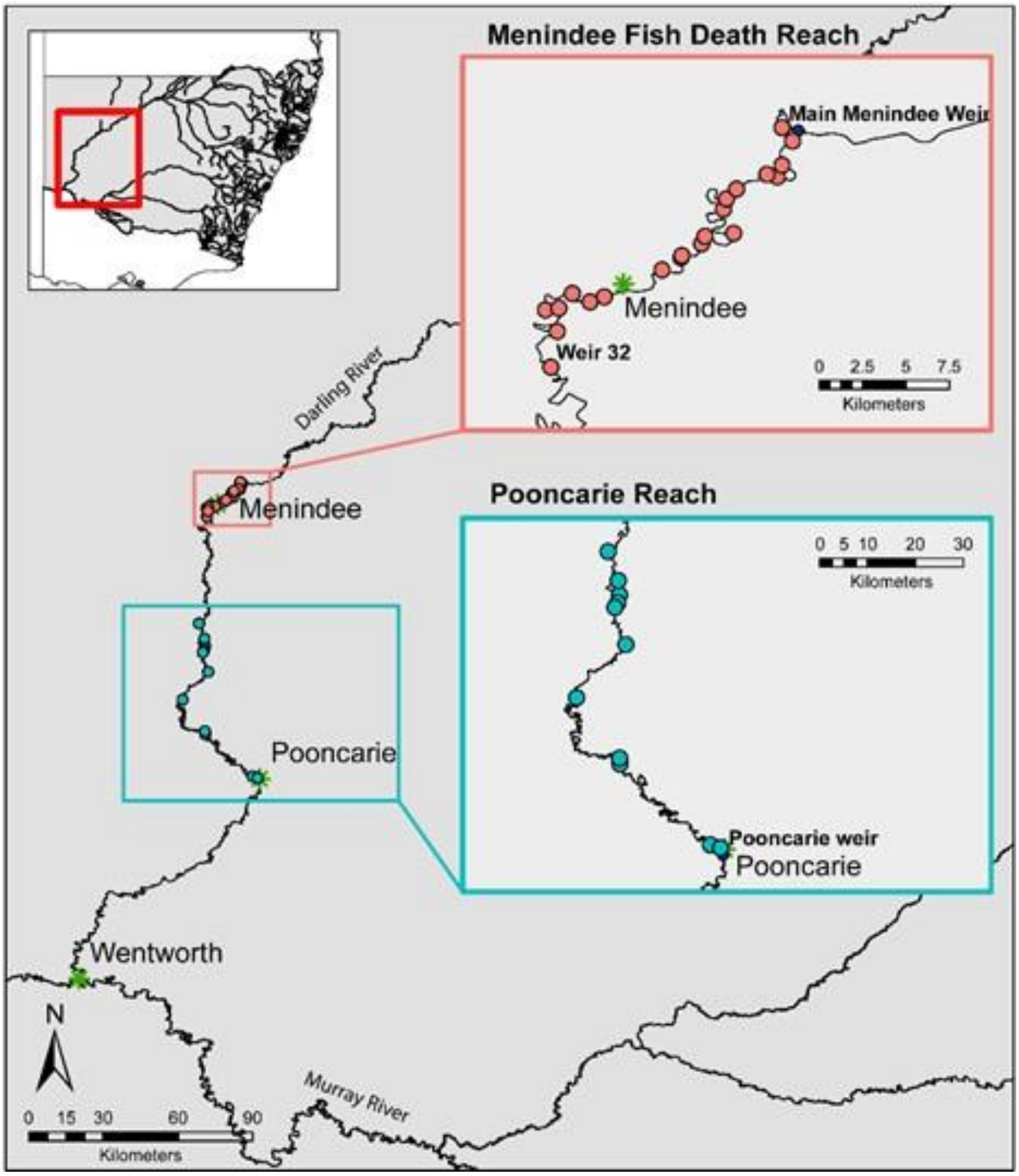

Figure 29. Sites within the Menindee Fish Death Reach and Pooncarie Reach at which fish community sampling was conducted in the LDBR between June 2019 and June 2021. Green asterisks indicate towns.

Reach comparison six months post Menindee fish kills (June 2019, Round 1)

In June 2019 electrofishing surveys were conducted at seven (7) sites within each reach, six months after the Menindee fish kills. Significantly lower abundances of Murray Cod, Bony Herring, Carp Gudgeon and introduced (pest) Goldfish were captured within the Menindee weir pool compared to surveys conducted at the same time in the LDBR between Weir 32 and Pooncarie (Figure 30). Only two (2) Murray Cod and one (1) Silver Perch were detected in the Menindee Weir pool in the June 2019 surveys, whereas 81 Murray Cod and four (4) Silver Perch were detected in the Pooncarie Reach with the same sampling effort. Carp abundance was also lower in the Menindee Weir pool, although the difference was not statistically significant. Fish kill investigations by DPI Fisheries noted that relatively few Carp had died during the Menindee fish kills, likely due to their high tolerance of low DO concentrations. The small-bodied native species Australian Smelt also showed no difference in abundance between the two (2) reaches in June 2019. This species is likely to have largely survived the fish kills by occupying the thin layer of aerated water at the surface of the river.

There was no obvious or significant difference in Golden Perch abundance between the two (2) reaches (101 individuals sampled in the Menindee Weir Pool compared to 107 in the Pooncarie Reach) despite the deaths of thousands of Golden Perch during the Menindee fish kills. This is likely because high numbers of Golden Perch were present in the Menindee Weir pool prior to the fish kills due to their tendency to migrate upstream but lack of fish passage from the Weir pool up to Lake Wetherell.

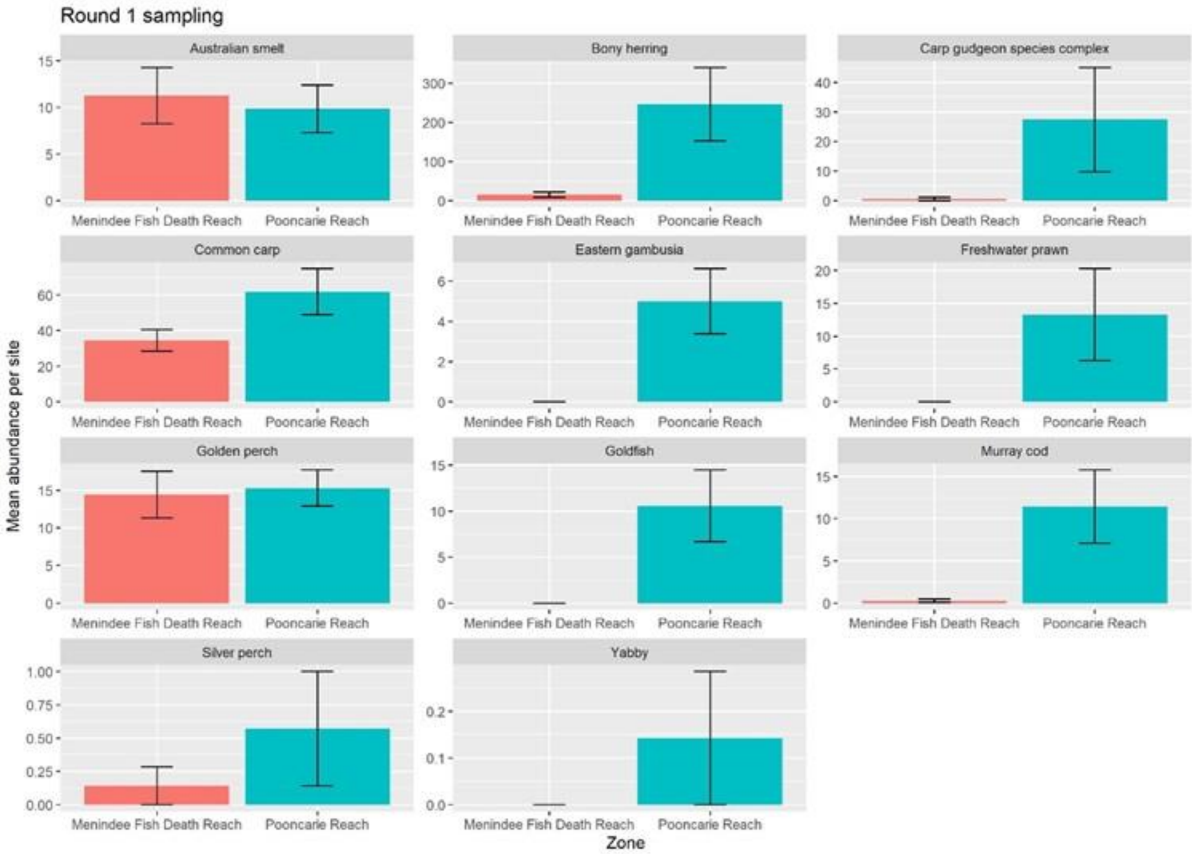

Figure 30. Mean abundance per site in the Menindee Fish Death Reach and Pooncarie Reach during Round 1 of sampling (June 2019, six months after the initial Menindee fish kills).

Menindee weir pool monitoring Rounds 1-4 (June 2019, October 2019, June 2020 and June 2021)

The abundance of Australian Smelt and Bony Herring in the Menindee weir pool decreased between Rounds 1 and 2, suggesting low breeding/recruitment after the Menindee fish kills, likely a result of conditions in the Menindee weir pool deteriorating through 2019 (Figure 28). Abundances of both species increased through Rounds 3 and 4 indicating some population recovery following the return of flow to the LDBR. For Bony Herring, this increase in abundance was primarily driven by juvenile fish (40-100mm) after flow returned in March 2020 (Figure 29). Abundances of Freshwater Shrimp and Yabbies in the Menindee weir pool also indicated some recovery from Rounds 2-4 after being absent in monitoring results during Round 1. Australian Smelt, Bony Herring, Freshwater Shrimp and Yabbies are all important food sources for larger bodied fish species and piscivorous birds.

No significant improvement in abundance has been detected for Murray Cod, or Silver Perch within the Menindee weir pool up to 2.5 years months following the fish kills (i.e. between Rounds 1 to 4) (Figure 31). Although no significant increase in the abundance of Golden Perch has been identified, Round 4 monitoring detected the presence of multiple juvenile size classes (100-200mm) in the Menindee Weir pool representing young-of-year and 1+ recruits (Figure 32). These juvenile Golden Perch are likely to be the result of spawning by adults upstream in the Barwon-Darling and its tributaries in response to flow events in early 2020 and again in early 2021. After flows returned throughout the Darling River in March 2020, the resulting young then drifted downstream with many reaching the productive nursery habitat offered by the Menindee Lakes.

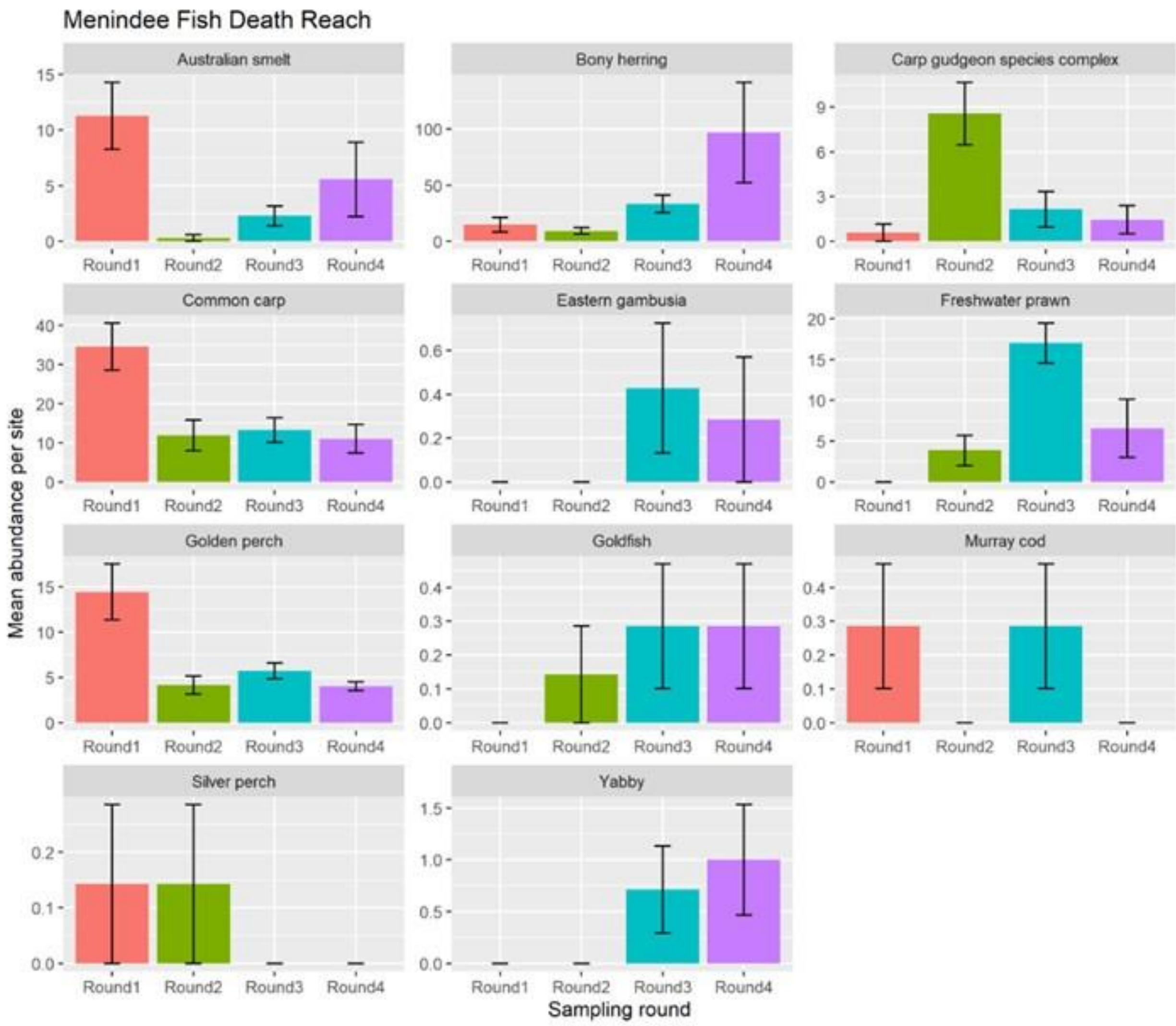

Figure 31. Mean abundances per site in the Menindee Fish Death Reach during Round 1 (six months after fish kills), Round 2 (eight months after fish kills) Round 3 (18 months after fish kills) and Round 4 (30 months after the Menindee fish kills).

Pooncarie Reach monitoring Rounds 1 to 4 (June 2019, October 2019, June 2020 and June 2021)

Wide scale fish kills occurred throughout the LDB downstream of Weir 32 between June 2019 and March 2020 as disconnected refuge pools contracted, and water quality deteriorated. Based on fish kill reports by DPI Fisheries we estimate thousands (1,000s) of Murray Cod were likely to have died in drying pools between Menindee and Ashvale. Few Golden Perch or Silver Perch were reported dead during 2019; however, this may be a result of dead individuals sinking or being removed by predators. Thus, we are unable to estimate the scale of deaths for these species, but it is also likely to be in the tens of thousands (10,000s). Hundreds to thousands of carp were also likely to have perished. Consequently, monitoring in the Pooncarie reach showed significant reductions in the abundance of Golden Perch, Bony Herring, Carp, and Carp Gudgeon between Rounds 1 and 3 (June 2019 and June 2020) (Figure 29). According to historical DPI Fisheries databases, the June 2020 monitoring recorded the lowest abundance of golden perch and bony herring since 2004 in the Lower Darling system.

Fish community surveys were again repeated in June 2021 (Round 4). Preliminary assessment of the results from these surveys indicated some recovery for all native fish species (except Silver Perch) between rounds 3 and 4 (June 2020 and June 2021) (Figure 32). Recovery of the Yabby population is not clear, although sample sizes are low, and electrofishing is typically not an effective way to sample Yabbies.

For Bony Herring, an increase in abundance was again (as in the Menindee weir pool) driven by juvenile fish (40-100mm in length) after flow returned in March 2020 (Figure 33). The recovery in populations of larger long-lived native species (i.e. Golden Perch, Murray Cod) in the Pooncarie reach was also driven by juvenile cohorts estimated to be 0+ and 1+ age classes (~40-150mm and ~60-200mm size classes respectively) (Figure 30). This result indicates some level of local breeding and recruitment success by Murray Cod since flow returned to the LDBR in March 2020, as well as dispersal of juvenile Golden Perch from the Menindee Lakes that were detected following inflows to the lakes in early 2020 and again in 2021. The flow events in the Northern Basin that ultimately contributed to both inflow events appear to have induced spawning by adult Golden Perch across multiple events in the Northern Basin (see next section). Targeted use of environmental water in the LDBR during 2020-21 has undoubtably contributed to the recovery in native fish in the Pooncarie reach.

The Round 4 results indicated the populations of pest fish (Common Carp, Goldfish and Eastern Gambusia) are yet to recover in the same manner as most native species (Figure 29). Whilst this is a positive outcome, we acknowledge these species are likely to gradually increase in abundance overtime.

Future monitoring results will inform the adaptive development and implementation of on-ground fish recovery activities (including, potential delivery of water for the environment and water management in 2020/21, restocking efforts, and habitat rehabilitation activities). Annual condition monitoring of the fish community in the LDBR will be critical in assessing recovery of the fish community in coming years (supported by operational or releases of water for the environment, or complementary recovery efforts), and will serve as a baseline record to which impacts/benefits resulting from future changes to water management or infrastructure in the system can be compared.

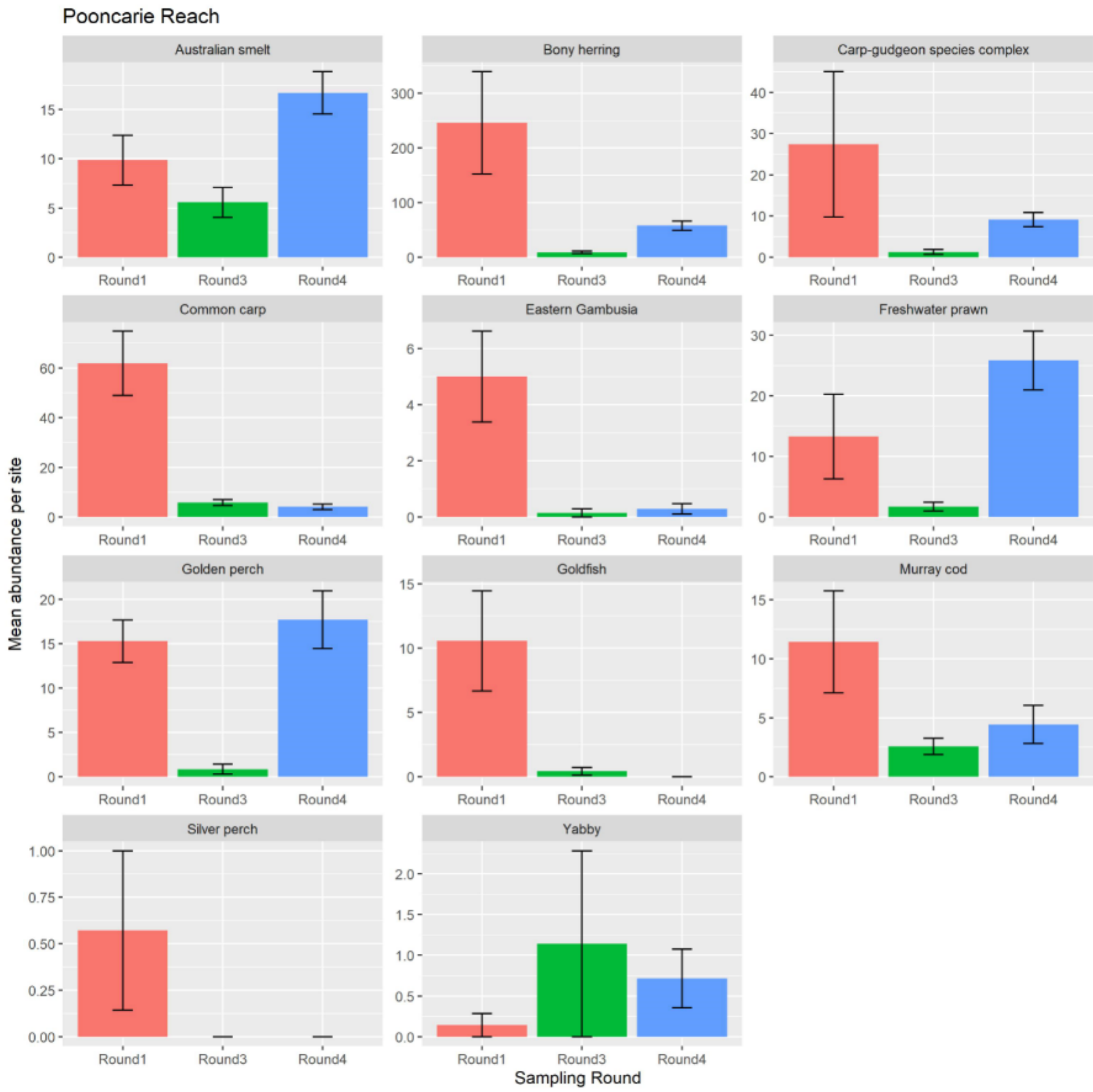

Figure 32. Mean abundance per site in the Pooncarie Reach during Rounds 1 and 3 of sampling (June 2019 and June 2020).

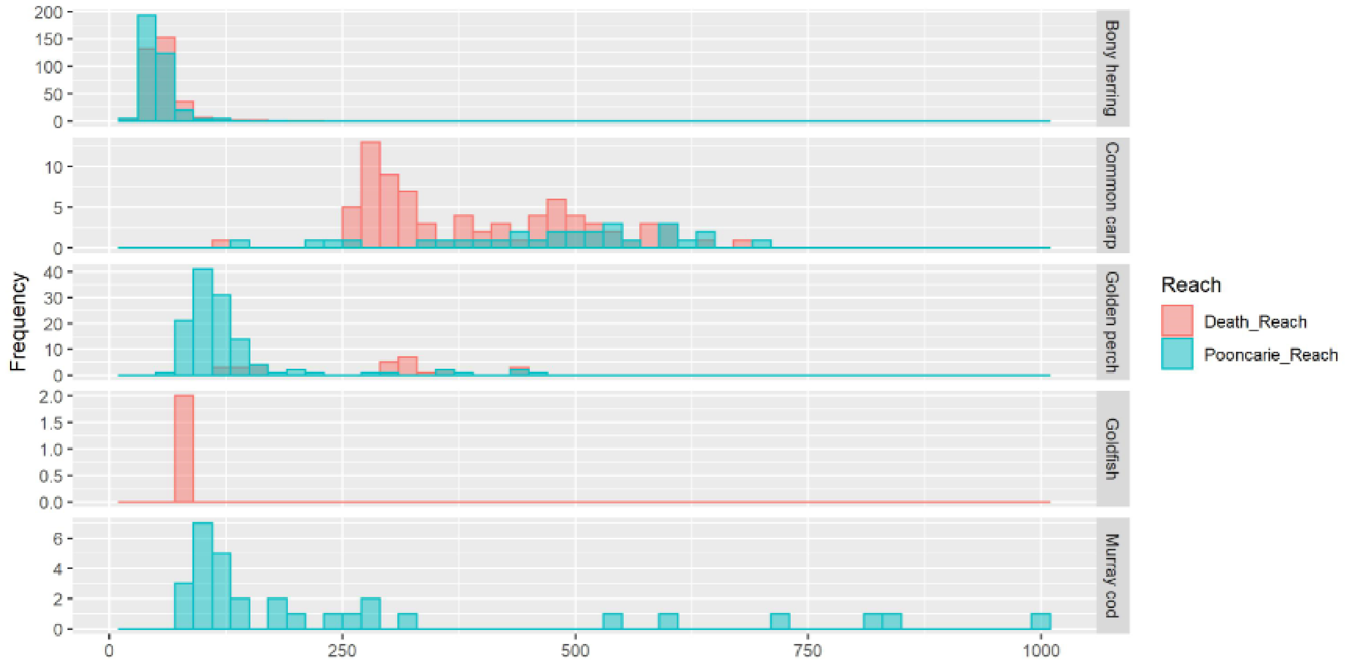

Figure 33. Length frequency plots for Golden perch and Bony Herring sampled in the Menindee Weir pool in June 2021 showing the presence of juvenile fish.

Golden Perch spawning and recruitment in the Darling-Baaka River

The northern Murray-Darling Basin (NMDB), includes half of the MDB comprising the mainstem Barwon-Darling River upstream of the Menindee Lakes System and its tributary inputs[3], comprises a unique native fish community supported by a diversity of aquatic habitats. While there are many perennial systems in the NMBD, these habitats are characterised by extreme climatic variability and associated hydrology. A changing climate in combination with extensive river regulation, water diversion and water extraction has exacerbated deteriorating ecosystem function across the region, primarily through reductions in the volume and frequency of inflows from tributaries into the mainstem Barwon-Darling River. From 2017-2019, minimal rainfall and inflows resulted in extended cease-to-flow events leading to disconnection of riverine habitats, drying of floodplains and wetlands, contraction of refuge pools, and drought-related fish kills.

Following heavy rainfall in parts of northern NSW and southern QLD in January and February 2020, and the associated increased inflows, the NSW Government initiated policy (section 324) and management actions to protect flows as they moved through the NMDB. Termed the 'Northern Basin First Flush', this event was predicted to provide numerous ecosystem benefits to a river system under extreme stress. Concurrent with the first flush, we undertook sampling for larval fish at nine (9) tributary and mainstem Barwon-Darling sites during March 2020, with the aim to determine which native fish species spawned in response to these protected flows and the spatial extent of this response.

Drift nets were deployed to sample early life-history fishes at three (3) tributary sites in the lower Moonie, Culgoa and Warrego rivers, as well as six (6) mainstem sites spanning over 1600 km along the Barwon-Darling River from downstream of Mungindi to upstream of the Menindee Lakes. There were eight (8) species of larval fish sampled in the study. This included six (6) native species (Australian smelt, *Retropinna semoni*; bony herring*, Nematalosa erebi*; carp gudgeon, *Hypseleotris* spp.*;* golden perch, spangled perch, *Leiopotherapon unicolor*; un-speckled hardyhead, *Craterocephalus stercusmuscarum fulvus*) and two (2) introduced species (common carp, *Cyprinus carpio;* eastern gambusia, *Gambusia holbrooki*). Golden perch larvae and juveniles were the most abundant species sampled and were captured at all sites *(n* = 2772). Daily ageing of golden perch was undertaken using otoliths (ear bones) to determine spawning dates and location-specific growth rates from 252 individuals, representing all sites and approximately 10% of the total catch.

The size distribution and estimated daily age of golden perch was indicative of both mainstem and tributary spawning during the first flush event. The mismatch between estimated spawning dates and river hydrology at some of the capture locations suggested that there was substantial

[3]. Major tributaries include the Macquarie, Namoi, Gwydir, Castlereagh, Macintyre and Condamine-Balonne rivers flowing from the east and the Moonie, Culgoa, Warrego and Paroo rivers originating in the north.

flow-assisted dispersal from spawning locations, although this was site-specific. For example, golden perch captured from the Barwon River near Walgett were estimated to range from 7-21 days old, with all hatch dates coinciding with high river discharge (**Error! Reference source not found.**) . In comparison, golden perch captured in flowing water habitats immediately upstream of Menindee Lakes were estimated to range from 1-82 days of age, with the hatch dates of many individuals corresponding to cease-to-flow conditions at this site suggesting substantial downstream dispersal in combination with localised spawning. Early life growth rates were highest at tributary sites (particularly in the Moonie River) in comparison to mainstem sites. Within mainstem sites, golden perch grew faster at sites in the upper reaches (Barwon River) in comparison to lower reaches (Darling River).

The present study provides an insight into the short-term environmental benefit from the first flush protection order enacted in 2020 across the NMDB. The importance of riverine flows for golden perch production includes spawning, transport and nursery functions. The contribution of young-of-the-year to in-channel and off-channel waterbodies (e.g. the Menindee Lakes) and water delivery to provide connectivity between nurseries and adult habitat should be considered in future research and management attention. The absence of silver perch is of notable concern given the tendency of that species to also drift as eggs, larvae and early juvenile phases of development.

Despite the current survey only sampling a single flow event, it demonstrated the large spatial scale that golden perch can respond to during increased discharge in terms of spawning locations and dispersal of drifting young. The results extend those presented in a previous analysis of a 2016-17 flow event in the region (Stuart and Sharpe 2020), with the addition of multiple tributary and mainstem spawning locations, including a likely combination of localised spawning and substantial downstream transport contributing to the Menindee Lakes nursery. A combination of natural flows associated with floods, releases of water for the environment, and the protection of natural flows, connectivity and hydraulic diversity relating to moderate rainfall events (e.g. early 2020) is required to restore conditions that support the flow related ecology of the fish assemblage and golden perch specifically in the Darling River catchment.

Restarting rivers guidelines (including LDBR case studies)

When water does begin to flow into dry river channels, or across the isolated floodplains, it can lead to risks of fish deaths downstream. Using the LDBR as a case study, DPI Fisheries contracted Dr Darren Baldwin from Rivers and Wetlands (Environmental consultancy) to document the information necessary for natural resource managers, water managers and river operators to understand:

- The risks to native fauna posed from restarting rivers
- The factors that increase those risks
- Potential management interventions to mitigate those risks; and
- Planning steps to undertake prior to river restarts.

The outputs include a report (Baldwin 2021), and decision support tool which is available online here: http://www.riversandwetlands.com.au/managing-river-re-starts/

Environmental flow delivery in the LDBR

After a prolonged period of no flow, the LDBR resumed flowing in early 2020 (Figure 34). This subsequently provided an opportunity to release environmental water into the LDBR from mid-September 2020 until mid-January 2021 to help boost the health of the river and support recovery of native fish after years of dry conditions. Environmental water was added to operational base flows to achieve a flow rate of approximately 400 ML at Weir 32 to coincide with the spring Murray Cod nesting and spawning season in 2020. After spawning by Murray Cod had been confirmed by DPI Fisheries monitoring, increased environmental water delivery was used to generate a brief pulse in late November to support survival and development of resulting Murray Cod juveniles, by inundating river benches and backwaters which in turn creates habitat and food sources for early life stages. The flow delivery was developed and supported with the co-operation of the community and collaboration and support of water delivery partners including the Commonwealth Environmental Water Office (CEWO), NSW Department of Planning, Industry and Environment, Energy and Science division (NSW DPIE EES), DPI Fisheries, NSW National Parks and Wildlife Service (NSW NPWS), the Arthur Rylah Institute (ARI - Victoria), WaterNSW and the MDBA.

The increased flows in spring-summer of 2020/21 were intended to support movement and (potentially) spawning by adult Golden Perch and Silver Perch in the LDBR, whilst Freshwater Shrimp, Mussels, and smaller native fish were also expected to benefit from the enhanced flows. Additionally, the releases of environmental water to the LDBR would also aid the dispersal of juvenile Golden Perch, that spawned in the Northern Basin and subsequently transported downstream during the earlier 2020 flow events, from the Menindee Lakes to the LDBR and Murray River.

Figure 34. Flow delivery to the LDBR in 2020-21, with period of flow enhancement through release of water for the environment in green.

Real-time monitoring by DPI Fisheries, before, during and after the environmental water release was conducted to assess the responses and outcomes for native fish. While the overall population of Murray Cod in the LDBR was low in 2020 (due to the impacts of fish deaths and cease-to-flow conditions) monitoring during delivery of the spring flows detected strong numbers of larval Murray Cod, indicating that the environmental water release has supported spawning. Juvenile Golden Perch were also detected during monitoring downstream of Weir 32, suggesting potential local spawning and dispersal of juveniles (from above Menindee Main Weir) was supported by the elevated flow period (Figure 35).

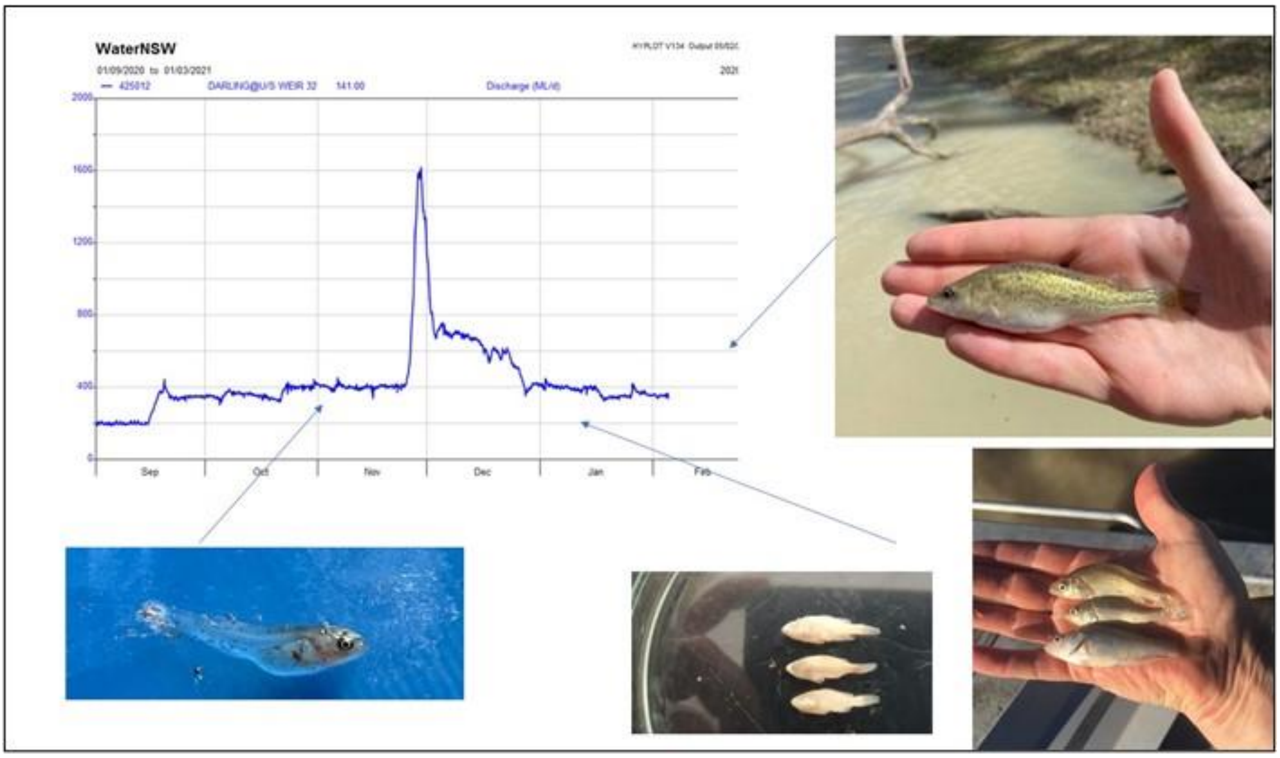

Figure 35. Monitoring by DPI Fisheries during managed release of water for the environment to the LDBR in 2020-21 detected good spawning response by Murray Cod, and dispersal of juvenile Golden Perch from the Menindee Lakes into the LDBR.

Wrap up

Fish communities throughout the Murray-Darling Basin have suffered a series of significant fish kill events in recent decades, culminating in the mass deaths of millions of native fish in the LDBR from 2018 through to 2020. The fish kills were linked to prolonged low flow or cease to flow conditions and extreme temperatures in which habitat condition and water quality deteriorated to lethal levels.

The scale of these events was unprecedented, and in the lead up to the 2019/20 summer season, NSW DPI held further concerns for fish deaths as a continuation of the dry and very low flow conditions persisted across the LDBR and broader MDB. Our objective was quite simple – to protect as many native fish as possible across priority reaches of the NSW MDB. Using the lessons learned from the past, including from the 2018/19 summer, emergency management efforts were focused on supporting priority refuge populations to enhance recovery when conditions improved.

DPI Fisheries developed the NSW Native Fish Drought Response program to help protect native fish stocks. The work focused on planning, preparedness, response and ultimately recovery activities, with efforts including:

- Formation of valley based technical advisory groups (VTAGs) to involve local experts in forming recommendations and decision making
- Monitoring activities, including water quality and fish community impacts
- The rescue and relocation of native fish, with a focus on threatened species
- Artificial aeration and water mixing in key reaches
- The targeted delivery of environmental water (where available)
- Fishing closures around artificial aerators.

Activities undertaken in the LDBR were central to the Native Fish Drought Response program, with DPI Fisheries working closely with local experts, First Nations communities, local communities and recreational anglers to complete appropriate actions at a significant spatial scale under extremely compressed timeframes that informed similar work in other valleys. The public's interest and involvement in the work was immense. In addition to helping with on-ground actions, many people engaged with DPI Fisheries staff across the LDBR and broader state, including through Drought Information sessions in the Northern Basin and the DPI Drought Bus, which toured throughout the State and was present at Menindee in October 2019.

The arrival of some much-needed rain in early 2020 and in early 2021 across parts of north-west NSW and southern Queensland gave native fish some reprieve, with many systems experiencing a resumption of flow. Significant in-flows were received in the Border Rivers, Peel, Namoi, Gwydir and Macquarie valleys and subsequently into the Barwon-Darling and LDBR. These flows did bring with them their own challenges for fish, with organic material loads impacting water quality during the initial flushes. However, the inflows resulted in connected systems across the Northern Basin, including along the Barwon-Darling and LDBR. These inflows into the Menindee Lakes and ultimately the re-connection to the Murray River, provided significant spawning, recruitment and dispersal opportunities for native fish.

The path to recovery will be long and will require action from communities and governments at a local and Basin-wide scale. Our actions under the Drought Response Program have focused on limiting the impact of immediate threats, however the more systemic issues that have impacted native fish populations remain. Meeting these challenges through strategic investment that operates at appropriate timeframes and scales will ultimately decide the fate of our native fish populations.

The work done over the 2019/20 summer across inland NSW will help inform and refine our future response to extreme events. Central to this has been the support of volunteers and the communities that partnered with us to achieve some fantastic outcomes for fish. With recent rainfall and improved medium-term forecasts for rainfall and inflows, we have been presented with an opportunity to be active participants in the recovery of native fish populations across the LDBR and broader Murray-Darling Basin.

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