June 14, 2023

Professor Hugh Durrant-Whyte
Office of the Chief Scientist and Engineer

Re: Proximate cause of the fish deaths In Weir 32 weir pool (Menindee) in March 2023

Dear Professor Durrant-Whyte

I am an aquatic biogeochemist and Principal of *Rivers and wetlands*[1] (see www.riversandwetlands.com.au for further information - including a current list of my publications). In late March I was engaged by the Murray-Darling Basin Authority (MDBA) to assist the NSW Department of Planning and Environment (DPE) with the ongoing management of water quality in Weir 32 weir pool following the fish deaths in the Darling-Baaka River[2]. The MDBA was particularly interested in the proximate cause of the fish deaths. With the MDBA's permission I have attached my initial report to them on the results of that enquiry (see File Note to the MDBA dated March 30, 2023, attached; noting that this is not the official position of the Murray-Darling Basin Authority or the NSW Department of Planning and Environment, nor have either organisation have had any editorial input into that report).

In brief, in my opinion, based on the available data, it is not possible to unequivocally assign a proximate cause to the fish deaths in Weir 32 weir pool in March 32. However, based on the data that is available, it highly likely that the fish died of hypoxia caused by the high biomass of both fish and algae in the weir pool at the time of death, coupled with a decrease of inflows of water (and more importantly, the entrained oxygen) from upstream sources. There is no evidence that the fish deaths in March were caused by inflows (either directly or indirectly) from Lake Wetherell into Weir 32 weir pool (see File Note to DPE titled "A critical evaluation of Williams and Schultz (2023)" dated April 12, 2023; attached - submitted with permission of DPE).

After on-going involvement with the management of water quality in Weir 32 following the fish deaths, my initial assessment of the fish deaths has only been reinforced. It has also given me the opportunity to reflect on the conditions in Weir 32, and why fish deaths in this particular stretch of the Darling-Baaka occur. I have summarised my reflections in the attached document (File Note to you, Dated June 12, 2023; noting again that this is my opinion and not the official position of the MDBA or the DPE, nor have either organisation had any editorial input into that report).

I am happy to expand on the points raised in the attached documents at interview if required.

Sincerely

Prof. Darren Baldwin
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[1] I am also an Adjunct Research Professor in the School of Agricultural, Environmental and Veterinary Sciences at Charles Sturt University.
[2] Up until March 30, after which time the contract has been with DPE.

File Note[1]

Subject: A preliminary assessment the of the sequence of events that led to the massive fish kill in Weir 32 weir pool (Menindee) on 16 -17 March 2023

Attention: Dr Janet Prichard - Murray-Darling Basin Authority
Dr Asitha Katupitiya - Murray-Darling Basin Authority

CC: Allan Raine - NSW Department of Planning and Environment
Cameron Lay - NSW Department of Primary Industries (Fisheries)

From: Darren Baldwin, *Rivers and Wetlands*

Date: March 30, 2023

1. Purpose

On March 16-17 there was a massive fish kill in the Weir 32 weir pool, mostly focussed upstream of the town of Menindee - with an estimated 20 million dead fish. *Rivers and Wetlands* was engaged by the Murray Darling Basin Authority to assist NSW Departments of Planning and Environment and Department of Primary Industry in the on-going management of the situation to help minimise the risk of future fish kills. In doing so, an ancillary task was to develop credible hypothesis/hypotheses on the proximate cause(s) of the fish kill that is consistent with all available data. This File Note is a preliminary assessment of the likely cause of the fish kills - or more properly, the sequence of events that led to the fish deaths. It is based on incomplete data[2] and, only the most salient points/calculations are covered. [3,4] If required, this File Note can be expanded into a more detailed report.

2. Synopsis

Given the available data it is not possible to unequivocally assign a definitive cause to the fish kill in mid-March 2023 at Menindee on the Darling River. The fish kill was most likely caused because of

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[2] For example, at the time of writing pesticide and herbicide data wasn't available.

[3] An understanding of key limnological processes, especially with respect to the cycling of oxygen in aquatic ecosystems is assumed.

[4] For example, this file note doesn't go to the question why there was such as a high biomass of fish in Weir 32 weir pool, only that they were there.

hypoxia. After discounting a number of potential causes for the hypoxia, the most credible sequence of events that lead to the fish kill are:

1. During February 2023, water with potentially low dissolved oxygen concentrations was being released into the top of Weir 32 weir pool directly from Lake Wetherell.[5] Furthermore, water from Lake Wetherell was also diverted into Lake Pamamaroo through the Lake Pamamaroo inlet. Because of the close proximity of the inlet to the outlet of Lake Pamamaroo, some of the water from Lake Wetherell was short-circuiting Lake Pamamaroo and entering the top end of Weir 32 weir pool. Fish deaths were recorded in Weir 32 weir pool at the time (The Guardian, February 23, 2023).
2. On February 25 the Lake Pamamaroo Inlet was closed and, by March 1 the Lake Wetherell Outlet was also essentially closed. This meant that the only water now entering the top end of Weir 32 weir pool was entering from Lake Pamamaroo (approximately 4300ML/day on March 1). This water was well oxygenated.
3. It is conjecture, but it is likely that the better water quality attracted fish, particularly bony bream, to the top end of Weir 32 weir pool during the oxygenated inflows (the Pied Piper effect). The large biomass of fish at the top end of Weir 32 weir pool was being sustained in a large part through oxygen in the outlet water from Lake Pamamaroo.
4. Outflow from Lake Pamamaroo to Weir 32 weir pool was slowly reduced starting on March 6. By March 16 flows from Lake Pamamaroo had reduced to 1250 ML/day.
5. The algal biomass in Weir 32 weir pool was also increasing during this period, possibly helped by nutrient recycling by the large biomass of fish, which would have contributed to a night time sag in oxygen levels
6. It is hypothesised that on the night of March 16 the combined respiratory load of the large biomass of fish and algae consumed all, or almost all, of the oxygen in the water column - resulting in the massive fish kill.

The fish kill has the hallmarks of a 'Black Swan' event (*sensu* Taleb, 2007)

3. Details

3.1 Discounting other potential causes of the fish kill.

3.1.1 Destratification:

The multiple fish kills that occurred in 2018/19 in weir 32 weir pool were likely caused by sequential destratification events that led to hypoxia throughout the water column (Baldwin 2019, Vertessy et al, 2019). Work by Mitrovic et al (2011) suggests that stratification of Weir 32 weir pool only occurs at flows less than about 350 ML/day. Flows into the top end of Weir 32 weir pool exceeded this threshold for the entire period of concern. Therefore, it is highly unlikely that stratification/destratification was involved in the March 2023 fish kill.

3.1.2 Recession of the 2022/23 Flood (a "classic" hypoxic event):

There was a large flood in the Darling River in 2022/23. Floods, particularly during the warmer months can lead to hypoxia and fish kills. However, as both the hydrograph and satellite imagery (Figure 1) shows, the flood pulse had clearly passed Menindee prior to the fish deaths. There is some evidence, again from satellite imagery (data not shown) that localised recession may have led to poor water in Lake Wetherell in March 2023, but by this time Lake Wetherell was essentially isolated from Weir 32 weir pool - discussed below.

[5] For approximate locations see Figure 2.

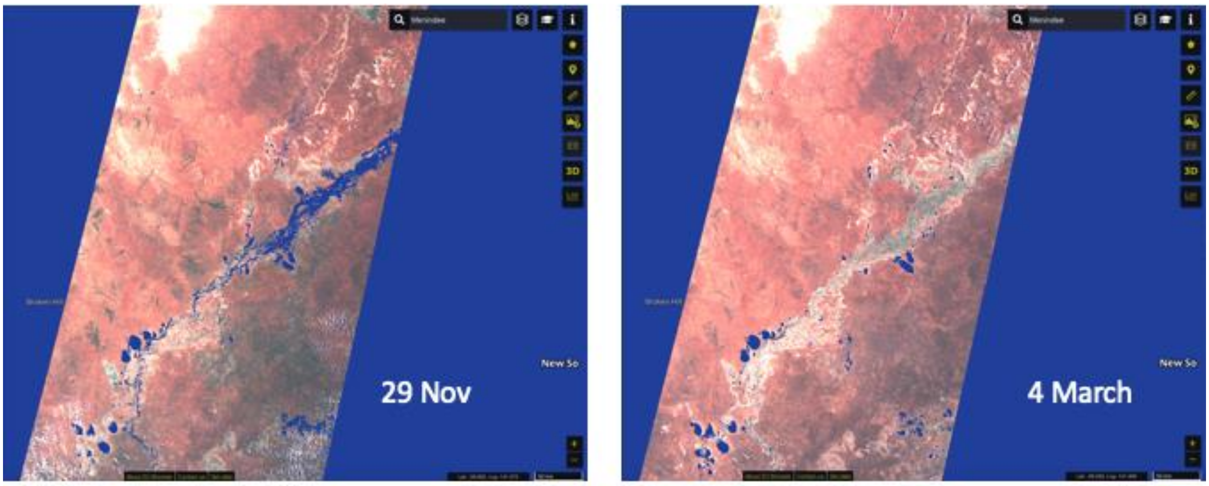

Figure 1: False colour Sentinel2 satellite imagery of the Darling River floodplain processed with the Water in Wetlands script (Willm et al, undated) highlighting water in blue.

3.1.3. Crash of an algal bloom:
During the 2018/19 fish kills at Menindee, media reports erroneously attributed the deaths to a crash in an algal bloom.[6] This idea has been previously shown to implausible (Baldwin, 2019).

Analysis of satellite imagery by Tracey Fulford (WaterNSW) using a custom script for algae (particularly cyanobacteria) has shown that algal biomass actually increased prior to the fish kill (data not shown but available on request). Fish that are detritivores and/or algal consuming species are good at recycling nutrients into the water column through ingestion and excretion. It is possible (but not proven) that the large volume of bony bream at the top end of Weir 32 weir pool may have contributed to the growth of algae.

3.1.4 Diurnal hypoxia caused by the algal bloom:
Algae produce oxygen during the day (through photosynthesis) and consume it at night. If there is sufficient algal biomass his can lead to transient hypoxia in the early hours of the morning prior to dawn. It is probable that this played a role in the fish kill in March 2023 (discussed below), but the observation that the fish kill was localised to the top end of Weir 32 weir pool, and not also in, say, Lake Wetherell (Figure 2) where there was extensive algal biomass, it was highly likely not to be the only factor.

[6] This zombie idea still persists.

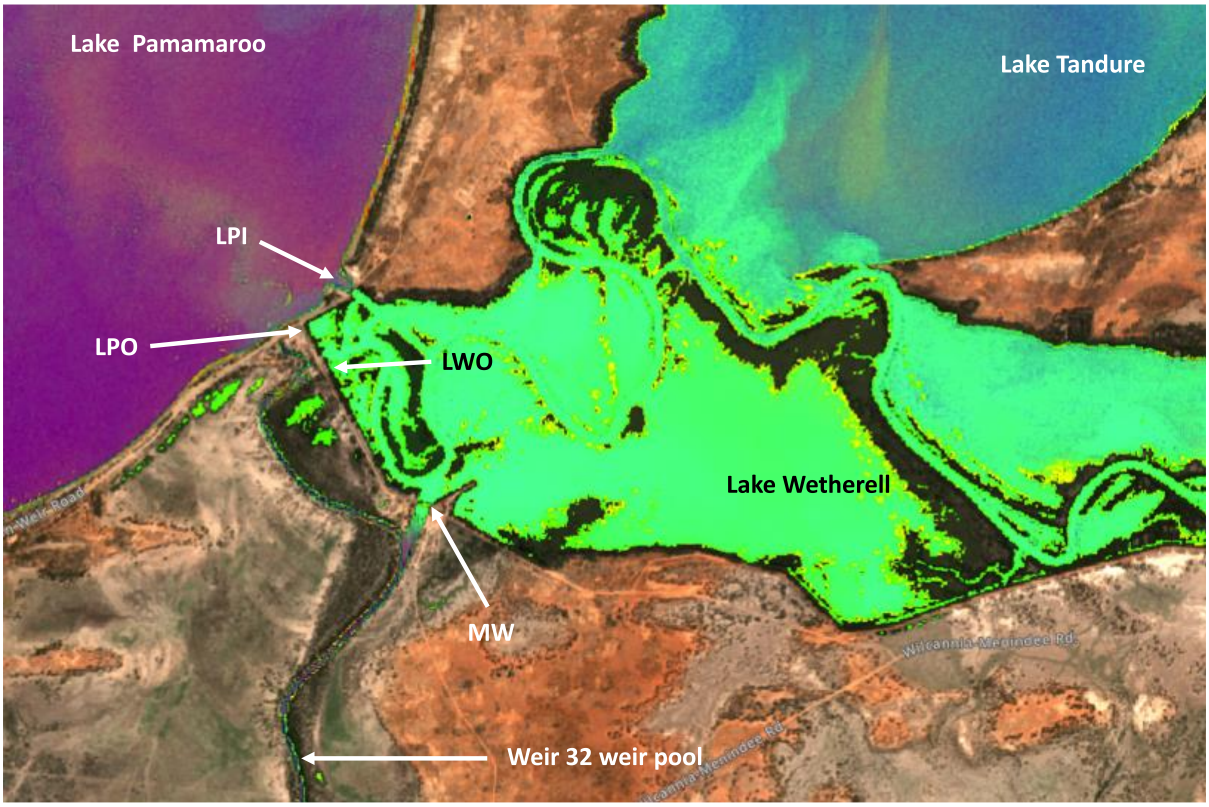

Figure 2: False colour Sentinel 2 satellite image of the bottom end of Lake Wetherell and the top end of weir 32 weir pool taken on March 14 processed with the APA script (Péliova et al, undated). Algal biomass is shown in green. MW = Main Weir; LPI = Lake Pamamaroo inlet; LPO = Lake Pamamaroo outlet; LWO = Lake Wetherell outlet.

3.1.5 Temperature:

Both the air and water temperatures were high in the area around Menindee during March. For example, water temperatures at Nellia Gaari in Lake Wetherell (Site 425060) reached above 29 ^{o}C in early March 2023 (Figure 3). At the time of the fish kill the water-temperature was still in the mid-to high 20's. Like algal biomass, the high water-temperature was probably a contributing factor to the fish kills, but because fish kills were not observed elsewhere at the same time, it was highly likely not to be the only factor. High water temperature:

- Stresses fish - the observed water temperatures are close to the putative lethal levels for some native fish
- Increases respiration - particularly microbial and algal respiration
- Decreases the solubility of oxygen in the water column.

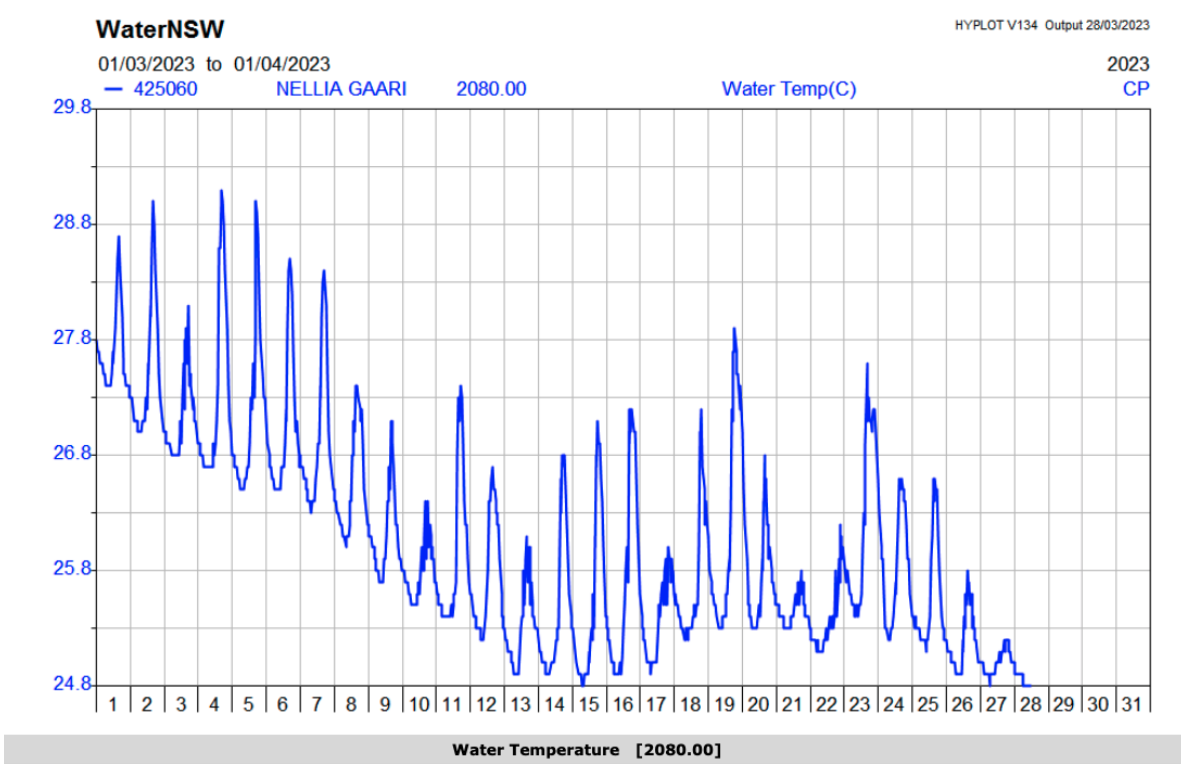

Figure 3: Temperature in Lake Wetherell at Nellia Gaari (Site 425060) during March 2023 (Image copyright the Crown in respect to New South Wales)

3.2. Factors that likely contributed to the fish kill

In the absence of any data to the contrary (e.g. pesticide analysis is pending) <u>the most likely cause of the fish deaths was hypoxia</u>. There is only sporadic information available so the following narrative is based on a certain degree of conjecture, speculation and approximate calculations (which I will highlight). However, the following scenario is the only plausible explanation that I can arrive at which fits all of the observations and available data. I propose that the hypoxia was caused by a combination of fish and algal respiration.

Professor Fran Sheldon, in an interview with The Guardian (The Guardian, March 23, 2023), was the first person to suggest that environmental respiration (particularly from the large fish biomass) could have contributed to the fish kill. So, the questions arise was there enough fish biomass to strip the oxygen out of the water column to the point where the fish died.

3.2.1 How much fish biomass was there?

The fish kill in March 2023 in Weir 32 weir pool was, for the most part, initially isolated to the region above Menindee township - it is approximately 20 km from Menindee to Main Weir. We don't actually know what the total fish biomass was in this reach immediately prior to the fish kill, but logically it would <u>at least</u> be equivalent to the biomass of fish that died during the event. Based on visual estimates (G. McCrabb and I. Ellis *pers. comm.*) somewhere in the order of 20 million fish died. Most were bony bream in the range of 20 - 100 g (wet weight). Therefore, assuming an average weight of the dead fish 50 g and assuming that the estimate of dead fish number is in the vicinity - then there were <u>at least</u> 1000 tonnes of fish in the approximately 20 km reach.

3.2.2 Could that large a fish biomass lead to hypoxia?

Our understanding of native fish physiology is less than ideal and, I was not able to locate respiration rates for bony bream. However, from Table 2 in Kepenyes and Varadi (1984) the average oxygen consumption for common inland aquaculture fish is 5200 ± 4100 mg O_2/kg/day (range from about 1000 - 10000 mg O_2/kg/day). Assuming a rate of 5000 mg O_2/kg/day, 1000 tonnes of fish would consume about 5×10^9 mg O_2/day. By contrast, at reasonable oxygen concentration (6 mg/L) a 20 km reach of water would contain about 1.8×10^{10} mg of O_2[7]. Therefore, in the absence of any other sources or sinks of oxygen in this reach then the oxygen in the reach would be consumed within about 3.5 days. Clearly, this is an absurd scenario as some oxygen would be replenished during the day, but it highlights the fact that this level of fish biomass would impose a substantial drawdown on the oxygen budget in the reach - especially if there is an algal bloom occurring at the same time. Although such a scenario seems unlikely the data presented below suggests that when conditions are less than ideal, as in the Weir 32 weir pool in March 2023, this biomass driven hypoxia is plausible.

There are other factors impacting on dissolved oxygen concentration in Weir 32 weir pool. There would have been reoxygenation coming from upstream flows (discussed later), photosynthesis, and exchange with the atmosphere; while deoxygenation could occur from sediment oxygen demand, and other sources of community respiration (including night time algal respiration). However, it is not possible to quantify these sources and sinks with the available information. At the time of the fish kill there were operating dissolved oxygen loggers located at Nellia Gaari (Site 425060) and upstream of Weir 32 (Site 425012). Neither accurately represent the conditions that occurred in Weir 32 upstream of Menindee township. Nellia Gaari is in Lake Wetherell, many river kilometres upstream of Weir 32 weir pool, while the oxygen concentration at the site upstream of Weir 32 was influenced by inflows from Lake Menindee. However, the dissolved oxygen concentrations at both indicate that oxygen levels in Weir 32 weir pool were likely compromised. Because of the algal bloom in Lake Wetherell, overnight dissolved oxygen concentrations at Nellia Gaari fell to about 1 mg/L through the first part of March (Figure 4), indicating night time respiration was placing pressure on oxygen levels. The diurnal signal was not as strong at the site upstream of Weir 32, but again, it was influenced by flows out of Lake Menindee (Figure 5).

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[7] Assuming an average depth of 3 metres and an average width of 50 metres

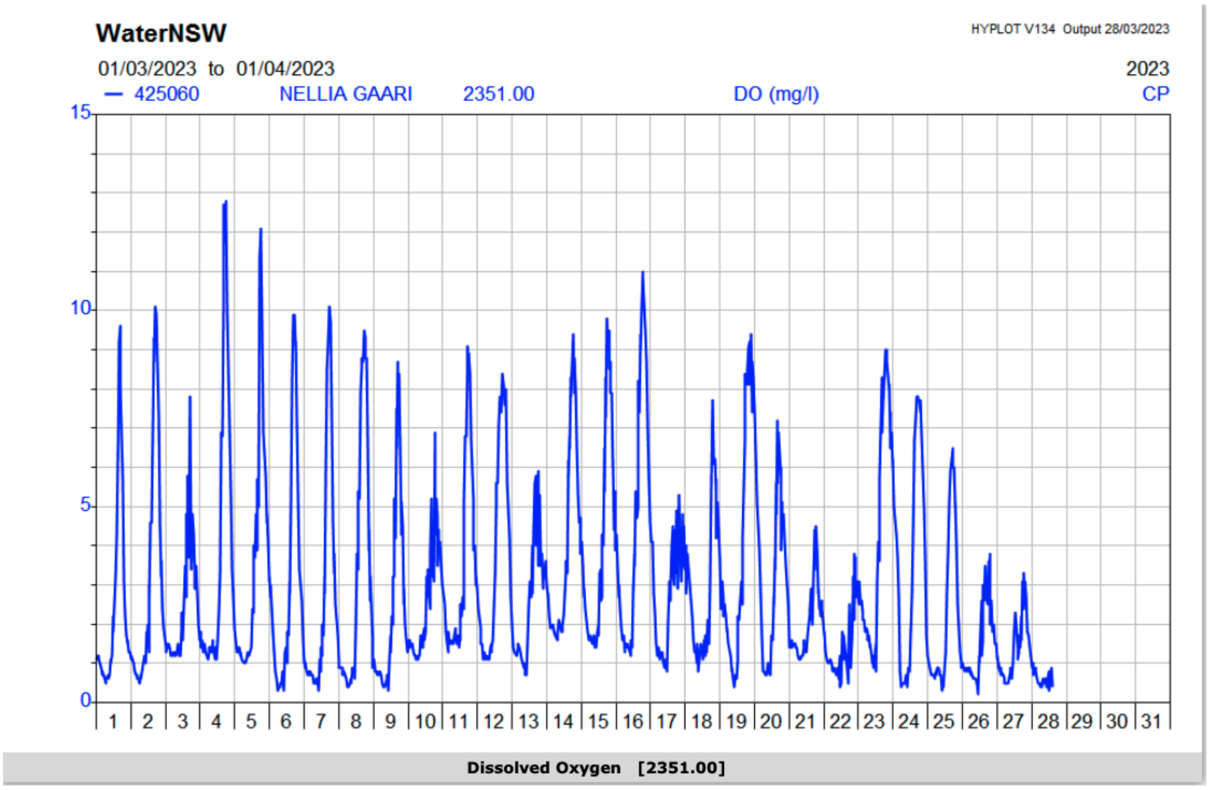


Figure 4: Dissolved oxygen concentration in Lake Wetherell at Nellia Gaari (Site 425012) during March 2023 (Image copyright the Crown in respect to New South Wales)

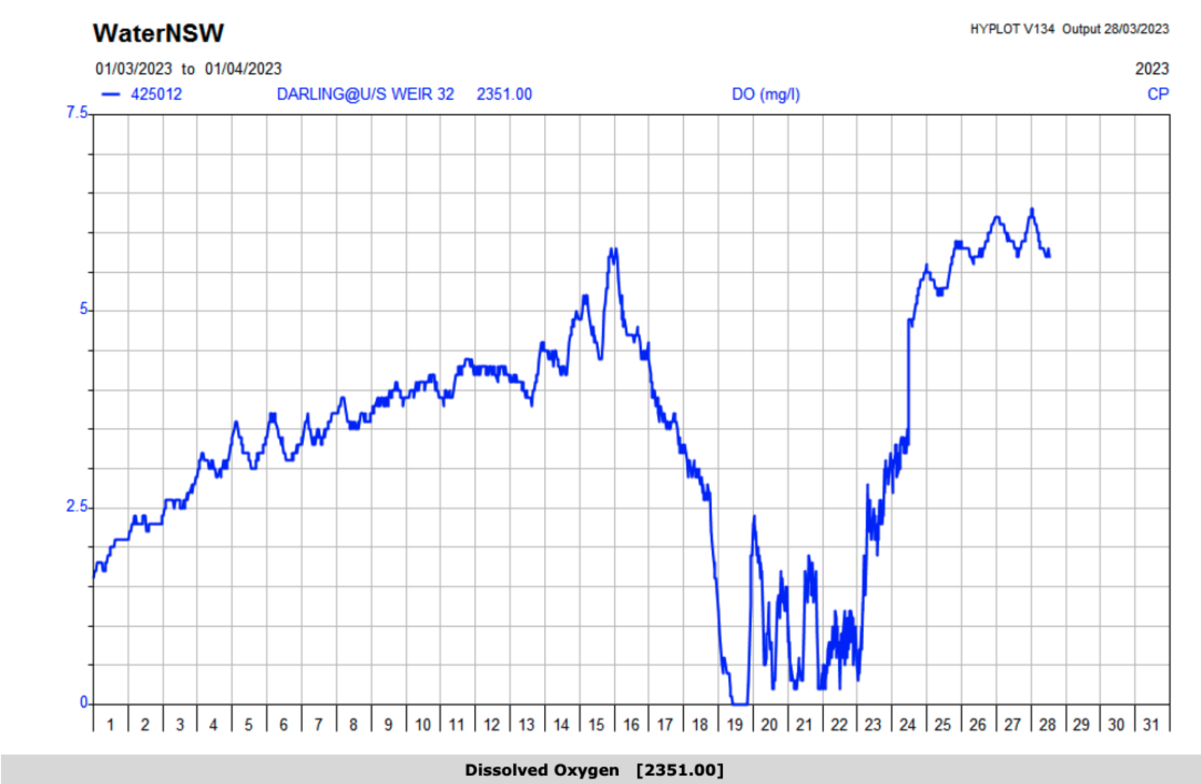


Figure 5: Dissolved oxygen concentration in Weir 32 weir pool, upstream of Weir 32 (Site 425060) during March 2023 (Image copyright the Crown in respect to New South Wales)

3.2.3 What was the impact of changing flows into Weir 32 weir pool from upstream sources?
Inflows into the top end of Weir 32 weir pool in February and March 2023, prior to the fish kill, can be divided into three distinct phases (Figure 6). In the first phase (until March 1) water was delivered to Weir 32 weir pool from Lake Wetherell through the Lake Wetherell Outlet (see Figure 2 for locations), and from the Lake Pamamaroo Outlet. However, satellite imagery shows that inflows from Lake Wetherell into Lake Pamamaroo that were occurring at the same time were being short circuited, with most of the flow from Lake Wetherell entering Weir 32 weir pool (Figure 8). In the second phase, from about March 1 until March 6 all the flows into the top end of Weir 32 weir pool essentially came from Lake Pamamaroo, at a constant rate of about 4000 to 4300 ML/day. In the 3rd phase, starting about March 6, the water entering the top-end of Weir 32 weir pool was still sourced only from Lake Pamamaroo, but the flow rate reduced in steps from about 4300 ML/day to 1250 ML/day by March 16. The fish kill likely occurred during the night of March 16/17.

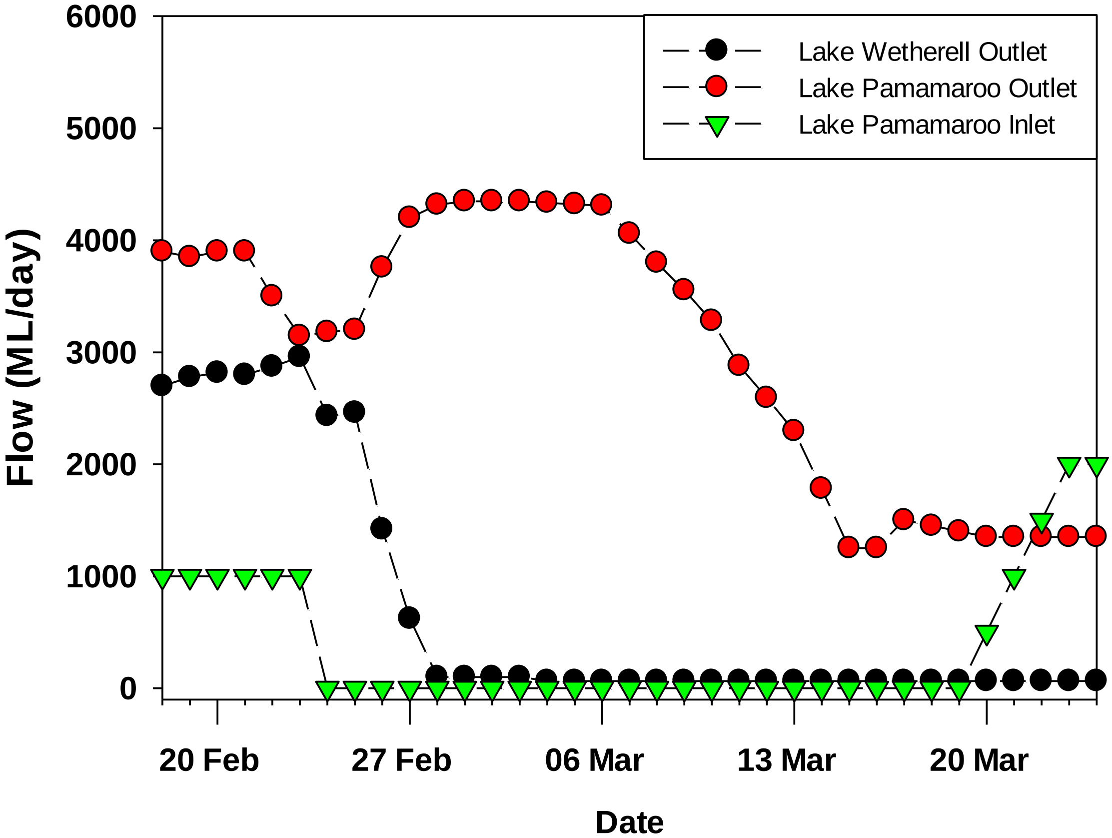


Figure 6: Flows from Lake Wetherell Outlet to Weir 32 weir pool (black circles), Lake Wetherell to Lake Pamamaroo through the Lake Pamamaroo Inlet (green triangles) and from Lake Pamamaroo to Weir 32 weir pool through the Lake Pamamaroo Outlet (red circles. for late February through March, 2023. (Data supplied by WaterNSW).

Flows from each of these phases have different implications for the fish kill. In the first phase water of unknown composition was entering into the top end of Weir 32 weir pool from Lake Wetherell - noting that fish kills were recorded in Lake Wetherell on both February 4 and 18-21 February, 2021 (DPI, 2023). During the second phase (and into the third phase) the water entering the top end of Weir 32 weir pool would likely be well oxygenated.[8] Although this cannot be confirmed, it is not beyond comprehension, that after being subjected to a period of potentially poor water quality fish, especially bony bream, would move upstream towards the better water quality, meaning the fish would be congregating toward the top end of Weir 32 weir pool (- a Pied Piper effect to coin a phrase). Finally, during the third phase the amount of water (and hence oxygen) was declining. If we assume that the dissolved oxygen concentration in the inflow from Lake Pamamaroo in the third phase was 6 mg/L, at the start of the phase, when flows were about 4300 ML/day, the inflows would be delivering about 2.6 x10^{10} mg of oxygen to the reach each day. At 1250ML/day, the inflow prior to the flows would be delivering 7.5 x10^{9} mg of oxygen to the reach each day. This is about the same amount of oxygen that the fish biomass was consuming each day.

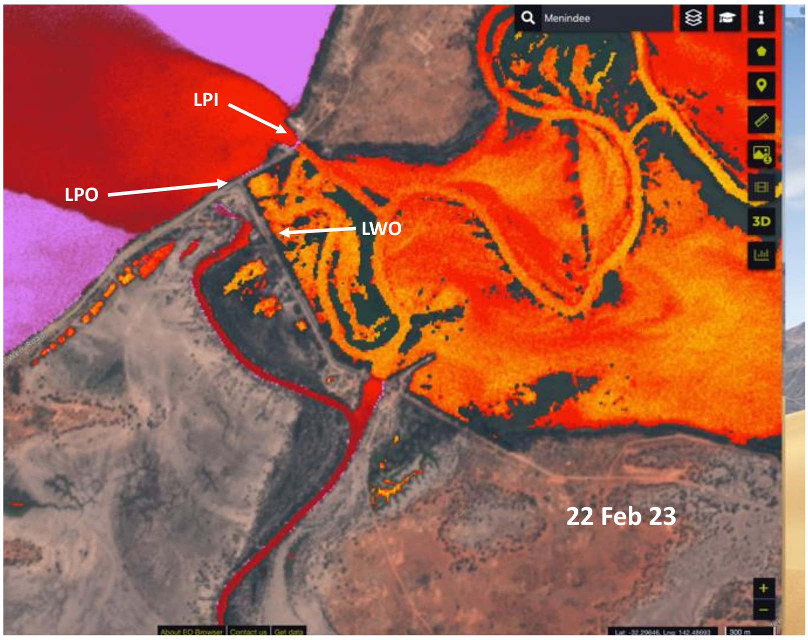


Figure 7: False-colour satellite image of Lake Wetherell, Lake Pamamaroo and Weir 32 weir pool taken on February 22 and processed with the Se2WaQ script (Sidónio and Pereira, undated) set to Parameter 4 (which optimises visualisation of both dissolved organic carbon as well as sediment). A clear plume of water can be seen exiting Lake Wetherell into lake Pamamaroo through the Lake Pamamaroo Inlet (LPI), but that plume also encroaches on the Lake Pamamaroo Outlet (LPO) indicating short circuiting.

[8] The latest data at time of writing was February 16,2023. At that time the dissolved oxygen concentration in the middle of Lake Pamamaroo was 9.35 mg/L (data source WaterNSW).

Figure 8: Same as Figure 7, but taken on February 27, after the lake Pamamaroo Inlet was closed.

3.3. Conclusion

If this hypothesis is correct we have a case where the sheer biomass of the fish was sufficient, in conjunction with other sinks for oxygen (sediment oxygen demand, night time algal respiration) to have tipped the system into hypoxia. In a sense, the fish contributed to their own death. Flow changes were not benign during the period. Inflows of oxygenated water from Lake Pamamaroo starting in March 2023 likely attracted the bony bream to the top end of Weir 32 weir pool. Then as the flows from Lake Pamamaroo were being ramped back, so was a source of oxygen to the fish.

It should be noted that this event does have the hallmarks of a 'Black Swan' event (sensu Taleb, 2007). The three attributes of a black swan events are:

- *Rarity* - As far as I am aware this is the first instance where dissolved oxygen has been impacted to the point of hypoxia by the respiration of an organism other than the microbiota (bacteria or algae) in a large, flowing system (see Baldwin, 2020).[9] In that sense the event wasn't <u>prospectively</u> predictable.
- *Extreme impact* - this is subjective, but at least from a human perspective this has garnered international attention, and undoubtedly has had a profound impact on the people of Menindee. Furthermore, it is probable that the decomposition of the dead fish that have accumulated on the bed of Weir 32 weir pool will lead to further hypoxic events.
- *Retrospective (not prospective) predictability* - as evidenced by this report.

4. Implications

The fish kill in mid-March 2023, has a number of implications for on-going management of water in the region (and indeed across the basin),

[9] Such events do occur when fish are isolated in pools or billabongs following flood recession or during drought.

1. Deliberately manipulating and moving water in the landscape comes at the potential risk to water quality, yet due regard is not paid to the potential for adverse outcomes. This is not the first time in the Murray-Darling Basin that changing flow regimes have resulted in the death of fish. Consideration of water quality should be integral to flow rules and water sharing plans across the basin.
2. Following on from the point above, there is insufficient monitoring to tell whether or not a management action will have an adverse outcome. Dissolved oxygen sensors are not always located in the right places, and monthly spot monitoring is insufficient to detect changes that may occur over days or weeks. Thought should be given to empowering locals by supplying equipment and training to pro-actively monitor their environment.
3. When managing flood recessions of large natural flows in highly regulated systems, there is a likelihood that a substantial amount of fish biomass can be trapped by infrastructure. Pre-emptive planning should be undertaken to minimise this eventuality.
4. At a more local level, a barrier, similar to a marine break wall needs to be constructed between Lake Pamamaroo inlet and outlet structures to prevent short-circuiting of the water (as discussed above). Lake Pamamaroo and Lake Menindee are natural aerators (Kerr et al, 2013) and should be used as such. Short-circuiting of the water in Lake Pamamaroo reduces this capacity.

5. References

Baldwin DS, (2019) *Stratification, mixing and fish deaths in the lower Darling River*. A report prepared for the Murray-Darling Basin Authority 68pp

Baldwin DS (2020) Water quality in the Murray-Darling Basin: The potential impacts of climate change In Ecohydrology from catchment to coast Murray-Darling Basin, Australia: Its Future Management (BT Hart, NR Bond, N Byron CA Pollino and MJ Stewardson (eds). Elsevier, Amsterdam, Netherlands. pp 137 - 159.

Department of Primary Industries (2023) Fish Kill in NSW. Available online at https://www.dpi.nsw.gov.au/fishing/habitat/threats/fish-kills; accessed April 28, 2023.

Guardian (February 23, 2023) Menindee mass fish kill: thousands of carp dead amid water quality fears. Available online at https://www.theguardian.com/australia-news/2023/feb/23/menindee-mass-fish-kill-thousands-of-carp-dead-amid-water-quality-fears

Guardian (March 23, 2023) Flood and Heat: why millons of fish are dying in western NSW. Available online at https://www.theguardian.com/australia-news/2023/mar/21/flood-and-heat-why-millions-of-fish-are-dying-in-western-nsw

Kepenyes J, Vardi L (1984) Chapter 21: Aeration and oxygenation in aquaculture in *Inland Aquaculture Engineering* United Nations Development Program Food and Agriculture Organization of the United Nations, Rome (ADCP/REP/84/21), available online at https://www.fao.org/3/x5744e/x5744e00.htm#Contents

Kerr J, Baldwin DS, Whitworth K (2013) Options for managing hypoxic blackwater events in river systems: a review. *Journal of Environmental Management* 114, 139-147.

Mitrovic SM, Hardwick L, Dorani F (2011). Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *Journal of Plankton Research* 33: 229-241.

Péliova A, Garcia-Lozano C, Sitjar J (undated) Aquatic plants and algal custom script detector (APA Script) available at https://github.com/sentinel-hub/custom-scripts/tree/master/sentinel-2/apa_script

Sidónio N, Pereira A (undated) Se2WaQ - Sentinel-2 Water Quality Script. Available at https://github.com/sentinel-hub/custom-scripts/tree/master/sentinel-2/apa_script

Taleb NN (2007) "The black swan: Chapter 1: the impact of the highly improbable" reproduced in The New York Times on-line.

Vertessy R, Barma D, Baumgartner L, Mitrovic S, Sheldon F, Bond N (2019) *Independent assessment of the 2018-19 fish deaths in the lower Darling River*.

Willm L, LeFebrve G, Davranche A, Campagna J, Redmond L, Merle C, Guelmami A Pouplin B (undated) Water in Wetland Index (WIW)- Sentinel 2 Version available at https://github.com/sentinel-hub/custom-scripts/tree/master/sentinel-2/wiw_s2_script.

Subject:	Further reflections on the fish deaths in the Darling-Baaka River in March 2023
Attention:	Professor Hugh Durrant-Whyte - NSW Chief Scientist and Engineer
CC:	Allan Raine - NSW Department of Planning and Environment Cameron Lay - NSW Department of Primary Industries (Fisheries) Craig Hardge - Murray Darling Basin Authority
From:	Darren Baldwin, *Rivers and Wetlands*
Date:	June 14, 2023

Purpose

On March 16-17 there was a massive fish kill in the Weir 32 weir pool, mostly focussed upstream of the town of Menindee on the Darling Baaka River. In late March 2023, *Rivers and Wetlands* prepared a File Note on their initial assessment of the likely proximate cause the fish deaths (attached). Since then *Rivers and Wetlands* have been assisting with the on-going management of oxygen levels in Weir 32 weir pool to minimise the risk of another fish kill. This note is an addendum to the original File Note to the MDBA for the purpose of testing the original hypothesis outlined in that File Note, and reflect on subsequent information and data that have been gleaned since.

Proximate cause of the fish deaths

Since the end of March there has been no new data that would change *Rivers and Wetlands* key propositions presented in the March 30 File note, namely:

- It is not possible to unequivocally ascribe a cause to the fish deaths that occurred in the Darling-Baaka River in mid-March.
- It is likely that the fish deaths were caused by excessive community respiration (fish, algae and sediment) coupled with a reduction of inflows into the top end of Weir 32 from Lake Pamamaroo and Lake Wetherell.
- It was a "Black Swan" event.

Specifically:

- The NSW Environmental Protection Agency (EPA) have released results of water quality analyses taken (March 21, 2023) following the fish deaths. The concentration of all agricultural chemicals tested were below detection limits[1] ; and the level of heavy metals detected were below Australian Guideline trigger levels. The only compound that could

[1] I haven't compared detection levels against lethal levels for these chemicals. It is possible that the detection level for a particular compound is above the lethal level for the same compound.

have potentially have contributed to the fish deaths was ammonia/ammonium. The concertation of ammonia in samples taken by the EPA on March 21, 2023 varied from 0.13 to 1.13 mg/L. The toxicity of ammonia/ammonium depends on pH. Free ammonia (NH_3) is substantially more toxic than ionised ammonium (NH_4^+), which is why the trigger levels for this compound were initially dependent on pH (Table 8.3.7 ANZECC and ARMCANZ, 2000). At the time of sampling the pH in Weir 32 varied between 7.5 and 7.9. The trigger levels for ammonia/ammonium are 1.61 mg/L at pH 7.5 and 1.13 mg/L at pH 7.9. These levels are similar to, or above, what was observed in Weir 32. Further, the levels of ammonia/ammonium in Weir 32 weir pool on March 21 were likely to be much higher than the levels during the fish deaths, because of decomposition of the dead fish.

- *Rivers and Wetlands* has separately addressed the assertion that the fish kill was caused by deliberate releases of water of poor quality from Lake Wetherell to the top of Weir 32 weir pool from Lake Menindee outlet (see attached). There was some leakage from Lake Wetherell Outlet to Weir 32 weir pool, but that only represented a few percent of the flow from Lake Pamamaroo.
- *Rivers and Wetlands* based its initial calculations on fish respiration on 20 million dead fish, subsequently Fisheries have updated their assessment of dead fish to about 30+ million fish (I. Ellis pers. comm.). This would mean the biomass of fish is at least 50% greater than initially used by *Rivers and Wetlands*, increasing the probability that a significant driver of the fish kill was fish respiration. Specifically, assuming 30 million fish with an average weight of 50 g = 1500 tonnes of fish (live weight). Assuming an uptake of 5000 mg O_2/kg live weight/day. This equates to 7.5 x 10^9 mg O_2 day (which doesn't take into account fish that didn't die in the event or other losses of through community respiration). At the time of the fish deaths, about 2.6 x 10^{10} mg/day was being delivered from upstream.
- The on-going management of the has been based on the premise that inflows from Lake Pamamaroo into Weir 32 weir pool is a substantial source (subsidy) of oxygen to the weir pool. While this doesn't prove that the original premise is correct, it certainly supports the hypothesis.

How long will the substantial sag in dissolved oxygen in Weir 32 weir pool continue for?

Since the fish deaths WaterNSW has been undertaking periodic longitudinal-surveys of dissolved oxygen concentrations in Weir 32 weir pool. In the latest survey (taken on June 5 & 6) there was a decrease in oxygen of nearly 6 mg/L from the Lake Pamamaroo outlet to the Lake Menindee outlet (a distance of about 31.5 km). This equates to a nett loss of about 2000 kg of oxygen, which needs to be subsidised from upstream flows to prevent further fish deaths.

The nett amount of oxygen consumed in this reach has decreased over time (see Figure 1), but appears to have levelled off at about 2000 kg. During the same period of time the daily average water temperature has fallen from about 25 ^{o}C at the end of March to as low as about 13 ^{o}C at the end of May. Given that most biotic processes that consume oxygen in a river reach are temperature dependant, it is not inconceivable that hypoxia may once again become an issue when the water temperature rises in spring.

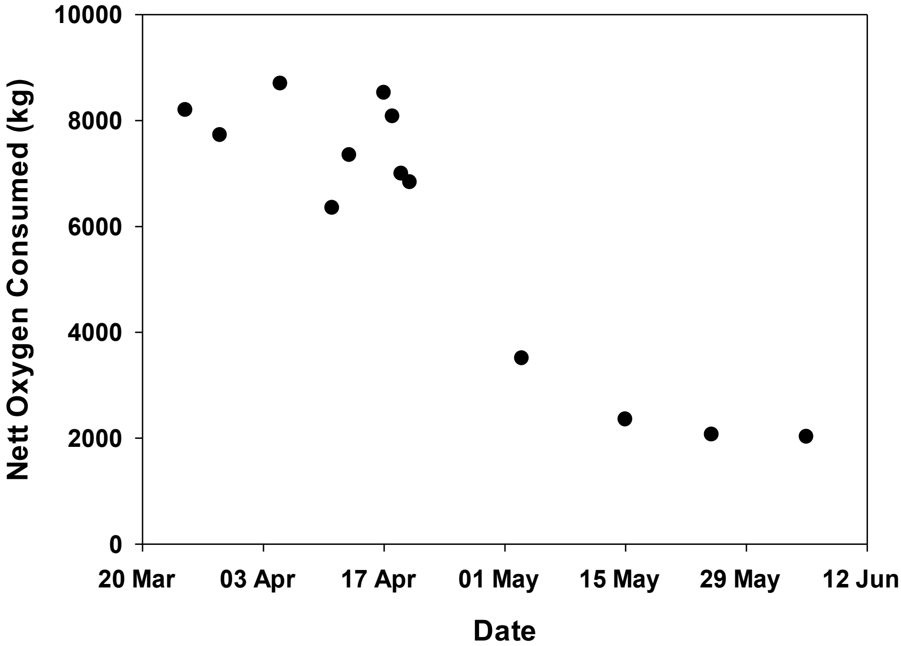


Figure 1: Nett oxygen consumption over time in Weir 32 weir pool in the reach between the Lake Pamamaroo outlet and the lake Menindee outlet. Nett oxygen consumption was calculated from WaterNSW longitudinal surveys.

Why do fish kills occur in Weir 32?

I was initially asked this question in a radio interview. At the time I was unable to answer the question. However, on reflection, I think there are three drivers of the fish deaths (given that the causes of the fish deaths in 2018/19 and 2023 are totally different).

1. The first cause was canvassed broadly in both the Vertessy (Vertessy et al, 2019) and Academy of Science reports (Australian Academy of Science, 2019) following the fish kills in 2018-2019, namely the harvesting of upstream flows, in government- and industry-controlled water storages.
2. Preferred flow delivery pathways. WaterNSW flows into the Darling-Baaka River are essentially metered at Weir 32. Their preference seems to be for flows to go from Lake Wetherell, into Lake Pamamaroo, then into Lake Menindee and finally, through the Lake Menindee outlet into Weir 32 weir pool[2]. This means that for most of the time there would be little or no flow in the reach from the Lake Pamamaroo outfall to the Lake Menindee outfall (about 32 river km). From an ecological perspective it would be preferable that flows across Weir 32 were first sourced from upstream sources (Lake Wetherell and/or Lake Pamamaroo) rather than from Lake Menindee. This would allow for some flow through all of Weir 32 weir pool - reducing the risk of stratification (the likely proximate cause of the 2018/19 fish deaths - Baldwin, 2019, Vertessy, 2019), and at the same time delivering oxygen from upstream.
3. There is a lack of effective fish passage from Weir 32 weir pool upstream into Lake Wetherell and Lake Pamamaroo. Essentially the fish in Weir 32 are blocked from migrating upstream because of the lack of fishways. Anecdotally, fish harvesting and dissolved oxygen concentration data indicated a substantial biomass of fish (both native and exotic) had congregated in the reach of Weir 32 immediately below Lake Wetherell and Lake

[2] This should be explored with WaterNSW.

Pamamaroo after the fish death event in mid-March. If these fish were able to migrate into either lake it would have reduced the demand for oxygen in Weir 32 weir pool.

Water 'accounting' should be expanded to include other values of water

Throughout the process of managing flows into Weir 32 weir pool to minimise another fish death, it is clear that the only 'currency' of water is volume. While that make sense on a pragmatic level, it doesn't consider the alternate values of water. For example, during the current event, water management was based on the subsidy of dissolved oxygen that could be delivered to Weir 32 weir pool. When it became necessary to re-instate inflows from Lake Wetherell to Lake Pamamaroo (about June 9 2023) it was clear that the dissolved oxygen concentration was lower in Lake Wetherell than in Lake Pamamaroo, and therefore of less effective value. Similarly, most of the water used in managing the on-going issue in Weir 32, was 'environmental water' to maintain the fish population; but this clearly created tension with some of the practitioners because this came with substantial lost opportunity cost (e.g. wetland inundation, bird breeding) - especially with the likelihood of an El Niño occurring this year starting to firm.

Recommendations following the fish deaths

In the original fie note, 4 implications were derived from the hypothesised cause of the fish deaths - each with recommendations attached, specifically:

1. Deliberately manipulating and moving water in the landscape comes at the potential risk to water quality, yet due regard is not paid to the potential for adverse outcomes. This is not the first time in the Murray-Darling Basin that changing flow regimes have resulted in the death of fish. Consideration of water quality should be integral to flow rules and water sharing plans across the basin.
2. Following on from the point above, there is insufficient monitoring to tell whether or not a management action will have an adverse outcome. Dissolved oxygen sensors are not always located in the right places, and monthly spot monitoring is insufficient to detect changes that may occur over days or weeks. Thought should be given to empowering locals by supplying equipment and training to pro-actively monitor their environment.
3. When managing flood recessions of large natural flows in highly regulated systems, there is a likelihood that a substantial amount of fish biomass can be trapped by infrastructure. Pre-emptive planning should be undertaken to minimise this eventuality.
4. At a more local level, a barrier, similar to a marine break wall, needs to be constructed between Lake Pamamaroo inlet and outlet structures to prevent short-circuiting of the water (as discussed above). Lake Pamamaroo and Lake Menindee are natural aerators (Kerr et al, 2013) and should be used as such. Short-circuiting of the water in Lake Pamamaroo reduces this capacity.

On reflection, I have a number of additional recommendations:

5. The construction of effective fish ladders which link the top end of Weir 32 weir pool to both Lake Pamamaroo and Lake Wetherell.
6. Following on from point 5, but also in line with the recommendation of Mitrovic et al (2011) of a minimum flow in Weir 32 weir pool to minimise thermal stratification which promotes algal blooms, a minimum flow (nominally 350 - 500 ML/day) be maintained throughout Weir 32 weir pool and not just the reach below the Lake Menindee outlet.
7. While the use of environmental water has been successful in preventing another large fish kill (at least at the time of writing), this is not the purpose of environmental water. Delivering environmental water to sustain the fish population in Weir 32 has come at a large

opportunity cost - especially as we may be moving into an El Niño period. There is a provision for water to be used to ameliorate poor water quality events, but only where the poor water quality impacts on consumptive use. The case should be broadened to include mitigating the effect of poor water quality on aquatic organisms - especially in cases where the poor water quality originated from managing flows.

8. Total removal of the old town weir. There is an old weir located just downstream of the railway bridge. It has been partially demolished but much of it is still standing. The longitudinal transects taken by WaterNSW often show that there is a substantial drop in dissolved oxygen concentration between stations upstream and downstream of the old weir. For example, there was a drop of 1.3 mg/L between a station located near the pump station (upstream) and a station near the Menindee township (downstream). The distance between the two stations is about 3.7 km. It is hypothesised that decaying fish are accumulating against the old weir structure, leading to the sag in dissolved oxygen.

References

ANZECC and ARMCANZ (2000) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.*

Australian Academy of Science (2019). *Investigation of the causes of mass fish kills in the Menindee Region NSW over the summer of 2018–2019*.

Baldwin DS, (2019) *Stratification, mixing and fish deaths in the lower Darling River.* A report prepared for the Murray-Darling Basin Authority 66 pp.

Kerr J, Baldwin DS, Whitworth K. (2013) Options for managing hypoxic blackwater events in river systems: a review. *Journal of Environmental Management* 114, 139-147.

Mitrovic SM, Hardwick L, Dorani F (2011). Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *Journal of Plankton Research* 33: 229-241.

Vertessy R, Barma D, Baumgartner L, Mitrovic S, Sheldon F, Bond N (2019) *Independent assessment of the 2018-19 fish deaths in the lower Darling River*.

File Note

Subject:	A critical evaluation of Williams and Schulz (2023)
Attention:	Allan Raine - NSW Department of Planning and Environment Veronica Silberschneider
From:	Darren Baldwin, *Rivers and Wetlands*
Date:	April 12, 2023

Purpose

Williams and Schulz (2023) released a report outlining their thesis on the fish kill in Weir 32 weir pool in mid-March 2023. Using Sentinel-2 satellite imagery they contend "that controlled releases of blackwater were made in the days leading up to the mass fish kill of March 2023"; and, by inference, these releases caused the fish deaths. This file note critically evaluates these claims.

Synopsis

There is little available evidence to support the central thesis of Williams and Schulz (2023). There were documented releases from Lake Wetherell outlet directly to Weir 32 weir pool (65 ML/day), but this represented (at most) only a few percent of the flows entering the weir pool prior to the fish kills. Processing Sentinel-2 imagery using scripts that can differentiate between water bodies with different algal or DOC/sediment concentrations indicate **if** there were any inflows into Lake Pamamaroo from Lake Wetherell immediately prior to the fish deaths, they would be best described as trivial, and could be from leakage across the control structure. An alternate explanation of the 'anomalies' identified in the satellite imagery of March 14 by Williams and Schulz (2023), is that it they are associated with water being drawn from other parts of Lake Pamamaroo because of releases from the lake. Finally, dilution modelling shows that 85% of inflows into the top end of Weir 32 weir pool (directly through Lake Wetherell outlet, or indirectly from short circuiting from the Lake Pamamaroo inlet to the outlet) would have needed to have come from Lake Wetherell to decrease dissolved oxygen below 2mg/L.[3]

Actual Flows

WaterNSW has supplied actual flows from Lake Wetherell into Lake Pamamaroo (Lake Pamamaroo inlet), from Lake Wetherell directly into Weir 32 weir pool (Lake Wetherell outlet) and from Lake Pamamaroo into Weir 32 weir pool (Lake Pamamaroo outlet) over the

[3] 2 mg/L is the notional concentration that large bodied native fish begin to die through oxygen starvation.

period of interest (Figure 1). Flows from Lake Wetherell to Lake Pamamaroo ceased on February 25, 2003 and recommenced on March 20 (i.e. after the fish kill). Flows directly from Lake Wetherell into Weir 32 weir pool were reduced to 65 ML/day by March 4, and remained at that level throughout most of March (Figure 1). These inflows directly from lake Wetherell into lake Pamamaroo represented between about 1 - 3% of total inflows into Weir32 weir pool above Menindee township.

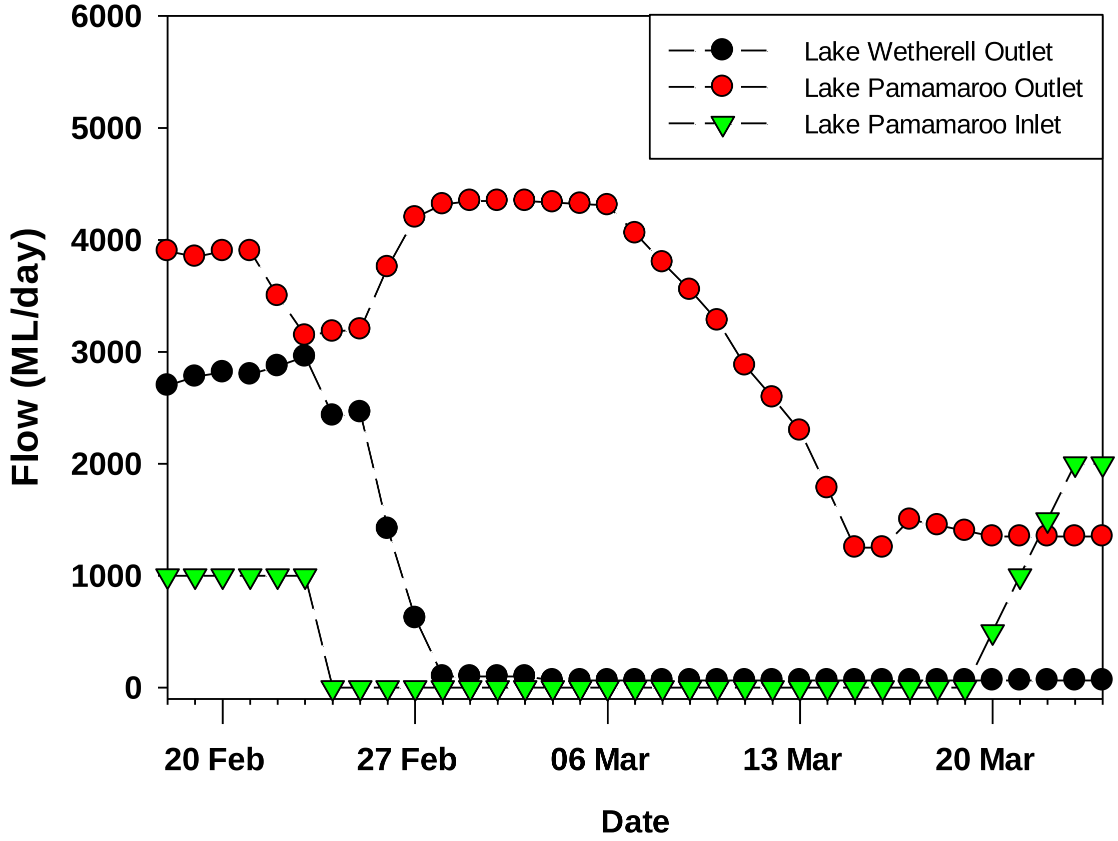


Figure 1: Flows from Lake Wetherell Outlet to Weir 32 weir pool (black circles), Lake Wetherell to Lake Pamamaroo through the Lake Pamamaroo Inlet (green triangles) and from Lake Pamamaroo to Weir 32 weir pool through the Lake Pamamaroo Outlet (red circles. for late February through March, 2023. (Data supplied by WaterNSW).

Sentinel 2 Imagery - Background

Sentinel 2 imagery is captured by 2 European Space Agency satellites, each equipped with Multispectral Imagers. The imagers collect data across 13 bands - the shortest wavelength band (B1) is centred at 442 nm (in the ultra-blue - close to the detection limit of the human eye), while the longest wavelength band (B12) is centred at 2190 nm, which is the infrared. These bands can be combined together to visualise different aspects of the environment. For example, combining band B2 (blue), B3 (green) and B4 (red) gives a good approximation of true (or natural) colour. This appears to be the basis of the images used in Williams and Schulz (2023). However, the various bands can also be combined in ways to specifically highlight different aspects of the environment. For example, the Aquatic Plants and Algae Custom Script Detector (APA; Péliova A et al., undated) is designed to highlight aquatic plants and algae, as well as suspended sediments. It shows land features in natural colour, open water in blue, algal density in shades of light green to yellow and suspended sediment in colours from brown, through red to purple.

One advantage of processing the satellite imagery through scripts like APA and Se2WaQ Sidónio N and Pereira A (undated)) is that it can differentiate between different water sources if they have different water chemistries (e.g. algal or sediment concentrations), and therefore, can indicate how they mix. For example, Figure 2, processed with the Se2WaQ script (set to parameter 4, which highlights DOC and suspended sediments), shows the sediment plumes entering Lake King from the Mitchell, Nicholson and Tambo Rivers (yellow is lowest sediment load, purple is the highest).[4]

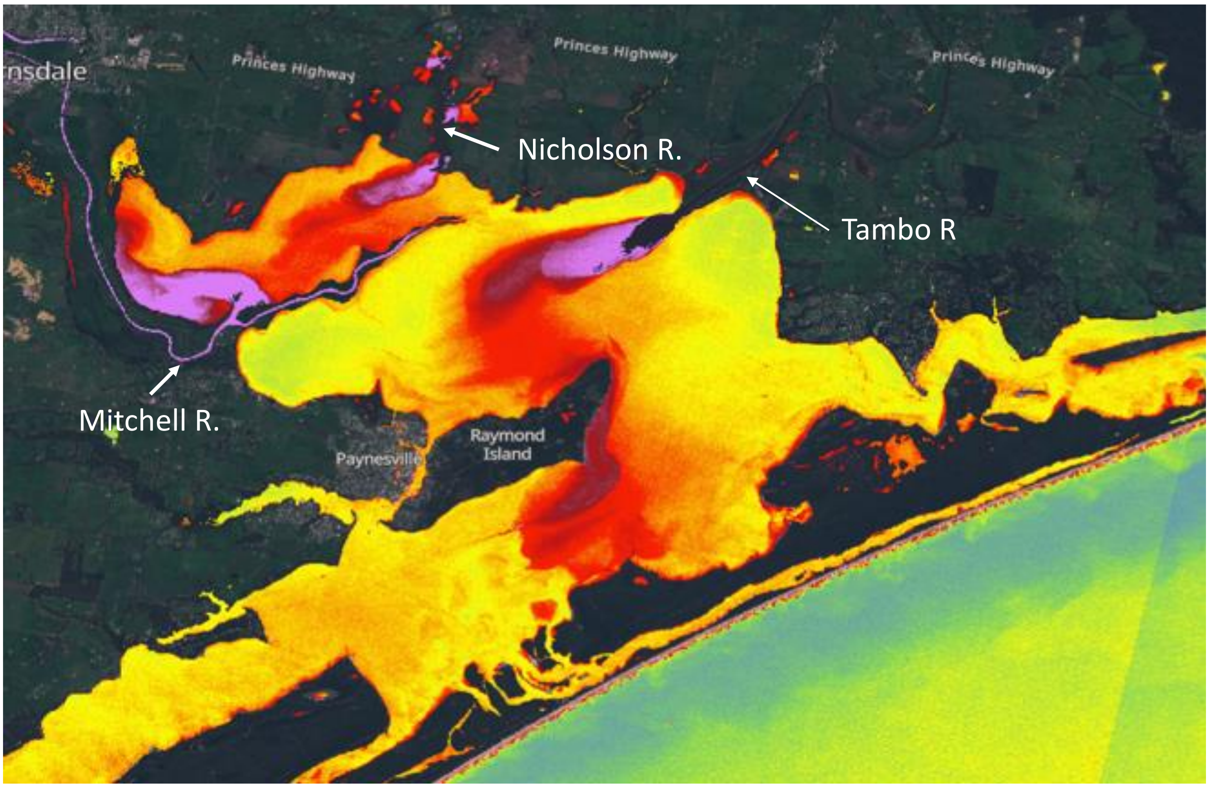


Figure 2: False colour Sentinel2 satellite images of Lake King (a Gippsland Lake) processed using the Se2WaQ script set to highlight suspended sediments. Yellow is the lowest suspended sediment concentration - purple is the highest. The image shows all the sediments are being delivered from the three rivers that flow into the lake.

Sentinel 2 Imagery of Lake Wetherell, Lake Pamamaroo and Weir 32 weir pool on March 14, 2023.

The key argument of Williams and Schulz is that water was being released from Lake Wetherell into Lake Pamamaroo on or immediately prior to the satellite pass on March 14. This 'blackwater' was then short circuited into Weir 32 weir pool. The water was low in dissolved oxygen, and this caused the fish death. There is no doubt that releases from Lake Wetherell into Lake Pamamaroo can short circuit into the Weir 32 weir pool if both the Lake

[4] July 2020, following a rainstorm, after the Black Summer Fires

Pamamaroo inlet and outlets are open. The key question then, is whether water was being released into Lake Pamamaroo from Lake Wetherell on or about March 14. The critical evidence presented by Williams and Schulz (2023) are their Figure 9 (which is a true colour image of the Lake Pamamaroo inlet and outlet on March 14, their Figure 11 (the same image but processed using photoshop enhancement of saturation and contrast to delineate the blackwater), Figure 12 (which showed different colour swatches purporting to show mixing) and their Figure 13 (which is processed in the same as their Figure 11 but is focused on the Lake Wetherell outlet [5] (I note in passing that using Photoshop to extract data from Sentinel 2 imagery is not necessarily incorrect, but is certainly unorthodox.)

Figure 3 Shows the 'true colour' sentinel 2 image of the area around the Lake Pamamaroo inlet and outlet on March 14 (Similar to Williams and Schulz Figure 9). The anomalies relied on by Williams and Schulz (2023) to indicate releases from Lake Wetherell to Lake Pamamaroo are highlighted. A few things to note. Firstly, the water in Lake Wetherell is green, more than black, indicating an algal bloom in Lake Wetherell. Secondly, the change in colour either side of the Lake Pamamaroo inlet is quite dramatic indicating little or no mixing has occurred (discussed in further detail below).

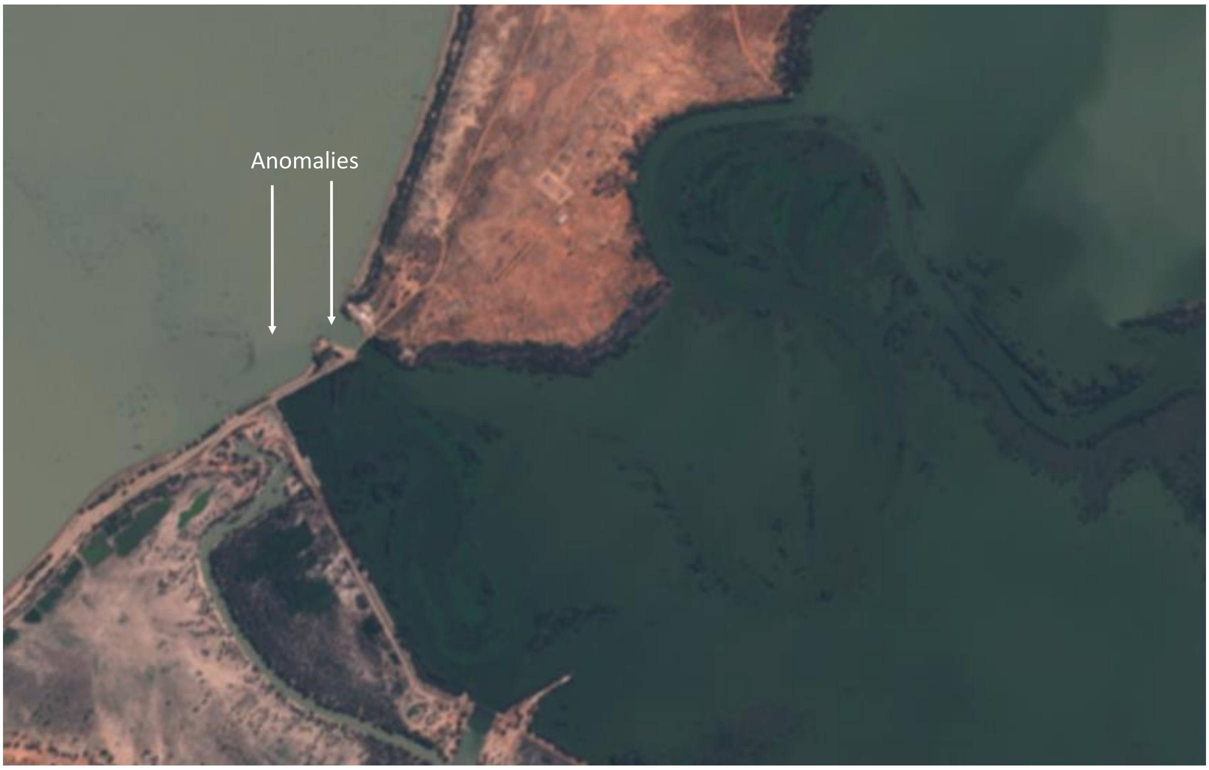


Figure 3: 'True Colour' Sentinel 2 image of Lake Pamamaroo (top left corner) and Lake Wetherell (bottom right corner) taken on March 14. Anomalies discussed in Williams and Schulz (2023) are indicated by arrows

[5] These images are not reproduced here so as not to infringe copyright - the reader is referred to Williams and Schulz (2023) to view the originals.

A similar image, although this time processed with the APA script, which highlights algal biomass, suggests that if there were flows coming from lake Wetherell they would be trivial, consist with leakage (Figure 4). Inflows from Lake Wetherell (high in algal density) to Lake Pamamaroo (low in algal density) would be obvious from the false colour satellite images. To make this point clearer, Figure 5 shows the same location as Figure 4, but taken on March 22 when the flow into Lake Pamamaroo from Lake Wetherell was 1000 ML/day.

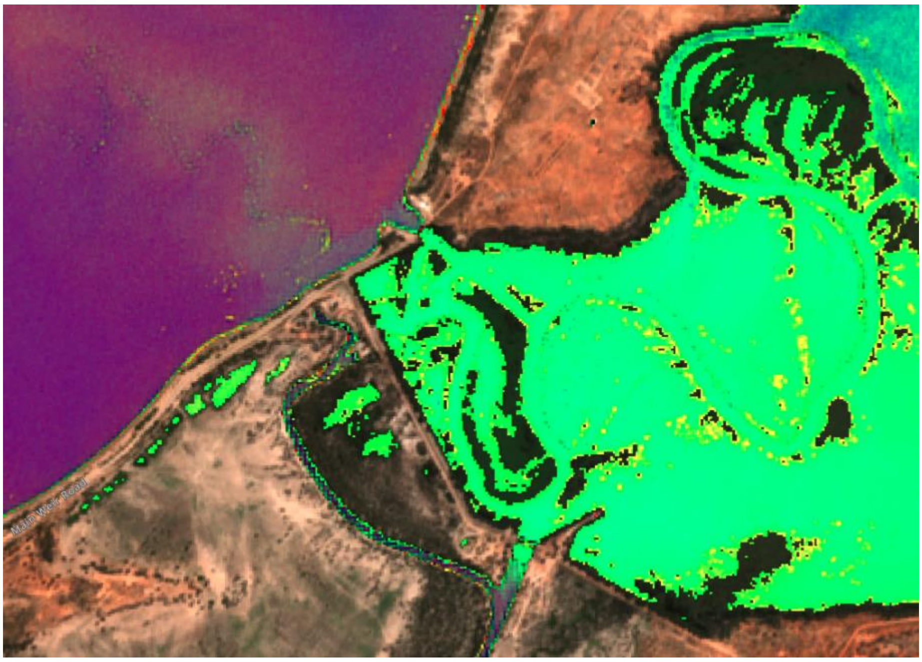


Figure 4: False colour Sentinel 2 satellite image of the same region as Figure 3, taken on March 14 and processed with the APA script. Green and yellow represent levels of high algal density. Purple is high concentrations of suspended sediments

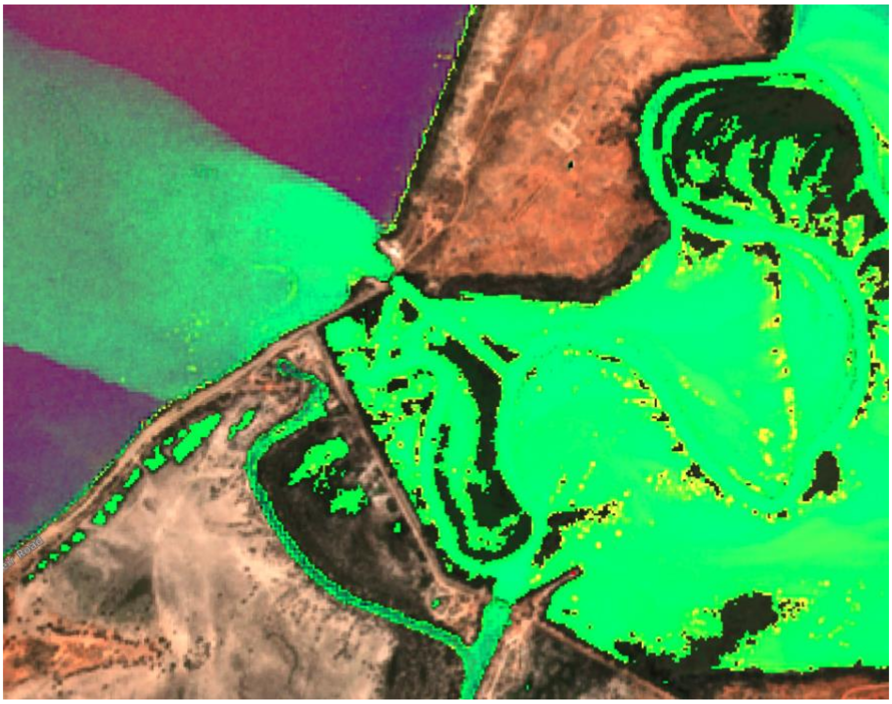


Figure 5: False colour Sentinel 2 satellite image of the same region as Figure 3, taken on February 22 (a period of moderate inflows into Lake Pamamaroo from Lake Wetherell)

processed with the APA script. Green and yellow represent levels of high algal density. Purple is high concentrations of suspended sediments

Furthermore, if we zoom out, an alternate explanation for the supposed anomalies on March 14 arises, namely the algal biomass, especially around the Lake Pamamaroo outlet, is being drawn to the outlet from the main body of the lake with the release of water into Weir 32 weir pool (Figure 6).

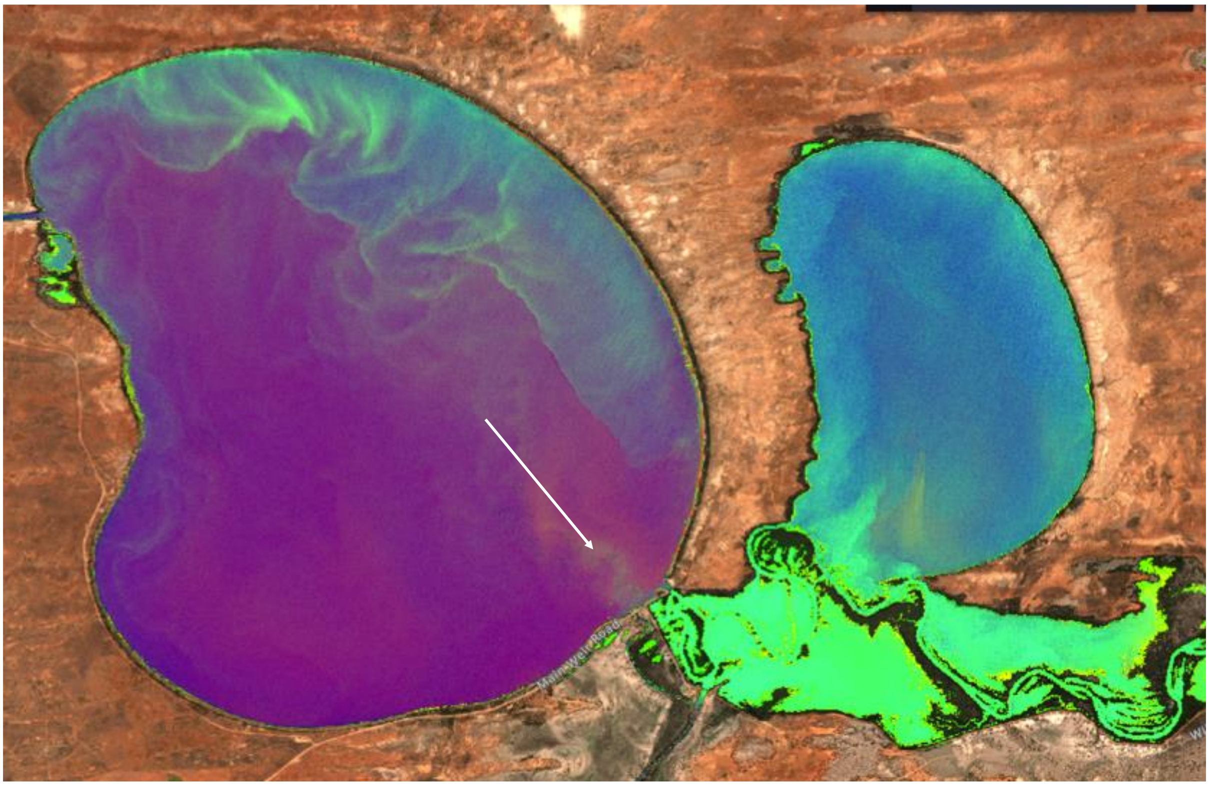


Figure 6: False colour Sentinel 2 satellite image of the whole of Lake Pamamaroo and Lake Tandure and the lower portion of Lake Wetherell taken on March 14 and processed with the APA script. Green and yellow represent levels of high algal density. Purple is high concentrations of suspended sediments. The arrow represents a potential flow path as water was being released from Lake Pamamaroo.

A similar pattern to images processed with the APA script can also be seen if the image is processed with the Se2WaQ script (set to parameter 4 which highlights DOC and suspended sediment; Figure 7). Firstly, if large amounts of water was entering Lake Pamamaroo from Lake Wetherell, we would expect to see a distinct plume where the two waterbodies (with different loads of suspended sediments) interact - e.g. as occurred on February 22 (Figure 8). Furthermore, analogous to Figure 6, one interpretation of the proposed anomalies reported by Williams and Schulz (2023) around the Lake Pamamaroo inlet and outlet is that water with a slightly lower turbidity is being drawn from the north of the lake (Figure 7).

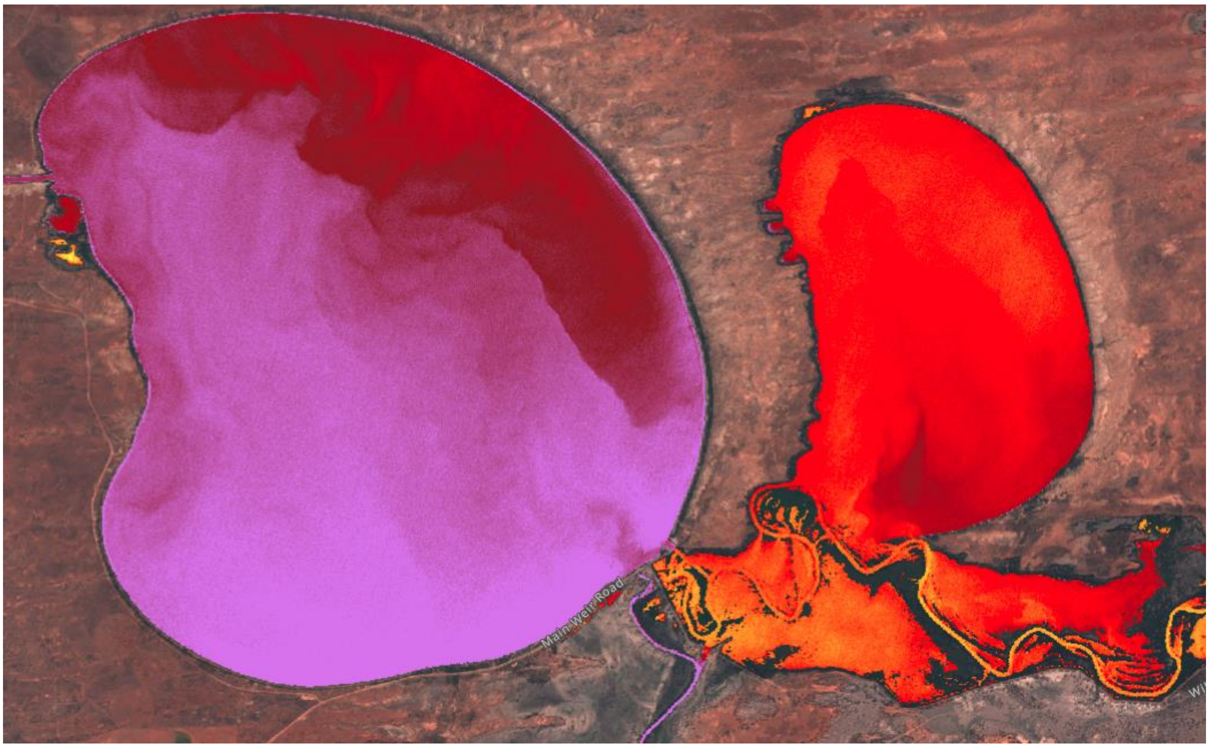


Figure 7: False colour Sentinel 2 satellite image of the whole of Lake Pamamaroo and Lake Tandure and the lower portion of Lake Wetherell taken on March 14 and processed with the Se2WaQ script. Concentrations vary from yellow lowest through red, to purple (highest)

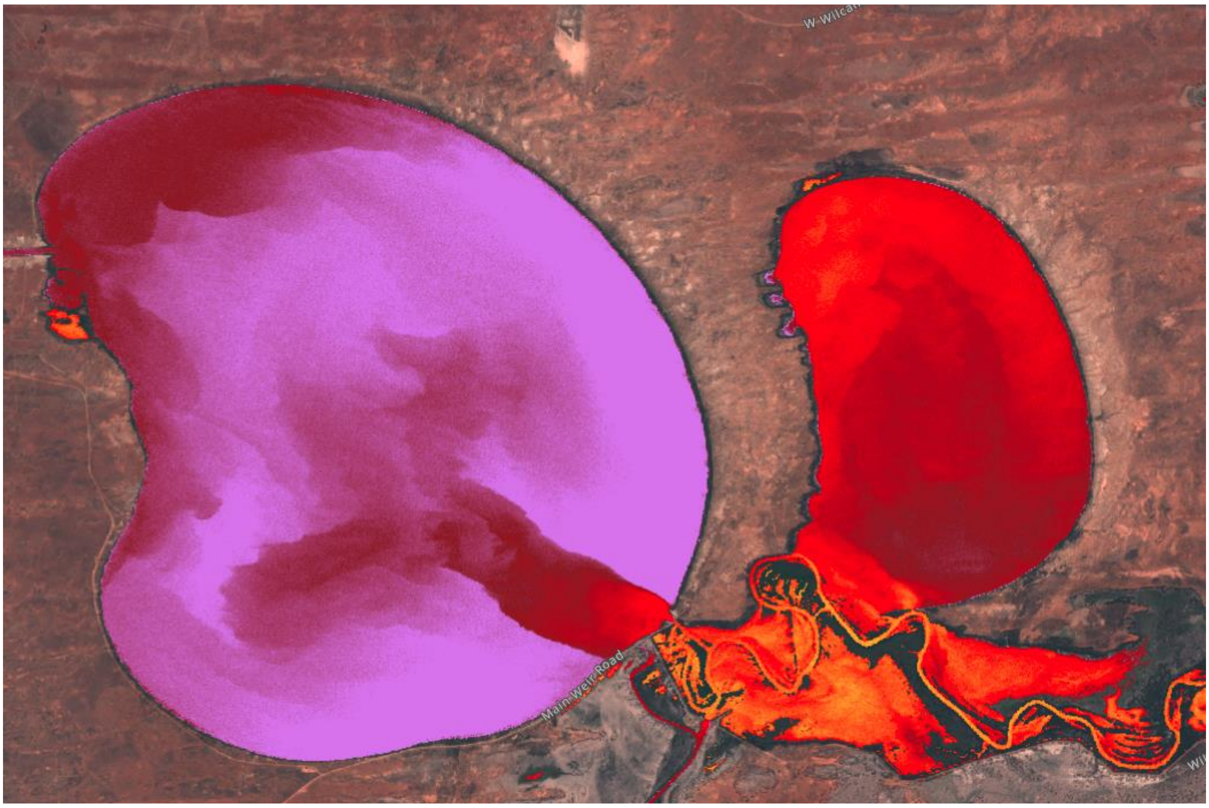


Figure 8: as per Figure 7, but taken on February 22, a period of moderate inflow from Lake Wetherell to Lake Pamamaroo.

The anomalies pointed out in Williams and Scholz (2023) Figures 12 and 13 can be explained by the 65 ML/day that was being released from the Lake Wetherell outlet (see above)

Modelled Dissolved Oxygen Concentrations

An alternate approach is a hypothetical - what percentage of Lake Wetherell water would be need to enter the top end of Weir 32 weir pool to drop the dissolved oxygen concentration to below 2 mg/L (the notional concentration that kills native fish e.g. Gehrke 1988) using a published model (Kerr et al, 2013). To populate the model we need total flows, nominal flows from Lake Pamamaroo and Lake Wetherell (which would be the sum of water both entering Weir 32 directly from the Lake Wetherell outlet and mixing with water from Lake Pamamaroo and the dissolved oxygen concentrations in both Lake Pamamaroo and Lake Wetherell.

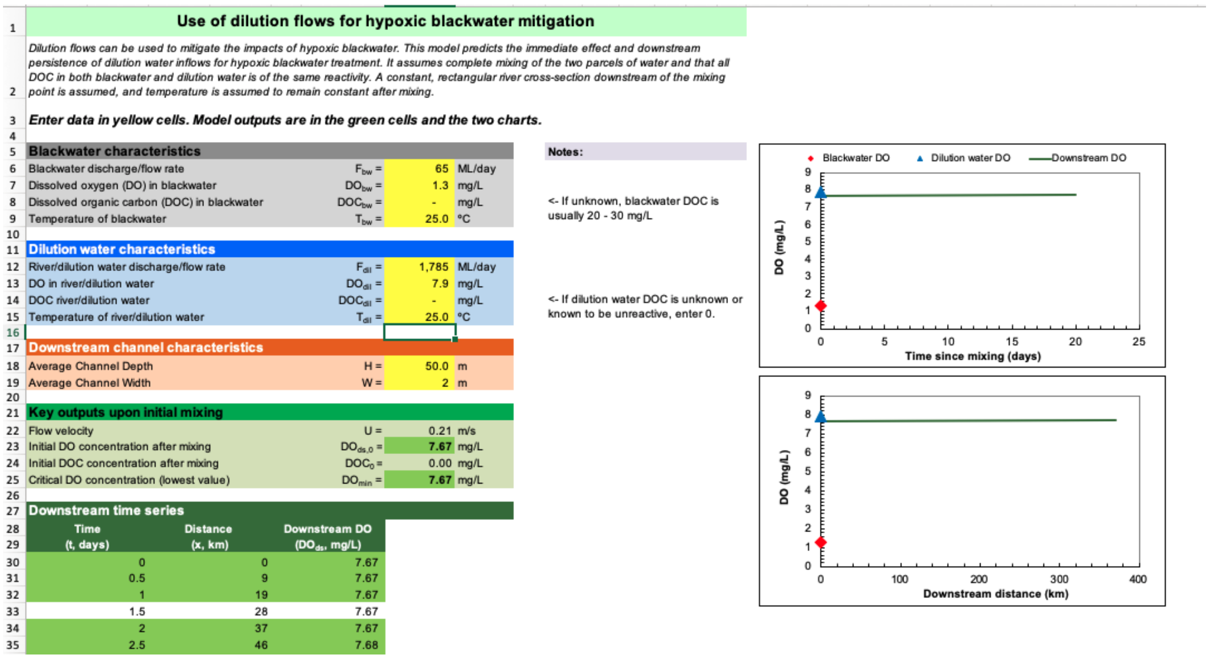
Total Inflows: here we use the data supplied by Water NSW for March 14, 2023 ≈ 1850 ML

Ratio of Lake Wetherell and Lake Pamamaroo flows: this is the variable we are testing for.

Dissolved oxygen concentration in Lake Pamamaroo water: monthly samples were taken in the middle of Lake Pamamaroo on 21 February (average concentration 7.7. mg/L) and 27 March (8.1 mg/L). For this exercise we will use the overall average of 7.9 mg/L

Dissolved oxygen concentration in Lake Wetherell: The average dissolved oxygen concentration at station 2 in Lake Wetherell on March 27 was 1.3 mg/L.

The first model run was based on the actual inflows on March 14, 2023 (1775 ML/day from the Lake Pamamaroo outlet) and 65 ML/day from the Lake Wetherell outlet. Dissolved oxygen concentration would decline by about 0.2 mg/L (from 7.9 to 7.7 mg/L) on mixing (Figure 9).



1	**Use of dilution flows for hypoxic blackwater mitigation**			
2	*Dilution flows can be used to mitigate the impacts of hypoxic blackwater. This model predicts the immediate effect and downstream persistence of dilution water inflows for hypoxic blackwater treatment. It assumes complete mixing of the two parcels of water and that all DOC in both blackwater and dilution water is of the same reactivity. A constant, rectangular river cross-section downstream of the mixing point is assumed, and temperature is assumed to remain constant after mixing.*			
3	***Enter data in yellow cells. Model outputs are in the green cells and the two charts.***			
4				
5	**Blackwater characteristics**			
6	Blackwater discharge/flow rate	F_{bw} =	65	ML/day
7	Dissolved oxygen (DO) in blackwater	DO_{bw} =	1.3	mg/L
8	Dissolved organic carbon (DOC) in blackwater	DOC_{bw} =	-	mg/L
9	Temperature of blackwater	T_{bw} =	25.0	°C
10				
11	**Dilution water characteristics**			
12	River/dilution water discharge/flow rate	F_{dil} =	1,785	ML/day
13	DO in river/dilution water	DO_{dil} =	7.9	mg/L
14	DOC river/dilution water	DOC_{dil} =	-	mg/L
15	Temperature of river/dilution water	T_{dil} =	25.0	°C
16				
17	**Downstream channel characteristics**			
18	Average Channel Depth	H =	50.0	m
19	Average Channel Width	W =	2	m
20				
21	**Key outputs upon initial mixing**			
22	Flow velocity	U =	0.21	m/s
23	Initial DO concentration after mixing	$DO_{ds,0}$ =	**7.67**	mg/L
24	Initial DOC concentration after mixing	DOC_0 =	0.00	mg/L
25	Critical DO concentration (lowest value)	DO_{min} =	**7.67**	mg/L
26				
27	**Downstream time series**			

Notes:

<- If unknown, blackwater DOC is usually 20 - 30 mg/L

<- If dilution water DOC is unknown or known to be unreactive, enter 0.

	Time (t, days)	Distance (x, km)	Downstream DO (DO_{ds}, mg/L)
30	0	0	7.67
31	0.5	9	7.67
32	1	19	7.67
33	1.5	28	7.67
34	2	37	7.67
35	2.5	46	7.68

Figure 9: Screen shot of the Blackwater Intervention tool dilution model based on actual flows. The dissolved oxygen concentration on mixing is found on line 23

The ration of inflows from the two sources was then varied until the dissolved oxygen on mixing reached 2 mg/L. Approximately 85 % of the inflows into the top end of Weir 32 weir pool (1550 ML/day) would needed to have come from Lake Wetherell to drop the dissolved oxygen concentration to 2mg/L on mixing (Figure 10). To lower the oxygen concentration to 4 mg/L would still require about 60% (1100 ML/day) of flows to have originated from Lake Wetherell.

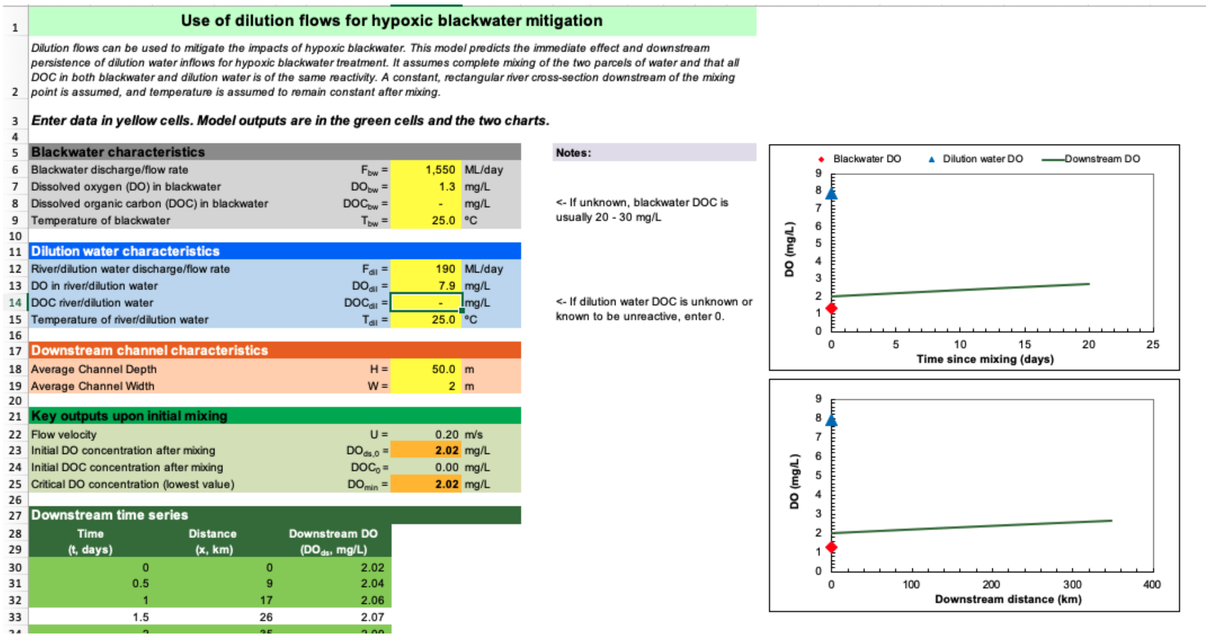


Figure 10: Screen shot of the Blackwater Intervention tool dilution model changed so that the final concentration of dissolved oxygen after mixing was about 2 mg/L (see line 23). flows.

5. References

Kerr J, Baldwin DS, Whitworth K (2013) Options for managing hypoxic blackwater events in river systems: a review. *Journal of Environmental Management* 114, 139-147.

Gehrke PC (1988) response-surface analysis of teleost cardiorespiratory responses to temperature and dissolved oxygen. *Comparative Biochemistry and Physiology* A 89, 587-592

Péliova A, Garcia-Lozano C, Sitjar J (undated) Aquatic plants and algal custom script detector (APA Script) available at https://github.com/sentinel-hub/custom-scripts/tree/master/sentinel-2/apa_script

Sidónio N, Pereira A (undated) Se2WaQ - Sentinel-2 Water Quality Script. Available at https://github.com/sentinel-hub/custom-scripts/tree/master/sentinel-2/apa_script

Williams M, Schulz D (2023) 2023 Menindee Mass Fish Kill: How it happened. A desktop investigating unravelling the operational decisions that preceded the death of 20 Million fish.