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Weir stratification and hypoxic water management - Murrumbidgee River 2019

Institute for Land, Water and Society
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Executive Summary

A fish mortality event occurred in Redbank Weir on the Murrumbidgee River on the evening of the 26th - 27th January 2019. Several thousand fish, including Murray cod, silver and golden perch and bony herring, died. The fish deaths coincided with the third fish kill event in the Darling River at Menindee. The fish deaths in the Murrumbidgee River at Redbank Weir were caused by mixing of the weir pool (destratification). That is, just prior to the fish deaths, the top approximately 1.5 metres of the water column was well oxygenated but the lower 4 metres of the water column had very low oxygen concentrations (hypoxic). A cool change arrived at Redbank Weir on the evening of the 26th - 27th January, which led to the mixing of the hypoxic bottom waters with the oxygenated surface water. Following mixing the dissolved oxygen concentration throughout the water column was lower than that required by fish, resulting in the death of fish. A blue-green algal bloom was occurring in Redbank Weir at the time of the fish deaths, but most likely only indirectly affected the fish deaths - probably through lowering the oxygen concentration in the surface water during the night through respiration.

Fish deaths were not observed in the other lower Murrumbidgee weir pools - Hay Weir, Maude Weir or Balranald Weir on the 26th - 27th of January. However, water quality in Maude Weir pool continued to decline. The weir pool remained stratified, with low dissolved oxygen concentrations in the bottom water. A rainfall rejection flow was set to reach Maude Weir pool by February 7th. Based on earlier research, it was predicted that if water levels remained constant in Maude Weir pool, the rainfall rejection flow would cause destratification and temporary hypoxia throughout the water column, which would likely result in fish deaths. Maude Weir pool was being lowered at the time as part of an environmental flow designed to improve fish habitat in Balranald Weir and improve fish passage between Redbank Weir and Hay Weir. A decision was made to continue to drawdown Maude Weir pool using environmental water. By the time the rainfall rejection flow had reached Maude Weir, all of the hypoxic bottom water had been exported downstream, with little apparent impact on downstream fish communities. The decision to use environmental water to allow for the drawdown of Maude Weir pool prevented fish deaths in the weir pool.

The rainfall rejection flow also had the potential to impact on the fish community in Redbank Weir. Following the fish deaths in late January, Redbank Weir pool re-stratified, and the bottom water once again became hypoxic. Once the rainfall rejection flow reached Redbank Weir it would most likely to have led to destratification and subsequent low dissolved oxygen concentrations throughout the water column. A decision was made to use environmental flows to export hypoxic water in Redbank Weir out onto the floodplain using existing infrastructure. As water with low dissolved oxygen concentrations was diverted out onto the floodplain, and was replaced by water with much higher oxygen concentrations from upstream, the dissolved oxygen concentrations in the weir pool improved. Improvement in dissolved oxygen concentration in Redbank Weir pool meant that when the rainfall rejection flows did reach Redbank Weir it didn't lead to hypoxia.

Following a review of the data collection undertaken as well as the management decisions taken, 13 recommendations are made around the issues of monitoring and reporting, river management and knowledge gaps:

Monitoring and reporting

While WaterNSW undertook weekly depth profiles for temperature and dissolved oxygen in the four weir pools, which proved important for the adaptive management of flows, it was not clear who the relevant agency actually was to undertake the monitoring and assessment of the relevant water quality data.

Recommendation 1: The agency responsible for monitoring and assessment of water quality during events like the one that occurred in the lower Murrumbidgee River needs to be identified. That agency should undertake weekly depth profiles of dissolved oxygen and temperature in the lower Murrumbidgee River weir pools from the beginning of November to the end of March, and transmit results to relevant staff in a timely manner - especially if low dissolved oxygen levels are encountered.

The sampling program undertaken by WaterNSW, while valuable, could have been improved by adjusting the location of sampling away from the influences of the weir structures, as well as sampling the whole water column. This last point was particularly important in Hay Weir pool, where the bottom 3 metres of the water column was not sampled, and therefore it wasn't possible to tell if it was hypoxic or not, which in turn would influence whether or not the water column would become hypoxic if mixing occurred.

Recommendation 2: The relevant agency should undertake representative depth profiles in all weir locations that include the entire water column.

Field spot samples were undertaken to help inform the management flows to minimise the risk of further fish kills in the lower Murrumbidgee River. However, a detailed interrogation of the data collected was only undertaken once the threat at Redbank Weir had passed. If the data was interrogated during the risk period, environmental flows out onto the floodplain would most likely have ceased earlier, resulting in some water savings.

Recommendation 3: If field staff are being deployed to undertake spot measurements because of the risk of a hypoxic event, additional resources should be allocated so that the information is promptly interrogated, to inform management. Ideally the interrogation should occur within 24 hours of data acquisition.

The telemetered oxygen probes in the lower Murrumbidgee River are all downstream of the weir structures, and therefore did not detect the onset of hypoxia in the bottom waters of either Maude or Redbank Weir pools. Furthermore, the probes, particularly downstream of Redbank Weir, proved to be unreliable. Telemetered temperature probes in the weir pool would have alerted the fact the weir pools were stratified. Field sampling could then have been used to determine the oxygen concentration throughout the water column.

Recommendation 4: Telemetered temperature probes are deployed through the water column in each of the four lower Murrumbidgee River weir pools, and the results are routinely inspected to determine the extent and strength of stratification.

River management

Rainfall rejection flows proved problematical. Capture of a rainfall rejection flow in Maude Weir pool in early February would have most likely resulted in fish deaths. A decision to capture subsequent rainfall rejection flows in Maude Weir pool resulted in stratification and the reduction of dissolved oxygen concentrations in the bottom water. Luckily the weir pool mixed before the onset of hypoxia.

Recommendation 5: A workshop is held with key stakeholders to determine the best way to manage rain rejection flows in the Murrumbidgee River so as to maximise economic benefit, but at the same time ensure no environmental impact.

It is likely that one of the reasons that fish deaths like the one observed in the Murrumbidgee River in 2019 have not been observed recently is that inter-valley water transfers from the Murrumbidgee to the Murray River valleys provided sufficient flow to stop the onset of prolonged stratification. However, if one or more of the weir pools are stratified, inter-valley transfer flows would most likely result in mixing. Whether or not mixing would lead to hypoxia would depend on the oxygen concentrations throughout the water column prior to the flow reaching the weir pool.

Recommendation 6: That low inter-valley transfer account status be identified as a key risk factor for stratification/fish kills by river operators, and communicated to other relevant agencies. The thermal status and oxygen concentrations in weir pools should be taken into consideration when planning inter-valley transfer flows.

Prolonged stratification is unlikely to form in shallow, flowing river reaches. Therefore, if climatic conditions are forecast that could lead to stratification, one strategy for minimising the risk of fish kills caused by hypoxia following destratification would be to temporarily 'decommission' the in-river storages in the lower Murrumbidgee River.

Recommendation 7: Develop a set of rules, based on both predicted temperatures and consumptive demand, to determine periods for the temporary drawing down of in-river water storages in the Lower Murrumbidgee River.

Recommendation 8: If in-river water storages cannot be temporarily drawn down during periods where there is an increased risk of destratification leading to hypoxia, then, if present, hypoxic bottom waters need to be managed as a normal part of the weir management. This may mean the release of hypoxic bottom water to downstream reaches; and if so the impact on downstream aquatic communities and water quality needs to be assessed.

Re-oxygenation of hypoxic water released from the bottom of weir pools occurs naturally in the free-flowing section of river. The rate of re-oxygenation is enhanced by turbulence. One way to increase turbulence in the free-flowing sections of river is to re-introduce large woody debris (snags). Re-introduction of snags also has benefits for the ecology of the river.

Recommendation 9: Increase the amount of large woody debris downstream of the Lower Murrumbidgee river weir pools to increase turbulence in the river, as well as providing habitat for large-bodied native fish, and a substrate for the growth of biofilms.

Knowledge gaps

Much of the planning associated with the adaptive management of flows to prevent further fish kills in the Murrumbidgee River in 2019 revolved around predicting the likelihood of future destratification events leading to hypoxia. Having a validated numerical tool to inform forecasting would have improved the certainty around forecasts. The tool could also be used in long-term planning of flows, as well as used in scenario testing. A three-phase approach is suggested firstly involving the development of a simple desktop tool, followed by field testing and validation, and finally integrating the tool into river management systems with automatic updating of actual and predicted climatic data.

Recommendation 10: Develop a tool that can predict stratification and destratification events in weir pools based on the predicted weather patterns, flows, and weir levels; and if they do destratify, whether or not it will result in hypoxia.

One of the observations from the monitoring program was that the rate of oxygen drawdown following stratification was much more rapid in some weir pools (e.g. Maude Weir pool) than in other weir pools (e.g. Hay Weir pool). This most likely is a consequence of different rates of oxygen consumption by bacteria in the sediments. Accurate predictions of hypoxia risks (Recommendation 10) requires a good understanding of the rates of oxygen consumption following the onset of stratification.

Recommendation 11: Initiate a study to determine the spatial variability in sediment oxygen demand in Hay, Maude, Redbank and Balranald Weir pools.

One of the tasks during the adaptive management of flows to prevent further fish kills in the Murrumbidgee river weir pools was predicting the dissolved oxygen in the water column if or when the weir pools mixed. This was based on mas-balance calculations using an (over-simplified) assumption that the weir pool profile was uniform. Predictions of the dissolved oxygen concentration in the weir pools following mixing would have been improved by a more detailed understanding of the weir pool bathymetry.

Recommendation 12: Prepare bathymetric maps of Hay, Maude Redbank and Balranald Weir pools.

Export of water with low dissolved oxygen concentrations from the bottom of the weir pools through undershot weirs most likely prevented fish kills in Maude Weir, and contributed to the prevention of potential fish kills in Redbank Weir. Modelling suggests that the hypoxic water is re-oxygenated in the free-flowing sections of the river (discussed above). Monitoring of future hypolimnetic releases of water can help refine these models.

Recommendation 13: Monitor oxygen levels downstream of undershot weirs during water releases to determine the rate of water re-aeration. This data can then be used to refine models so they specifically reflect conditions in the lower Murrumbidgee River.

1. Objectives

On the 31st of January thousands of dead fish, including Murray cod, golden perch, silver perch bony herring (bream) and carp were observed in Redbank Weir on the Murrumbidgee River (NSW DPI, undated). The fish kill coincided with the last of three major fish kills upstream of Weir 32 on the Darling River (Vertessy et al, 2019)

The objectives of this report are to:

1. Determine the proximate cause or causes of the fish kill that occurred at Redbank Weir in late January 2019.
2. Examine management responses to the fish kill, specifically the use of environmental water, to improve fish habitat and mitigate poor water quality conditions in Redbank Weir and, prevent other fish kills in Maude and Balranald Weir pools.
3. Report on monitoring efforts before, during and immediately after the fish kill in order to inform future monitoring programs.
4. Make recommendations on potential ways the river can be operated into the future to minimise fish kills.

2. Data

This report is based on data collected from a number of sources:

Telemetered instantaneous flow, and where available, dissolved oxygen and temperature were obtained from the WaterNSW real time website (www.realtimedata.waternsw.com.au) for the sites *Carathool Bridge* (site number 41000281), *Downstream of Hay Weir* (410136), *Downstream of Maude Weir* (410040), *Downstream of Redbank Weir* (410041), *North Redbank Channel at Glendee* (41000255) and *Downstream of Balranald Weir* (410130).

In-river storage heights were obtained from the WaterNSW real time website (www.realtimedata.waternsw.com.au) for the sites Hay Storage (41010928), Maude Storage (41010941) and Redbank Storage (41010966).

Air temperature data was obtained from the Bureau of Meteorology Climate Data Online (www.bom.gov.au) for the towns of Menindee (Station number 047019) and Balranald (Station Number 049002).

Weekly depth profiles of water temperature and dissolved oxygen concentration at Hay, Maude, Redbank and Balranald Weir pools (Figure 1) for the period 21st January - 27th March 2019 were supplied by WaterNSW to the NSW Office of Environment and Heritage (OEH). Depth profiles were taken near the weir structure.

Spot water temperature and dissolved oxygen concentrations profiles were collected by OEH and Charles Sturt University staff at:

- Four sites (0 - 2 km) downstream of Maude weir on the 30th January 2019;
- at up to 6 sites (0-4 km) upstream of Redbank Weir on the 3rd January and 5th, 9th, 10th, 11th and 13th February;
- Up to 7 sites (0-5 km) downstream of Redbank Weir on the 3rd January and 5th, 9th, 10th, 11th and 13th February;
- At Balranald Caravan Park on the 6th and 10th February;

- At up to 8 sites (0 - 4 km) upstream of Balranald Weir on the 7th, 10th 12th and 13th February.

Logged continuous dissolved oxygen concentrations and water temperatures were collected using D-Opto data loggers (Zebra Tech) deployed at three depths (near-surface, mid-column and near-bottom) at:

- Woolpress Bend (approximately 18.5 km above Redbank Weir (coordinates -34.33428, 143.89517) from the 7th February 2019 to 18th March 2019;
- Approximately 1 km upstream of Redbank Weir (coordinates -34.37588, 143.78741) from the 7th February 2019 to 18th March 2019;
- Adjacent to Balranald Caravan Park (coordinates-34.646200, 143.562470) from the 14th January 2019 to the 18th March 2019;
- Approximately 500m upstream of Balranald Weir (coordinates -34.665048, 143.495650) from the 14th January 2019 to the 18th March 2019.

Figure 1: Location of the four weir pools along the Lower Murrumbidgee River.

3. January 26th - 27th Fish Kill

Although the fish kills were first reported on the 31st January 2019, eye-witness accounts place the fish kill on the night of the 26th - 27th January. The fish kill that occurred at Redbank Weir on the Murrumbidgee River on the 26th -27th January was almost definitely caused by destratification of the weir pool, which mixed the bottom 3.5 - 4.5 m of the water column in the weir pool (which contained very low oxygen concentrations) with slightly better oxygenated surface water. The dissolved oxygen in the now mixed water column was below the lethal threshold for fish, and they died (discussed in more detail in Section 3.2). Generally, large bodied native fish begin to show signs of distress at oxygen concentrations of about 4 mg/L (Gehrke 1988) and mortality begins at concentrations of between 2 mg/L (Gehrke, 1988) and 3 mg/L (Small et al., 2014).

3.1 Stratification

At its simplest, in very low- or non-flowing waterbodies during the day, the surface of the waterbody heats up more rapidly than the deeper water. The warmer surface water is less dense than the colder bottom water so they tend not to mix. During the night the surface water cools down, and if it cools to the same or lower temperature than the bottom water mixing occurs. However, if the surface water does not cool down sufficiently, mixing does not occur so that during the next day, the temperature difference between the surface and bottom waters increases, strengthening the degree of thermal stratification and making it harder to mix the following evening. Ultimately this can lead to the situation where the surface water and deeper water do not mix for a prolonged period - they are separated by a clear temperature boundary (called the thermocline) and the waterbody is said to be **stratified.**

Oxygen levels in the surface waters are continually replenished from the atmosphere. However, during stratification, because the surface water and deeper waters don't mix, oxygen levels in the bottom water are not replenished. As oxygen in the deeper water is consumed through respiration (particularly by microorganisms in the sediment at the bottom of the waterbody) the oxygen concentration begins to fall. Therefore, we can end up with the situation where the waterbody is separated into two distinct layers - a warm, relatively well oxygenated surface layer and, a cooler, oxygen-depleted bottom water.

In deep waterbodies like large lakes and reservoirs, where the thermocline is well below the surface, stratification can last for many months - or even indefinitely. In shallow waterbodies, where the thermocline is shallower and the temperature difference between the surface and the bottom is not as great as in deeper waterbodies, the surface and bottom layers are more easily mixed by periodic climatic events such as storms or cool changes. Strong winds, lower air temperatures and increased inflows (either from rain events or managed flows) can all lead to the breakdown of stratification. This is discussed in more detail in Appendix 1. As the surface and bottom water mix, the overall water temperature will fall, as will the concentration of dissolved oxygen.

Weir pools are susceptible to periods of stratification and destratification. They are much deeper than free flowing sections of the river and therefore for the same volume of flow per unit of time, flow velocities are reduced, therefore more likely to stratify. However, they are usually not very deep (typically 5 -10 metres in Australian lowland rivers) so climatic conditions can lead to sporadic destratification (Bormans and Webster 1997, 1998; Mitrovic et al., 2011). Furthermore, because of the low flow velocity weir pools tend to be deposition zones, so the bottom sediments accumulate carbon, and therefore sediment oxygen demand tends to be higher in weir pools than in free-flowing sections of river.

3.2. The Redbank Weir Fish Mortality Event

The fish mortality event on the 26th-27th January coincided with a cool change - with maximum air temperatures falling from 47 °C on the 25th January to 25 °C on the 27th January (Figure 1).

Dissolved oxygen and temperature profiles recorded on the 24th January clearly showed that Redbank Weir was stratified - with a temperature difference between the surface and bottom water of about 4 °C (Figure 3A). While there wasn't a distinct thermocline, there was a distinct oxycline at about 2 metres (Figure 3B). The dissolved oxygen concentration below about 2 metres was less than the concentration known to be lethal for large bodied native fish (Gehrke 1988; dotted line - Figure 3B).

The Redbank Weir pool was re-sampled on the 29th January. The dissolved oxygen concentration throughout the water column was close to 0 mg/L (Figure 3D). Interestingly, 3 days after mixing a thermocline had again formed (Figure 2C).

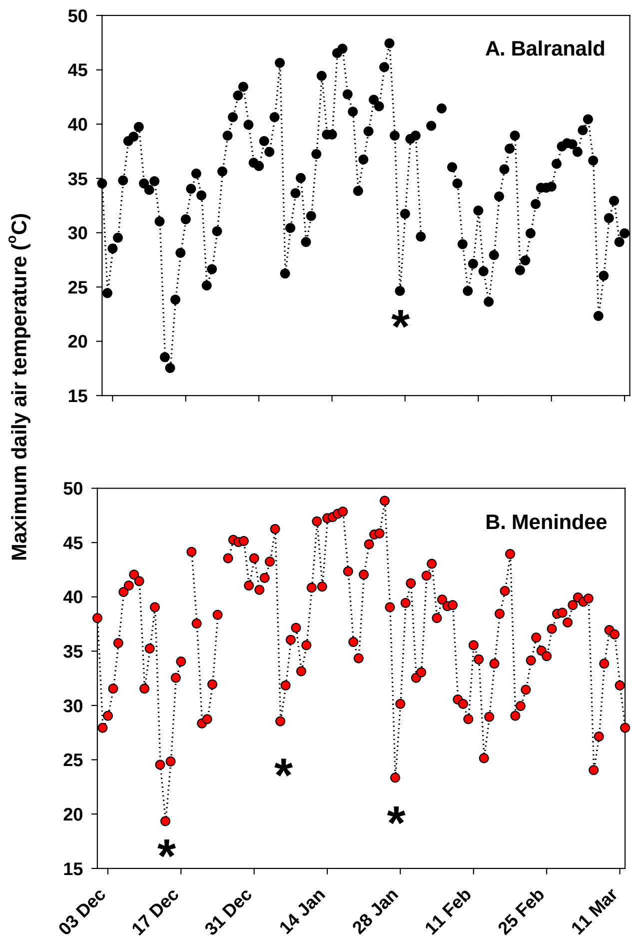

Figure 2: Maximum air temperatures recorded at Balranald (top panel) and Menindee (bottom panel) from December to mid-March 2019. The * symbol indicates instances of the death of a large number (≥ 5000) of fish in Redbank Weir on the Murrumbidgee River and upstream of Weir 32 on the Darling River.

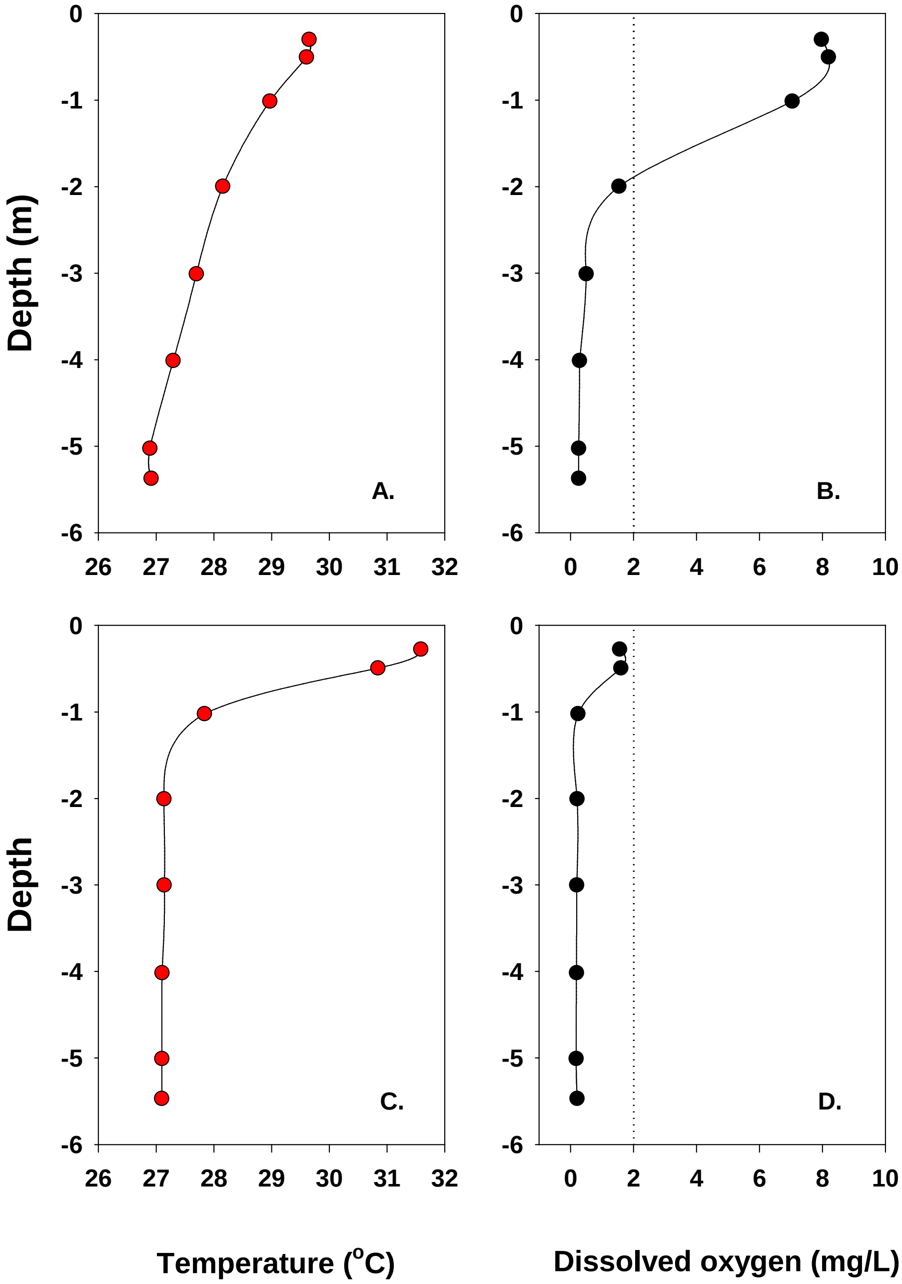

Figure 3: Temperature (A) and dissolved oxygen concentration profiles (B) in Redbank Weir pool on the 24th January 2019 compared to temperature (C) and oxygen profiles (D) measured on the 29th January.

3.3. Why didn't fish kills occur earlier, or in other weir pools?

The fish kill on 26th - 27th January at Redbank Weir occurred at the same time as a fish kill in the Darling River at Menindee, and was associated with the same cold front (Figure 2). Interestingly 2 other cold fronts in mid-December 2018 and early January 2019 both resulted in fish deaths at Menindee. A small number of dead fish (<10) were reported in Redbank Weir in December and in early January in Balranald Weir pool (NSW DPI, undated), but there is insufficient data to determine if these were caused by destratification.

Although both Hay Weir pool (Figure 4A) and Maude Weir pool (Figure 4C) were thermally stratified prior to the cool change arriving on the 26th- 27th January, dissolved oxygen in the bottom waters at both sites were generally quite good (Figure 4B and D respectively; but also see Section 4.2). Prior to the cool change arriving, Balranald Weir pool - at least at the sampling site near the weir wall, was mixed (Figure 4 E and F; but also see Section 4.4).

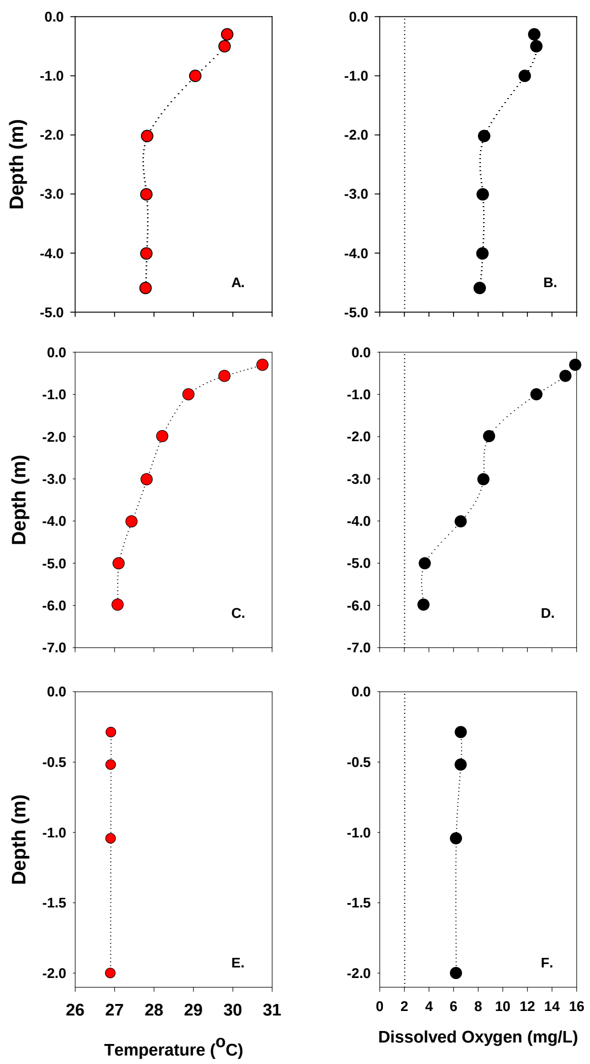

Figure 4: Temperature (A) and dissolved oxygen (B) profiles in Hay Weir pool, temperature (C) and dissolved oxygen profiles (D) in Maude Weir pool and temperature (E) and dissolved oxygen(F) profiles in Balranald Weir pool prior to the cool change that resulted in the fish kill in Redbank Weir.

3.4 Role of Blue-Green Algal Blooms in the fish kills

At the time of the fish kill the blue-green algae counts were at amber alert levels in Redbank Weir pool (Water NSW Algal Alert Bulletin - 14th February 2019; although actual biovolumes were not reported). It is doubtful that the fish deaths were directly attributed to the blue-green algal bloom. High levels of blue-green algae were observed in Hay, Maude and Redbank Weirs in December 2018, without any evidence of fish deaths (Figure 5). That is not to say that the blue-green algae did not indirectly contribute to the fish deaths observed at Redbank Weir. Algae produce oxygen during photosynthesis (which occurs only during the daytime), but consume oxygen during respiration. This means that during bloom conditions the dissolved oxygen levels in the surface layer can be quite high during the day, while during the night the levels fall. The diurnal shifts in oxygen levels can be quite extreme. Both undersaturation and supersaturation will be harmful for native fish. At low oxygen concentrations it is difficult for the fish to get enough oxygen for respiration. At oxygen above about 120% saturation air bubbles can form on fish gills, preventing them from functioning effectively (gas bubble disease - e.g. see Weitkamp and Katz, 1980). Therefore, while the algal bloom did not directly impact on the fish population, the algal bloom's impact on oxygen concentration in the surface layer may have indirectly impacted on the fish population by putting them under oxygen stress.

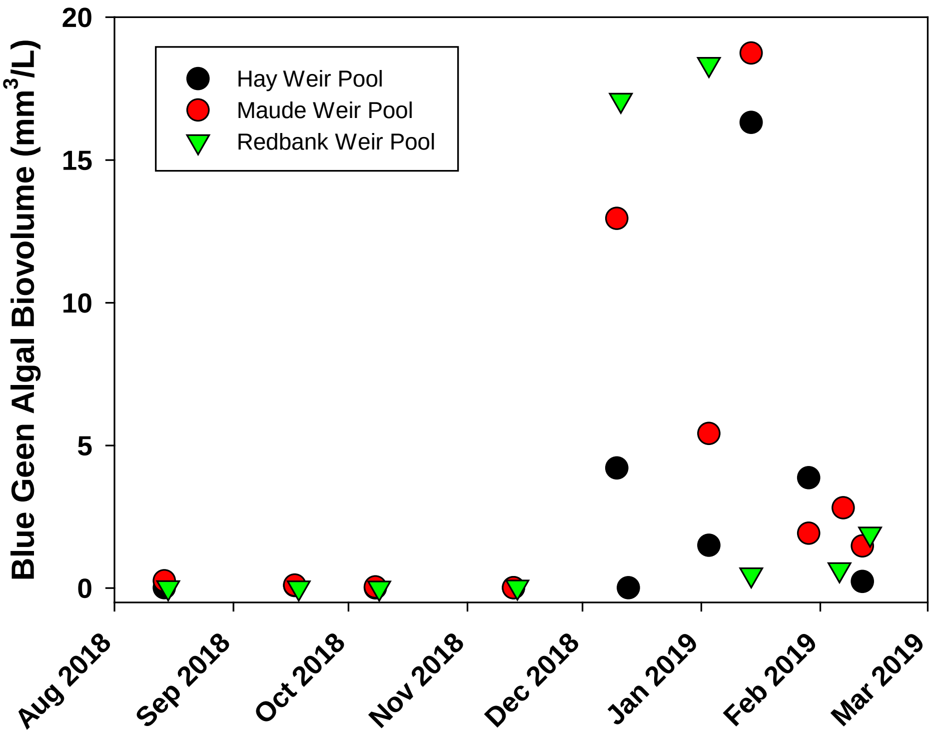

Figure 5: Blue-green algal biovolume recorded in Hay (black circles), Maude (red circles) and Redbank (green triangles) Weir pools from August 2018 until mid-March 2019.

The main blue-green algal species in Redbank Weir was identified by WaterSNW as *Dolichospermum sp*, previously called *Anabaena sp.* This species is known to produce toxins including saxitoxin; a potent neurotoxin. Saxitoxins are quite stable, water soluble, tasteless, odourless and can be bioaccumulated in freshwater fish. Saxitoxin can kill fish (e.g. Oberemm et al, 1999). Although it is possible that the fish deaths were caused by (or at least heightened) by algal toxins, the observation that there were no fish deaths prior to the end of January, when an algal bloom was in place in December, suggests that exposure to algal toxins was not the principal cause of the fish mortality event.

3.5 Why haven't these types of fish kills been observed in the Murrumbidgee River before?

Generally, in the last decade, fish kills in the Murrumbidgee have been associated with blackwater events. Blackwater events occur when flood waters, rich in organic carbon leached from floodplain litter returns to the main river channel. If microbes can consume the dissolved organic carbon in the floodwater faster than it can be replenished from the atmosphere, the oxygen levels in the water columns can become anoxic - resulting in fish kills. Blackwater events have been observed in the Murrumbidgee in 2010 (Whitworth et al., 2012), 2012 (Whitworth et al., 2013) and, to a lesser extent 2016 (J. Maguire, *pers. comm*).

Although there have been reports of fish deaths attributable to destratification of pools in the Darling River, none of the previously reported fish kills in the Murrumbidgee River can unequivocally be attributed to destratification (although there are a couple of potential instances - discussed in more detail in Appendix 2).

One of the reasons that made 2019 unusual is the extreme temperatures recorded in January. The Bureau of Meteorology reports that the mean number of days in January when the maximum daily temperature is ≥ 35 ^{o}C at Balranald is 9.3 days and the mean number of days when maximum daily air temperature is ≥ 40 ^{o}C is 3.2 (Figure 6). January at Balranald was unusually hot, with 22 days that had maximum daily air temperatures ≥ 35 ^{o}C of which 11 were ≥ 40 ^{o}C. Air temperature is strongly linked to both stratification and destratification in weir pools (Webster and Bormans 1997 and 1998 - also see Appendix 1). Furthermore, because the rate of microbial respiration (the driver of anoxia in the hypolimnion; e.g. Baldwin et al, 2014) increases with increasing temperature, warmer temperatures means a greater likelihood of anoxia in bottom waters. Furthermore, warmer temperatures place stress on large-bodied fish. Because native fish are cold-blooded (ectotherms), as the water temperature increases, so should their metabolic rate and hence their oxygen requirements. A metastudy (Clarke and Johnston, 1999) suggests that for every 10 degree rise in temperature (between 0 and 30 ^{o}C) causes a 2.4 times increase in resting oxygen metabolism. Furthermore, resting oxygen metabolic rate increases with body weight. Therefore, the warmer the water (and the bigger the fish) the more oxygen the fish will require.

Another contributing factor this year may have been the lack of inter-valley water transfers between the Murrumbidgee and Murray Rivers. Since the introduction of inter-valley water trade in the late 1990's, the underlying trend has been for water allocations to be transferred (sold) from the Murrumbidgee to the Murray Valley. These allocations are accumulated into an IVT account (administered by Water NSW and DOI Water), which is physically called on to reconcile IVT account balances to prevent bulk shares of water being distorted between the two water supply systems. MDBA (Murray) river operators have called on IVT accounts during the peak irrigation demand period (over the hottest summer conditions) when needed to boost capacity to supply Sunraysia and South Australian demands. These flows are – by coincidence - likely to have had the effect of preventing, or alleviating, stratification in lower Murrumbidgee weir pools.

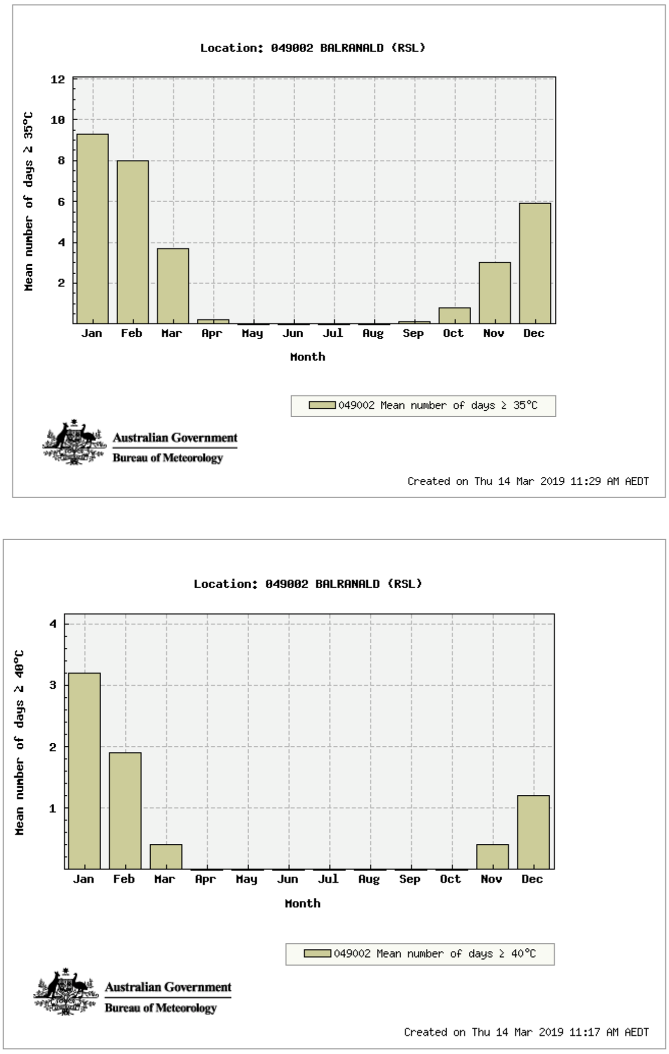

Figure 6: Mean number of days per month with temperatures ≥ 30 ^{o}C (top panel) and ≥ 40 ^{o}C (bottom panel) at Balranald (source - Bureau of Meteorology).

However, the water market in 2018/19 reversed the direction of IVT into the Murrumbidgee – which may be attributed to the development of both cotton and horticulture in the Murrumbidgee valley, and the likely effect on water market/demand. The absence of IVT account volumes available to order to the Murray contributed to very low flows in the lower Murrumbidgee over mid-summer for the first time in many years. To illustrate this point, Figure 7 shows the flow downstream of Balranald Weir from November 2014 to March 2015 compared to the same period in 2018/19. In 2014/15, for most of the period from the beginning of December to the end of February the flow downstream of Balranald Weir was greater than 1500 ML/day. Given the attenuation of flows between Redbank Weir and Balranald Weir, the flows at both Maude and Redbank Weirs would most likely have been higher. Although the relationship between flow and stratification is complex (see Appendix 1), Bormans and Webster (1998) showed that stratification, at least at Maude Weir, only occurred at flows less than about 1000 ML/day. Therefore, in years with substantial inter-valley transfers, it is unlikely that stratification could develop in the lower Murrumbidgee River weir pools because of relatively high flows.

However, without environmental water orders or intervalley transfers, under the Murrumbidgee River Water Sharing Plan, the minimum legislated daily flows for the Murrumbidgee River at

Balranald Weir are 254 ML/day in December, 186 ML/day in January and 180 ML/day from February to the end of April (NSW Government, 2016; also see Appendix 3).

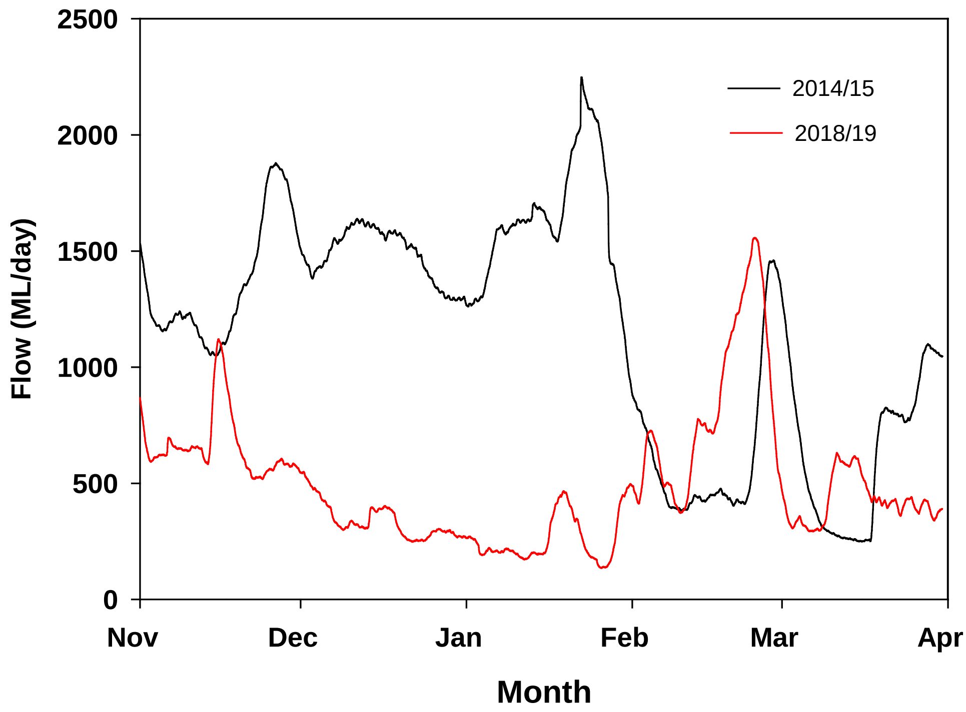

Figure 7: Flows downstream of Balranald from November to March (inclusive) in 2014/15 (black line) and 2018/19 (red line).

4. Flows, Weir Pools and Water Quality

This section explores the relationship between flows and dissolved oxygen in the 4 lower Murrumbidgee River weir pools from late January to early April 2019. Particular emphasis is given to assessing the effectiveness of environmental water in mitigating or preventing hypoxic events. Although clearly interconnected, each weir pool will be considered separately.

4.1 Hay Weir Pool

Dissolved oxygen and temperature have been monitored in Hay by WaterNSW on a weekly basis since 21st January 2019. Low dissolved oxygen concentrations were only observed once during that period. Dissolved oxygen concentrations were around 2.7 mg/L below a depth of 4 metres on 6th March (Figure 8). However, it must be noted that although the weir pool level steadily increased from about 6.6 metres at the beginning of January 2019 to 8.6 metres (near full capacity), where it remained essentially constant until the beginning of April, dissolved oxygen and temperature profiles were only measured to a maximum depth of 5.5 metres. Therefore, it is possible that bottom water may have been hypoxic at other times.

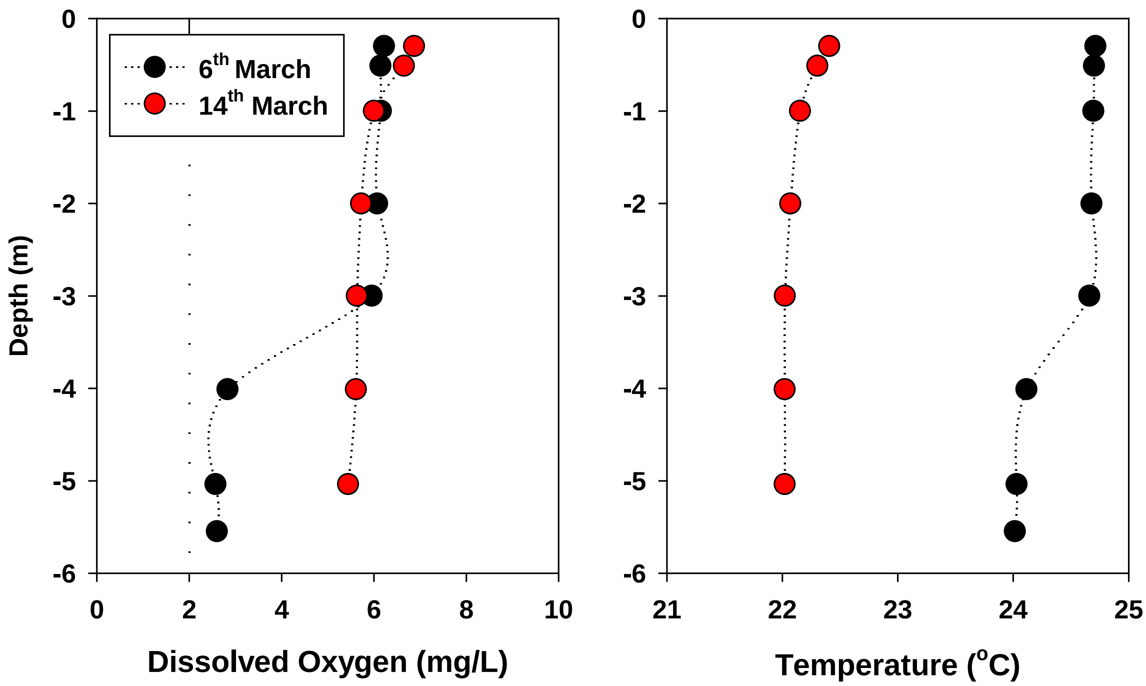

Figure 8: Dissolved oxygen (left panel) and temperature (right panel) profiles in Hay Weir pool measured on the 6th March (black circles) and 14th March (red circles).

The lack of apparent hypoxia in Hay Weir pool up until the beginning of March is most likely a consequence of inflows into the weir pool, which either prevented stratification from occurring in the first place or deepened the surface mixed layer. Based on flows recorded at Carrathool Bridge (Site 41000281) there were four pulses of flow into Hay Weir pool with peak flows above 2000 ML/day in January, and two pulses (both rainfall rejection flows, which will be discussed in more detail in Sections 4.2 and 4.3) in February - with flow peaks of about 3500 ML/day (Figure 9). It is of note that flows passing through the Hay Weir pool in December 2018 and January 2019 were predominantly environmental flows on transit to the lower Murrumbidgee River wetlands (J. Maguire, OEH, pers. comm.) It was only after the middle of February that inflows into Hay Weir pool consistently fell to below about 1000 ML/day. After the onset of the low inflow period, hypoxia was observed in deeper water in Hay Weir pool on the 6th March. The weir pool remixed following a cool change on 13th March, with no adverse impacts on water quality (Figure 8).

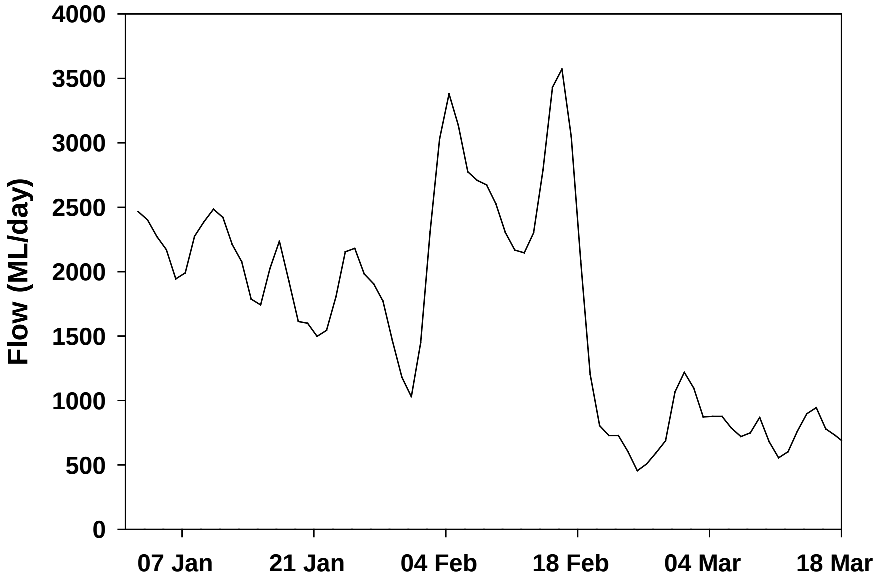

Figure 9: Flows in the Murrumbidgee River measured at Carathool Bridge, upstream of Hay Weir, from the beginning of January until mid-march, 2019.

4.2 Maude Weir Pool

An environmental flow was planned prior to the fish kill in Redbank Weir. From mid-January to early April 2019 the plan was to increase total flows over Balranald Weir by 200 ML/day above that stipulated in the Murrumbidgee River Water Sharing Plan (see Appendix 3) by lowering the water level in Maude Weir pool. The objectives of the environmental watering event were to improve native fish habitat and water quality in Balranald Weir pool and simultaneously to lower the water level in the Maude Weir pool to the point where the gates could be removed to allow for fish passage between the weir pool and the downstream reach. Drawdown of Maude Weir pool commenced on about the 24th January.

As noted above (at Section 3.2) dissolved oxygen concentrations were adequate in Maude Weir pool prior to the fish kill at Redbank Weir. However, the dissolved oxygen levels in the bottom water in Maude Weir pool had substantially declined by 29th January (Figure 10)[1]. Average dissolved oxygen levels below 2 metres fell from 6.2 mg/L on the 21st January to 2.4 mg/L on the 29th of January.

Because Hay Weir pool was at capacity, the rain rejection flows discussed in Section 4.1 (Figure 9) would be passed through Hay Weir and would reach Maude Weir on or about the 7th February - with flows estimated to be above 2000 ML/day. Bormans and Webster (1998) presented data that indicated that flows above about 1300 ML/day could destratify Maude Weir pool (derived from their Figures 1 and 2).

Mass balance calculations estimated that if the rate of oxygen depletion in the bottom water observed between the 21st and 29th of January remained the same and, the water level was kept at 4.5 metres, by the time the rainfall rejection flow reached Maude Weir pool the bottom water would have been hypoxic (< 2mg/L). The increased peak discharge created by the rainfall rejection

[1] The temperature data recorded in Maude Weir Pool on the 21st and 29th January suggests that the cool change that caused Redbank Weir Pool to mix, cased a significant weakening of the thermocline in Maude Weir Pool, but did not cause destratification (data not shown).

flow would have exceeded 1300 ML/day, causing destratification (as indicated by Bormans and Webster 1998). The subsequent mixing means the oxygen concentration throughout the water column would have fallen to about 1 mg/L, before recovering.

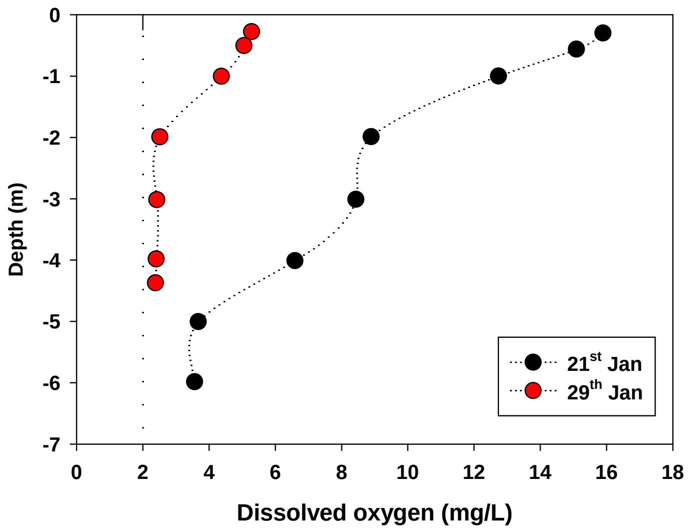

Figure 10: Dissolved oxygen profiles in Maude Weir pool on the 21st January (black circles) and 29th January 2019. The dashed line is the concentration of dissolved oxygen that can cause fish deaths.

The decision was made to continue the drawdown of the weir pool (Figure 11). Because Maude Weir is an undershot weir, water would be drawn from the bottom waters, hence the water with the lowest dissolved oxygen concentrations would be removed from the weir pool and flushed downstream (discussed in Section 5). By the time, the rain-rejection flows reached Maude Weir pool, the weir level was at 2.48 m (Figure 11). Dissolved oxygen concentrations in the weir pool on the 7th February were between 6.3 - 6.4 mg/L throughout the water column. Therefore, it can be strongly argued that lowering the water level in Maude Weir prevented fish kills in the weir pool.

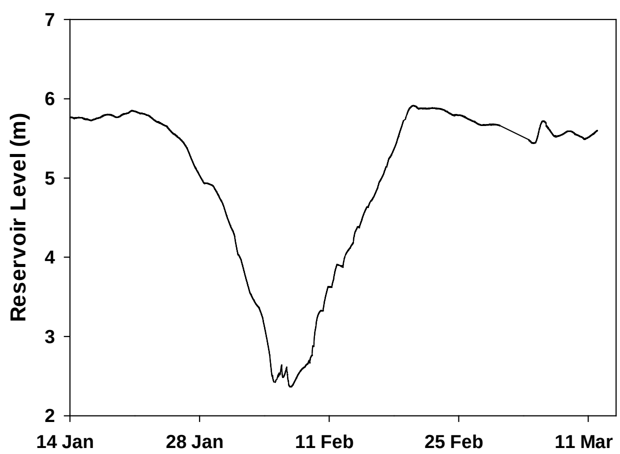

Figure 11: Water levels in the Maude Weir pool measured from mid-January to mid-March 2019.

A decision was made by WaterNSW in mid-February to capture the rain rejection flow in Maude Weir. Alternatively, for the drawdown to continue, the volume of water that would have been captured in the Maude Weir in-river storage would need to be debited from environmental water holder's accounts. This meant that the gates were never fully removed from Maude Weir, and hence conditions for fish passage were never attained.

By the 6th March an oxycline had begun to reform in Maude Weir pool, when the weir pool was at close to full capacity. On the 6th March dissolved oxygen concentrations at the surface of the weir pool was about 10 mg/L, while the bottom water concentration was 4.6 mg/L. The weir pool destratified following a cool change on the 13th March, but dissolved oxygen concentrations remained above 6 mg/L throughout the water column (data not shown).

4.3 Redbank Weir

4.3. 1 Flow decisions

As noted in Section 3, fish kills occurred in Redbank Weir on the 26th- 27th January 2019. At the time of the fish kill event Redbank Weir was nearly at full capacity (Figure 12). Just prior to the fish kills, the water being released from Maude Weir to increase the flow over Balranald Weir (see Section 4.2 above) was allowed to pass through Redbank Weir (marked as A on Figure 13) with increased flows starting on the 25th January.

It is unlikely the increase in flows (from about 350 ML/day to about 650 ML/day) would have been enough to disrupt the thermocline and directly cause the fish kills. Although the flows from Redbank Weir had not substantially changed between the 25th January (when increased flows commenced) and the 30th January, a thermocline had reformed by the 29th January (Figure 3) and had significantly deepened by the 30th January (Figure 14).

At the Technical Advisory Group meeting on the 29th January, the collective decision was to consider the drawdown of Redbank Weir as well as continuing the drawdown of Maude Weir. The initial drawdown of Redbank Weir pool coupled with the continued drawdown of Maude Weir pool, resulted in greater than expected flows below Redbank Weir - peaking at about 2000 ML/day (marked at B on Figure 13). This resulted in a total of about 4000 ML being moved downstream between the 31st January and 2nd March.

In addition, an option to remove a build-up of dead fish carcasses in and around the Glendee offtake inlet channel was discussed. By diverting the water containing the carcasses through the Glendee regulator, a source of additional carbon (from decomposing fish) could be removed from the main stem, thereby reducing the risk of fuelling further fish kills. A total of 200 ML of water was diverted through the Glendee regulator on the 31st January to help remove dead fish out of Redbank Weir pool.

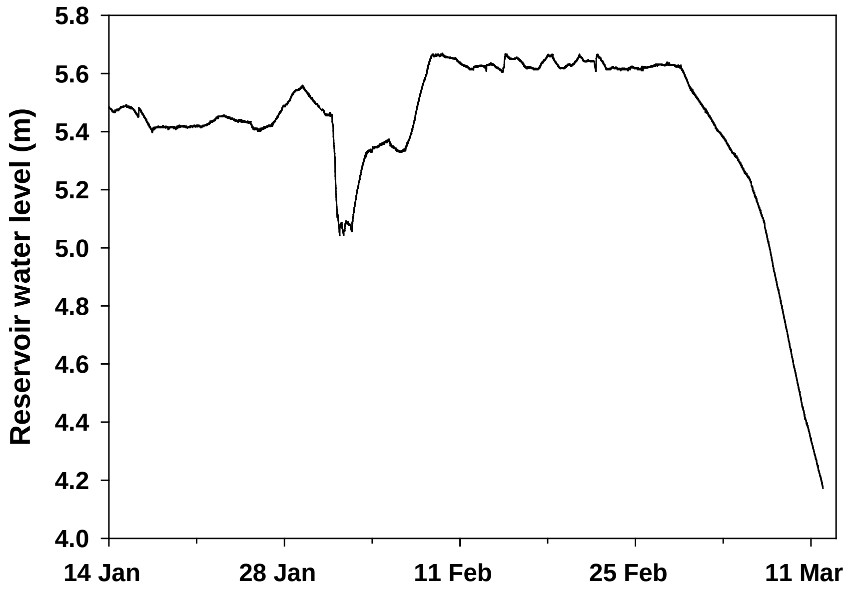

Figure 12: Water levels in Redbank Weir from mid-January to mid-march 2019.

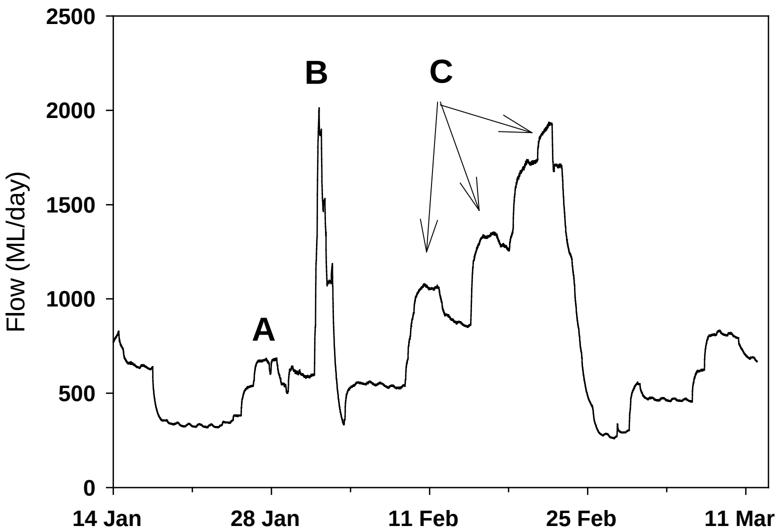

Figure 13: Flows from Redbank Weir from mid-January to mid-March 2019. Increases in flows from the weir pool were associated with the original planned environmental flow (A), Increased flows associated with simultaneously drawing down Maude and Redbank Weir pools (B) and rain rejection flows from upstream of Hay Weir pool (C).

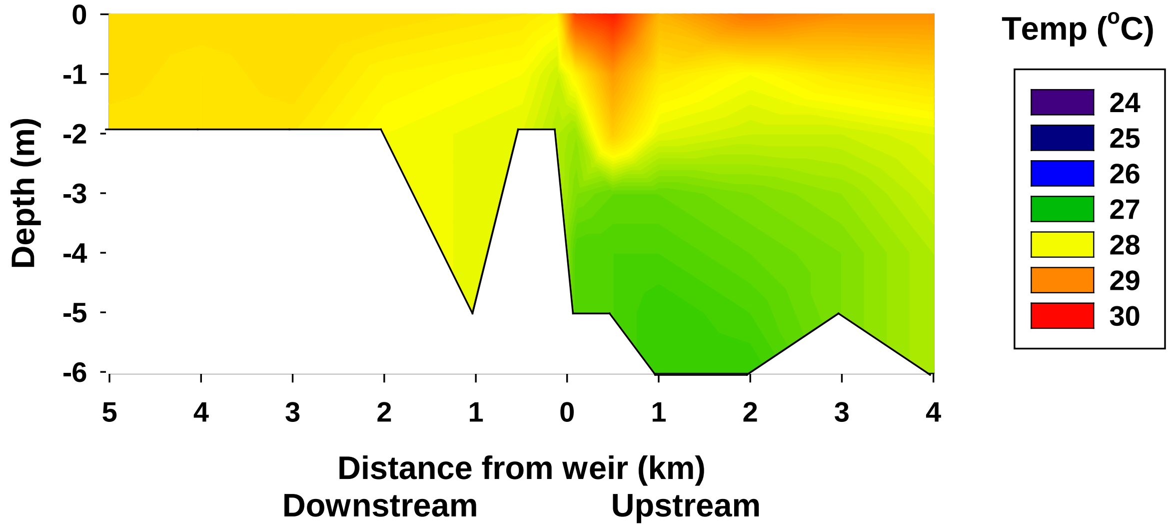

Figure 14: A contour plot of temperature upstream and downstream of Redbank Weir. The plot was constructed from a series of temperature depth profiles taken on the 30th January 2019.

On the 30th January WaterNSW announced that rain rejection flows above Hay Weir would result in higher flows in the lower Murrumbidgee River over the next few weeks (see Figure 9). As noted in Section 4.2, to prevent catastrophic destratification, the drawdown of Maude Weir pool continued. That would mean that the flow pulse couldn't be retained behind Maude Weir, and therefore would reach Redbank Weir (albeit with some attenuation of the flow peak), on about the 9th February. If not retained by Redbank Weir, it was expected that the increased flow would shunt a large volume of water low in dissolved oxygen (Figure 3 - also see Section 4.3.2 below), downstream towards Balranald Weir pool. A decision was made at the Technical Advisory Group Meeting on the 1st February 2019 to divert as much low dissolved oxygen water as possible from Redbank Weir pool on to the adjacent floodplain prior to the rain rejection flows reaching Redbank Weir by opening the Glendee, Yanga 1AS, Yanga 1ES and Patto's Pipe regulators (e.g. see Figure 15). A total of about 10,500 GL of water was ultimately diverted onto the floodplain in the first 3 weeks of February, approximately half of which was diverted prior to the arrival of the rain rejection flow at Redbank Weir on the 9th March.

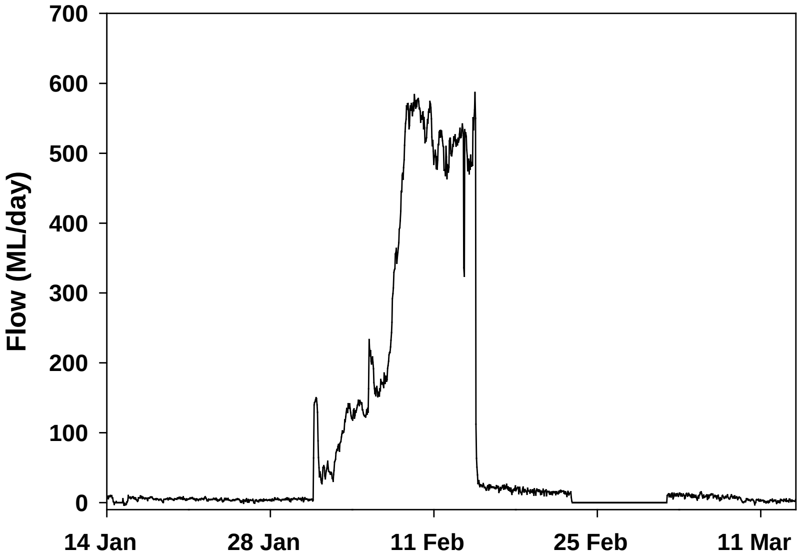

Figure 15: Flows from Redbank Weir through the North Redbank Channel at Glendee from mid-January to mid-March. The initial inflow was aimed at removing dead fish from the weir pool. The remainder of the flow was to divert water of poor quality from the weir pool onto the floodplain.

4.3.2 Dissolved oxygen

Following the mixing on the 26th of January that resulted in the fish kill event at Redbank Weir, the dissolved oxygen concentration behind the weir structure was particularly low. Figure 16 is a 2-dimensional (depth x length) representation of dissolved oxygen concentrations upstream and downstream of Redbank Weir based on a series of dissolved oxygen depth profiles taken on the 30th January 2019. Below a depth of about 0.5 m, all of the water in the weir pool (to at least 4 km upstream of the weir structure) was hypoxic. Immediately upstream of the weir structure there was a slight improvement in dissolved oxygen concentrations as slightly better oxygenated surface water was entrained with hypoxic bottom water as the water was released through the undershot weir. Immediately downstream of the weir structure there was a significant improvement in dissolved oxygen concentrations. This was most likely driven by re-oxygenation of water caused by turbulent mixing as the water passed under the weir - this is discussed in more detail in Section 5.

After the initial re-oxygenation at the weir wall, the dissolved oxygen concentration then decreased as the water moved further downstream (Figure 16). This suggests an additional source of bioavailable carbon driving microbial respiration, and hence oxygen concentration drawdown. The most likely source of carbon were the fish killed in Redbank Weir, which were washed downstream. If this was the case, then the decision to open up the Glendee Regulator to move fish carcases from the weir pool to the floodplain likely improved the dissolved oxygen concentration in the reach below Redbank Weir (less fish carcasses, less microbial respiration, improved oxygen concentrations).

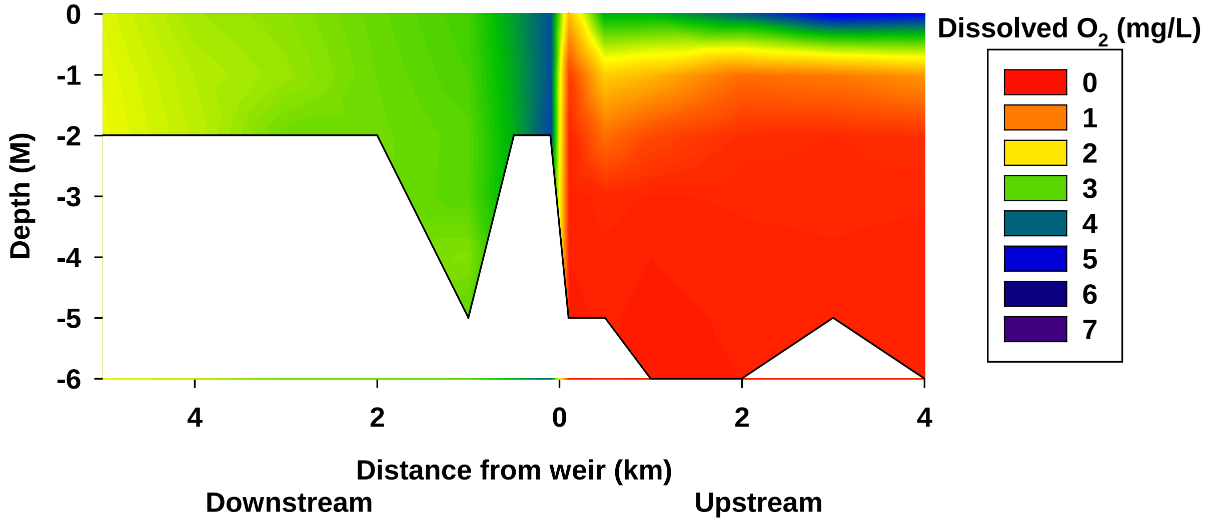

Figure 16: Dissolved oxygen concentrations upstream and downstream of the Redbank Weir Structure on the 30th January, 2019.

By the 5th February, the combination of the 4000 ML outflow downstream from Redbank Weir (from the 31st January to 2nd February), commencement of outflows from Redbank Weir onto the floodplain, and inflows of oxygenated water from upstream lead to an improvement of dissolved oxygen concentrations in the weir pool (Figure 17). The improved dissolved oxygen concentration profile downstream of the weir structure most likely reflected the higher concentrations of dissolved oxygen in both the surface and bottom waters in Redbank Weir, and the transport of the dead fish further downstream.

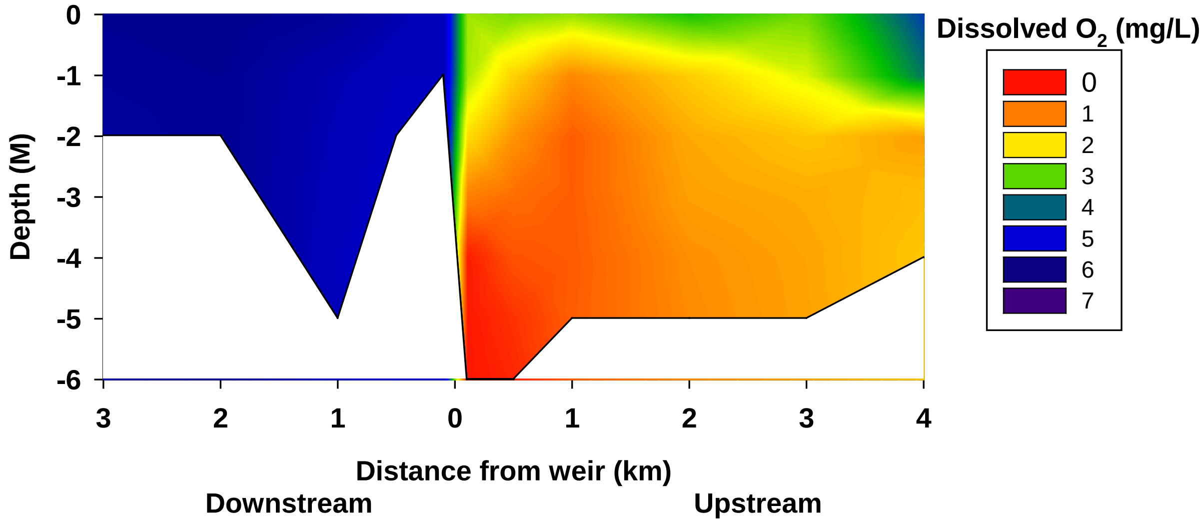

Figure 17: Dissolved oxygen concentrations upstream and downstream of the Redbank Weir Structure on the 5th February, 2019.

By the time the rain rejection flows reached Redbank Weir the dissolved oxygen concentrations behind the weir structure were suitable for large bodied native fish (Figure 18). Furthermore, the dissolved oxygen concentration in the rain rejection flows was quite good - in part because of the decision to drawdown Maude Weir.

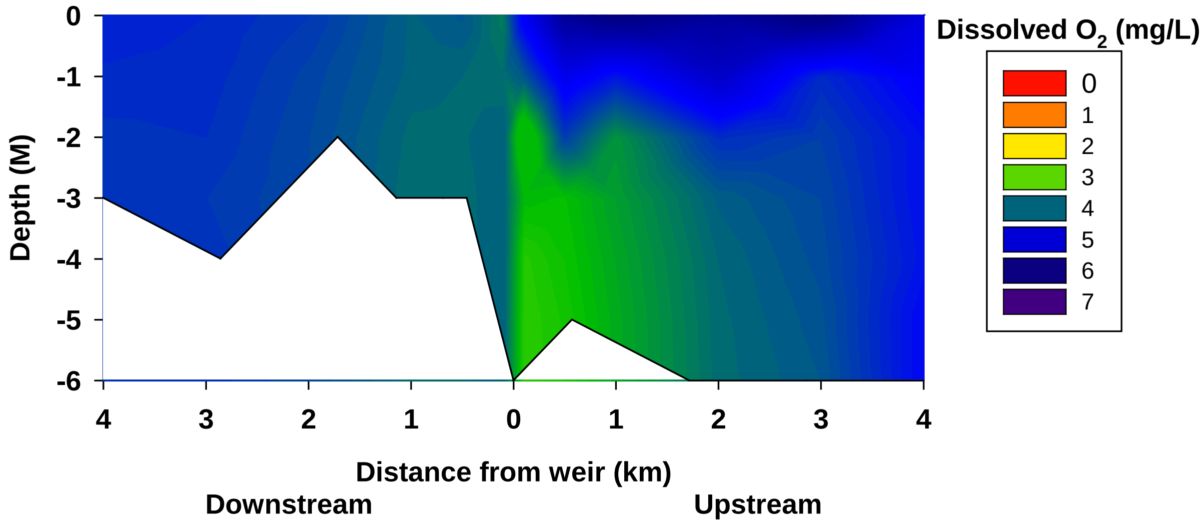

Figure 18: Dissolved oxygen concentrations upstream and downstream of the Redbank Weir Structure on the 9th February, 2019.

The dissolved oxygen concentrations in the weir pool continued to improve over the next several days (Figure 19)

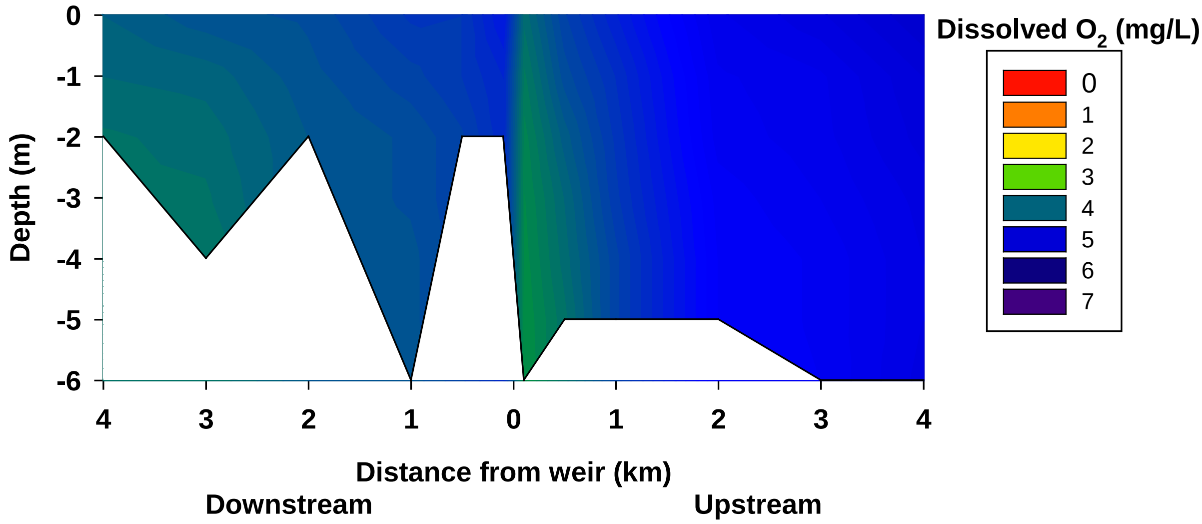

Figure 19: Dissolved oxygen concentrations upstream and downstream of the Redbank Weir Structure on the 11th February, 2019.

Dissolved oxygen and temperature loggers were deployed at sites approximately 1 km and 18.5 km (at Woolpress Bend) upstream of the Redbank Weir Structure from the 7th February to 17th March 2019. Both sites remained well mixed up until about the 24th of February when stratification commenced - with a corresponding decline in dissolved oxygen concentrations in the bottom water (Figures 19 and 20). The observation that stratification occurred at Woolpress Bend, 18.5 km upstream of the Redbank Weir Structure gives some indication of the length of the Redbank Weir pool (Figure 20). The commencement of stratification at both sites coincided with a substantial fall in inflows into the weir (Figure 22).

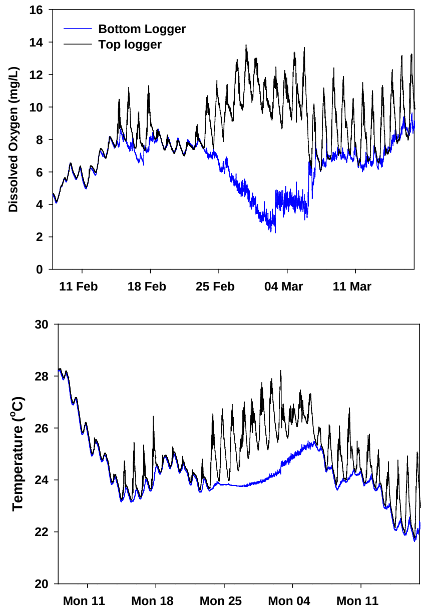

Figure 20: Dissolved oxygen concentration (top panel) and temperature (bottom panel) recorded at Woolpress Bend (approximately 18.5 km upstream of the Redbank Weir Structure from early February to mid-March 2019. The black trace is from the surface and the blue trace is from the bottom of the pool.

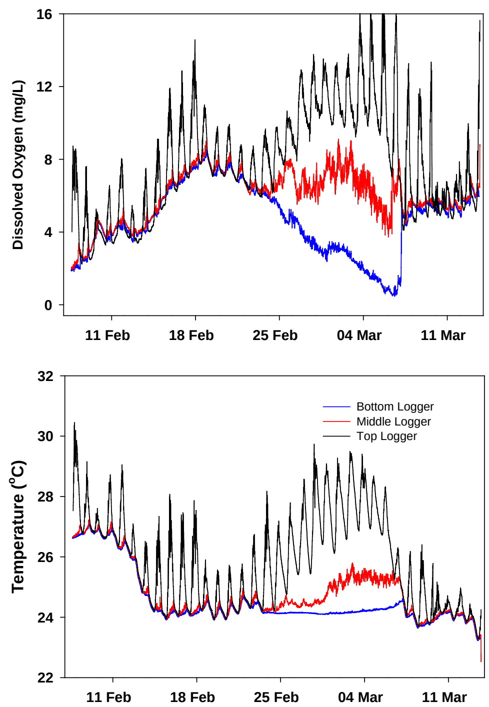

Figure 21: Dissolved oxygen concentration (top panel) and temperature (bottom panel) recorded at a site approximately 1 km upstream of the Redbank Weir Structure from early February to mid-March 2019. The black trace is from the surface, the red trace from mid-depth and the blue trace is from the bottom of the pool.

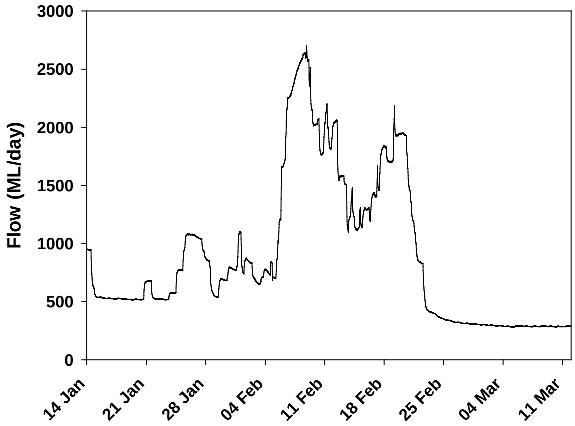

Figure 22: Flows recorded downstream of Maude Weir on the Murrumbidgee River from mid-January to mid-March, 2019. It takes water approximately 3 days to flow from Maude Weir to Redbank Weir.

Stratification continued in Redbank Weir pool until the 6th March, when a cool change arrived. Destratification associated with this cool change was also observed in Maude Weir (see Section 4.2) and Balranald Weir (see Section 4.4).

As an aside, dissolved oxygen depth profile was undertaken in Redbank Weir by WaterNSW the day prior to the arrival of the cool change (Figure 23). A simple mass balance calculation[2] based on the depth profile indicated that the dissolved oxygen concentration on mixing should have been about 5mg/L. The observed dissolved oxygen concentration on mixing at the site 1 km upstream of Redbank Weir Structure (taken from the data loggers) was about 4.2 mg/L - indicating the robustness of using simple mass balance calculations for predicting the likelihood of hypoxia on mixing.

4.4 Balranald Weir

The water quality in Balranald Weir was anomalous. As noted in Section 3, prior to the cool change that resulted in the fish deaths at Redbank Weir, Balranald Weir pool was relatively well mixed (Figure 4) with no evidence of hypoxia in the bottom waters (Figure 24.) Following the cool change on the 26th - 27th January the dissolved oxygen through the water column fell to between 1 and 2 mg/L (Figure 24). However, unlike Redbank Weir, where most of the water column was still hypoxic (Figure 17), by the 6th February, dissolved oxygen concentrations throughout the water column were above 4 mg/L (Figure 24).

While it is clear, is that Balranald Weir pool thermally destratified on the 26th- 27th January (Figure 25), the lowest dissolved oxygen concentrations weren't observed following mixing, as would be expected, but rather several days later - around the 29th and 30th January (Figure 26). Furthermore, the short period of hypoxia in the surface water was not associated with the observed death of any fish.

[2] It assumes a simple U-shaped channel with a flat bottom. The dissolved oxygen concentration between one depth and the next is assumed to be constant. It is also assumed that the profile goes to the bottom of the weir pool. The dissolved oxygen concentration at each depth where a measurement was taken is multiplied by the difference in depth between that measurement and the one immediately above it. The [O_2] x depth are then summed across the depth profile and divided by the total depth to give the approximate dissolved oxygen concentration on mixing.

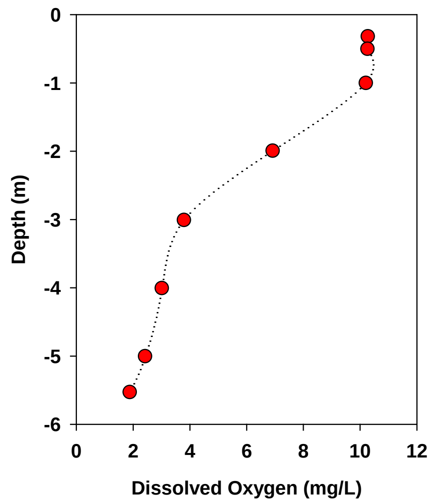

Figure 23: Dissolved oxygen profile taken in Redbank Weir on the 5th March 2019.

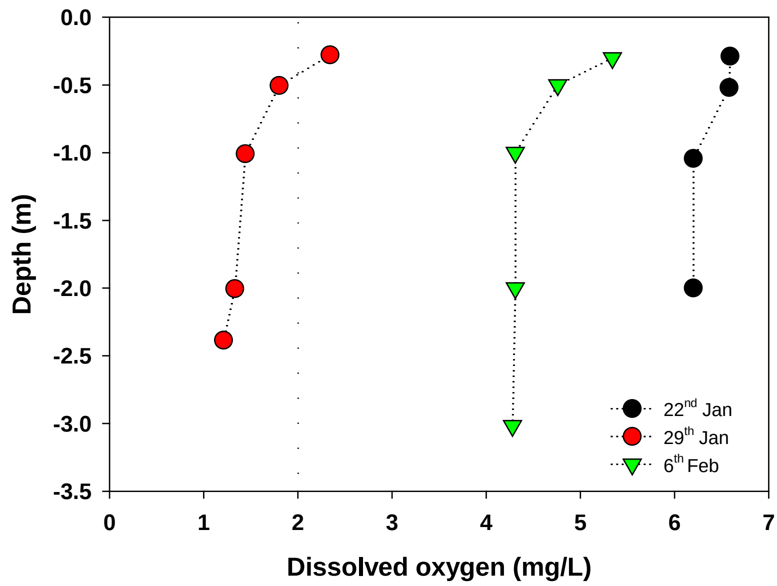

Figure 24: Dissolved oxygen profiles at the Balranald Weir pool monitoring site on the 22nd January (black circles), 29th January (red circles) and 6th February (green triangles). The dashed line indicates the dissolved oxygen concentration below which large-bodied native fish die.

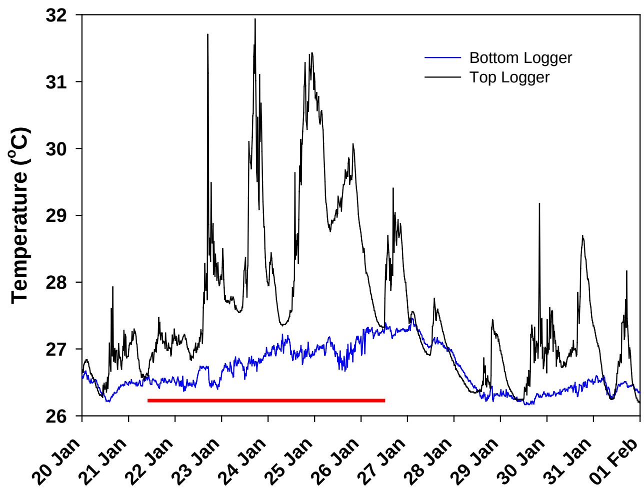

Figure 25: Temperature in the surface (black trace) and the bottom waters (blue trace) in Balranald Weir from the 20th January to the 1st February 2019. The period of stratification (where there is a difference in temperature between the surface and bottom waters) is indicated by the red bar.

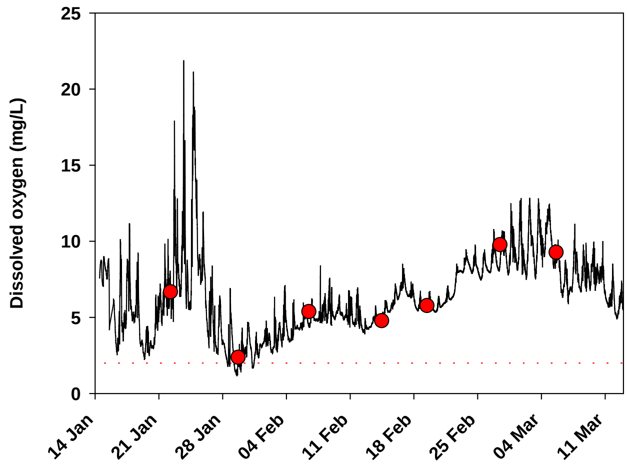

Figure 26: Dissolved oxygen in the surface water near the Balranald Weir Structure measured by a continuous logger (black trace), and by manual measurements (red dots).

One possible explanation of the unusual changes in the oxygen profiles was the location of both the WaterNSW sampling location and the location where the oxygen concentration loggers were located. The oxygen concentration loggers deployed as part of this investigation were placed about 200 metres upstream of the Balranald Weir Structure adjacent to an area that was dredged to provide fill for the construction of the weir structure ("Borrow Pit" Figure 27). While most of the Balranald Weir pool is relatively shallow (2 - 4 m), the dredged zone is up to 7.6 m deep. It is probable that this relatively small, but deep, pool turned over on the 26th January. Because the deep pool is in a hydrologic backwater, its influence on dissolved oxygen concentrations in the main channel (where the oxygen sensor is located) would not be immediate - it would rely on transfer of water from the backwater to the main channel. Because the zone is relatively small, the impact on dissolved oxygen would be only transient.

Figure 27: Location of the dissolved oxygen logger relative to the deep, artificial pool's location near Balranald Weir (background image from Google Earth).

Like Redbank Weir pool, Balranald Weir pool also re-stratified at the end of February - beginning of March (Figure 28), without any adverse environmental effects following mixing on the 6th March.

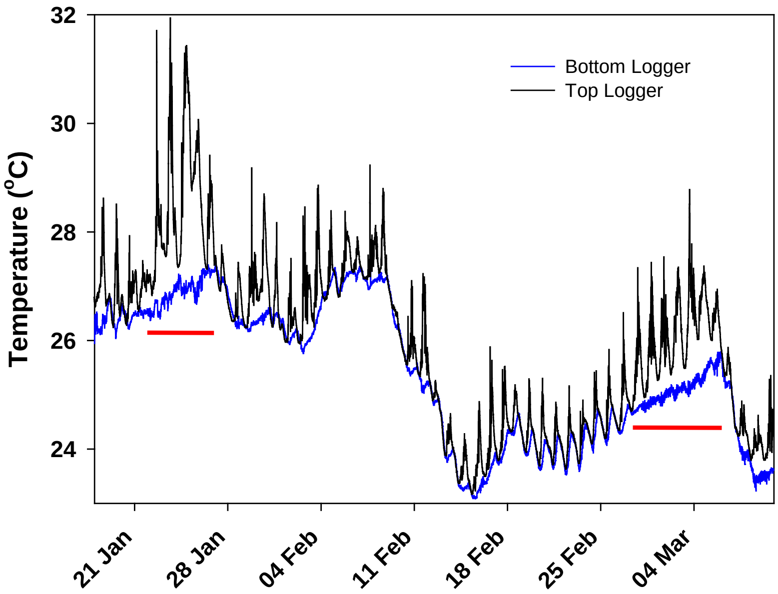

Figure 28: Temperature in the surface water (black trace) and bottom waters (blue trace) in Balranald Weir from mid-January to the mid-March 2019. The red bars indicate periods of persistent stratification in the weir pool.

5. Free Flowing Reaches and Re-oxygenation

There is approximately 300 river kilometres between Hay Weir and Balranald Weir, of which about 60 kilometres is constrained within weir pools. The remainder are free flowing river reaches. Section 4 discusses instances where water with low dissolved oxygen concentrations were released from both Maude and Redbank Weir pools, without any observed fish deaths in the downstream reaches. For example, Figure 29 shows the surface dissolved oxygen concentration in the Murrumbidgee River adjacent to the Balranald Caravan Park, approximately 100 river kilometres downstream of Redbank Weir and 20 km upstream of Balranald Weir. The travel time between Redbank Weir and Balranald Township is approximately 3 days. Therefore, on the face of it, there should have been a deterioration in dissolved oxygen concentration in the Murrumbidgee River adjacent to Balranald Caravan Park starting from about the 29th January (3 days after the cool change caused the fish deaths at Redbank Weir); and certainly, by the 2nd - 3rd February, by which time the peak flow (marked as B, Figure 13) would have reached Balranald. In fact, the dissolved oxygen at Balranald increased over this time period (Figure 29).

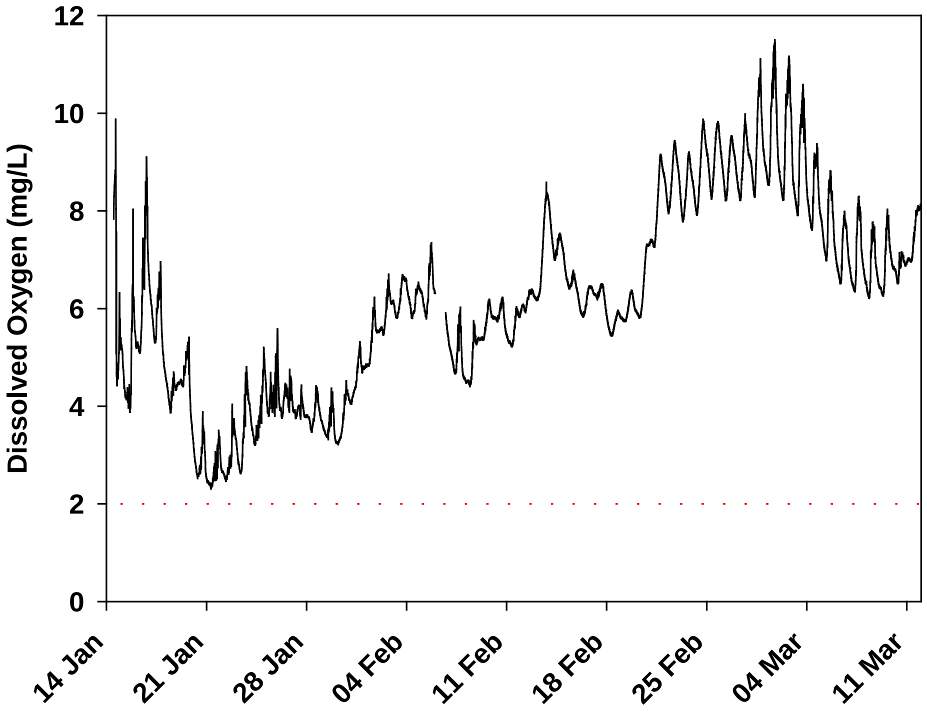

Figure 29: Surface dissolved oxygen concentration in the Murrumbidgee River adjacent to the Balranald Caravan Park. The dashed line represents the concentration of dissolved oxygen that is lethal to large-bodied native fish.

As shown in Figure 16, part of the reason is that moving water either over or under a weir structure creates oxygenation (Butts and Evans, 1983). Indeed, using weir structures to create localised zones of oxygenation is one of the strategies that can be used to manage blackwater events (Kerr et al., 2013). Unfortunately, undershot weirs are far less effective at re-oxygenation compared to overshot weirs (Butts and Evans, 1983).

Notwithstanding localised re-oxygenation from water passing under Redbank Weir, the principal reason that we didn't see low dissolved oxygen concentrations persist very far downstream of either Redbank or Maude Weirs is because flowing river channels are much more efficient at re-aeration than slow- or non-flowing weir pools. As noted in Section 3, re-aeration of waterbodies comes from the atmosphere. The rate of re-aeration depends on a number of factors including:

- The surface area to volume ratio;
- Flow velocity;
- Turbulence;
- Wind speed and precipitation (Rixen et al., 2008).

While the differences in wind speed and precipitation shouldn't be appreciably different immediately upstream and downstream of an impoundment, the other three factors are different. Impounded stretches of rivers are, for the most part, deeper than the free-flowing sections of river (e.g. see Figures 15 - 18), but, for weir pools along the Murrumbidgee River, the channel width is usually similar in both. Therefore, the surface area to volume ratio is much higher for free-flowing sections of river than in weir pools, making re-aeration in the free-flowing sections more efficient. Similarly, because the free-flowing sections of river have a similar width to the impounded sections, but are much shallower, for the same volumetric flow, the flow velocity has to be higher, again leading to greater re-aeration. Finally, because of friction at the riverbed-water interface, flowing sections of the river are more turbulent than impounded sections, again leading to increased rates of re-aeration in flowing sections.

Both the *Blackwater Risk Assessment Tool* (Whitworth and Baldwin, 2016) and the *Blackwater Intervention Assessment Tool* (Whitworth et al, 2013) have modules that can be used to calculate the rates of re-aeration in flowing sections of a river channel. Using the *Dilution Flows* module in the Blackwater Intervention Assessment Tool and setting the dissolved organic carbon concentration to 1 mg/L shows that at a flow of 1500ML/day, a dissolved oxygen concentration of 1 mg/L (typical of flows from Redbank Weir in late January 2019) and assuming an average river depth downstream of the weir of 2 m and a river width of 25 m, the model predicts that the dissolved oxygen concentration 15 kilometres downstream of the weir would be about 3.6 mg/L (Figure 30) - high enough to support large-bodied native fish.

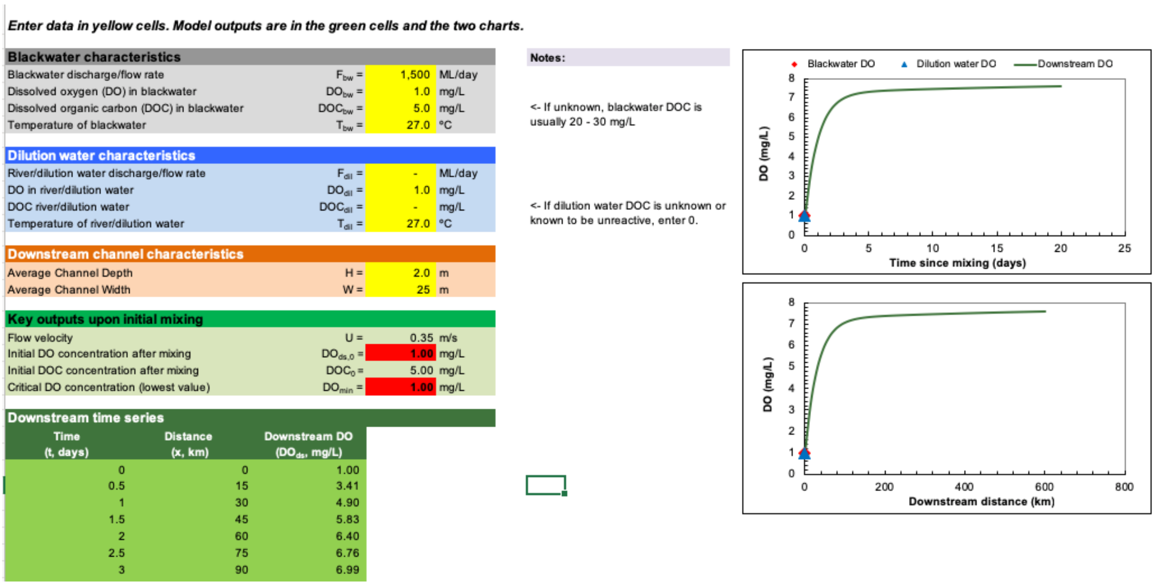

Figure 30: Screen shot from a run of the *Blackwater Intervention Assessment Tool* dilution module to estimate re-oxygenation downstream of Redbank Weir.

6. Recommendations

6.1 Monitoring and reporting

There were a number of sources of water quality information prior to and following the fish deaths in Redbank Weir, some of which were more helpful in informing management decisions than others.

6.1.1 Weekly depth profiles of weirs by WaterNSW staff

As part of its original watering plan to deliver an additional 200 ML/day across Balranald Weir, OEH approached WaterNSW to undertake weekly depth profiles in the 4 lower Murrumbidgee River weir pools. WaterNSW had previously included depth profiles in its monitoring program, but had ceased undertaking them in recent years. The depth profiles proved very valuable in assisting management of the lower Murrumbidgee River during the summer of 2019. Firstly, because Redbank Weir was sampled several days prior to the fish deaths on the 26th January, unlike the earlier fish kills in the Darling River, it was possible to unequivocally assign the cause of the fish kill to destratification - setting the blueprint for the management of the other weir pools - especially Maude Weir pool. Secondly, by having relatively frequent assessments of the dissolved oxygen profiles in the weir pools it was possible to:

1. Undertake mass-balance calculations to predict the dissolved oxygen concentrations in the weir pools if they did mix.
2. Use changes in oxygen concentrations in the bottom water over time to calculate the sediment oxygen demand in each of the weir pools and therefore predict dissolved oxygen in the bottom water into the future.

Both of these factors contributed to the decision to continue, and even accelerate, the drawdown of Maude Weir pool prior to the arrival of the rain rejection flows (discussed in more detail Section 4.2), and hence preventing a likely fish kill event.

What wasn't clear during the event was whether or not WaterNSW was the relevant agency to actually undertake sampling, nor was it clear who was actually responsible for the interpretation of the collected data. This should be clarified prior to the next summer.

Recommendation 1: The agency responsible for monitoring <u>and assessment</u> of water quality during events like the one that occurred in the lower Murrumbidgee River needs to be identified. That agency should undertake weekly depth profiles of dissolved oxygen and temperature in the lower Murrumbidgee River weir pools from the beginning of November to the end of March, and transmit results to relevant staff in a timely manner - especially if low dissolved oxygen levels are encountered.

The weekly depth profiling in the weir pools could be improved. As noted in Section 4.4, the location of the sampling station in Balranald Weir produced a slightly misleading assessment of the risk of hypoxia in the weir pool following the cool change on the 26th- 27th January. The location of the site needs to be moved further upstream - and especially upstream of the pool excavated during the construction of the weir. This would require taking the depth profile from a boat. Furthermore, although Hay Weir pool was at near full capacity for most of the period (about 8.7 m), depth profiles were only taken to a depth of 5.5 m. It is assumed that the reason that the profiles only extended to 5.5 m is that the lead on WaterNSW's water quality probe was that long. The problem with not measuring the dissolved oxygen concentration throughout the whole water column is that it is not possible to do a complete mass balance calculation and hence predict what the dissolved oxygen concentration would be in the water column if mixing occurred. The dissolved oxygen concentration on mixing would be substantially different if the bottom 3 metres were hypoxic or it was saturated with oxygen.

Recommendation 2: The relevant agency undertake representative depth profiles in all weir locations that include the entire water column.

6.1.2 Targeted spot measurements

Field staff from both OEH and CSU were sent out in the field to record dissolved oxygen and temperature profiles upstream and downstream of Maude, Redbank and Balranald Weirs immediately following the fish kill event in Redbank Weir. It is expensive to deploy a sampling team, and the data collected was invaluable in determining the extent of the issue - in particular how dissolved oxygen concentrations were behaving upstream and downstream of Redbank Weir prior to the arrival of the rain-rejection flows (Section 4.3). However, at the time a full analysis of the data (similar to Figures 15-18) was not undertaken until after the risk to water quality in Redbank Weir had passed. This meant that more water than necessary was diverted onto the floodplain. Water quality in the weir pool was acceptable by the time the rain rejection flow reached the weir structure (Figure 19), but water was diverted onto the floodplain for several more days (Figure 15). This would be less likely to have occurred if the data from the spot measurements had been fully interrogated as soon as possible after sampling.

Recommendation 3: If field staff are being deployed to undertake spot measurements because of the risk of a hypoxic event, additional resources should be allocated so that the information is promptly interrogated, to inform management. Ideally the interrogation should occur within 24 hours of data acquisition.

6.1.3 Telemetered dissolved oxygen and temperature probes.

WaterNSW has telemetered dissolved oxygen and temperature probes immediately downstream of Maude, Redbank and Balranald Weirs. The probes were installed in response to recent hypoxic blackwater events in the Murrumbidgee River. The advantage of these probes is that they can give information in almost real-time and it is freely accessible through the WaterNSW Real Time Water Data website. Unfortunately, these probes proved less than helpful during the recent events in the lower Murrumbidgee River.

The dissolved oxygen measured downstream of Redbank Weir by the WaterNSW telemetered probe, both before and after the fish kill event, is presented in Figure 31. Although hypoxic water was being released from the bottom of Redbank Weir, prior to the 26th January, the measured dissolved oxygen concentration immediately downstream of the weir pool appeared to be within acceptable levels. As noted in Section 5, water is partially re-aerated as it moves under the weir, therefore, because of the location of the dissolved oxygen probe, it could not identify that the water in the hypolimnion upstream of the weir was actually hypoxic. Following the fish deaths, the probe was offline for several days (marked as A on Figure 31). The dissolved oxygen downstream of the weir then apparently fell from about 4 mg/L to below 1 mg/L, coinciding with the release of approximately 4000 ML out of the weir marked as B on Figure 13). However, it is not possible to determine if this observed fall was real or simply an artefact. A similar decline in dissolved oxygen concentration was recorded by the probe on the 13th February (marked as B on Figure 31). However, spot measurements taken in the field showed that the actual dissolved oxygen concentration immediately downstream of Redbank Weir was actually about 4.5 mg/L (Figure 32).

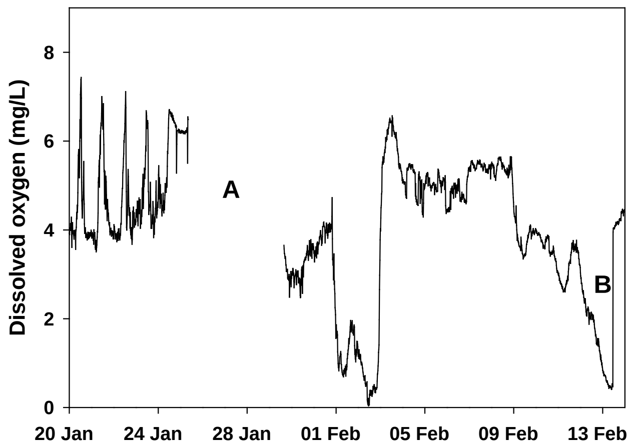

Figure 31: Apparent dissolved oxygen concentrations immediately downstream of Redbank Weir measured using WaterNSW's telemetered dissolved oxygen probe from mid-January until mid-February, 2019.

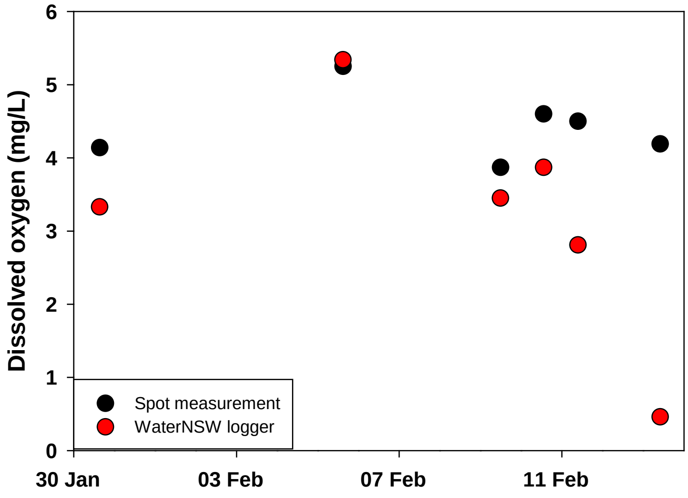

Figure 32: Dissolved oxygen concentrations measured immediately downstream of Redbank Weir determined by spot measurements during CSU and OEH field trips (black circles) and using WaterNSW's telemetered dissolved oxygen probe (red circles).

It was not only the probe below Redbank Weir that had issues during the Summer/Autumn of 2019. Figure 33 shows the apparent dissolved oxygen concentration downstream of Balranald Weir from mid-January to mid-March 2019. Until the end of January, the probe registered the normal diurnal variation expected during an algal bloom. Then, for a period of about 3 weeks (marked by the red line on Figure 33), the diurnal variation disappeared, only to reappear at the end of February. Without independent corroboration it is not possible to unequivocally state whether the observed dissolved oxygen concentrations are real or not.

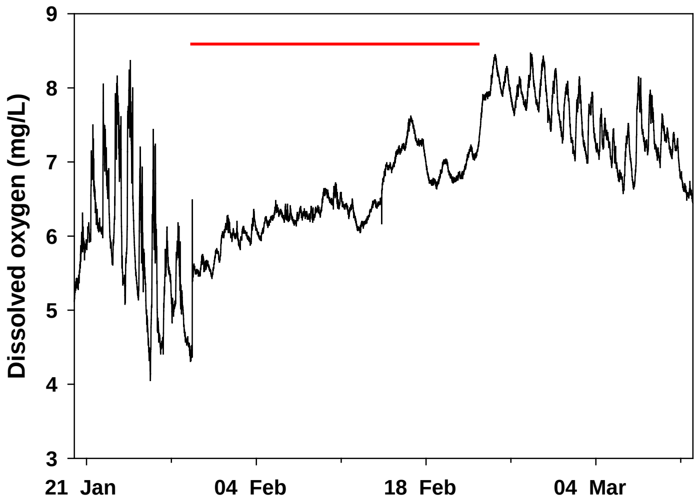

Figure 33: Apparent dissolved oxygen concentrations immediately downstream of Balranald Weir measured using WaterNSW's telemetered dissolved oxygen probe from mid-January until mid-March, 2019.

Dissolved oxygen probes are subject to fouling by biofilms, leading to false readings, and therefore require quite frequent (weekly to bi-weekly) cleaning when deployed in lowland rivers. Because the fish deaths in Redbank Weir can be attributed to destratification, rather than rely on dissolved oxygen probes to determine if there are potential issues, it is recommended to install telemetered temperature probes in the weir pools. Temperature probes are not susceptible to the same reliability issues as dissolved oxygen probes, and therefore should be more reliable. If a sufficient number of probes are deployed through the depth profile in each weir pool, it would be possible to determine if a weir pool has started to stratify, in which case a team could be sent into the field to determine the extent of deoxygenation throughout the water column.

Recommendation 4: Telemetered temperature probes are deployed through the water column in each of the 4 lower Murrumbidgee River weir pools, and the results are routinely inspected to determine the extent and strength of stratification.

6.1.4 Non-telemetered dissolved oxygen and temperature probes.

The non-telemetered d-optos appeared to provide relatively reliable data, although they were not without their issues. For example, from about the 18th of February to the 25th February, the middle dissolved-oxygen probe at Woolpress Bend recorded lower dissolved oxygen concentrations than the surface or bottom probes - both of which showed that the water column was actually well mixed (Figure 34).

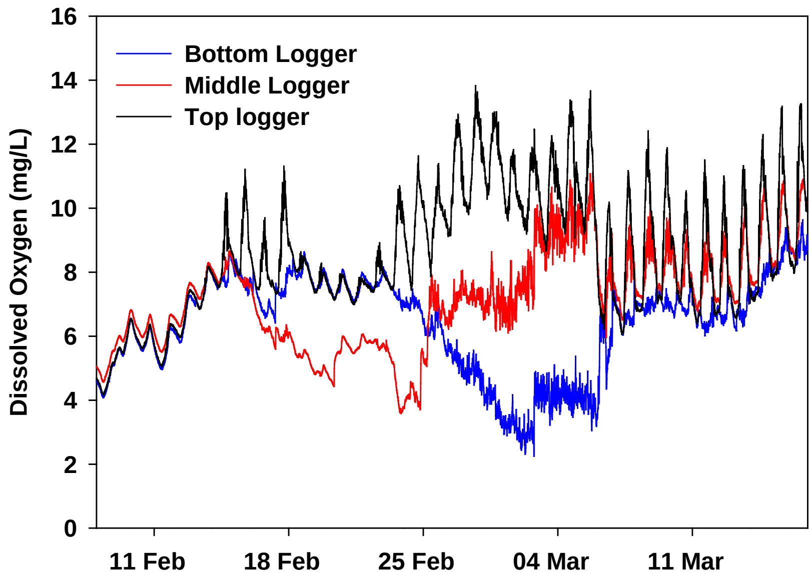

Figure 34: Recorded dissolved oxygen concentrations from the surface, mid-water and bottom of Redbank Weir pool at Wool Press Bend taken measured between mid-January and mid-March, 2019 (c.f. Figure 20)

6.2 River Management

6.2.1 Rainfall rejection flows

The original targets of the environmental watering in early 2019 were to increase flows over Balranald Weir by 200 ML/day by drawing down Maude Weir pool to the point where the weir gates could be fully removed. This would have simultaneously improved fish habitat in Balranald Weir, help flush blue-green algae out of Balranald Weir and, improved fish-passage from the Redbank Weir to Hay Weir. Following notification that rain-rejection flows were to pass downstream of Hay Weir, a decision was taken to lower Maude Weir pool in a bid to stop destratification and hypoxia (discussed in Section 4.2). However, notwithstanding the environmental consequences, during a subsequent Technical Advisory Group Meeting (TAG meeting # 10 - February 11th, 2019) the group was informed that if Maude Weir was to remain open, any of the rain rejection flows that passed through the weir would need to be credited to an environmental water account. The policy disconnect between capturing rain-rejection flows on the one hand, and protection of the aquatic environment on the other is concerning.

Recommendation 5: A workshop is held with key stakeholders to determine the best way to manage rain rejection flows in the Murrumbidgee River so as to maximise economic benefit, but at the same time ensure no environmental impact.

6.2.2 Inter-valley transfers

In the past, inter-valley transfer delivery – at suitable times coinciding with the peak of summer – has possibly performed an unintended function of preventing stratification in lower Murrumbidgee weir pools. In the absence of inter-valley transfer orders (from the Murrumbidgee River to the Murray River) there is a higher likelihood that the lower Murrumbidgee will be operated (under regulated flow conditions) to low flow targets, increasing the likelihood of stratification. Moreover, if they do occur, such transfers have the potential to breakdown stratification in weir pools which could lead to temporary hypoxia in the weir pools and subsequent fish deaths.

Recommendation 6: That low inter-valley transfer account status be identified as a key risk factor for stratification/fish kills by river operators, and communicated to other relevant agencies. The thermal status and oxygen concentrations in weir pools should be taken into consideration when planning inter-valley transfer flows.

6.2.3 Weir pool operation

As noted in Section 5, free-flowing river reaches are significantly less likely to stratify, and therefore potentially lead to fish kills. Because of the changing climate, the factors that led to the fish kill event in Redbank Weir pool are likely to become more frequent into the future. One way of preventing future fish kills in the future is to operate as much as is feasible of the lower Murrumbidgee River as if it is a free -flowing river - especially if extreme maximum air temperatures are predicted. This would effectively mean periods of time when one or more of the on-river storages are effectively drawn down.

Recommendation 7: Develop a set of rules, based on both predicted temperatures and consumptive demand, to determine periods for the temporary draw down of in-river water storages in the Lower Murrumbidgee River.

If it proves impossible to totally drawdown the in-river water storages, then hypoxic bottom waters need to be actively managed. This would require:

- Active monitoring to determine the extent of hypoxia in the weir pools (see Section 6.1);
- Assessing the likelihood of mixing;
- Predicting the dissolved oxygen concentration that would eventuate following the mixing event;
- Estimation of the amount of hypoxic bottom water that would need to be released to prevent hypoxia through the water column following mixing;

- Preventative pre-release of hypoxic water through undershot weirs prior to the mixing event;
- Assessment of the impact of hypoxic water releases on downstream water quality and aquatic communities.

Managing the hypoxic water in such a manner would still allow the weirs to be used as in-channel storages, but it would require are much more active, and monitoring intense, approach.

In addition, there may be opportunities to coordinate environmental water orders between the Murray and Murrumbidgee River systems for environmental demands downstream of the Murrumbidgee confluence. While held environmental water is not a panacea to managing lower Murrumbidgee weir pool stratification, some synergies may exist at times. Temporary re-routing of environmental orders from the Murray to the Murrumbidgee Rivers may prevent stratification. However, such strategies should not be assumed by river operators, as environmental water holders may need to avoid compromises to other priority environmental outcomes.

Recommendation 8: If in-river water storages cannot be temporarily drawn down during periods where there is an increased risk of destratification leading to hypoxia, then, if present, hypoxic bottom waters need to be managed as a normal part of the weir management. This may mean the release of hypoxic bottom water to downstream reaches; and if so the impact on downstream aquatic communities and water quality needs to be assessed.

6.2.4 Re-snagging

The Murrumbidgee River was extensively de-snagged in the second half of the 19th Century to facilitate the riverboat trade (e.g. Philips, 1972). Snags (large woody debris) are not only habitat for large-bodied native fish and sites for energy capture (Baldwin et al, 2016), but also creates turbulence, which in turn increases the rate of oxygenation (see Section 5). Re-snagging the river reaches downstream of weir structures should lessen the impact of hypoxic water releases from weir pools.

Recommendation 9: Increase the amount of large woody debris downstream of the Lower Murrumbidgee river weir pools to increase turbulence in the river, as well as providing habitat for large-bodied native fish, and a substrate for the growth of biofilms.

6.3 Knowledge Gaps

6.3.1 Weather, flows and destratification

One of the key questions faced during February and March 2019 was whether or not the weir pools would destratify, either because of changes in the weather or because of inflows. At the time, estimates of whether or not any of the weir pools would destratify, particularly as a result of inflows, were based on empirical observations in Maude Weir made in the mid 1990's (Bormans and Webster, 1998). As noted in Appendix 1, Bormans and Webster (1997) have developed a mathematical relationship that can be used to predict whether or not Maude Weir would stratify or destratify depending on factors such as depth, air and water temperature, solar irradiation, wind speed, flow and humidity. This relationship could be used to form the basis of a tool which would give river managers much better confidence in predictions of weir pool stratification and destratification. In particular, it could be used to develop look-up tables or flow rules to help minimise hypoxic destratification events.

It is envisioned that the development of the tool would be conducted in three stages. The first stage would develop, test and calibrate the algorithms to be used in the final product. The output of this phase of the project would be a simple, but functioning model for predicting hypoxia in weir pools. This tool would require the manual entering of climatic and flow data. The next part of the project would involve the collection of water and sediment quality data to refine the algorithms used in the tool as well as refining the tool predictions for specific weir pools. In last phase of the project the tool will be integrated into WaterNSW (or other organisations) river operations systems, with automatic updating of actual and predicted climatic data through an interface with the Bureau of Meteorology.

Recommendation 10: Develop a tool that can predict stratification and destratification events in weir pools based on the predicted weather patterns, flow velocity and weir level and, if they do destratify, whether or not it will result in hypoxia.

6.3.2. Sediment oxygen demand

In order to more accurately predict the likelihood of hypoxia following destratification, it would be beneficial to understand the spatial variability of oxygen drawdown in the hypolimnion caused by sediment oxygen demand. As noted in Section 4, the rate of oxygen drawdown in Maude Weir appeared to be substantially greater than in Hay Weir at the beginning of February. Why preliminary estimates of sediment oxygen demand can be gleaned from the weekly water quality profiles taken by WaterNSW, they are only estimating and are no substitute for empirical studies.

Recommendation 11: Initiate a study to determine the spatial variability in sediment oxygen demand in Hay, Maude, Redbank and Balranald Weir pools.

6.3.3. Bathymetry

As noted in Section 4, as part of the adaptive management of the weir pools during February and March 2019, mass balance calculations were used to estimate the potential dissolved oxygen following mixing based on dissolved oxygen concentration profiles. The calculations, by necessity were based on a simple 'U' shaped river profile. If more detailed bathymetric information was available, it would lead to better estimates of the risk of hypoxia following mixing.

Recommendation 12: Prepare bathymetric maps of Hay, Maude Redbank and Balranald Weir pools.

6.3.4 Monitoring of hypolimnetic releases on downstream dissolved oxygen concentrations

In Section 6.2.3 it was suggested that pre-release of hypoxic hypolimnetic water through undershot weirs could be an effective strategy for managing weir pools at risk of hypoxic destratification. This approach relies on effective re-oxygenation of the hypoxic bottom water in the free-flowing sections of the river downstream of the weirs. This approach is supported by modelling (see Section 5), however the model accuracy could be improved if parameterisation was specific for the free-flowing sections of the Murrumbidgee River.

Recommendation 13: Monitor oxygen levels downstream of weirs during hypolimnetic water releases to determine the rate of water re-aeration. This data can then be used to refine models so they specifically reflect conditions in the lower Murrumbidgee River.

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Appendix 1 - Factors affecting stratification and destratification in weir pools.

During the 1990's Bormans and Webster (1998) developed a computational model of temperature profiles in the Maude Weir pool on the Murrumbidgee river and free flowing section of the Murray River based on the freely available Princeton Ocean Model (see www.ccpo.odu.edu/POMWEB/). Their model was used to develop a specific criterion for the formation and destruction of thermal stratification in turbid rivers (Bormans and Webster 1997) which was tested against observed stratification in both the Murrumbidgee and Murray Rivers. The criterion is a non-dimensional parameter (R) which can be calculated from location, time of year, time of day, amount of cloud cover, air and water temperature, flow velocity, wind speed, water depth, turbidity and % humidity viz:

$$R = \frac{U^3}{H\left(Q_{net} - \frac{2Q_i}{HK_d}\right)\frac{\alpha g}{\rho C_\rho}}$$

Where:

U = depth averaged flow velocity

H= Water depth

$\alpha =$ thermal expansion coefficient which depends on water temperature

g = gravity acceleration

$\rho =$ density of water which is temperature dependent

K_d = light attenuation co-efficient (a measure of turbidity)

Q_i = net downward short-wave radiation (the amount of sunlight which depends on location, time of year, time of day and amount of cloud cover).

Q_{net} = net surface heat flux into the water column ; $Q_{net} = Q_i - Q_B - Q_S - Q_E$

Q_B = upward long-wave thermal radiation which is dependent on surface water temperature

Q_S = upward sensible heat flux which depends on wind speed, water temperature and air temperature

Q_E = Heat flux due to evaporation which depends on wind speed, water temperature, air temperature and humidity.

For R values of less than 35,000, stratification was always observed in Maude Weir pool and the Murray River while at values greater than 55,000, stratification broke down.

Appendix 2 - Historical Fish Kills in the Lower Murrumbidgee River.

As noted in Section 3.4, recent fish kills in the Murrumbidgee River can all be attributable to blackwater events. In order to determine if destratification events had occurred in the lower Murrumbidgee River previously I searched the National Library of Australia's *Trove* database of digitised newspapers using the search terms "Murrumbidgee", "River" and "Dead Fish". A total of at least 8 instances of fish kills were reported that could have occurred in the lower Murrumbidgee River[3]:

- January 1905 (*Adelong and Tumut Express and Tumbarumba Post*, 27/1/1905 p.2)
- March 1907 (*Evening News*, 7/3/1907, p. 5)
- February 1915 (*The Riverine Grazier*, 26/2/1915, p. 4)
- December 1919 (*The Gundagai Times and Tumut, Adelong and Murrumbidgee District Advertiser*, 2/12/1919, p. 2)
- December 1929 (*The Riverine Grazier*, 13/12/1929, p. 2)
- Around March 1932 (*Mudgee Guardian and North-Western Representative*, 17/3/1932, p. 4)
- January 1939 (*The Murrumbidgee* Irrigator, 10/1/1939, p. 2) and
- February 1945 *(Lithgow Mercury*, 5/2/45, p.2).

In many instances, the actual date the fish kills observed was not recorded. The news reports were explored for potential triggers of the fish kills. Also, the maximum air temperatures recorded at Kooringal, near Wagga Wagga (Station number 072151) immediately prior to the report of the fish kill was then examined to see if there was a pattern of extremely warm temperatures followed by a cool change.

The fish kills in January 1905, February 1915, December 1919 and February 1945 coincided with either flooding or a significant rise in the river height. The January 1905 news repours specifically mention runoff from burned areas - which is known to be toxic to fish. One report from the February 1915 fish kill speculated that the fish kill was caused by fisherman dynamiting the river - but it would more likely be blackwater. The December 1919 report said that the storm waters turned the water "yellow and thick" which caused "lobsters in their thousands" to crawl out onto the river banks - a sign of hypoxia. A similar account of "lobsters" on the banks was given for the February 1945 report. Of the four reports associated with a rising river, this one may have been due to flows disrupting a thermocline - discussed below).

It was not possible to determine the reasons for the fish kills in December 1929 or January 1939. There were no reports of flooding, and the temperatures preceding the reports of the fish deaths were generally quite mild.

The fish kills in March 1907, March 1932 and December 1945 could possibly have been caused by destratification of pools as all occurred at a time when there were periods of relatively warm temperatures followed by a cool change. However, the maximum observed air temperatures prior to the reported fish kills were not as extreme as that observed in January 2019. The most likely candidate for destratification as a cause of fish kills in the Murrumbidgee River was around March 1932. The fish kill was actually reported in the *Mudgee Guardian and North-Western Representative*

[3] Some of the reports did not specify a location beyond 'the Murrumbidgee River'.

on 17th March 1932. No date of the fish kill was reported rather "[a] press report states that the number of fish found dead in the Murrumbidgee River is the chief topic of discussion among fisherman at present". The report goes on to speculate the fish deaths were the result of dynamiting. An examination of air temperatures at Koorinagal showed that there was a period from mid-January to early February 1932 where the maximum daily temperature remained in the high 30's and low 40's - reaching 44 ^{o}C on 28th January. The temperature then fell to 28 ^{o}C on 2nd February and 19 ^{o}C on 6th February.

One report of fish deaths which is consistent with destratification as the proximate cause of death occurred near Thelangerin on the Lachlan River in February 1915 (Figure A1).

A party of local sports who undertook a fishing trip to the Lachlan by motor on Sunday witnessed a rather unique spectacle there. They fixed as the site of their operations some big holes in the river bed below Thelangerin. When they arrived at the spot where they intended to begin operations they found a hole which was literally teeming with fish, which could be seen swimming about in the clear water, ranging from codfish of 20lbs or so down. As the fish could not be induced to rise to the spoonbait freely, the party divested themselves of their clothes, and, arming themselves with sticks, waded into the water which was comparatively shallow. By this means they stirred up the water, and caused the fish to rise to the surface, when they were successful in bludgeoning over 60lb. weight with the waddies they were carrying. Subsequently they motored to a spot further up the river, and found the surface of the holes there white with dead fish. Within a distance of two miles they declare that they saw at least 500 dead fish, some of them being excellent specimens of cod. As there was still a fair quantity of water in the holes the only reason the party could give for the mortality amongst the fish was the very weedy nature of the water. The effect of the sand

Figure A1 - Source: *The Riverine Grazier* 9/2/15 p. 2.

Appendix 3 - Legislated Daily and Monthly Minimum Daily Flows in the Murrumbidgee River at Balranald

Section 30 (1) of *Water sharing plan for the Murrumbidgee Regulated River Water Source 2016* states that "A minimum daily flow in megalitres per day (***ML/day***) must be maintained throughout the water year in the Murrumbidgee River at Balranald gauge (410003), as calculated using the following formula:

$$300 + (0.4 \times (95\text{th percentile natural daily flow for the month}) - 300)$$

where the ***95th percentile natural daily flow*** is the daily flow for each month that is exceeded in 95% of the days in that month.

Note.

The 95th percentile natural daily flow is a computer generated number using hydrologic conditions that existed prior to regulation and modelled over the entire period of flow information held by the Department. The hydrologic model is the one that, at the time, is approved by the Minister for determining natural flows in this water source."

Which equates to:

Month	Daily flow rate (ML/day)	Monthly total
July	829	25669
August	1087	33697
September	1330	39900
October	1030	31930
November	568	17040
December	254	7874
January	186	5766
February	180	5040
March	180	5580
April	180	5400
May	297	9207
June	429	12870