WATER QUALITY AND MURRAY COD: TEMPERATURE AND DISSOLVED OXYGEN IN POOLS OF THE UPPER MURRUMBDIGEE RIVER

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Dissolved oxygen (DO) concentrations and high temperatures are known to adversely affect fish populations in rivers. While thermal and oxygen stratification are rare under natural conditions in upland river systems significant reductions in flow caused by water abstraction, can result in low DO concentrations and high temperatures. The effects of flow and geomorphic character on DO concentrations and temperatures in pools were investigated between 2011 and 2014 in the upper Murrumbidgee River. Dissolved oxygen and temperature were recorded at hourly intervals in six pools ranging in depth from 3 to 7 m and known to provide important habitat for Murray cod. High water temperatures and low DO concentrations were observed at all sites and were most common between January and March. Antecedent air temperatures and the geomorphic character of the pools were important determinants of water temperatures. Deep pools in confined bedrock reaches displayed cooler water temperatures at depth and are likely to provide fish with refuge from high water temperatures. Such deep pools were most likely to experience persistent low DO conditions, particularly at depths beyond 4 m. Flows of up to 300 ML/day had little effect on the probability of low DO concentrations at depth which means that flow manipulation is unlikely to improve DO conditions at the deepest points of the river. There is sufficient variation in pool morphology along the river to provide fish with refuge from high temperatures and low DO conditions, however fish must be able to move to access suitable conditions.

1 INTRODUCTION

Adult Murray cod (*Maccullochella peeli)* favour deep water habitats, such as pools, dominated by large wood [1,2]. They display high site fidelity with well-defined home ranges. Murray cod are known to be susceptible to poor water quality conditions within pool environments [3]. The key water quality conditions known to have adverse effects on fish populations are low Dissolved Oxygen (DO) concentrations and high temperatures, both of which are influenced by flow conditions. Concentrations of DO of less than 4 mgL^{-1} are considered to be detrimental for native fish, and below 2 mgL^{-1} leads to altered behaviour and often fish kills [4-6]. Temperatures of greater than 30 ^{o}C are also considered stressful for Murray cod [7].

Low DO concentrations occur in river systems as a consequence of stratification processes [8] or flow events that cause a very large biological oxygen demand (e.g. summer flooding [9]). It is generally expected that the physical structure of upland rivers creates sufficient turbulent flow to mix the water column ensuring that oxygen is well distributed throughout the water column and water temperatures remain attenuated from atmospheric temperatures. Consequently, within Australia, low DO concentrations in pools are generally thought to be associated with lowland rivers yet there are examples of low DO concentrations occurring in upland streams particularly in the deep pools in rivers under periods of zero to low summer stream flows [8]. The role of flow in the establishment and persistence of both thermal and oxygen stratification means that the abstraction of water has the potential to exacerbate stratification, further altering DO concentrations and temperatures in riverine pools and increasing adverse consequences for native fish.

The upper Murrumbidgee River in the Australian Capital Territory (ACT) is a typical south eastern Australian valley-controlled upland river with a cobble-boulder bed and complex bed morphology. The river is home to a population of Murray cod, which favour deep pools distributed along the river. Infrastructure has recently been constructed to enable the transfer of up to 100 $MLday^{-1}$ of water from the Murrumbidgee River into Googong Reservoir via Burra Creek to become part of ACT's water supply network. The diversion of water during summer periods potentially extends the duration of low flow periods in the river raising concerns about the water quality for Murray cod within the reach. Little is known about the relationship between flow,

geomorphic character, DO and temperature characteristics along the upper Murrumbidgee River. This paper reports on an investigation of DO concentrations and temperatures in pools between 2011 and 2014 in the upper Murrumbidgee River.

2 METHODS

2.1 Study Site

This study was conducted in 6 pools located along 48 km of the Murrumbidgee River (450–600 m Above Sea Level) downstream of Angle Crossing west of Canberra city in the Australian Capital Territory (ACT), southeast Australia (Figure 1, Table 1). The water transfer pipeline (hereafter M2G) is positioned immediately upstream of Angle Crossing and thus river reaches between Angle Crossing and the Molonglo River confluence are expected to be most affected by flow diversion (Figure 1).

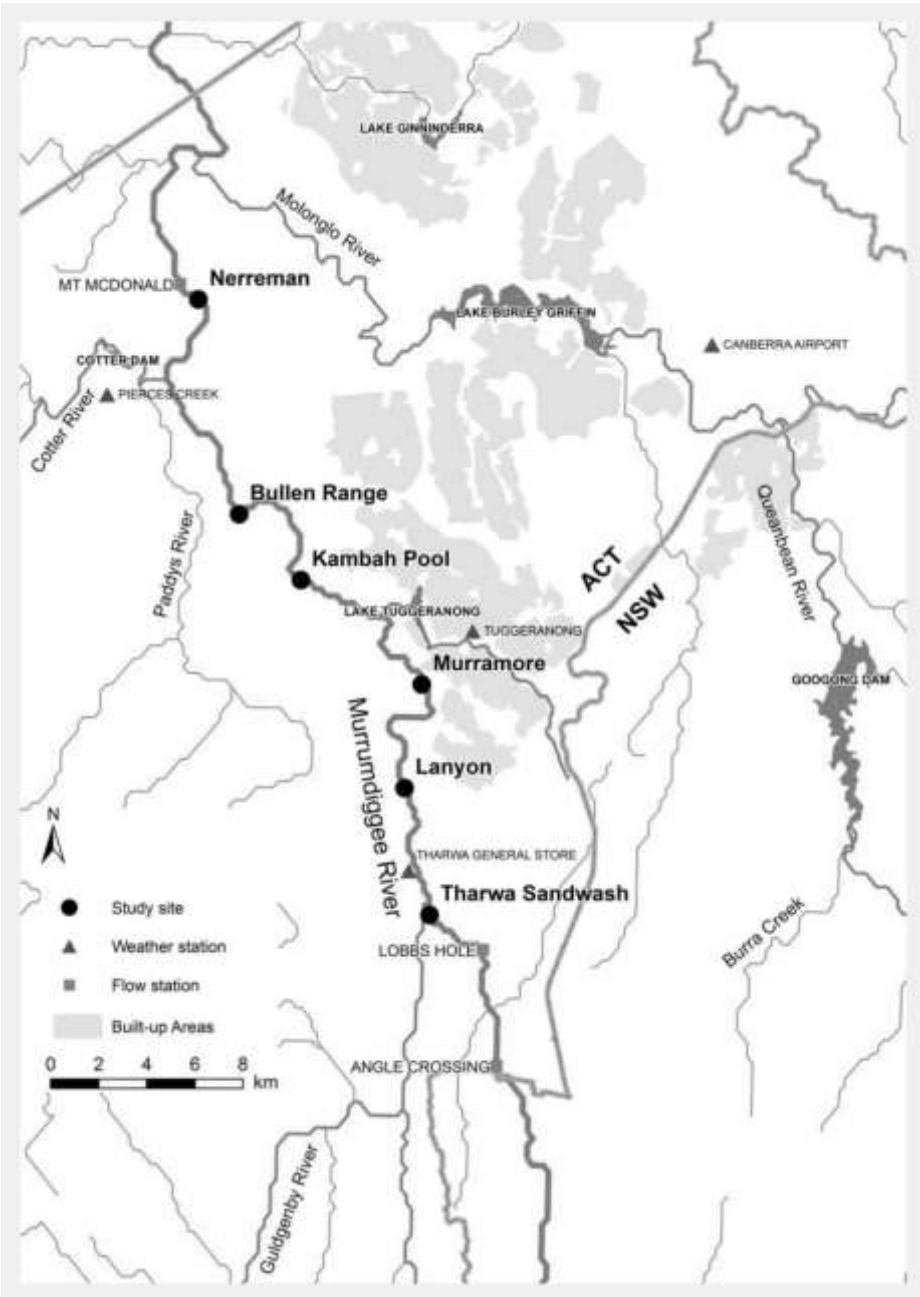

Figure 1. Water quality monitoring locations on the Murrumbidgee River, ACT. The M2G water extraction point is immediately upstream of Angle Crossing. From [10]

Table 1. Details of the water quality monitoring sites.

Site name	Max depth (m)	Mean depth (m)	ASL (m)	River width (m)	River Slope (%)	Valley description
Tharwa	3.0	0.5	570	33	0.08	Low gradient, confined valley with floodplain pockets
Lanyon	3.7	0.7	560	63	0.08	Low gradient, open valley
Murramore	7.0	2.0	560	41	0.37	Low gradient, confined valley with floodplain pockets
Kambah Pool	7.0	1.7	540	37	0.23	Low gradient, confined valley
Bullen Range	4.5	1.0	490	65	0.27	Low gradient, confined valley with floodplain pockets
Nerreman	3.0	1.0	450	32	0.19	Low gradient, confined valley with floodplain pockets

2.2 Field measurements and data analysis

Temperature and DO profiles were recorded at the deepest sections of the study pools during summer-autumn periods. These summer-autumn periods are when hypoxic conditions are most likely (low oxygen, <4 mgL^{-1}) and/or thermally stressful conditions (>30 ^{o}C) for Murray cod could occur [7]. Temperature and DO concentrations were recorded hourly at a range of depths using MiniDOT sensors (2 GB memory; Precision Measurement Engineering Inc.; CA, USA) attached to chains. Additional temperature pendant sensors (HOBO ® 8 K and 64 K memory; Onset Computer Corporation, MA, USA) logged water temperature half-hourly and were used to augment data collection at all sites.

Climate data were obtained from nearby meteorological stations to determine the effect of climate and flow conditions on stream temperature and DO concentrations. Daily rainfall and air temperature data from Canberra City, Tuggeranong, and Tharwa General Store weather stations were used (data provided by the Bureau of Meteorology, BOM: http://www.bom.gov.au/climate/data) for comparison with historical climate conditions. Hourly air temperature data from the more proximate Pierces Creek meteorological station were used for river-air temperature comparisons over the study period (data provided by the 'Australian Laboratory Services', ALS Global). Murrumbidgee River flow proximal to study sites was measured (from upstream to downstream) at Angle Crossing, Lobbs Hole Creek, and Mount McDonald flow stations (data provided by ALS Global). Angle Crossing flow was used for comparisons with river temperature and dissolved oxygen data.

Temporal trends in DO and water temperature, as well as air temperature and flow, were plotted using R [11] and Tableau [12]. Plots were visually assessed for periods where the water temperatures exceeded 30 ^{o}C and DO concentrations were below 4 mgL^{-1} and 2 mgL^{-1}. Data from the months between September and May were assessed in relation to the flow and environmental conditions, which may have contributed to the DO concentrations and water temperatures.

2.3 Modelling

A probabilistic approach to water quality modelling was used to investigate the environmental conditions that result in low DO and high temperature conditions occurring in the river. Bayesian Networks (BNs) were used to model the probability that DO would be below 2 mgL^{-1} and 4 mgL^{-1} and that temperatures would be above 30 ^{o}C given certain flow and climate conditions. This approach is similar to that used by Dyer et al. [13] to model water quality threshold violations in relation to different climate futures. Observed flow, air temperature, DO and water temperature data were used to generate frequency distributions of the measured quantities using the automated expectation maximization learning algorithm in Netica (www.norsys.com). To investigate the effect of flow or air temperatures on DO concentrations or water temperatures, the model was manipulated and the changes in probability of violating the water quality thresholds were observed.

3 RESULTS

The study was conducted over three very different summer periods: 2011/2012 was characterized by low air temperatures, high rainfall and high flows in the river; 2012/2013 had average air temperatures, low rainfall and moderate flow within the river; and 2013/2014 experienced above average air temperatures, very low rainfall and low flow in the river (Figure 2).

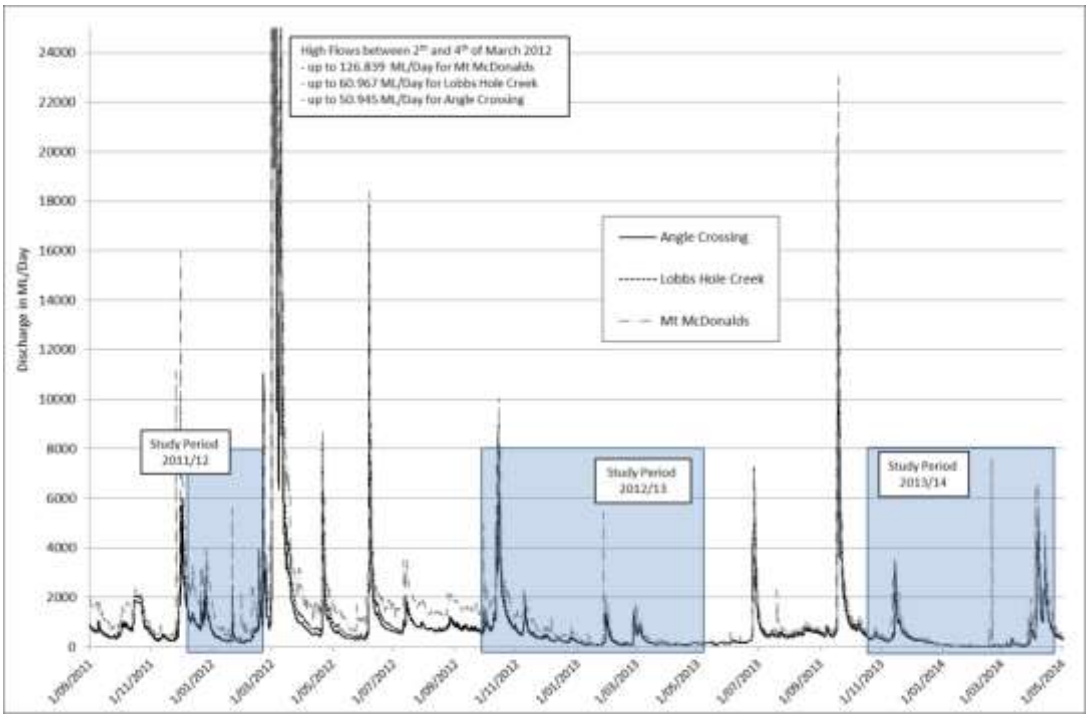

Figure 2. River flow at Angle Crossing, Lobbs Hole Creek, and Mt McDonald flow stations along the Murrumbidgee River. The shaded sections represent the period of time during which water quality loggers were deployed.

3.1 Temperatures

During the 2011/2012 study period river temperature did not exceed 30 ^{o}C at any site or time and were mostly below 25 ^{o}C. During the 2012/2013 season surface water temperatures approached and occasionally exceeded 30 ^{o}C in early January. This coincided with an extremely hot period that saw air temperatures approach 40 ^{o}C during the day and remain above 25 ^{o}C at night. The high water temperatures were most marked at Nerreman and Kambah Pool. In 2013/2014 the water temperatures were again above 30 ^{o}C in mid and late January at all stations (data not shown).

Vertical variation of temperature within pools was not noticeable during 2011/2012. However during 2012/2013 and 2013/2014 surface water temperatures were often warmer than sub-surface temperatures particularly during January and February. Vertical variations were most obvious at Kambah Pool and Bullen Range, and least obvious at Lanyon and Nerreman. This suggests the deeper confined pools were more likely to develop temperature stratification than the shallow pools in broad valleys. Shallower pools appeared to respond more quickly to variations in air temperatures than deep pools in narrow valleys, with this response amplified during low flow periods. This indicates that during periods of low flow and high temperatures, the deeper pools in confined bedrock dominated reaches of the river have cooler water temperatures at depth are therefore likely to provide fish with refuge from higher water temperatures.

3.2 Dissolved Oxygen

Dissolved oxygen concentrations were well above the threshold considered desirable for aquatic ecosystems (4 mgL^{-1}) at all sites and all depths during the 2011/2012. The exception to this was a short period at Murramore where concentrations dropped to 3 mgL^{-1} in the middle of the water column for several days (Figure 3). A

combination of hot weather and reduced flow corresponded with depleted DO conditions during the 2012/2013 and the 2013/2014 seasons.

All sites (with the exception of Murramore in 2012/2013) experienced very low DO concentrations, particularly within the deeper parts of the pools where DO concentrations of less than 2 mgL-1 were observed (Figure 3). The greatest number of low DO events were recorded at Kambah Pool – as one of the deepest pools – and at Tharwa Sandwash – as the shallowest pool. While all pools displayed short periods of low DO concentrations, most were associated with the diurnal cycles of oxygen in the river, persisting for fewer than 8 hours. Numerous periods of greater than two days with DO concentrations <2 mgL^{-1} and < 4 mgL^{-1} occurred during the study period (Figure 3). These were most prevalent at depths of greater than 3.0 m, but were also observed once at a depth of only 2.0 m at Bullen Range.

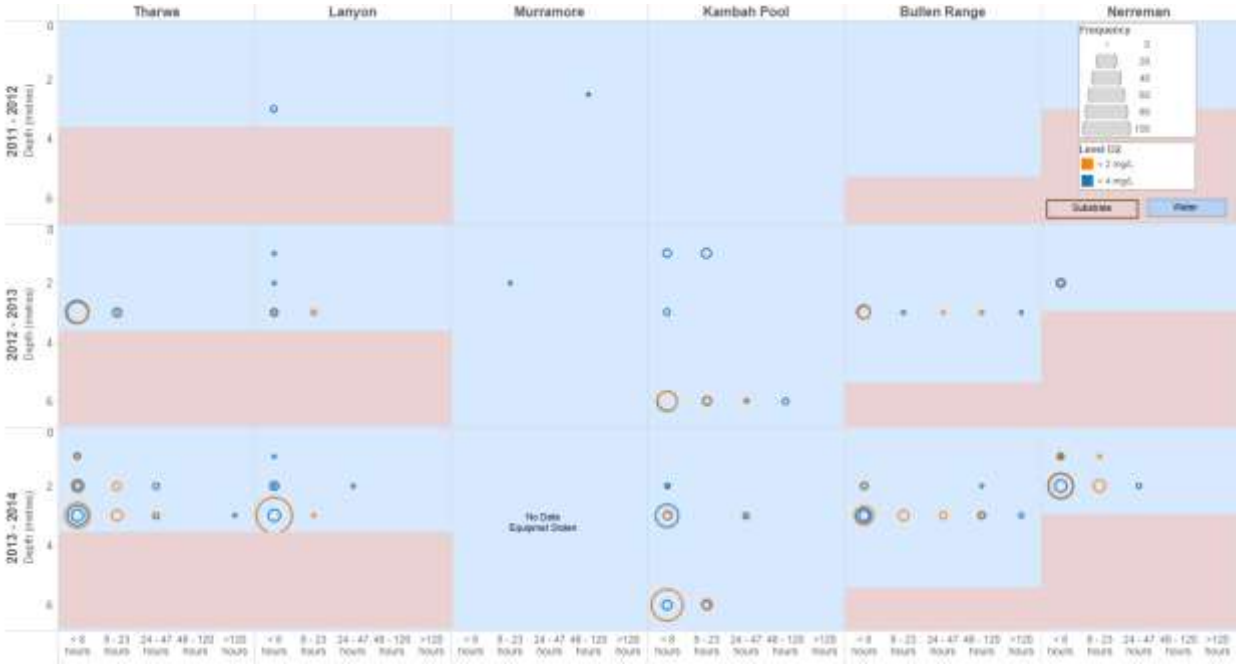

Figure 3. Frequency and duration of low concentrations of DO at all sites for all three study periods.

3.3 Probabilistic modelling

Data from December to March was used within a BN model to develop a predictive model of low DO conditions. The model structure is illustrated in Figure 4. The model is constrained by a lack of input data for very low flow conditions (only 3% of values were less than 20 $MLday^{-1}$) but could still be used to test the probability of low DO conditions occurring relative to flow and climate conditions.

Analysis indicates that DO concentrations are most sensitive to depth, followed by flow and average air temperature (Table 2). Interestingly location has less influence on the DO concentrations suggesting that in spite of the observed variations between sites, there is a general similarity of behaviour along all of the sites.

Outputs from the model indicate that as flows decrease the probability of DO concentrations dropping below 4 mgL^{-1} increases markedly. Temperature appears to have a minimal effect on the probability of DO dropping below 4 mgL^{-1}, but a lack of co-occurring low flow/low temperature inputs to the model may be masking a temperature response. Flow also has little effect on the probability of low DO concentrations at 6 m depth, except for flows of <20 ML day^{-1}. However flow has the greatest influence for 2.0 and 3.0 m depth. Thus the lower the flow, the greater the probability of low DO concentrations throughout the water column. This low DO is markedly reduced with flows of greater than 100 $MLday^{-1}$ suggesting that if low DO conditions were to become a problem, a pulse of flow between 100 and 150 ML day^{-1} should improve water quality.

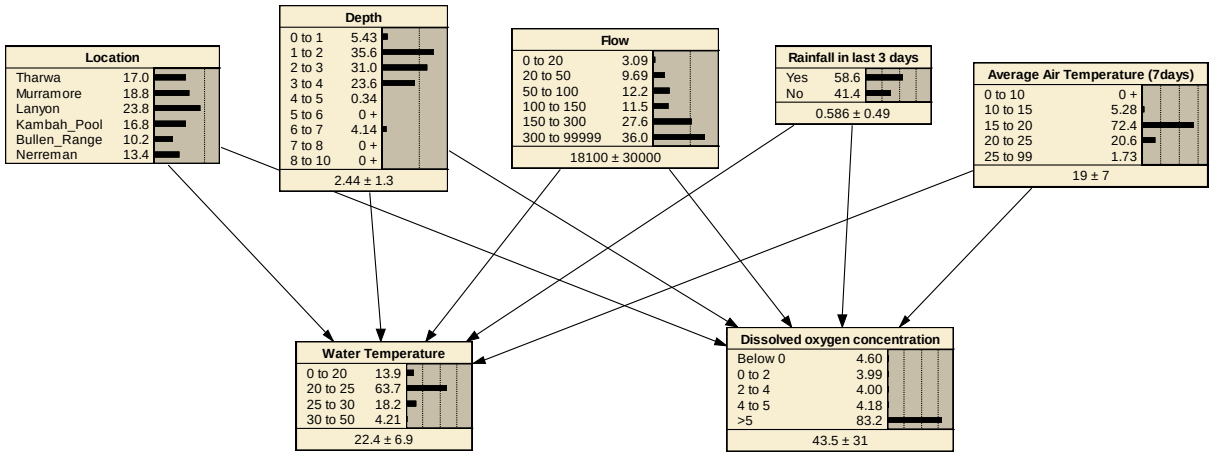

Figure 4. Compiled Bayesian Network model for DO concentrations in the upper Murrumbidgee River. Model results are shown for all sites and all depths.

Table 2. Sensitivity of DO to findings at another node

Node	Variance Reduction	Percent	Variance of Beliefs
DO	358.9	100	0.177
Depth	65.56	18.3	0.014
Flow	54.87	15.3	0.008
Average Air Temp	30.92	8.61	0.008
Station	24.08	6.71	0.004
Rainfall in last 3 days	10.35	2.88	0.003

4 DISCUSSION

Classic well-developed oxygen or thermal stratification (as described in [14]) was not observed within the pools of the study region, instead a more gradual decrease in temperature and DO through the water column was observed. Low DO concentrations were most prevalent from 3 to 6 m depth within deep pools, although during periods of low flow and high air temperatures low DO concentrations were observed throughout the water column. At a specific site and depth, DO concentrations fell below 2 mgL^{-1} for as long as 2–5 days, and below 4 mgL^{-1} for more than five days, but typically periods at these concentrations were much shorter and consistent with diurnal cycles. The occurrence of low temperature and DO conditions in deep river pools has been observed by other authors, with [8] noting that pools greater than 5 m deep were likely to behave similarly to lakes during very low stream flows. Large deep pools, such as Kambah Pool, are most likely to experience persistent low DO conditions, particularly at 6 m depth. These pools are also likely to be key habitat for Murray cod.

River temperatures were generally below those of concern for native fish however there were periods when surface water temperature exceeded 30°C for short periods of time. Stream structure and valley position appeared to influence river temperatures with the deeper pools in confined bedrock dominated reaches of the river have cooler water temperatures at depth. This means that during periods of low flow and high temperatures, these pools are likely to provide fish with refuge from high water temperatures.

Low DO conditions occurred at all sites and were observed during all summer months, however, they were most common between January and March when the river experiences low flow conditions and air temperatures are greatest. January to March is outside the critical time for spawning of Murray cod, but is the period when young cod are developing and adults have returned to home pools [15, 2]. Extended periods (i.e. greater than two days) of low DO concentrations in deeper pools during low flows and high air temperatures coincides with the times that these pools may provide temperature refuges for fish and low flows potentially prevent adult cod migration from escaping adverse conditions.

There was not an obvious flow or temperature threshold that appeared to trigger low DO conditions, rather a number of contributing environmental conditions. Flows below 50 $MLday^{-1}$ have the greatest probability of producing low DO conditions throughout the water column, irrespective of the daily temperature. Flows of up to 300 $MLday^{-1}$ have little effect on the probability of low DO concentrations at 6 m deep, so flow manipulation is unlikely to improve low DO conditions at the deepest points of the river. Once flow is between 50 and

100 MLday^{-1} the probability of low DO concentrations at 2 m depth is greatly reduced, and flows of between 100 and 150 MLday^{-1} reduce the probability of low DO concentrations at 3 m depth. While flow manipulation has the potential to improve DO concentrations in the river quite rapidly, the observations during the study period suggest that improvement is likely to be short lived and exist only while flows are increased.

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