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Reconnecting River Country: Hypoxic Blackwater Time Series Assessment

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Reconnecting River Country: Hypoxic Blackwater Time Series Assessment

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Executive summary

The NSW Reconnecting River Country Program is exploring ways to relax physical, policy and operational constraints on the delivery of water for the environment to wetlands and low-lying floodplains in the Murray and Murrumbidgee catchments. While relaxing constraints has expected benefits for both floodplain and riverine ecosystems, there is a potential risk that water returning from the floodplain will contain high concentrations of dissolved organic carbon (DOC). During warmer months, high DOC concentrations can accelerate rates of dissolved oxygen (DO) consumption by microbes, resulting in low concentrations of DO that can be fatal to some aquatic fauna. Several recent large-scale hypoxic events have occurred in the Murray, Murrumbidgee and Edward Kolety–Wakool rivers that were caused by natural floods during warm periods.

The purpose of the study was to: (1) assess the likelihood that flow regime changes proposed in the Reconnecting River Country Program would increase the frequency of hypoxic blackwater events; and (2) provide a time series of likely hypoxic blackwater events for modelled flow regimes used to assess the ecological risks and benefits of the program. We used a modelling approach to predict the occurrence of hypoxic blackwater from modelled hydrological data with different operational limits on the delivery of environmental water. This study was informed by monitoring of leaf litter, DOC and DO concentrations from past hypoxic blackwater events, and research into the mechanisms that contribute to hypoxic conditions.

The assessment for the Murray project area used inundation modelling to relate river discharge rates to the distribution of water on the floodplain during different sized flow events. From this, a classification scheme was developed that considered flow magnitude, timing, litter loads and interannual variability in temperature. The hydrological and inundation relationships are not as well understood for the Murrumbidgee project area, so an alternative approach was taken using observed carbon concentrations to develop a predictive relationship with flow.

The assessment found that hypoxic blackwater events are uncommon in both systems, with six events predicted in 124 years of model time series data for the Murray system and 12 events for the Murrumbidgee. In both cases, hypoxic blackwater events were linked to large, natural flow events. The model predictions match the occurrence of known hypoxic blackwater events in recent years. The assessment outcomes suggest that given the relatively small volume of environmental water available compared to natural flood events that typically trigger hypoxic blackwater, together with operational guidelines that will prevent environmental water releases at times of high risk, it is unlikely the planned environmental flows being investigated by the program, by themselves, could result in large-scale hypoxic events. Further, the likelihood of hypoxic blackwater occurring can be assessed beforehand through modelling, and the planned flow changed to minimise the likelihood.

1 Introduction

1.1 The Reconnecting River Country Program

Flow impoundment and diversion has altered the hydrological regime of many floodplain rivers in the Murray–Darling Basin, reducing the frequency and duration of overbank flow events and causing widespread impacts to flood-dependent ecological communities. State and federal governments collectively hold water entitlements for use in supporting river and floodplain ecological communities to mitigate these impacts. However, the use of these entitlements in the Murray and Murrumbidgee catchments is subject to operational restrictions ('constraints') that limit the effectiveness of delivered environmental water.

The Reconnecting River Country Program is investigating options to relax or remove some of these constraints or physical barriers, allowing for environmental water to be used for more frequent environmental flows that connect wetlands and low-lying floodplains than is currently possible. Although these improvements to the flow regime are expected to benefit ecological outcomes for floodplain river communities along the Murray and Murrumbidgee rivers (DPE 2022b, c; see also Junk et al. 1989; Colloff and Baldwin 2010), there is a perceived risk that managed floodplain inundation could increase the likelihood of low-oxygen conditions associated with floodwater (also called 'hypoxic blackwater').

The program is undertaking a range of assessments examining the risks and benefits of proposed changes to environmental water use in the Murray and Murrumbidgee valleys (DPE 2022b, c). The purpose of the work described here was to understand the scale of this likelihood, and to support the water quality risk assessment (McInerney et al. 2022), and fish population modelling (Todd et al. 2022), by providing a time series of likely hypoxic blackwater events under a range of modelled hydrological scenarios.

1.2 Hypoxic blackwater

Plants that grow on floodplains, including grasses, water plants and trees, contribute to a store of living and dead organic matter (collectively called 'leaf litter') that accumulates on the floodplain floor (Robertson et al. 1999; Francis and Sheldon 2002). When water flows across the floodplain, this organic matter leaches dissolved compounds into the overlying water column, including dissolved organic carbon (DOC) and nutrients (Howitt et al. 2007) that can turn the water dark in colour (hence the term 'blackwater'). These nutrients can help sustain primary productivity while the DOC can be used as an energy source by microorganisms which, in turn, can be consumed by other organisms in the food web. Hence, blackwater plays an essential role in the supply of energy to animals within floodplain river ecosystems, contributing to periods of increased resource availability that coincide with high flow events (Junk et al. 1989; Baldwin et al. 2016). However, when the microorganisms consume DOC they also consume dissolved oxygen (DO) from the water column and if this consumption rate is very high it can potentially lead to hypoxia (low DO concentrations harmful to aquatic animals).

Hypoxia: Aquatic animals, including fish invertebrates and microbes, use oxygen for respiration in the same way that animals do on land. Being adapted to live in water, these animals obtain oxygen from the surrounding water through specially adapted breathing apparatus (e.g. gills) or by passively absorbing DO through their skin or outer membranes. DO in the water is consumed by animals when they respire and is replenished via either exchange with the atmosphere and/or by oxygen-producing submerged plants and algae (Figure 1). The atmospheric replenishment of oxygen occurs more rapidly when water is moving and shallow and is slower when water is still and deep. This replenishment rate is known as 'reaeration' and under normal riverine conditions it provides a continuous supply of oxygen to the water column.

Overall, the combined rate that oxygen is consumed by aquatic animals rarely exceeds the rate of reaeration, meaning DO concentrations are typically very high. However, elevated concentrations of dissolved organic matter can elicit high rates of oxygen consumption by floodplain microorganisms, and, in extreme cases, this can cause DO to decline. Although sensitivity to low oxygen varies among aquatic species (Small et al. 2014) concentrations of DO below 4 mg/L are considered to be harmful to large-bodied fish while concentrations below 2 mg/L can be lethal (Gehrke 1988). Adverse impacts of hypoxic blackwater have also been reported for shrimp, crayfish (King et al. 2012) and emerging zooplankton (Ning et al. 2015).

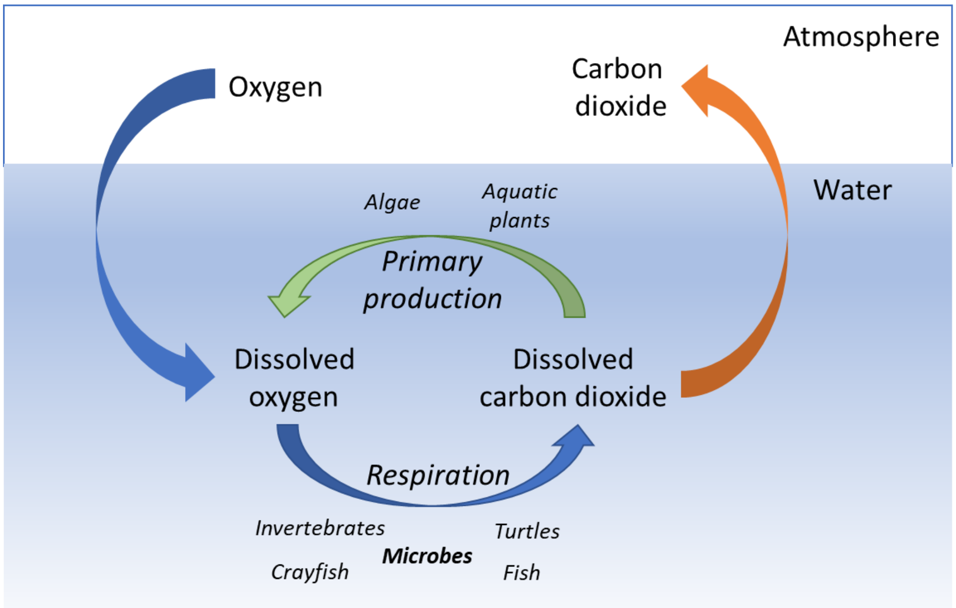

Figure 1: Broad controls on the consumption of DO in aquatic systems

Blackwater can cause hypoxia at scales ranging from individual wetlands or river reaches (Hladyz et al. 2011) up to hundreds or even thousands of kilometres of river channel (Whitworth et al. 2012). During large-scale flood events water from the floodplain re-enters the river at multiple points, moving to and from the river to the floodplain while accumulating DOC as it travels downstream.

Hypoxic blackwater events in Australia typically originate from forested floodplain rivers, particularly those of the heavily forested southern Murray–Darling Basin where high litter loads can accumulate over a short period. Historically, hypoxic blackwater events are likely to have been rare, with occasional hypoxic events reported during flooding that follows extended dry periods. Low-lying floodplains in these systems would have been inundated relatively frequently. For example, modelling indicates that, in the absence of river regulation, Koondrook–Perricoota Forest would have experienced no flooding in only three years between 1895 and 2019 compared to 21 years predicted under current regulated conditions (Figure 2). Many of these mid-range flow events are now impounded by dams, diverted, or extracted for consumptive use and the frequency, extent and duration of floodplain and wetland inundation events has declined (Pittock and Finlayson 2011; Leblanc et al. 2012; Frazier and Page 2006).

These changes to patterns of inundation allow for detritus to accumulate in heavily forested, low-lying parts of the floodplain over several years, reducing intermittent terrestrial carbon inputs to adjacent riverine habitats (Baldwin et al. 2016) while increasing the risk of widespread hypoxic conditions (Whitworth and Baldwin 2016). After four years of dry conditions the amount of accumulated leaf litter stabilises (Whitworth and Baldwin 2016). Climate change is also thought to play a role in the risk of hypoxic blackwater by reducing rainfall runoff, creating protracted periods of drought (Whitworth et al. 2012). Widespread drought between 2000 and 2010, combined with river regulation, meant that large parts of both the Murray and Murrumbidgee river floodplains hadn’t been inundated for several decades, contributing to widespread and severe hypoxic blackwater and contributing to the deaths of large numbers of aquatic animals when flooding occurred in 2010 (King et al. 2012; McCarthy et al. 2014; Whitworth and Baldwin 2016).

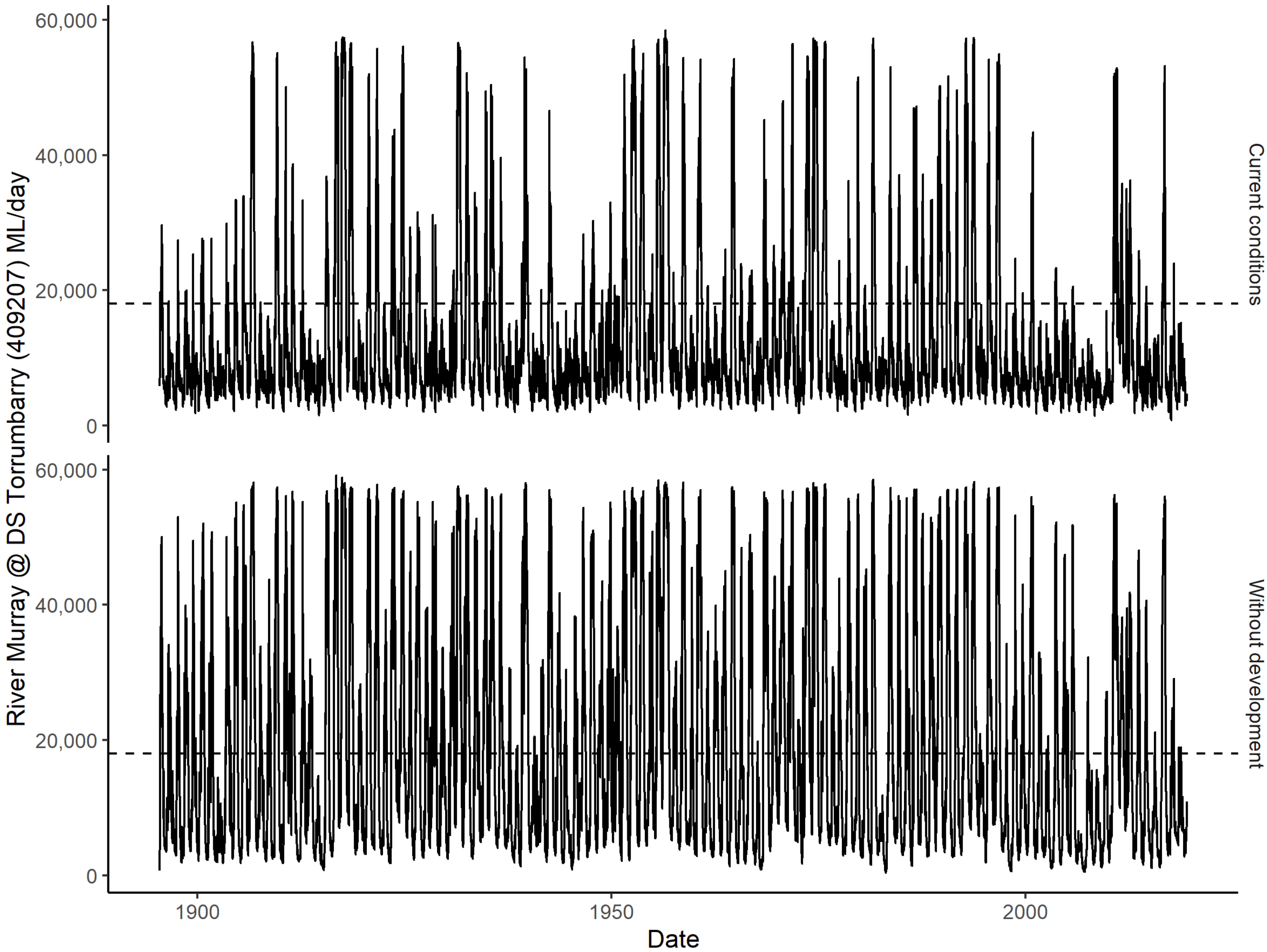

Figure 2: Modelled discharge rate for the River Murray at Downstream Torrumbarry Weir (409207) under the regulated regime ‘current conditions’ and the system without water impoundment and diversions ‘without development’

The horizontal dashed line shows the discharge rate where flows begin to enter Koondrook–Perricoota Forest.

1.3 Hypoxic blackwater in the Murray, Murrumbidgee and Edward Kolety–Wakool rivers

There have been a number of hypoxic blackwater events in the southern Murray–Darling Basin in the recent past: 2000–01, 2009, 2010–11, 2012 and 2016.

2000–01: A hypoxic blackwater event occurred in the Edward Kolety–Wakool River system at the end of 2000 and the beginning of 2001 (Mosig 2001), although it didn't receive very much coverage in the media, nor was it monitored. Prior to the event, the last flood of a similar magnitude was in the winter of 1998. The blackwater event was characterised by a peak flow of about 70,000 ML/d (during early September 2000, followed by a second peak of about 90,000 ML/d in early November (Figure 3; unless otherwise stated, all flow rates are at the gauge downstream of Yarrawonga Weir on the Murray River (409025)).

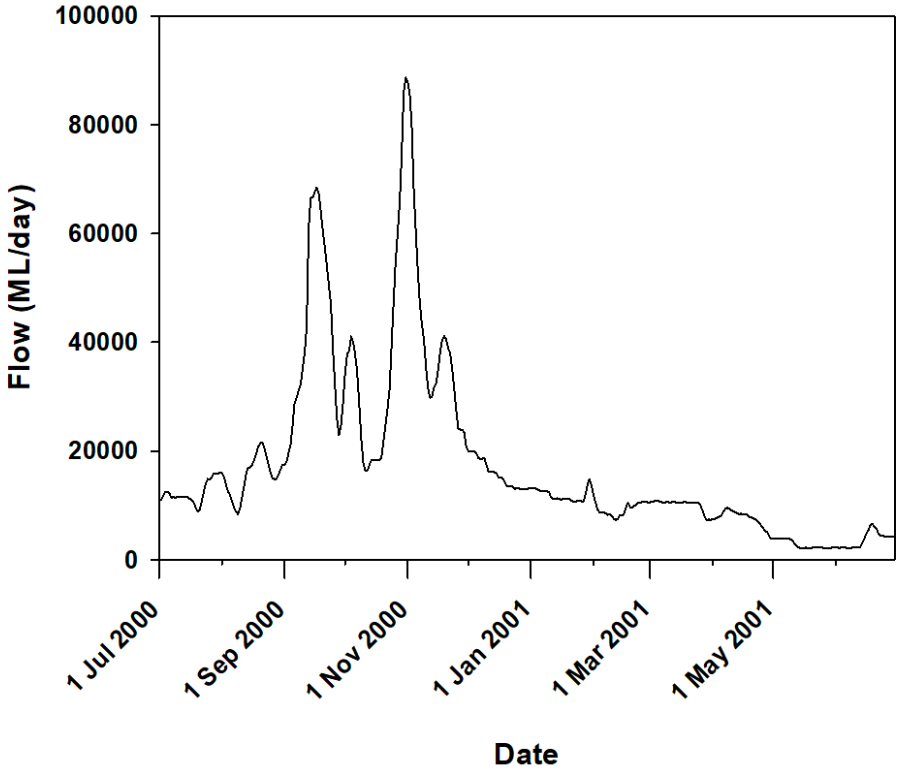

Figure 3: Discharge rate at the Murray River Downstream of Yarrawonga Weir (409025) during the 2000 hypoxic blackwater event

The flood was augmented by 341 GL of environmental water (Stewart and Harper 2002), most of which was delivered in December to prolong the flood to assist with a bird breeding event in Barmah Forest (Figure 3).

2009: Fish kills were recorded in Colligen Creek and Merrin Creek, both in the Edward Kolety–Wakool system in January and February 2009 (Baldwin and Whitworth 2009) and the Niemur River in February 2009 (Cooper 2009). All fish kills were caused by controlled low flow releases of water down channels. At least in the case of the Colligen and Merin creeks, the channels had been reduced to a series of pools. There was only minimal monitoring of the events (Baldwin and Whitworth 2009) but eye-witness accounts of the fish kills have been recorded (Cooper 2009). A key feature of the kills was the extremely hot weather at the time of the releases.

2010–11: A massive hypoxic blackwater event occurred in 2010 and 2011 which impacted the Murray, Murrumbidgee and Edward Wakool river systems. The event was extensively monitored, and there are various accounts of it in the scientific literature (e.g. Whitworth et al. 2012), so will only be dealt with briefly here. The event in the Murray River was characterised by an initial flood peak of about 100,000 ML/d in early September 2010, followed by a subsequent flood peak of about the same magnitude in mid-December 2010 (Figure 4).

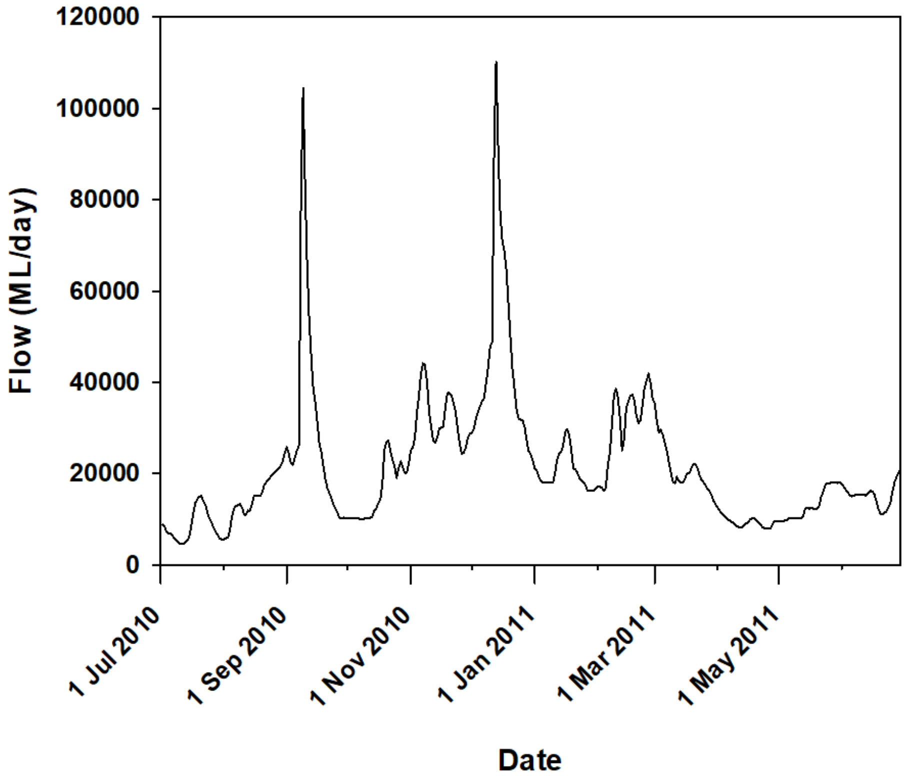

Figure 4: Discharge rate at the Murray River Downstream of Yarrawonga Weir (409025) during the 2010–11 hypoxic blackwater event

Prior to the flood in September 2010, the last peak of similar magnitude was recorded in 2000 (discussed above). There was a flood peak of about 50,000 ML/d in the winter/early spring of 2003, about 40,000 ML/d in 2004 and 30,000 ML/d in 2005. Therefore, the floodplain on the Murray River had not been flooded to any large extent since the beginning of 2006. Fish kills were reported in the Wakool River in early October 2010, and therefore were associated with the first flood pulse in September (ABC 2010).

In the Murrumbidgee River, the pulse of water in September 2010 was rather muted, but there was a significant flow in January 2011, with a flood peak of about 20,000 ML/d at Balranald Gauge (Station 410130 – Figure 5). Flooding in the Murrumbidgee River system during 2010–11 resulted in a brief period of hypoxia at sites upstream of the Lower Murrumbidgee floodplain (approximately upstream of Hay), and severe and persistent hypoxia in the river channel downstream of the floodplain (near Balranald) (Whitworth et al. 2012).

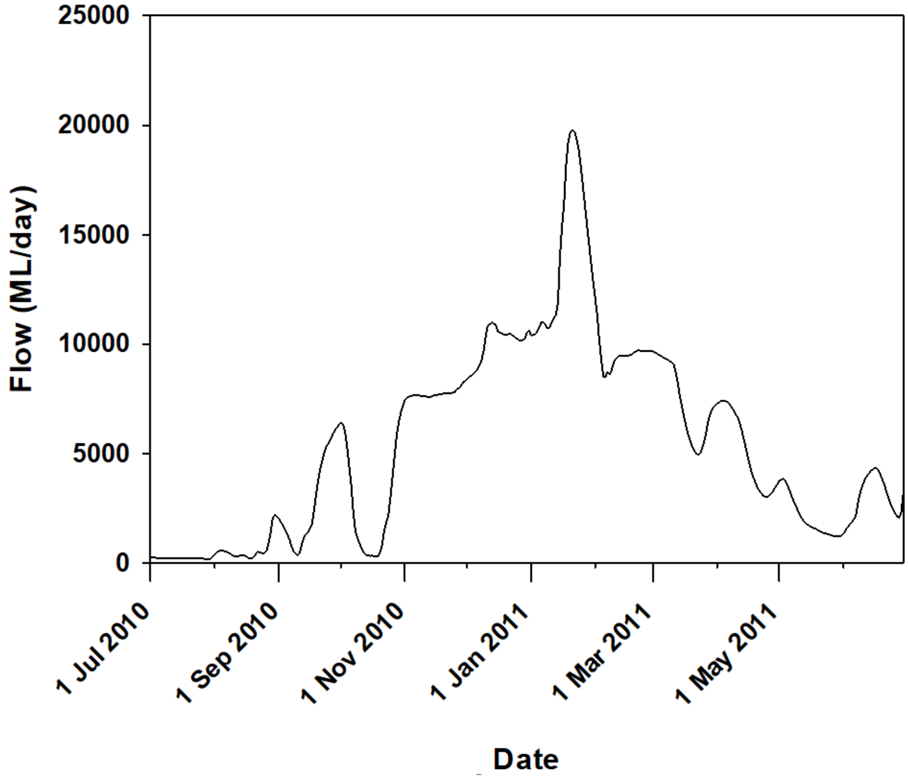

Figure 5: Discharge rate at the Murrumbidgee River Downstream of Balranald Weir (410130) during the 2010–11 hypoxic blackwater event

2012: A hypoxic blackwater event occurred in March and April 2012 throughout parts of the Murray and Murrumbidgee systems (Whithworth and Baldwin 2012); although the duration and extent was nowhere as extensive as the 2010–11 event (Figure 6) mostly because a large proportion inundated in the 2012 event had previously been inundated in 2010–11.

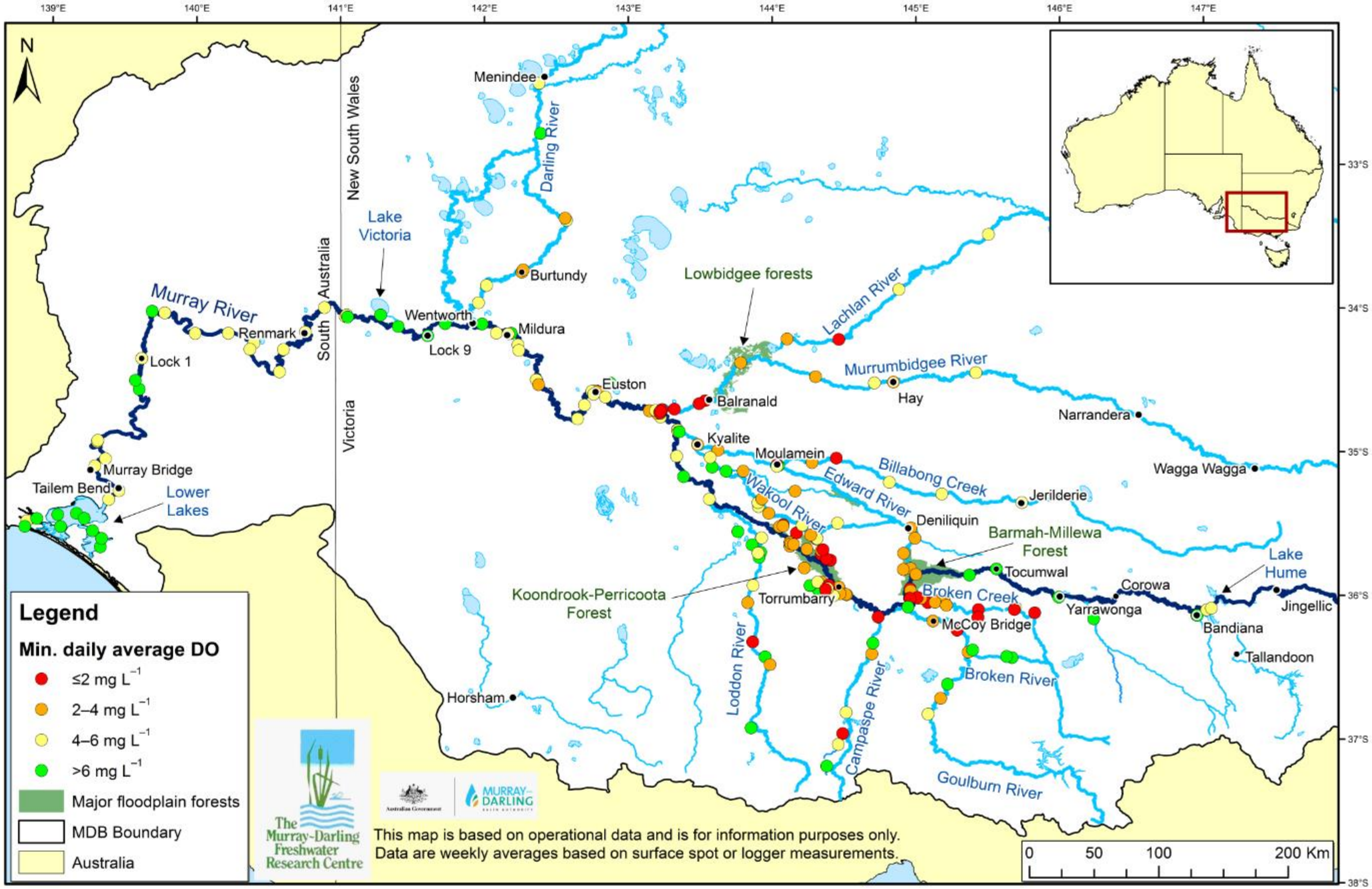

Figure 6: Minimum (daily average) surface DO concentration recorded at sites monitored 28 February – 21 May 2012 (reproduced from Whitworth and Baldwin 2012 under a Creative Commons Licence to the Murray–Darling Basin Authority)

Extensive rainfall in March 2012 resulted in peak flows of about 60,000 ML/d at Yarrawonga and about 35,000 ML/d at Balranald (data not shown). A short-lived pulse of blackwater from the Barmah–Millewa Forest impacted on the Murray and Edward Kolety–Wakool river systems. Brief pulses of blackwater also occurred with flow pulses in the lower Goulburn and Campaspe rivers, as well as Broken Creek, and would have contributed to DO depletion in the Murray River. Blackwater from the Koondrook–Perricoota Forest had a minor impact on the Wakool River. The most severe and prolonged hypoxic blackwater generation occurred in the Murrumbidgee River and Billabong Creek catchments, and this impacted on downstream reaches of the Edward and Murray rivers. These catchments experienced larger flood magnitudes in 2012 than in 2010–11, inundating some floodplain areas that had not been flooded for more than a decade. Therefore, despite the drought having been considered to have broken in spring 2010, post-drought flooding remained a key driver of hypoxic blackwater generation during 2012.

2016: Extensive flooding through the region of interest created hypoxic blackwater in the Murray, Murrumbidgee and Edward Kolety–Wakool rivers. Peak flows at Yarrawonga were approximately 180,000 ML/d during October (Figure 7) and about 30,000 ML/d at Balranald in early November (data not shown). The flows in the Murray River in particular inundated areas that had not been inundated in a very long time. For example, the peak flow at the Doctors Point gauge in Albury was about 100,000 ML/d, causing extensive flooding; a level not reached since 1996.

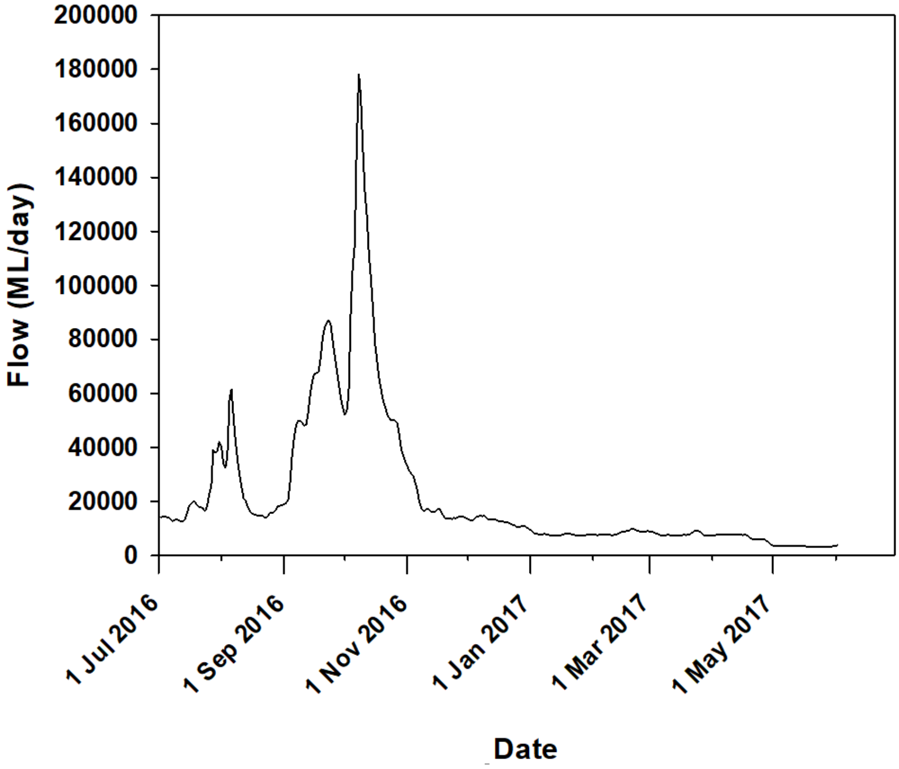

Figure 7: Discharge rate at the Murray River Downstream of Yarrawonga Weir (409025) during the 2016 hypoxic blackwater event

In addition to the known blackwater events in the Murray, Murrumbidgee and Edward Kolety–Wakool rivers, there are at least 18 contemporaneous newspaper accounts of fish death events, most of which can be attributed to hypoxia (see Appendix A). One key observation from the newspaper accounts is that, with the possible exception of extensive fish deaths throughout the southern Murray–Darling Basin in 1929–30, most of the fish deaths appear to be localised (although this could simply represent under reporting of events).

1.4 Implications of historical and observed hypoxic blackwater occurrence for modelling

Several points arise from this analysis of the nature of hypoxic blackwater events in the southern Murray–Darling Basin:

1. Although hypoxic events tend to occur in the summer months, even September flows can generate hypoxia if enough area is flooded (e.g. the 2010 event).
2. A flood earlier in the year does not preclude the formation of hypoxia. Several of the recent blackwater events were characterised by an early spring flood followed by a similar flood during summer.

   It has been assumed that the initial flood would leach the DOC from the litter on the floodplain (e.g. Howitt et al. 2007), therefore limiting the likelihood of hypoxia in the subsequent flood. While it has been shown experimentally that the amount of DOC that can be extracted from red gum litter that has previously been flooded is actually quite low (typically less than 10 per cent of the total amount of DOC that could be extracted – Whitworth et al. 2013a), it is possible that flooding actually induces new litter fall. While there is no evidence that this occurs for red gums, a study by Pook (1985) of leaf dynamics in *Eucalyptus maculata* dominated forests (NSW coast and tablelands) suggests this may be possible. This study extended over a severe drought in 1979–80, followed by drought-breaking rains in February 1981 and a period of above-average rainfall thereafter, and found that eucalypt leaf fall for the 12 months July 1980 – June 1981 (inclusive) was 3.7 t ha^{-1}, 60 per cent higher than the average leaf fall recorded during non-drought years. When examined by season, spring 1980 leaf fall was found to be about 3.5 times the average of other years, whereas summer 1980–81 leaf fall was unusually low, presumably because the bulk of readily abscised foliage had already been lost in spring. After the February rains, leaf fall increased again to a peak in autumn 1981, concurrent with a flush of new foliage. The autumn peak and a later peak in winter, were also coincident with heavy rains, suggesting that the physical effects of rain and/or wetting–drying cycles may have enhanced leaf shedding. A key knowledge gap is whether flooding induces greater litter fall in red gum forests, especially after an extended period without flooding.

   Another point arising from this observation is that it is critical to measure litter loads, rather than relying on estimation (modelling). Too little is known about the dynamics of organic matter accumulation for it to be accurately modelled; however, litter loads can be easily estimated by field monitoring.
3. Prior to 2000 (during the current era), hypoxic blackwater events (especially in the lowland sections of the Murray, Edward Kolety–Wakool and Murrumbidgee rivers) were either rare, or alternatively under-reported. For example, most of the fish deaths in the Murrumbidgee were associated with freshes, or single storms that cause localised inundation, rather than large over bank floods (Appendix A). Localised heavy rainfall can contribute to hypoxic blackwater events that affect individual waterbodies or short reaches, and although these events may coincide with increased flows in the channel, they are not necessarily associated with widespread hypoxic blackwater.

It is possible that large overbank hypoxic blackwater events were rare, not because flooding was less frequent in the past, but indeed the opposite. For example, modelling by the Murray–Darling Basin Authority indicates that in the absence of river regulation during the period from 1889 to 2010, Koondrook–Perricoota Forest would have been flooded in all but six years (see supplementary material in Baldwin et al. 2016). With more frequent flooding the overstory vegetation on the floodplain would be in good condition, potentially reducing litter fall. Further, annual flooding would have leached the carbon from the previous year's litter fall. Therefore, carbon would be less likely to accumulate on the floodplain to levels where it could lead to hypoxia. Furthermore, flooding would be more likely to occur during the cooler months (associated with winter rainfall and snow melts). The cooler the temperature the slower the microbial respiration, and therefore the lower the likelihood that the rate of DO consumption would exceed the rate at which it could be replenished from the atmosphere.

2 Modelling hypoxic blackwater for the program

Conceptually, the factors driving hypoxic blackwater events are well known (Figure 8); however, translating that knowledge into a functioning model is difficult in practice because there are multiple sources of uncertainty. Here we describe the sources of model uncertainty.

Litter loads are highly variable in space and time: The amount of accumulated leaf litter on an inundated floodplain limits the amount of leachate that can be produced by flood flows. Observed litter loads in floodplains along the mid-Murray are typically around 500 g/m^2 ± 200 g/m^2 (Hladyz et al. 2011; Baldwin 2021) but can vary between zero and 1500 g/m^2 at any one floodplain (e.g. Baldwin 2021). Furthermore, depending on tree condition and weather, monthly litter fall can be as high as about 300 g/m^2.

Although broad trends of litter accumulation are expected to be related to the frequency and duration of inundation, flooding likely imparts both positive and negative effects on litter accrual depending on the vegetation type, time of year and the length of time since last flooded. There is insufficient data to predict litter loads at broad spatial scales through time.

Floodplain hydrology: Hydrological events that exceed bankfull will contribute varying amounts of water to the floodplain, some of which may return to the river depending on flow paths through different floodplain areas and losses to the soil and to evaporation. Mechanistic models attempt to define the interaction between this floodplain flow volume and any organic matter it encounters before returning to the river. The amount of water that moves onto the floodplain and returns to the river is expected to be inconsistent through time and difficult to quantitatively model.

Inundation extent: Areal estimates can be used to define the amount of accumulated leaf litter that interacts with the overbank flow volume. Inundated areas are estimated using an instantaneous discharge rate measured (or modelled) at an indicator site where the resulting inundation extent has been informed using either hydraulic modelling or previously mapped inundated extents. In many cases the amount of time a flow rate is exceeded is critical to the inundation extent, in addition to the height achieved, and this is not always considered by inundation models. Moreover, the amount of time water resides on the floodplain after the flow peak has passed is not included in any of the inundation models that are currently available. Over or underestimates of floodplain inundation and/or residual inundation can substantially alter the results calculated from mechanistic modelling.

Temperature: There are several temperature-dependent variables that influence hypoxic blackwater (Figure 8). Although the seasonal and interannual variation in water temperature can be easily predicted using observations in river systems, its variation across floodplains cannot be modelled. Water temperature in turbulent river channels is typically uniform; however, on the floodplain water temperature can be stratified, highly variable, and affected by the growth of aquatic vegetation.

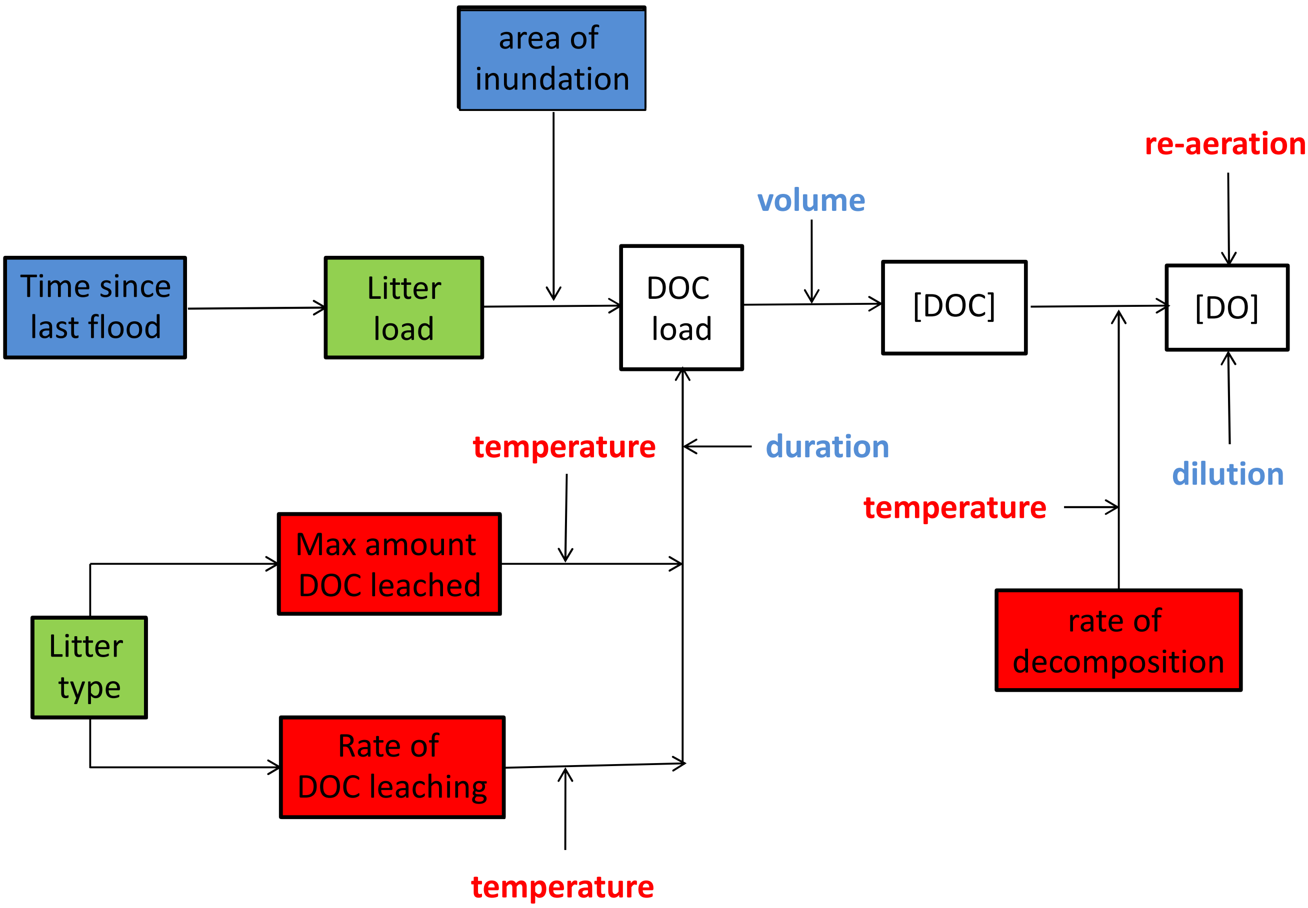

Figure 8: Mechanistic drivers of hypoxic blackwater in rivers (from Whitworth and Baldwin 2016)

To our knowledge there are three published blackwater models applicable to the current study:

- The original blackwater model (Howitt et al. 2007) was more a conceptualisation than a functioning model that could be applied across multiple sites.
- The Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin 2016) was an updated version of the original model by Howitt et al. (2007). It included temperature dependency in key algorithms (which was missing in the original model). It also included the ability to include some flood (e.g. duration) and floodplain characteristics (albeit rather simplistically). It was designed to model blackwater at a single floodplain during a single event to allow water managers to predict the risk of hypoxia following a managed event.
- DODOC (Mosley et al. 2021) is a plugin for the SOURCE flow modelling platform. DODOC essentially uses the same algorithms that underpin the BRAT, but has the potential to model more complex floodplains and multiple floods.

We initially attempted to use the DODOC plugin to model hypoxic blackwater for the program, but were unable to calibrate the model to observed DOC concentrations or observed hypoxic events. A large part of this difficulty arose from calculating litter accumulation, which in DODOC is based on time-since-last flood (a similar approach to that used by the original blackwater model; Howitt et al. 2007). However, this approach has proven to be inaccurate, mostly because of the high variability of litter loads on floodplains (discussed above). Subsequently, in the BRAT the initial litter loading is an input, rather than being calculated in the program, and preferably based on actual measurements of leaf litter loading.

As noted above, the BRAT was designed to examine a single event in a single floodplain, and therefore not suited for the interrogation of the 124-year time series used in the current assessment. Because neither model by itself could be used, an alternative, risk-based strategy was developed. Because of data limitations (particularly in the Murrumbidgee River) the approach used was slightly different between river valleys.

3 Assessment overview – Murray catchment

3.1 Approach

The approach taken to determine the impact of changing constraints in the Murray River is presented graphically in Figure 9.

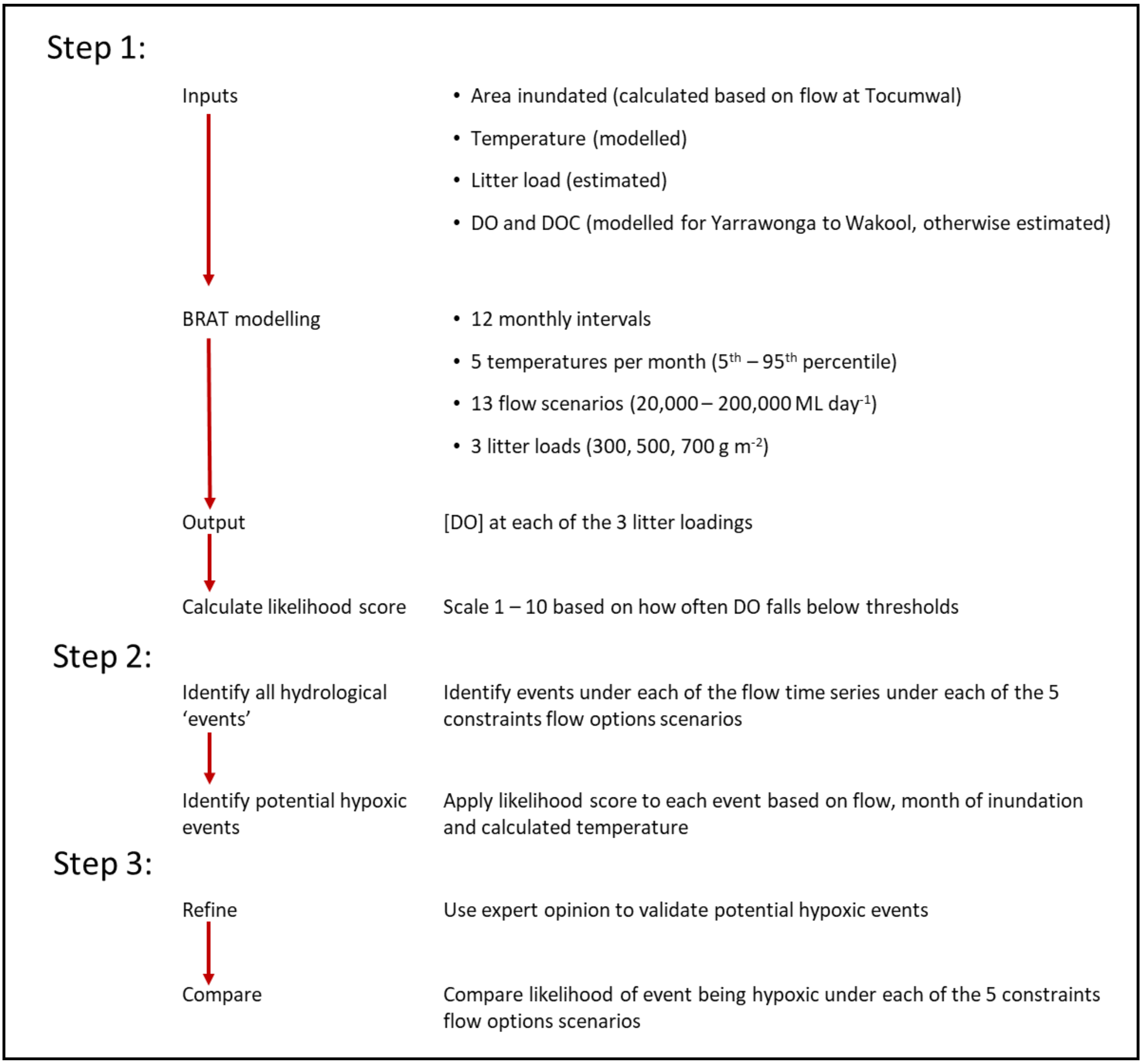

Figure 9: Steps used for identifying likely hypoxic blackwater events in time series data for the Murray project area

Step 1: Categories of flow events were identified (based on flow magnitude, timing and water temperature) and then evaluated for their likelihood of hypoxia using the BRAT (described further below). This provided a lookup table of event categories and associated hypoxia likelihood scores (1 to 10).

Step 2: The modelled 124-year flow time series were then broken down into flow 'events' and the likelihood of each flow event creating a hypoxic event was assessed using the lookup table.

Step 1 was repeated for three leaf litter load scenarios and step 2 was repeated for all five flow scenarios reflecting the flow limit options being investigated by the program. Because we do not have the water temperature for the corresponding time series, this was also modelled.

Step 3: Classified events were reviewed, with consideration given to antecedent conditions as potential drivers, or mitigating factors, of possible hypoxic blackwater events.

3.1.1 The Blackwater Risk Assessment Tool (BRAT)

The BRAT was developed for predicting the likelihood of hypoxia resulting from inundation of floodplains during discrete flow events at a single floodplain. The model uses a simplified representation of floodplain hydrology, and operates across a fixed floodplain area that is configured to reflect a flow event of a specified height, duration and inundation extent. The BRAT and its companion tool, the Blackwater Intervention Assessment Tool (BIAT; Whitworth et al. 2013b), have been used to evaluate the risk of hypoxic blackwater arising from flow deliveries in Gunbower (Whitworth and Baldwin 2016), Barmah–Millewa (e.g. Baldwin 2021), Koondrook–Perricoota Forest (Watts et al. 2021) as well as the lower Murrumbidgee River floodplain (Wolfenden et al. 2018) and to evaluate the success of hypoxia mitigation strategies (Wassens et al. 2017). The BRAT is designed to be used to scenario-test individual flow events.

Key inputs to the BRAT are:

- time of year OR water temperature
- duration of overbank flows entering the floodplain
- maximum floodplain outflow rate
- concentration of DOC in water flowing out to the floodplain
- maximum inundation area on the floodplain
- transit time of water flowing across the floodplain
- the characteristics of dilution water (volume, DOC and DO – if known)
- the amount and type of litter on the floodplain.

Complex, multi-peak floodplain flows cannot be easily represented. The BRAT can be applied where floodplain inundation and hydrology are well understood but cannot be easily applied to long time series. Maximum inundated extent is estimated from a separate inundation model; however, the duration of water on the floodplain varies for each BRAT model.

3.2 Study area

In the Murray River project area the single largest floodplain, and the largest source of DOC during flood events, is the Barmah–Millewa Forest (Figure 11). The role of Barmah–Millewa Forest in generating hypoxic blackwater has made it a focus of previous risk assessments (e.g. Howitt et al. 2007; Joehnk et al. 2020; Baldwin 2021). Modelling focused on the occurrence of hypoxia in the river channel immediately downstream from where floodplain flows return.

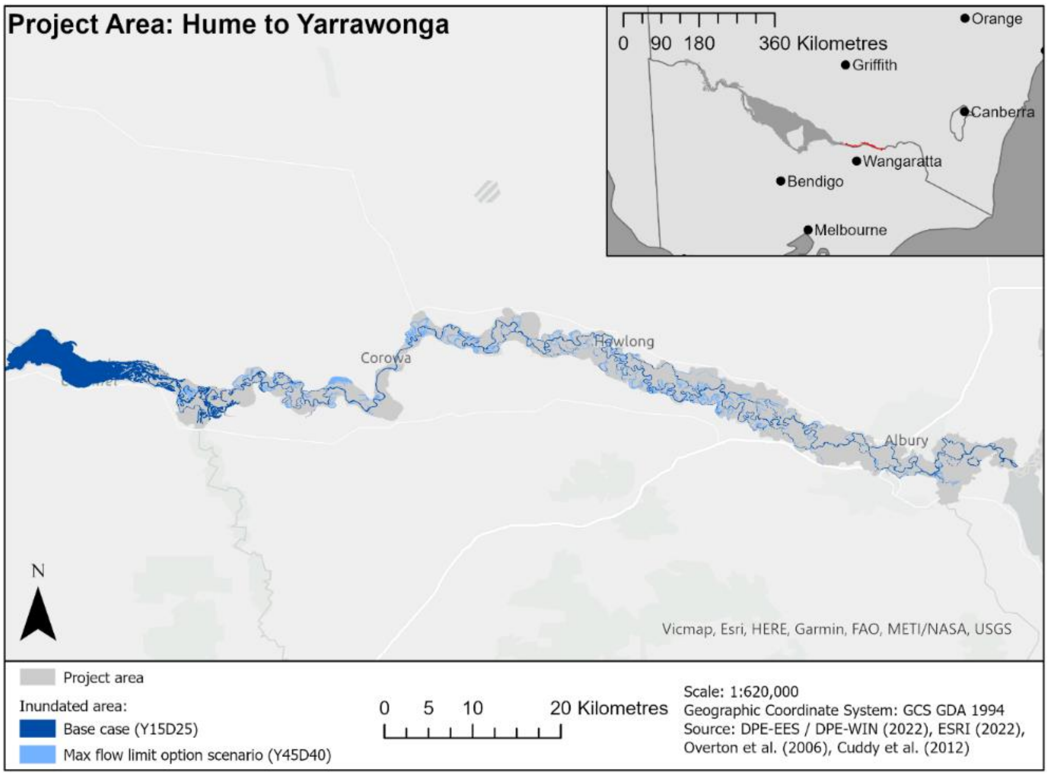

Figure 10: The Murray River between Hume and Yarrawonga weirs showing estimated inundation extents (from the River Murray Floodplain Inundation Model – 'RiM-FIM') for the base case flow option discharge rate (25,000 ML/d at Doctors Point) and the maximum flow option discharge rate (40,000 ML/d at Doctors Point)

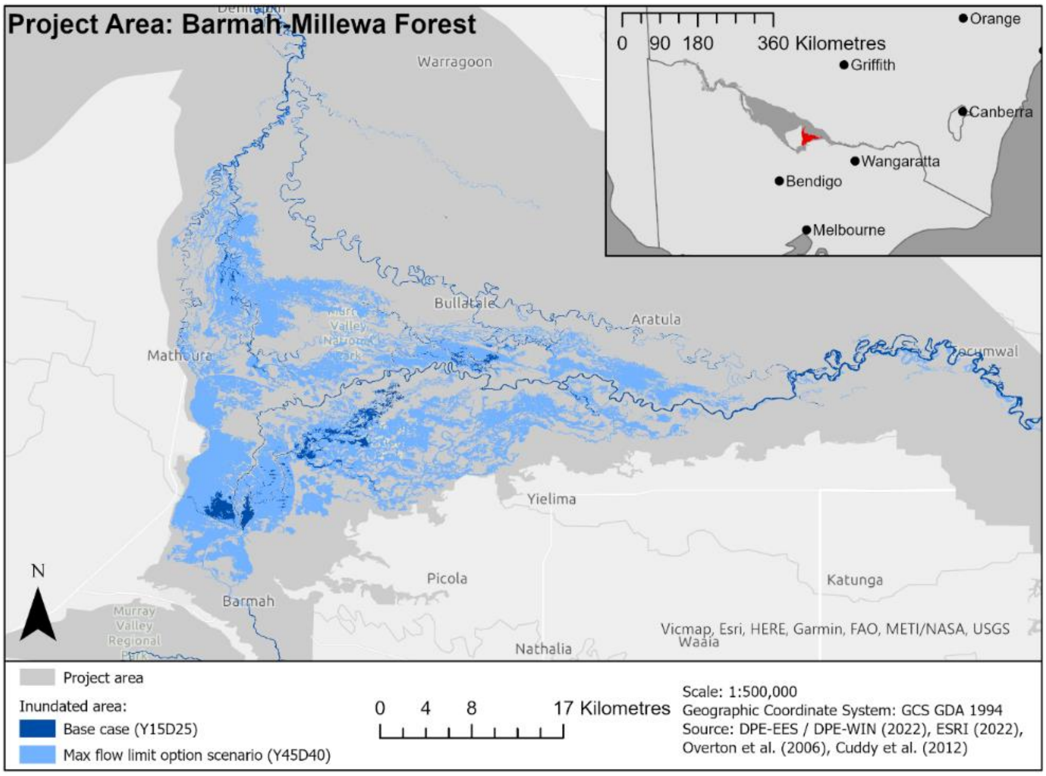

Figure 11 :The Murray River between Tocumwal and Barmah / Deniliquin showing estimated inundation extents (from the RiM-FIM) for the base case flow option discharge rate (15,000 ML/d at Yarrawonga) and the maximum flow option discharge rate (45,000 ML/d at Yarrawonga)

This map shows inundation extents for Barmah Forest, which is the largest individual floodplain area in the Murray River system.

3.3 Scenario modelling

Hypoxic blackwater risk scenarios were developed to capture the range of potential variability in flow event size, time of year, temperature and litter load. Overall, 780 individual event types were created, each using three different litter loads (Table 1).

Table 1: Factors, levels and value ranges used to develop scenarios for the Murray River hypoxic blackwater likelihood assessment

Factor	Number of levels	Range of values considered
Event size (peak flow rate at Tocumwal)	13	20,000 to 200,000
Month	12	
Temperature	5	5th to 95th percentile
Litter load	3	300 g/m^2 to 700 g/m^2

3.3.1 Hydrological parameters

The scenarios included 13 different hydrological events, each with an increasing peak discharge rate (Table 1, Appendix B). Each Barmah–Millewa scenario was paired with an ‘inflow scenario’ that was used to scale the likely contribution of DOC and DO from the Hume–Yarrawonga reach entering Barmah–Millewa Forest reach used to assess hypoxic blackwater likelihood. A separate inflow series was calculated because although hypoxia is not expected to occur in the Hume–Yarrawonga reach, this area will contribute to DOC entering the forested area downstream. Unlike the main Barmah Forest model, the Hume–Yarrawonga inflow series only used the median water temperature.

For both reaches, the hydrological configuration assumed the following:

- ‘dilution volume’ is the volume up to the bankfull height and remains in-channel – this is a fixed value used across all scenarios
- ‘peak inflow’ was calculated as the ‘peak flow rate’ at the upstream indicator site minus the estimated dilution volume
- ‘maximum outflow’ was calculated as half of the ‘peak inflow’
- time taken for water to flow across the floodplain was 7 days (Barmah) and 2 days (Hume–Yarrawonga)
- ‘total volume delivered to the floodplain’ was determined iteratively using the BRAT by adjusting the volume parameter until the hydrological model produced the correct peak inflow.

To estimate DO and DOC inflow concentrations from the Hume–Yarrawonga reach for each model scenario at Tocumwal, flow peaks at Tocumwal were matched with commensurate flow peaks upstream. For the Hume–Yarrawonga inflow scenarios, the inundation extent from the RiM-FIM is linked to flows at the Corowa gauge; however, flow volumes to the floodplain were represented at the Murray River downstream of the junction with the Ovens River.

To estimate equivalent peak flow rates for Corowa and Downstream Ovens Junction, peaks at Tocumwal were routed upstream using the Flow Peak Tracker tool (DPE 2022a). This tool uses observed flow records to match flow peaks as they pass any two gauging stations and calculates a relationship that can be used to interpolate flow rates between the two gauges. For the current study, peak flow rates representing flows at Tocumwal were first routed upstream to the Murray River below the junction with the Ovens River. There is no physical gauge located at this site, so for hypoxic blackwater modelling, flows were recorded at the equivalent location in the Source hydrological model ('Default Link #18' in the River Murray Model version 5.10.0 23012022). This ensured that inflow rates included flow contributed from the Ovens River. Flow peaks at Default Link #18 were also routed to the Corowa gauge.

Flow peak tracking analysis was carried out for the period between 1990 and 2022. For the Default Link #18 to Tocumwal reach, 80 individual flow peaks were identified ranging from 12,000–177,000 ML/d at Tocumwal. For the Corowa to Default Link #18 reach, 73 individual flow peaks were identified ranging from 16,000–158,000 ML/d at the downstream location (Figure 12).

3.3.2 Inundation extents

Each hydrological scenario uses an estimate of the maximum floodplain inundation extent.

For the Hume–Yarrawonga reach the inundated area was estimated using the RiM-FIM inundation rasters. These rasters are indicated by flow rates at the Corowa gauge (409002). To determine maximum inundation area, flows at the junction of the Ovens River were routed upstream to Corowa using the method described above (Figure 12).

For the Barmah–Millewa reach, the maximum inundated area for each scenario was calculated using outputs from the hydrodynamic model for Barmah–Millewa Forest (Water Technology 2011) for discharge rates below 100,000 ML/d, and the RiM-FIM for rates above 100,000 ML/d. Both of these inundation models are indicated by peak flow rate at Tocumwal (gauge ID 409207); however, the RiM-FIM inundation extents were excluded from the final analysis (see below).

All scenario events were modelled with the flow peak occurring in the middle of the month.

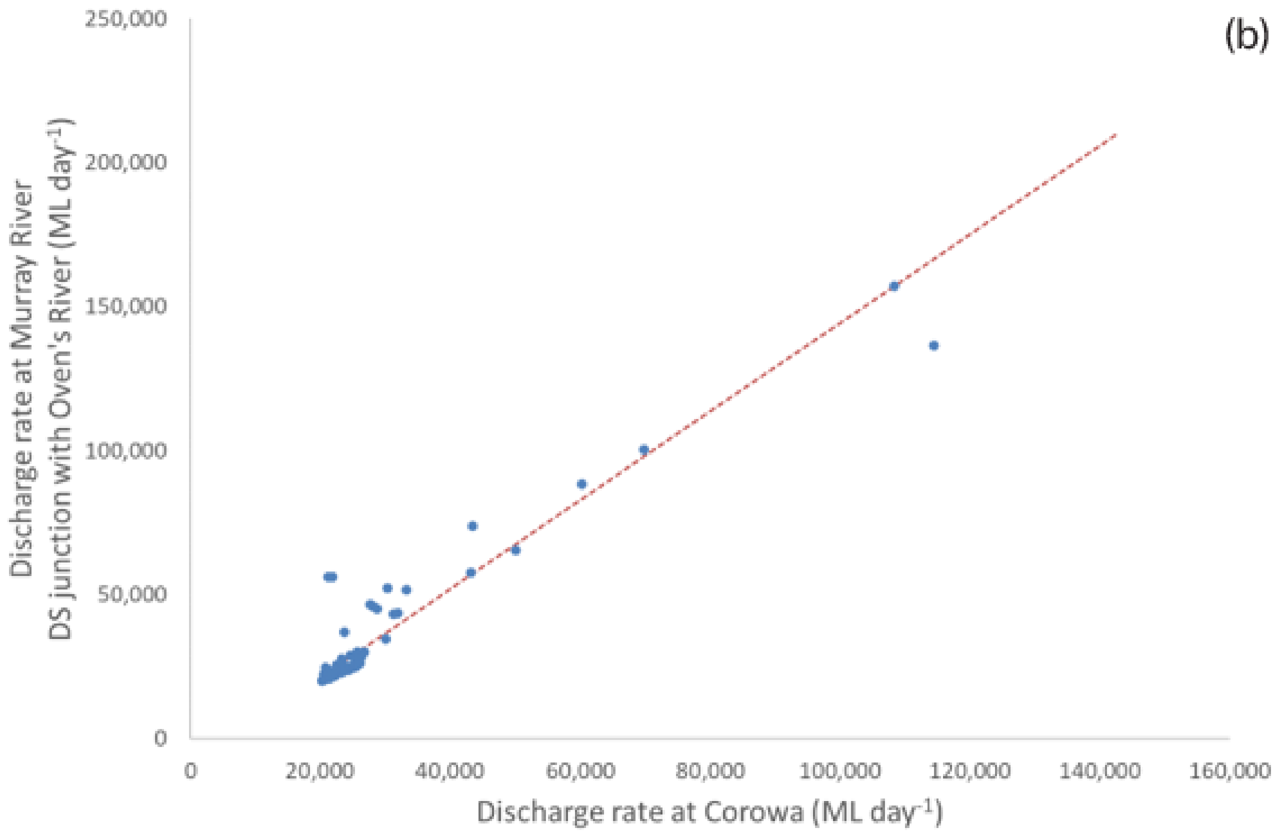

Figure 12: Flow peak tracking results for (a) Downstream Ovens Junction to Tocumwal (409207); and (b) Corowa (409002) to Downstream Ovens junction

Flows in the Murray downstream of the junction with the Ovens River were estimated using Source model outputs for Default Link #R18.

Table 2: Hydrological and inundation parameters used to define hydrological scenarios for the Hume–Yarrawonga and Barmah–Millewa study reaches

Corresponding flow peaks for the two reaches were determined using the Flow Peak Tracker tool (see above). Peak inflows were calculated as the peak discharge in the Murray minus an estimated bankfull height of 20,000 ML/d. Maximum outflows and total volumes were calculated using the BRAT (Whitworth and Baldwin 2016).

Event size			Hume–Yarrawonga				Barmah–Millewa			
Peak at Tocumwal (ML/d)	Peak at Corowa (ML/d)	Peak at Downstream Ovens River confluence (ML/d)	Peak inflow (ML/d)	Maximum outflow (ML/d)	Total volume (GL)	Maximum area (ha) [1]	Peak inflow (ML/d)	Maximum outflow (ML/d)	Total volume (GL)	Maximum area (ha) [2]
20,000	23,500	26,700	6,700	3,350	59	470	12,500	6,000	240	20,700
30,000	30,000	36,500	16,500	8,250	144	1,478	22,500	11,000	430	30,200
40,000	37,000	47,000	27,000	13,500	236	5,655	32,500	16,000	620	38,150
50,000	43,500	57,000	37,000	18,500	325	8,233	42,500	21,000	810	44,150
60,000	50,000	67,500	47,500	23,750	416	11,419	52,500	26,000	1,005	50,420
70,000	56,500	77,500	57,500	28,750	504	12,066	62,500	31,000	1,200	59,160
80,000	63,000	87,500	67,500	33,750	591	12,578	72,500	36,000	1,390	68,990
90,000	69,500	98,000	78,000	39,000	683	13,044	82,500	41,000	1,585	79,910
100,000	76,000	108,000	88,000	44,000	770	13,437	92,500	46,000	1,775	83,650
125,000	92,250	133,500	113,500	56,750	994	14,286	117,500	58,500	2,255	97,350
150,000	108,500	158,500	138,500	69,250	1,213	14,929	142,500	71,000	2,735	110,470
175,000	124,750	184,000	164,000	82,000	1,445	15,469	167,500	83,500	3,215	120,250
200,000	141,000	209,500	189,500	94,750	1,660	15,873	192,500	96,000	3,695	128,870

[1] Areas in the Hume–Yarrawonga reach are taken from the RiM-FIM.

[2] Areas where Tocumwal discharge rate is <100,000 ML/d are taken from the Barmah–Millewa hydraulic model, otherwise from the RiM-FIM.

3.3.3 Inflow DOC and DO concentration

The inflow DOC for the Hume–Yarrawonga reach was calculated using the long-term median DOC concentration (3 mg/L) recorded at Heywoods (below Lake Hume on the Murray River) using data from the Victorian Water Measurement Information System (DELWP 2022; 3 mg/L). The temperature-adjusted saturated DO concentration from BRAT was used for the inflow DO concentration. The median DO and DOC from the BRAT runs for the Hume–Yarrawonga reach were used as the inputs for the corresponding Yarrawonga–Wakool BRAT runs.

3.3.4 Water temperature

Each hydrological scenario was run using five alternative temperature time series calculated from the long-term average water temperature recorded at Tocumwal (Figure 13). Temperature series were calculated using the 5th, 25th, 50th, 75th and 95th percentile values for each day of the year using the entire time series (15 March 2002 to 4 July 2021). Each time series of percentiles was smoothed using a loess fitting function (with a span of 0.1). Each scenario used a subset of water temperature from the relevant percentile time series and the scenario month. This allowed for the likelihood assessment to adjust with warmer and cooler periods.

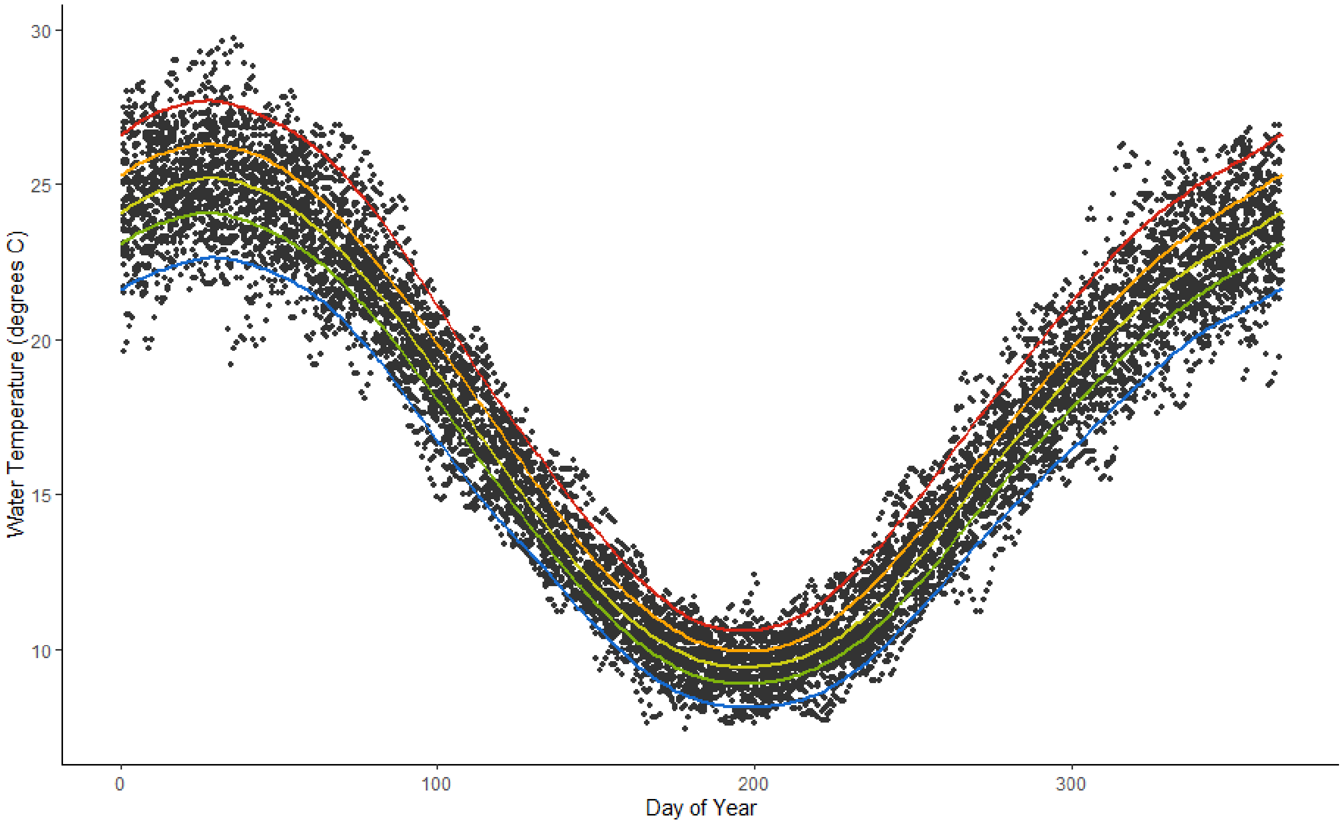

Figure 13: Observed water temperature (C°) for the Murray River at Tocumwal (ID 409202) for the period 10/6/2010 to 2/5/2021 plotted against the day of the year

3.3.5 Operating the BRAT

The BRAT was scripted in the R coding environment (R Core Team 2022) to allow for multiple scenarios to be run. The coded version (BRAT-R) was tested and developed to replicate the operation of the BRAT, with the addition of a user-specified temperature input time series.

The BRAT produces a time series of DO concentrations, representing the interaction of water with litter on the floodplain and the resulting carbon and oxygen concentrations in the receiving river. The BRAT-R was operated for each Murray River hypoxic blackwater scenario, recording the lowest DO concentration in each model run.

3.3.6 Scoring framework and amendments

Murray Valley

Overall, three potential leaf litter scenarios (low, moderate and high) were run for each combination of flow event height (n=13), month (n=12) and temperature regime (n=5; Table 1). A hypoxia likelihood score was calculated using the lowest recorded DO value after dilution in each of the three leaf litter scenarios (Table 3). A score of '8' or above indicates that the event resulted in at least one day where DO was less than two for the 'moderate' litter load scenario and so hypoxia is therefore 'likely' under typical conditions. A score of '7' suggests the event is only expected to cause hypoxia when litter load was unusually high.

For the Hume–Yarrawonga reach, when the full 780 different scenarios were run, none produced a risk score of '10', three produced a risk score of '9' and none produced a risk score of '8'. Of the three that produced scores of '9', all were at the 95th percentile of temperature and only occurred in January (2) or February (1) when it was highly unlikely that, given current knowledge, an environmental flow would be delivered.

For the Yarrawonga to Wakool Junction reach the initial scores showed a predicted decline in hypoxic blackwater risk associated with increasing flow rates, particularly above 90,000 ML/d. A review of the data revealed proportionally smaller increases in floodplain extent at higher flow thresholds in the inundation model, suggesting an increasing ratio of flow volume to floodplain surface area as peak flow height increases. Although it is possible that higher flow rates might lead to reduced hypoxic blackwater risk via dilution, it was decided that for this modelling exercise:

- there is as yet no strong evidence to support this outcome other than modelling
- the RiM-FIM modelling is possibly less reliable at very large, uncommon flow rates where there is less data available for verification
- a conservative approach would be adopted where the hypoxic risk at higher flow rates would inherit the same risk observed at the 90,000 ML/d inundation extent.

We note that constraints-level flow rates (15,000–45,000 ML/d) fall well within the range of values from the more reliable hydraulic model outputs for Barmah–Millewa Forest.

The final scores used for the assessment for the Yarrawonga–Wakool Junction are presented in Appendix B.

Table 3: Hypoxia likelihood scores determined using the results from each of three litter load scenarios run for each event

Each row represents a possible combination of scenario DO results and the assigned risk score. Numbers in the left two columns indicate the number of litter load scenarios where the criterion (<2 or <4) was met. Grey shading indicates combinations that are not possible (i.e. you cannot have DO<2 and not have DO<4).

Number of litter scenarios with DO<2	Number of litter scenarios with DO<4	Hypoxia likelihood score
0	0	1
1	0	NA
2	0	NA
3	0	NA
0	1	2
1	1	5
2	1	NA
3	1	NA
0	2	3
1	2	6
2	2	8
3	2	NA
0	3	4
1	3	7
2	3	9
3	3	10

Edward Kolety–Wakool system

The hydrology, flow paths and associated inundation for sub-reaches of the Edward Kolety–Wakool are much more complex than for the Barmah–Millewa reach and it was decided that a mechanistic approach described above would not work for this part of the system. Instead, we used the Barmah–Millewa results as a surrogate for hypoxia in the Edward Kolety–Wakool by adding an additional two points to the likelihood score for Barmah. This provides an indication of the likely frequency of large-scale events, assuming that likelihood is tied to events in the Murray. One of the principal reasons to include the Edward Kolety–Wakool River system in this analysis was as an input to the Fish Population Model (Todd et al. 2022) that is also being used in the program. The Fish Population Model includes a representation of Murray Cod deaths arising from large-scale hypoxic blackwater events.

3.3.7 Comparing the five constraints scenarios

Because the risk scores for the Hume–Yarrawonga reach were, with three exceptions, below ‘8’ and the three scores of ‘9’ only occurred under exceptionally hot conditions, and in months (January and February) when environmental flows are unlikely to be authorised, we infer that raising flow limits is highly unlikely to result in hypoxia for this reach.

Defining 'events' in the time series

Each flow option hydrological time series was analysed to identify discrete overbank flow events >20,000 ML/d at Tocumwal. In many cases, multiple flow peaks occur as part of a longer overall event with continuous flows to the floodplain. Individual ‘events’ were differentiated using the modelled discharge rate at Tocumwal, Barmah and the modelled return flow volume from Barmah Lake. This allowed for flow events with multiple peaks to be classified as part of the same event via the following rules:

- events begin when flows first exceed 10,000 ML/d at Tocumwal
- event ‘peaks’ occur where the discharge rate for a single day is greater than the maximum discharge rate for seven days before and after
- events cease after return flows from Barmah and Millewa forests are expected to have ceased (as indicated by Source model return flows for Barmah Forest)
- the overall event peak used to evaluate the likelihood of hypoxic blackwater is the highest magnitude individual peak within each event.

Each hydrological event was described in terms of its maximum peak discharge, the timing (month) of that peak, and median modelled water temperature. These three parameters were used to match each event to one of the scored event scenarios (Appendix B), rounding up or down to the nearest scenario for each parameter (peak height, timing and temperature). For events with clustered flow peaks, the hypoxia likelihood assessment was only applied to the largest individual peak in the series (for example, see Figure 14). This approach assumes that this highest flow is likely to inundate the greatest area and that subsequent high flows within the same event are not expected to carry the same carbon-loading. For lesser subsequent peaks, the likelihood is assumed to be negated by the antecedent flow. This approach cannot account for antecedent flows that are likely to mitigate hypoxic blackwater.

The percentile temperature range for each hydrological event was determined by matching the median modelled water temperature for the event (see next section) with the median observed water temperature for the same period.

In a small number of cases where the evaluated outcome was ‘borderline’ (i.e. there was some uncertainty around a hydrological or timing classification and the classification heavily influenced the assigned hypoxic blackwater likelihood), the model was re-run for a specific event using the actual date of the peak flow.

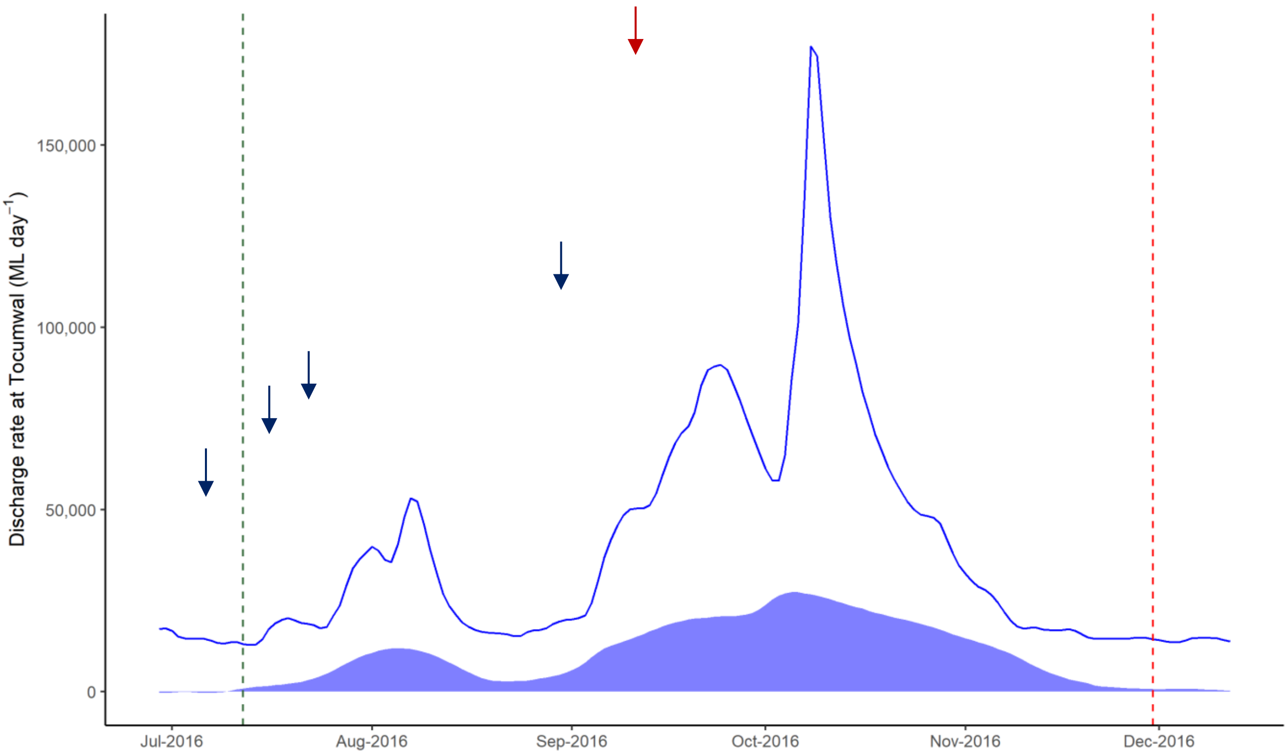

Figure 14: Observed discharge rate (ML/d) at Tocumwal for the 2016 flood event showing the beginning (vertical green dashed line) and end (vertical red dashed line)

Blue arrows indicate flow peaks within the event (i.e. individual peaks that occur while return flows are continuous). The red arrow shows the peak that was used for the hypoxia likelihood evaluation.

Modelling water temperature in the time series

Water temperature was predicted using a gradient tree boosting algorithm. Test and train datasets were built through random sampling of the observed water temperature time series dataset into equal proportions (50:50).

A suite of hydrological and climatic predictor variables were used in the model that capture a range of mechanistic controls on riverine water temperature and approximate lags inherent within the Murray and Murrumbidgee rivers. These predictor variables include:

- maximum discharge on the preceding day (ML)
- sum of maximum discharge for the preceding seven days (ML)
- maximum surface air temperature on the preceding day (°C)
- sum of maximum surface air temperatures for the preceding seven days
- minimum surface air temperature on the preceding day (°C)
- sum of minimum surface air temperatures for the preceding seven days
- total rainfall on the preceding day (mm)
- cumulative rainfall for the preceding seven days (mm)
- solar radiation on the preceding day (MJ/m^2)
- cumulative solar radiation for the preceding seven days (MJ/m^2)
- day of year (Julian date).

Rainfall and solar irradiation data were extracted from the SILO database (DES 2022) from the pixel spatially coincident with the gauge site. Observed water temperature data were obtained from the WaterNSW ‘Continuous water monitoring network’ website (WaterNSW 2022). The constructed models were applied to the Y15D25 flow option scenario to generate a modelled temperature time series for Tocumwal and Barmah.

Expert review

The above method provides a conservative estimate of hydrological events with an increased likelihood of hypoxia in each flow option time series. There are several aspects of hypoxic blackwater, in particular the accumulation of leaf litter through time and the role of antecedent hydrology in regulating leaf litter loads, that cannot yet be quantitatively modelled.

The purpose of the expert review was to examine each potential hypoxic event to consider whether the event was likely given the antecedent hydrology. The expert review also considered whether delivered flows that might create hypoxia would be delivered given existing risk assessment practices. Environmental water is collaboratively managed by state and federal agencies in consultation with technical experts, following a process of ongoing refinement (adaptive management). Hypoxic blackwater is one consideration that is managed in this way. The process involves assessing the risk of hypoxic blackwater and identifying possible mitigation options before releases are made. In some cases, monitoring and risk assessment may be carried out during the managed event, allowing water managers and river operators to adjust releases. In a small number of cases, flows exceeded thresholds of higher likelihood and it was determined that these would not be delivered operationally, meaning flows would be delivered earlier, at a lower flow rate, or not at all. In practice, decisions about environmental water releases are made with consideration of monitored leaf litter loads that cannot currently be modelled.

3.4 Results

Out of 124 years assessed across all flow scenarios, the initial assessment identified 17 potential flow events in the Barmah–Millewa model, and 37 events in the Edward Kolety–Wakool model with an increased risk of hypoxia in one or more of the program’s flow option scenarios. The expert assessment revised the number of years down to six likely hypoxic blackwater events in the Barmah–Millewa model and 15 events in the Edward Kolety–Wakool (Figure 15, Figure 16, Table 4).

The rational for these decisions (Appendix C) noted antecedent conditions, where events were preceded by substantial floodplain inundation during cooler months ahead of peak flows, and thresholds in the evaluation framework as the basis for many of the revised outcomes. These thresholds occur where there are large differences in either predicted inundation extent or water temperature in adjacent scenarios, and so a relatively large difference in hypoxia likelihood is observed depending on what flow category or month the event is classified into (see Appendix B). In a small number of cases, the review identified delivered flows where operational decisions are expected to prevent events from being delivered.

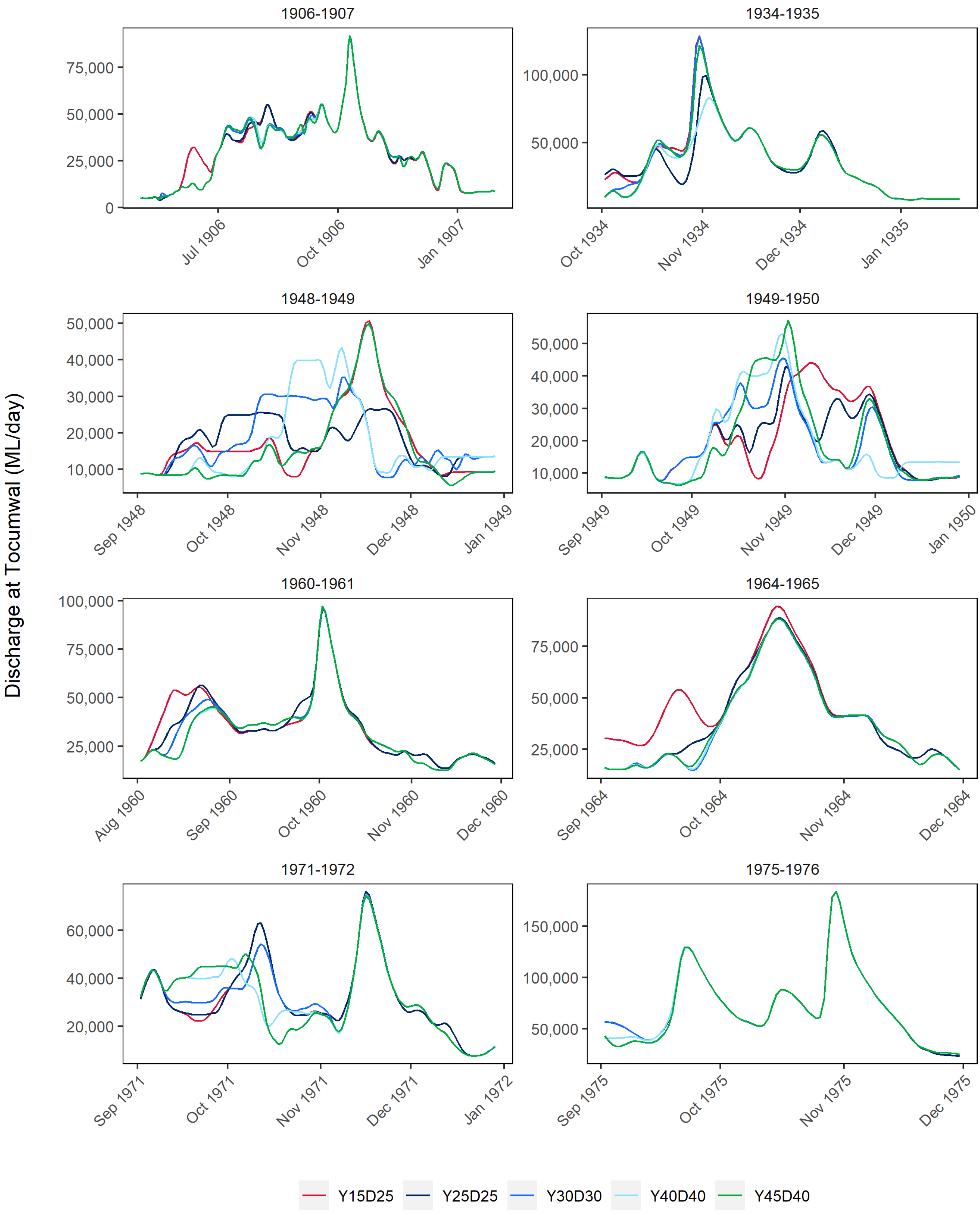

Figure 15: Discharge rates at Tocumwal for flow events determined to be associated with possible hypoxia either at Barmah or in the Edward Kolety–Wakool (part 1 of 2)

Note the variable y-axis.

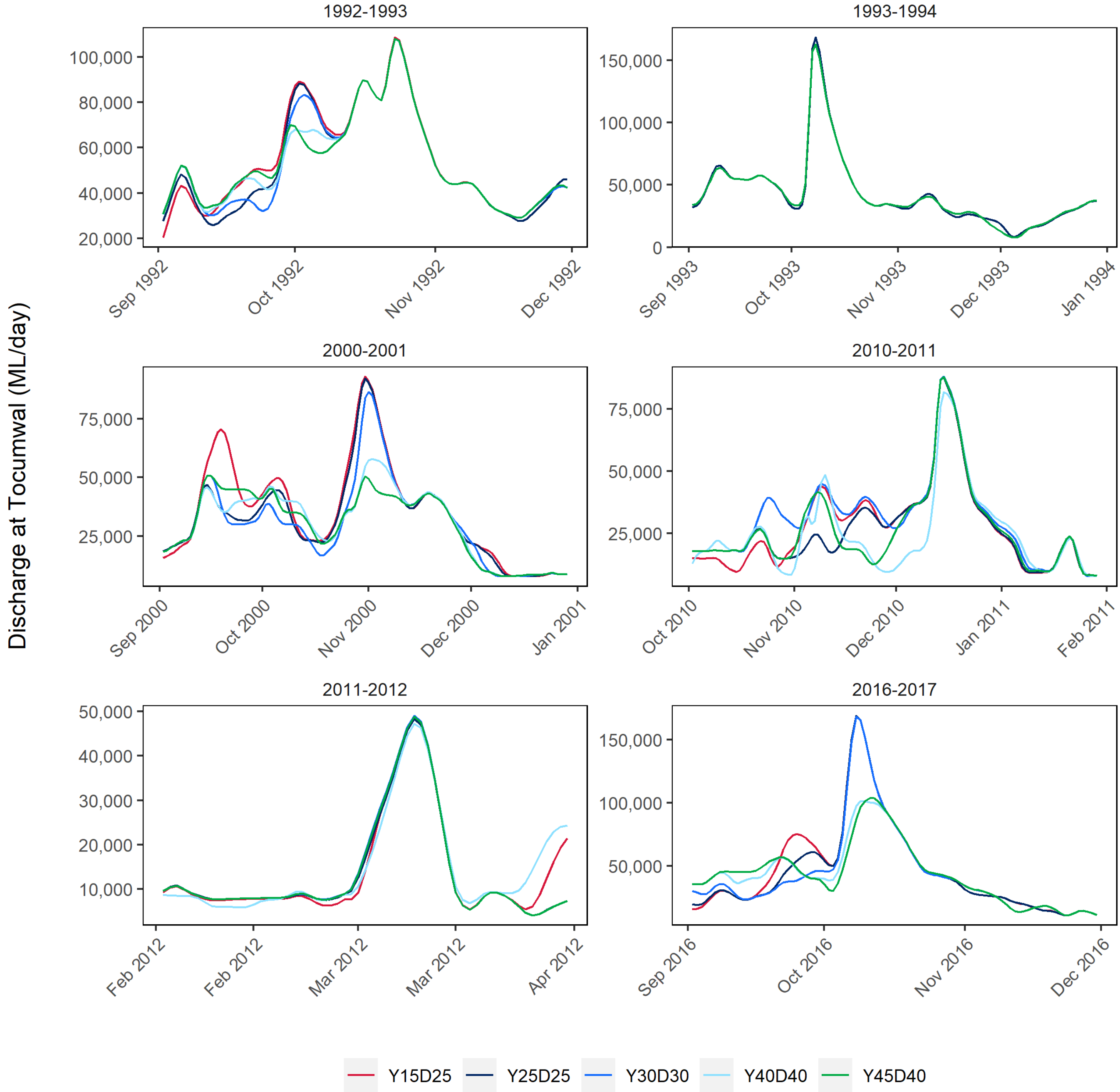

Figure 16: Discharge rates at Tocumwal for flow events determined to be associated with possible hypoxia either at Barmah or in the Edward Kolety–Wakool (part 2 of 2)

Note the variable y-axis.

Table 4: Hypoxic blackwater events in the Edward Kolety–Wakool only (grey cells) and both at Barmah and in the Edward Kolety–Wakool (black cells)

The orange cells show an event that was added to the time series after the data were provided to Todd et al. (2022).

Scenario	1895 –1900	1901–1910	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2019
Y15D25													
Y25D25													
Y30D30													
Y40D40													
Y45D40													

3.5 Discussion – Murray hypoxic blackwater time series

The results from the hypoxic blackwater time series assessment for the Murray project area suggest that widespread hypoxic blackwater events occur rarely in the Murray River system and typically result from large, unregulated hydrological events. Hypoxic blackwater events occur when high concentrations of DOC arise during periods of increased water temperature, and there have been three of these events in the Murray since 2010. The hydrological modelling used for the present study predicts that summer floods are very rare, and that when they do occur they are often preceded by longer events with continuous flows to the floodplain during cooler months that are expected to help regulate floodplain carbon loadings. Isolated, large flow peaks are uncommon from November onwards (Figure 17).

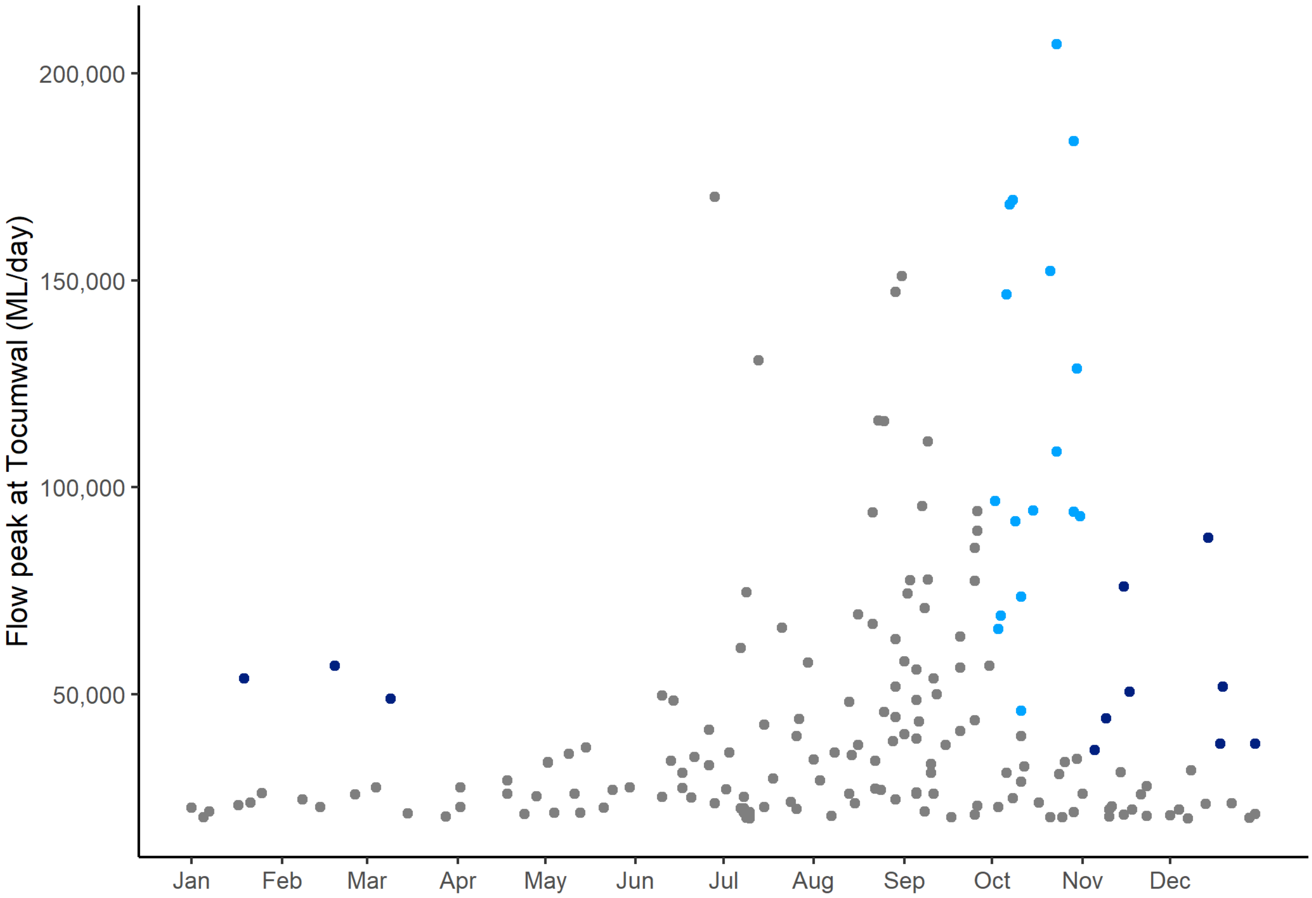

Figure 17: Flow peaks for the Y15D25 scenario (all years) showing the event timing (x-axis) and peak flow rate (y-axis)
Colours show initial hypoxia likelihood scores (grey = no hypoxia expected, light blue = hypoxia possible in the Edward Kolety–Wakool, dark blue = hypoxia possible at Barmah).

In the Murray Valley, flows to Barmah–Millewa Forest can generate sufficient DOC to cause in-channel hypoxia in reaches immediately downstream if flows occur during warmer months. Moreover, the DOC sourced from these events can be added to carbon loads in receiving systems (such as the Edward Kolety–Wakool), increasing the likelihood of hypoxia elsewhere in the Murray even when hypoxia may not occur as a direct result of return flows from Barmah–Millewa.

Consequently, results also predict that hypoxia occurs more than twice as often in the Edward Kolety–Wakool than in the Murray mainstem. With too little known about the floodplain hydrology of the Edward Kolety–Wakool for quantitative modelling, the hypoxic blackwater model used for this study is a coarse approximation. While we have linked hypoxia severity in the Edward Kolety–Wakool to the occurrence of high DOC events in the Murray, the accumulation of floodplain litter is likely to vary substantially from the Murray. Although anecdotal evidence suggests that hypoxia is a lot more common in the Edward Kolety–Wakool, the dynamics of litter accumulation and its relationship with both inundation and vegetation community types remain poorly quantified. There are periods when litter loads in the Edward Kolety–Wakool may be very different to Barmah–Millewa, creating different hypoxic blackwater likelihoods.

3.5.1 Potential for the program to create new hypoxic blackwater events with managed environmental water deliveries

The time series assessment found no evidence that the program's flow option scenarios will contribute new hypoxic blackwater events in the Murray or Edward Kolety–Wakool project areas. The flow rates targeted by environmental water under the flow option scenarios being considered by the program (DPE 2022b) are high enough to inundate low-lying areas of Barmah–Millewa Forest and could contribute to in-channel hypoxia, but only if temperatures are also very high (McInerney et al. 2022). The hydrological modelling used for the assessment assumes operational rules that limit release of environmental water, meaning the latest that flow peaks could occur at Tocumwal are during mid-November. The seasonal increase in water temperature, and potential for very high leaf litter loads, could mean that some deliveries in November could increase the likelihood of hypoxia. The decision to release environmental water within individual years is made using on-ground information about leaf litter load and forecast air temperatures that can only be represented in a semi-quantitative way by the current study.

3.5.2 Potential for the program to reduce the risk of hypoxic blackwater events with managed deliveries of environmental water

The hypoxia likelihood assessment found a small number of examples (1948–49, 2016–17) where constraints relaxation was predicted to reduce the likelihood of hypoxic blackwater occurring in the Murray project area. This occurs where relaxed constraints lead to more environmental water being used ahead of subsequent unregulated flood events, reducing the peak magnitude of these unregulated flows by creating airspace in storages (Figure 15, Figure 16). The addition of environmental water at higher flow rates also has the potential to reduce litter loads ahead of the larger event. In 1948–49, modelled delivery of environmental water under program scenarios substantially reduced the size of the subsequent flow event, but only for the Y25D25 flow option scenario. It is unclear why the model reduced discharge rates only for this flow option; however, the assessment concluded that the risk was much less in this case. In 2016–17, the reduced peak magnitude across all flow option time series was not found to be sufficient to prevent hypoxia occurring. In both examples, reducing the likelihood of hypoxia is not a targeted outcome of the use of environmental water.

It is unlikely that unregulated flood events can be predicted with enough certainty or with sufficient lead-time for environmental water to be intentionally used to reduce the likelihood of hypoxia. Other uses of environmental water that might be used to reduce the likelihood or severity of hypoxic blackwater, such as recession management, fall outside the scope of this assessment.

3.5.3 Limitations of modelling and potential improvements

The model used to identify potential hypoxic blackwater events in the Murray project area uses a coarse representation of floodplain hydrology and inundation extent. For this reason, the model outputs are not used quantitatively. Some of the assumptions and simplifications used to generate scenarios introduce thresholds to the scoring that lead to a clumsy application of the initial likelihood assessment. This means many flow events were classified as potentially hypoxic but were removed in the subsequent review steps. The consequences for the assessment are that the model for the Murray system is more conservative.

The Goulburn River (and to a lesser degree the Campaspe River and Broken Creek) contribute inflows to the Murray downstream of Barmah Forest that can add considerably to DOC concentrations in receiving reaches of the Murray. Due to time and data limitations, the current method assumes that large flows down the Goulburn River are broadly coincident with flows in the Murray. However, we acknowledge that this may not adequately represent the role of the Goulburn River in all cases and that hypoxic blackwater events could be made worse, or even be caused in the Murray, by these inflows.

Improvements to the approach used in this study include improved model inputs:

- more accurate inundation modelling
- in-depth understanding of floodplain hydrology (export and return flow volumes, floodplain losses)
- estimated inflows from the Goulburn River and other Victorian tributaries

and changes to the scenario framework such as:

- re-operate BRAT with specific event timing for each event
- re-operate BRAT with a time series of actual modelled daily flow rates rather than an assumed hydrograph.

4 Modelling overview – Murrumbidgee River

4.1 Approach

Unlike the Murray project area, inundation models for the Murrumbidgee were incomplete (DPE 2022c) at the time of this project and could not be used to predict inundation extents needed for BRAT hypoxia modelling. Therefore, a different approach was undertaken for the Murrumbidgee River. Specifically, flow was used to predict the concentration of DOC that could be generated during a flood, and a likelihood score was assigned based on that concentration and water temperature. Scenarios were then compared using the same approach as outlined for the Murray River.

4.2 Study area

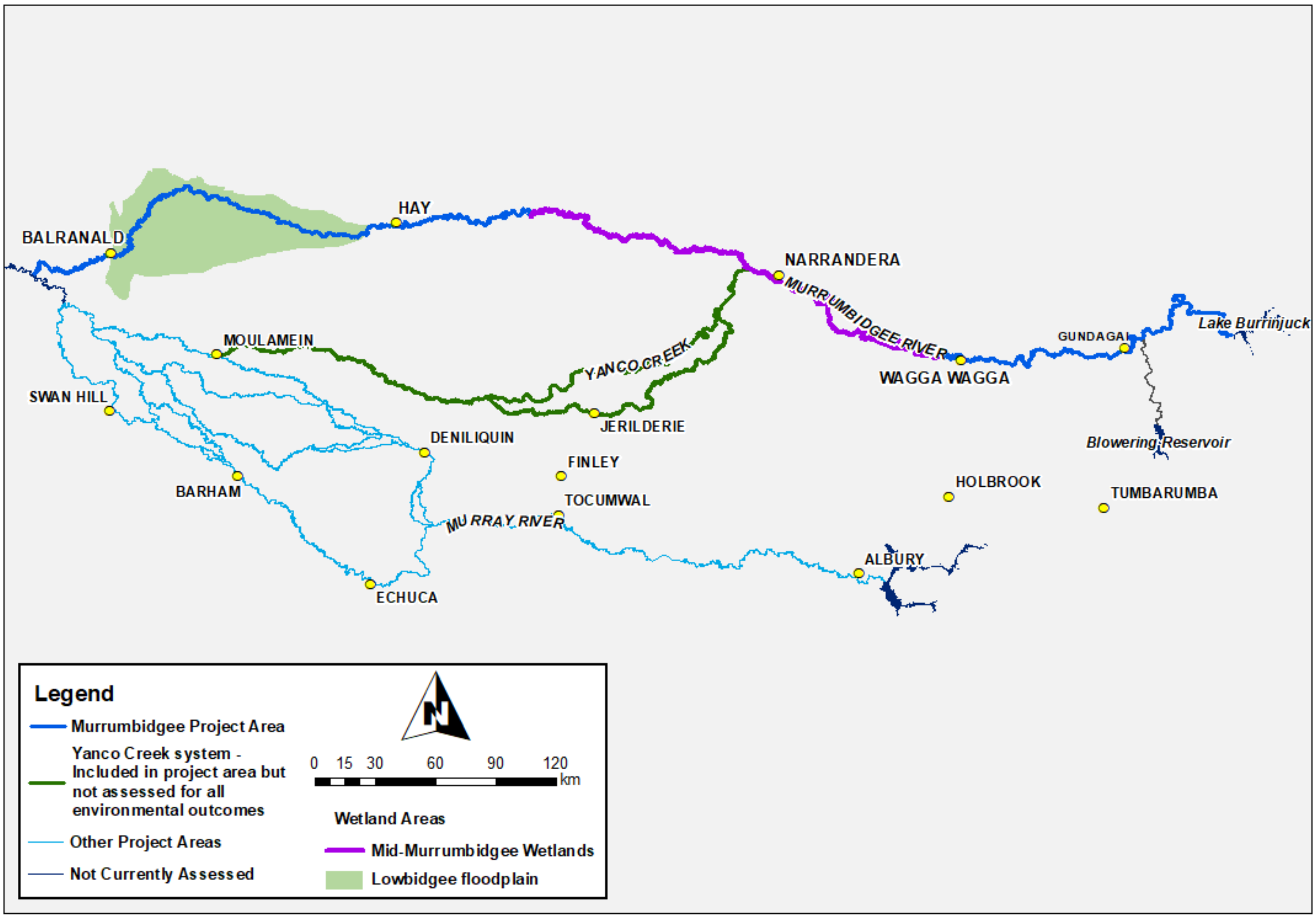

Figure 18: The program project area, emphasising the Murrumbidgee River

Historical accounts of hypoxic blackwater in the Murrumbidgee (Appendix A) suggest widespread hypoxic blackwater in the mainstem is largely limited to reaches downstream of Hay Weir. These events result from the longitudinal accumulation of DOC via overbank inundation of floodplain areas, and include DOC leached in the mid-Murrumbidgee that gets added to DOC leached from the Lower Murrumbidgee floodplain. There are accounts of fish deaths arising from hypoxic blackwater in other parts of the catchment (Appendix A); however, these are possibly caused by localised heavy rainfall rather than overbank flows. The following assessment focuses on the Murrumbidgee River at Balranald, downstream of the Lowbidgee floodplain, where there is a suitable time series of both DOC and flow.

4.3 Modelling

4.3.1 DOC and hydrological data

The DOC data used for this study has been collected as part of the River Murray Water Quality Monitoring Program and is collected at Balranald by WaterNSW on behalf of the Murray–Darling Basin Authority. All results were sourced from the HYDSTRA database. The time series includes DOC observations collected at irregular intervals from the early 1990s to the present, with a gap of several years between 2015 and 2017 (Figure 19). All data are reported to the nearest 0.1 mg between 1993 and 2017 and to the nearest 1 mg from 2018 onwards. A small number of datapoints were taken from DOC monitoring collected during the 2016 flood event as part of the Commonwealth Environmental Water Office Long-Term Intervention Monitoring program (Wassens et al. 2017). All data were rounded to the nearest 1 mg for analysis, reflecting the lowest reported accuracy in the DOC time series data.

Hydrological observations for Hay, Maude, Redbank and Balranald were obtained from the WaterNSW 'Continuous water monitoring network' website (WaterNSW 2022).

Figure 19: Observed DOC concentrations collected from Downstream Balranald Weir (410130)

Data were sourced from the HYDSTRA database. Results are rounded to the nearest 1 mg.

4.3.2 Flow inundation thresholds and hydrological predictors

Predicting DOC as a function of flow required selection of hydrological predictor variables that correlate with potential DOC sources on the floodplain. A range of hydrological predictors were considered using observed flow rates at Hay, Maude, Redbank and Balranald flow gauges including:

- daily flow rates
- cumulative seven-day flow rates
- cumulative 30-day flow rates
- maximum 30-day flow rates
- maximum cumulative 30-day flow rates.

We initially used a boosted regression analysis to predict DOC concentration from these variables using observed hydrological data. However, because of issues with the hydrological model time series (see Section 4.3.4) we instead selected three predictor variables that explained the most variation in DOC concentration at Balranald and limited the analysis to a small number of triggers that were more readily described and understood. In order of decreasing influence the three best predictors were the maximum 30-day discharge downstream of Redbank Weir, the maximum 30-day discharge downstream of Maude Weir, and the maximum cumulative 30-day discharge downstream of Hay Weir (Figure 20).

For each parameter, thresholds were estimated to identify hydrological conditions where DOC concentrations were likely to exceed 12–15 mg/L (see Wassens et al. 2017 for more context). The interpretation was aided by both expert knowledge of overbank thresholds relevant to the gauges used, and step changes in the fitted function calculated by the boosted regression analysis. Hypoxic blackwater is typically associated with DOC concentrations of >20 mg/L (Whitworth and Baldwin 2016). Occasions where all three of the predictor variable conditions were met were considered likely to result in DOC concentrations within the range associated with hypoxia at Balranald, depending on water temperature (see Section 4.3.3).

4.3.3 Temperature thresholds

The parameters in Section 4.3.2 were used to identify days in the hydrological time series where DOC concentrations were expected to exceed 15 mg/L. These days were then given a hypoxia likelihood score based on water temperature, using temperature thresholds identified using the BIAT (Table 5). The scoring method assumes no hypoxia when temperature is <15°C at any DOC concentration.

Table 5: Temperature thresholds and hypoxia likelihood scores used for the Murrumbidgee hypoxic blackwater assessment

Temperature thresholds assume a DOC concentration of >15 mg/L.

Temperature range (°C)	Likelihood score
>23	10
20–23	9
18–20	8
15–18	7
<15	1

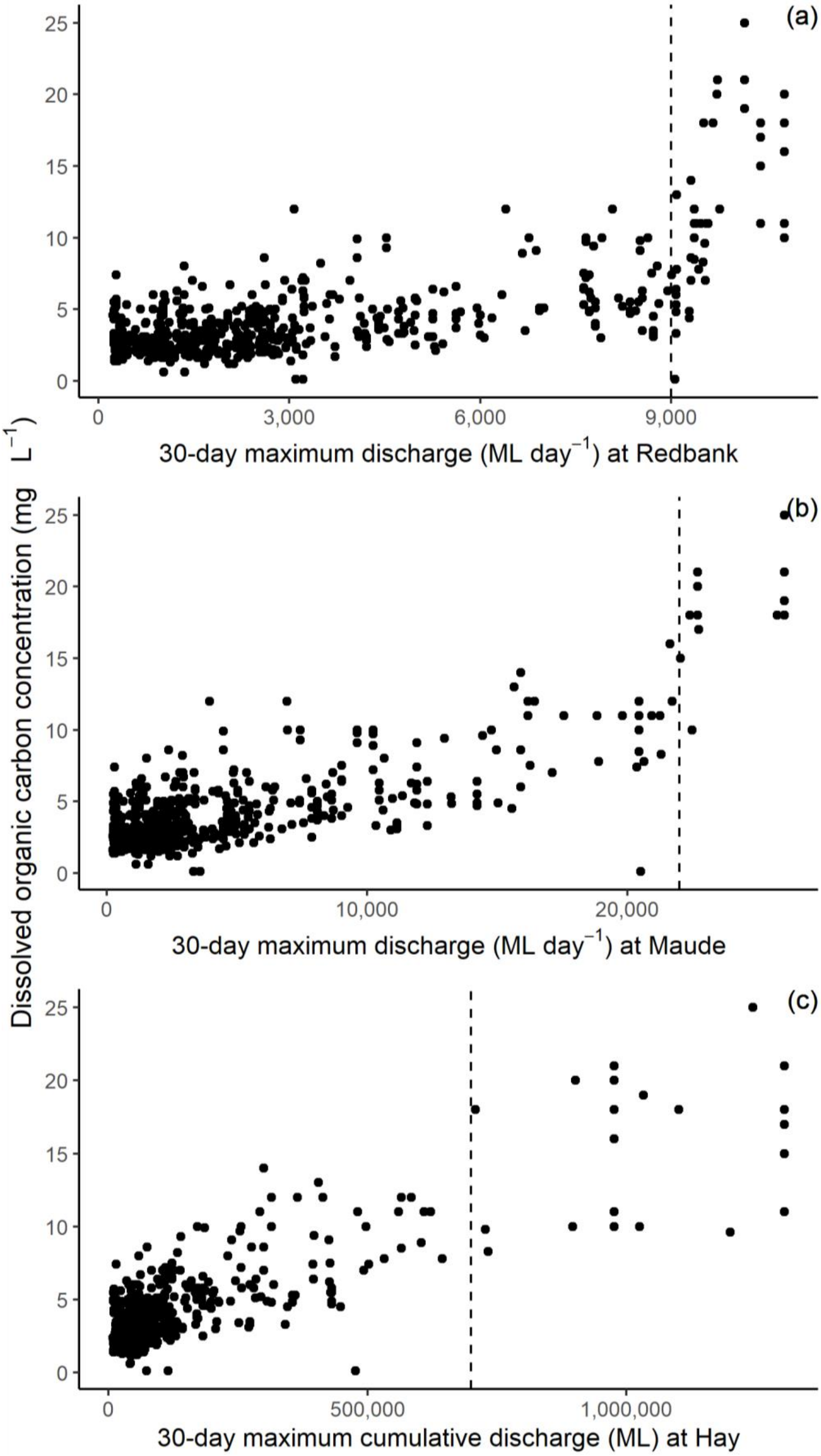

Figure 20: Observed DOC concentration at Downstream Balranald Weir (410130) against (a) maximum 30-day flow at Downstream Redbank Weir (410041); (b) maximum 30-day flow at Downstream Maude Weir (410040); and (c) maximum cumulative 30-day flow at Downstream Hay Weir (410136)

Vertical lines indicate thresholds used to delineate DOC concentrations greater than 15 mg/L.

4.3.4 Transformations of hydrological data

The modelled Source hydrological time series for the Lower Murrumbidgee does not accurately represent observed flows for the same time period, particularly for large flow events that are much greater in magnitude in the modelled flows. Modelled flows increasingly overestimate flows above 25,000 ML/d (Figure 21). However, the minimum inundation thresholds used for hypoxia prediction fall below the range of values where the model is thought to be more accurate. Put another way, the ‘trigger’ thresholds above which we observed high DOC concentrations fall within the more accurate part of the model and all flows above those rates can be assumed to generate higher DOC concentrations.

The Source model time series for the Murrumbidgee is undergoing continued development; however, the version of hydrological data available for this study contained discrepancies in the Lowbidgee. Because of this uncertainty, the hydrological time series was not used to evaluate differences in the likelihood of hypoxia specific to each of the constraints flow options; however, some results for the individual flow time series have been included in this report for additional context. We note that operational decisions prevent the release of large volumes of environmental water during warmer months (DPE 2022c; McInerney et al. 2022). For the current assessment, we sought to generate a single time series of likely hypoxic blackwater events to inform the Murray cod fish population model. Doing so required standardising the datasets to limit the impact of potential errors:

1. Calculate the daily median discharge rate across the four flow option time series to create a single time series.
2. For each daily flow rate in the 124-year model time series, calculate the percentile of that flow value in the model time series and replace the model discharge rate with the discharge rate for the equivalent percentile in the observed discharge time series. The percentile for the model time series is calculated using only those model discharge rates where the model and observed time series overlap.

Results for the standardisation (Figure 21) show alignment between the frequency of observed and model flow rates. This means the maximum flow rate in the model time series cannot exceed flow rates in the observed 1990–2018 time series; however, the standardisation allows for cumulative 30-day flow rates needed for blackwater prediction that would otherwise be overestimated.

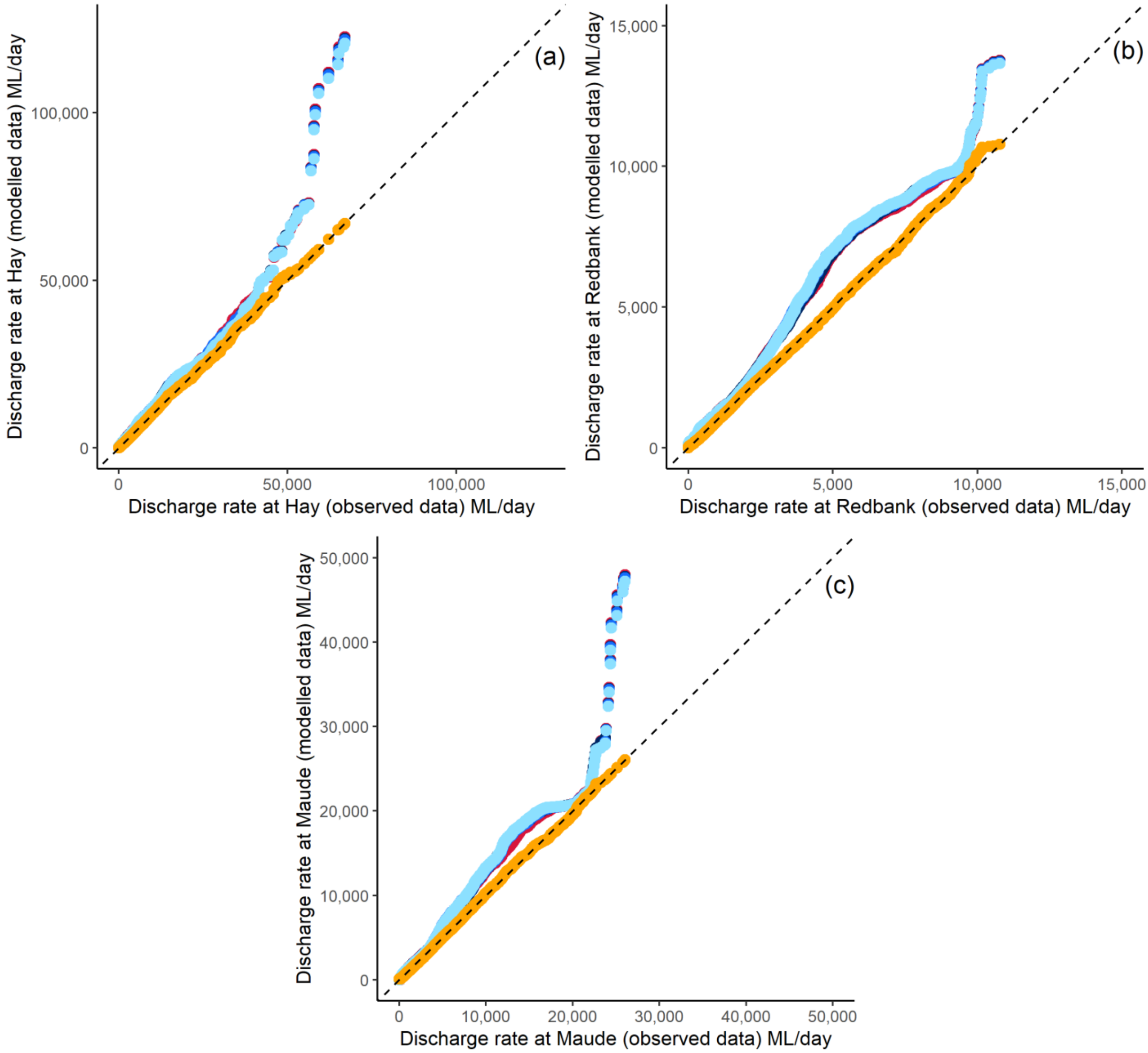

Figure 21: Quantile–quantile plots comparing observed flow data against modelled flow rates for the Murrumbidgee River at (a) Downstream Maude Weir (410040); (b) Downstream Redbank Weir (410041); and (c) Downstream Hay Weir (410136)

Data are for the period 1/1/1990 to 1/7/2018. Each colour indicates a different flow option time series. Orange symbols are the aggregated, transformed model time series used for the analysis. The dashed line shows a 1:1 relationship.

4.3.5 Model application and expert panel

The thresholds in Sections 4.3.2 and 4.3.3 were used to score the likelihood hypoxia for each day of the standardised model time series. These daily results were used to identify hydrological events associated with increased likelihood of hypoxic blackwater. The results were then reviewed by an expert panel of environmental water managers and scientists with extensive experience of the Murrumbidgee River and/or hypoxic blackwater. The panel focused their review on that received a likelihood score of >7.

The panel discussed each predicted hypoxic blackwater event, considering whether antecedent hydrology, modelled water temperature was likely to increase or decrease likelihood. Notes on the decisions and outcomes are available in Appendix D.

4.4 Results

4.4.1 Validation

The scoring method was first applied to the observed flow data (1980–2022), identifying three high risk periods, each coinciding with known hypoxic events (January 2011, March 2012 and November 2016). There were no periods where hypoxia is known to have occurred at Balranald but where the model failed to identify an increased likelihood.

4.4.2 Model time series

Analysis of the consolidated model time series identified 20 separate hydrological events that had the potential to cause hypoxia at Balranald. Of these, the expert panel identified 11 as being likely hypoxic events (Figure 22, Figure 23). In most cases, the panel cited antecedent flows, particularly lengthy periods of floodplain inundation prior to higher-risk flows, as the main mitigating factor (see Appendix D). All events showed some degree of antecedent watering before peak flows.

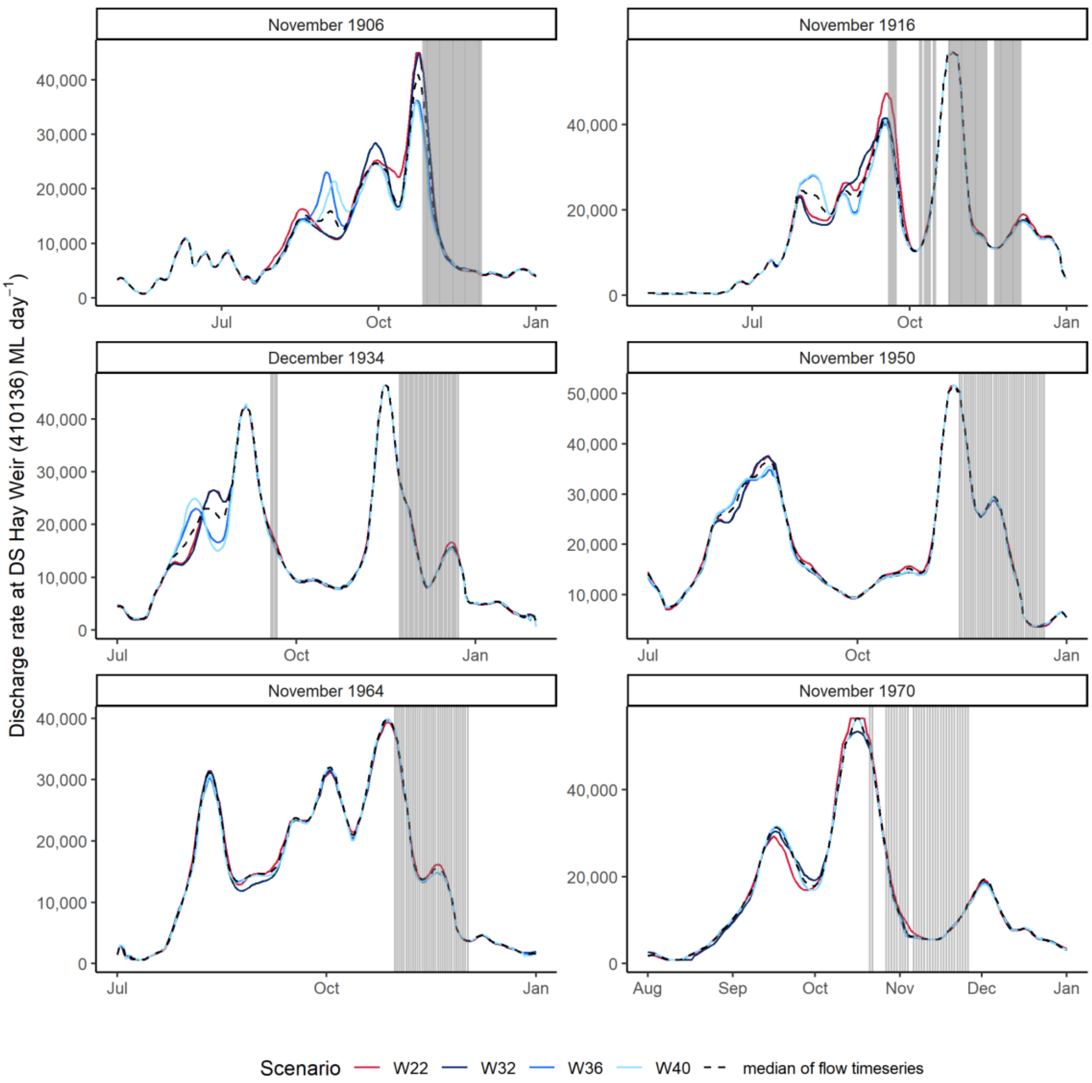

Figure 22: Standardised discharge rate (ML/d) at Downstream Hay Weir (410136) for events associated with an increased risk of hypoxia at Balranald (part 1 of 2)

Vertical grey lines show dates when the likelihood of hypoxia is increased.

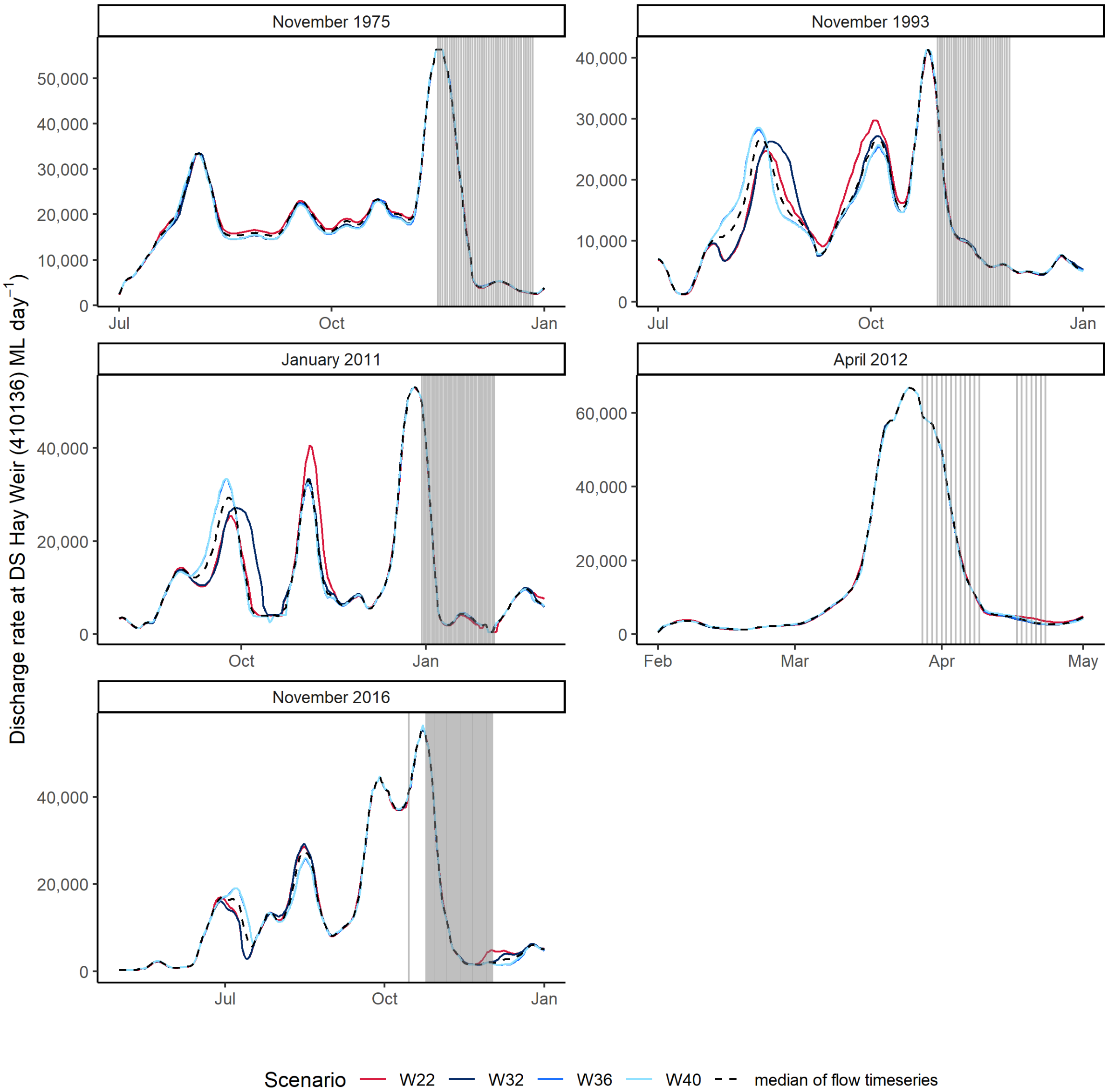

Figure 23: Standardised discharge rate (ML/d) at Downstream Hay Weir (410136) for events associated with an increased risk of hypoxia at Balranald (part 1 of 2)

Vertical grey lines show dates when the likelihood of hypoxia is increased.

Table 6: Hypoxic blackwater events at Balranald (black cells)

The blue cells show where hypoxic events were reported for individual flow option time series; however, these differences were disregarded for the final assessment (see Section 4.3.4). The open square shows an event that was evaluated as likely to be hypoxic, but not expected to have contributed to widespread fish kills.

Scenario	1895 -1900	1901–1910	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2019
Median													
W22													
W32													
W36													
W40													

4.5 Discussion – Murrumbidgee hypoxic blackwater time series

The accuracy of the time series assessment for the Murrumbidgee project area is affected by uncertainty around the size and duration of overbank flow events in the Source hydrological model. The results presented in this assessment use a standardised discharge dataset. The assessment predicts that large-scale hypoxic blackwater events in the Lower Murrumbidgee are caused by infrequent, large, unregulated flow events where substantial return flows are expected to occur during warmer months. This finding is consistent with results for the Murray project area, the water quality assessment for the program (McInerney et al. 2022) and supporting literature.

Overall, hypoxic blackwater occurrence is slightly more common in the lower Murrumbidgee than in the Murray mainstem. Generally, high DOC concentrations are observed at Balranald only when there have been substantial return flows from the broader floodplain (i.e. when flows move through the Gayini Nimmie-Caira in addition to other low-lying forested areas).

4.5.1 Potential for flow options to create or mitigate hypoxic blackwater events

Due to uncertainties around the modelled size and duration of overbank flow events in the Lower Murrumbidgee, the assessment does not attempt to differentiate potential differences among flow option scenarios. However, it should be noted that the standardised results (Figure 22, Figure 23) do not indicate any substantial changes to flows that would increase the likelihood of hypoxia associated with large, unregulated flow events. The delivery of environmental water in the Murrumbidgee follows principles of adaptive management, with ongoing evaluations of hypoxia blackwater risk before and during managed events (e.g. Wolfenden et al. 2018). Moreover, the hydrological model used for the Murrumbidgee project area limits releases of environmental water to before November, meaning flow peaks could arrive as late as 20 November (assuming a 20-day travel time for events of this size). Environmental flow releases under the program's flow options aim to reach target flow rates for approximately five days at Wagga Wagga. Five-day events of <45,000 ML/d at Wagga Wagga are expected to attenuate significantly once they have reached Hay and are not expected to contribute sufficient DOC to create hypoxic conditions. It is likely that the hydrological model used for the current study overestimates volumes that reach the Lowbidgee floodplain, even with a standardised dataset.

4.5.2 Limitations of modelling and potential improvements

Modelling used to identify and evaluate hypoxic blackwater risk in the Murrumbidgee project area is based on simple correlative relationships between flow and observed DOC. There will be events with size, duration and timing that fall outside the range of observations, limiting the effectiveness of the approach. However, because the model aims to identify hydrological conditions where a single key DOC threshold is exceeded, values beyond the range of the data are expected to elicit higher DOC concentrations.

The modelling here also makes use of a long-term DOC dataset collected at a single location. It is unlikely that this data collection will have coincided with peak DOC concentrations across all events and, moreover, with increasing flow rate and hydrological complexity we expect DOC will become increasingly difficult to quantify. Carbon concentrations that exceed the trigger threshold of 12–15 mg/L only occur during four events in the overall time series. For these reasons, the DOC concentrations in the observed series are treated as conservative estimates.

The underlying hydrological model is not able to accurately reflect the attenuation of large hydrological events, and so overestimates both the inundation extent and volume of water moving onto the floodplain. The standardisation used here helps create a more realistic representation of losses and attenuation as flows move along the Murrumbidgee mainstem.

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Appendix A – Historic accounts of fish deaths in the Murray, Murrumbidgee and Edward Kolety–Wakool rivers

This appendix examines newspaper accounts of fish kills in the region of interest and using current knowledge of fish behaviour when faced with hypoxia, explores whether or not they were caused by a blackwater event. This approach is not without its limitations. Only the more spectacular fish kills tend to be reported in the media (Nowak et al. 2005), meaning that many (if not most) historic fish deaths will remain unreported. This is especially true of fish deaths during large floods. The emphasis on reporting during floods would likely be on the flood itself, and the flood's damage to life, property and livestock, rather than on the impacts to fish. Furthermore, newspaper reporting in Australia was framed through the colonial experience and generally 'excluded, misunderstood and ignored Aboriginal people and culture' (Peters 2017), as well as other non-European perspectives (e.g. Isakhan 2010). Therefore, the eye-witness accounts of historic fish deaths in the Murray–Darling Basin are exclusively from a European perspective. Notwithstanding these limitations, the newspaper accounts do offer an opportunity to interpret contemporaneous accounts of fish deaths in light of our current understanding of their likely causes. In particular, hypoxia can be inferred from the behaviour of aquatic organisms. Evidence of hypoxia includes large fish at the surface gasping for air, or alternatively they are reported as lethargic and easily caught by hand. In addition, reports of large numbers of yabbies and crayfish either congregating in shallow water or leaving the water altogether also indicate hypoxia.

Murray River: A search of the National Library of Australia's digitised newspapers identified nine fish kill events in the Murray River starting from 1865:

1. July 1865, Euston. 'The lagoons lakes and creeks that are not running are literally teaming with dead fish.... [t]he thermometer has been as low as 26° [Fahrenheit], and the lagoons covered with ice an inch thick....', *South Australian Weekly Chronicle*, 29 July 1865; a similar story also appeared in the *Sydney Morning Herald*, 24 July 1865. This event appears to have been caused by extremely cold weather.
2. December 1883, Moama. 'The Murray commenced to fall here on the 29th.........[g]reat numbers of dead fish have been floating down the river recently.' *Sydney Mail and New South Wales Advertiser,* 15 December 1883. This event may have been a blackwater event, caused by flooding, but it was not possible to locate flow records for the Murray River prior to 1895.
3. January 1892, Albury. 'There has been extraordinary mortality among the fish in the Murray River during the past day or two. The river has been very low for some weeks and is fordable in all but a few places. Owing to sluicing operations on the Mitta Mitta River ..... the water has been greatly discoloured. This pollution has been going on for some time, and the fisherman have noticed that the fish taken from the muddy portion of the river are sickly and lack animation.' This event was likely caused by sluicing operations in the upper catchment. An extraordinary amount of sediment was mobilised because of gold mining activity, much of it enriched with arsenic (Davies et al. 2018) and mercury (Davies et al. 2015).

4. February 1912, unknown location. ‘Disappointment still walks in the tracks of anglers whom make frequent and fruitless visits to the Murray River.......... The billabongs and lagoons adjacent to the Murray River are literally covered with heaving dead fish from 1 lb to 15 lb. Various reasons have been advanced for this condition, but it would seem the only correct one is that the waters are so low that during the burst of hot weather, when the thermometer ranged from 93 to 108 degrees [Fahrenheit] in the shade the waters practically boiled, and thus killed the fish.[1] Another reason is that the moon's rays have penetrated the shallow waters and affected fish life[2].’ *Leader*, 24 February 1912.
5. February 1915, South Australia(?). ‘It will be remembered that after the dirty water killed so many fish that everyone said it would take 20 years to make up for the loss, but for the next three years there were more fish biting than had been known for 30 years.’ *Daily Advertiser*, 6 September 1920. The increase in fish biomass is consistent with what we know happens following a blackwater event. As noted below, there was a summer flood on the Murrumbidgee River in February 1915 which resulted in dead fish.
6. June 1915, Murray Bridge. ‘On Monday last, the dairyman on the Hon. J. Conwan's station collected 530 dead fish from the bank of the river in a distance of 480 yards. This was from one side of the river only and will show the effects of salt on the river.’ *The Observer*, 10 July 1915. This fish kill could be a result of salt. The levels of salt reported at the time were ‘chlorine, calculated as sodium chlorine [sic], 600 grains’ – or about 8,550 mg/L NaCl (equivalent to EC).
7. October 1929 – February 1930, most of the Murray River and its tributaries. There are multiple accounts of fish deaths in the Murray River and its tributaries at the end of 1929 and the beginning of 1930. ‘Grave concern is felt by the officers of Fisheries and Game Department, states yesterdays *Argus*, at reports received from places on the Murray and its tributaries of the deaths of hundreds of Murray cod. The dead fish have been seen floating on the surface of the water by persons living in places as far apart as Mildura, Nagambie and Albury. Reports of similar occurrences have been received by the Department from the Fisheries and Game Department of South Australia, where the professional fishermen of the Murray are greatly perturbed. “The cause of death of the fish is a complete mystery” said the chief inspector of the department.....’ *The Riverine Herald*, 29 November 1929. Fish were also reported as dying in the Darling River: ‘Word has been received by Mr Arthur Wilkinson that large numbers of fish are also dying in the Darling, where they are to be seem caught on every snag.....The trouble of the Darling he thinks might be due to freshwater coming down that river, having a similar effect to that of the 1902 rise.’ *Murray Pioneer and Australian River Record*, 1 November 1929.

   Trueman (2011), citing Cadwallader (1977)[3], ascribes the fish kills to water releases from Lake Hume (prior to commissioning) that had been treated with copper sulfate to kill algae. This may explain local kills, but not concurrent kills in, for example, the Goulburn River. Nor would it explain kills a lot further downstream. At this stage I have not been able to determine the

[1] Noting this is actually well below the boiling point of water.
[2] This hasn't been scientifically proven.
[3] The original article has not been sighted.

cause of the fish kills in 1929–30. Certainly, the hydrology of the Murray River and its main tributaries do not suggest a hypoxic blackwater event.

8. November 1931, Echuca. ‘Numerous dead fish ranging in weight from half a pound to seven pounds have been noticed floating down the Murray River in the vicinity of Echuca during the course of the past week, but fisherman have been able to advance any reason for this high mortality. It will be recalled that last year many fish died in a similar mysterious manner.’ *The Riverine Herald*, 3 November 1931.
9. November 1995, Mildura. ‘Spray used in the campaign against grasshoppers is killing off thousands of yabbies. The yabbies are considered pests by irrigators along the Murray River because they block water pumps.’ *The Argus*, 25 November 1955.

Edward Wakool River system: There is only one reported fish kill event in the Edward Kolety–Wakool River system in historical newspaper accounts, and it is obvious that this was a hypoxic blackwater event:

1. 1879: ‘Since the heavy rains things have gone very wrong with the Edward River. The water, from some cause or other, is as black as ink, and the banks are strewed with dead perch and cod. The lobsters too, have apparently had a very uneasy time of it… thousands of these creatures were to *be found along* the bank.’ *Sydney Mail and New South Wales Advertiser*, 23 February 1878.

   ‘The water in the River Edward is in colour as black as ink and therefore unfit for domestic purposes. The cause is said to be the immense quantity of gum leaves washed into the stream by the recent heavy rain, and other matter which has found its way therein. The liquid seems to have become thoroughly impregnated with some poisonous substance, as the fish are floating on the surface in great numbers quite dead; and on Tuesday last large numbers of crayfish jumped out of the water and crawled over the banks in preference to staying in the river.’ *Australian Town and Country Journal* (Sydney), 23 February 1878.

Murrumbidgee River: There have been numerous accounts of fish deaths in the Murrumbidgee River, many of which can be specifically linked to storms or flooding; however, most are restricted to the river upstream of Wagga Wagga:

1. January 1905, downstream of Gundagai. ‘Fish are reported to have died in large numbers between Gundagai and Wagga one day last week (says the *Independent*.) The mortality was due to the discoloration in the river caused by storm waters. The storm waters came from the burnt out country and were an inky black colour. The fish sickened and rose to the surface.’ *Adelong and Tumut Express and Tumbarumba Post*, 27 January 1905. This could have been a blackwater event, or from fires. No rise is noted in the hydrograph at Wagga Wagga gauge (Station no. 410001) coinciding with this fish kill (data not shown).
2. March 1907, Adaminaby. ‘A report has been received by NSW Fisheries Board from police at Adaminaby respecting the alleged dynamiting of fish in rivers in the Murrumbidgee district, to the effect they were able to get evidence of dead fish floating about …. but there was no evidence of dynamite being used.’ *Evening News*, 7 March 1907. While it is true that dynamite was much more easily sourced than now[4], this is possibly a blackwater event.

[4] There is a newspaper account of a boy of 12 losing his hand when fishing with dynamite.

3. November 1914, Wagga. Trueman (2011) cites a NSW fisheries report indicating a large fish kill occurred near Wagga Wagga in 1914. ‘Reports from several places on the Murray River System indicated great mortality among fish. One such report came from Wagga Wagga; on investigation the cause was found to be the sudden inrush of muddy water, due to an exceptionally heavy thunderstorm, containing a large quantity of surface soil, dead leaves, eucalyptus bark, &c., which polluted the stream to such an extent that it is assumed for a time the consistency of pea soup. Many of the older and weaker fish were suffocated by it. This occurred at Wagga in November, the loss of fish being very great.’
4. February 1915, Wagga. ‘Flood in Murrumbidgee. Fishing Extraordinary. All day on Sunday dead sheep by the score, rabbits in hundreds, and great quantities of fish of all sizes, and occasionally pigs, were to be seen floating down the swollen stream. The water had assumed the colour and almost the consistency of pea soup, and the mud had the effect of partially stupefying the fish. As they floated down they struggled blindly and persistently towards land. The populace of Wagga and other parts held high carnival all day Sunday. Thousands of people lined both banks of the river, armed with all manner of weapons and nets for capturing fish. Many adopted the simple method of clubbing the fish on the head as they floated past on the outer edge of the stream.’ *The Argus*, 24 February 1915. The hydrograph at Wagga Wagga gauge showed a sharp peak to about 15,000 ML/d in February 1915. Interestingly, flows during the preceding winter and spring were low compared to other years, indicating the potential build-up of litter in the catchment (data not shown).
5. December 1919, Gundagai(?). ‘Friday was a great day for fish in the Murrumbidgee and anglers were out with gaff hooks instead of with rod and line. The consequences of this was that the storm waters made a good rise in the river which turned the water yellow and thick, causing the fish to come to the surface and float, while lobsters in their thousands crawled out to the banks where millions of shrimp lay dead.’ *The Gundagai Times and Tumut, Adelong and Murrumbidgee District Advertiser*, 9 December 1919.
6. December 1929, location unknown. ‘There have apparently been 110 complaints about dead cod in the Murrumbidgee, but then there are so very few cod in this river as a result of the extensive netting operations in recent years.’ *The Riverine Grazier*, 13 December 1929. This report of dead fish is coincident with fish kills throughout the Murray–Darling basin at the time (see above).
7. March 1932, location unknown. ‘A press report states that the number of fish found dead in the Murrumbidgee River is the chief topic of conversation among fisherman present…The opinion shared by many is that explosives are being used.’ The hydrograph at Wagga Wagga gauge shows a peak in flow (to about 17,000 ML/d) that coincides with the appearance of dead fish.
8. February 1945, Tumbalong. ‘The Murrumbidgee River rose a couple of feet a few hours after [a] local storm and since then rubbish that had been swept down was worse than any flood as it was below as well as above the water. The banks of the river seemed to be alive with lobsters from tiny shrimp to very large lobsters. They came out of the water in an unending procession.’ *Lithgow Mercury,* 5 February 1945.

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Appendix B – Scenario risk scores (Yarrawonga to Wakool Junction)

Event peak (ML/d)	Temperature percentile	January	February	March	April	May	June	July	August	September	October	November	December
20,000	5th	4	4	3	1	1	1	1	1	1	3	4	4
30,000		4	4	3	2	1	1	1	1	1	3	3	4
40,000		10	10	7	2	1	1	1	1	2	3	9	10
50,000		10	10	7	2	1	1	1	1	2	6	9	10
60,000		10	10	7	2	1	1	1	1	2	6	9	10
70,000		10	10	7	2	1	1	1	1	2	6	9	9
80,000		10	9	7	2	1	1	1	1	2	6	7	9
90,000		10	9	7	2	1	1	1	1	2	6	7	9
100,000		10	9	7	2	1	1	1	1	2	6	7	9
125,000		10	9	7	2	1	1	1	1	2	6	7	9
150,000		10	9	7	2	1	1	1	1	2	6	7	9
175,000		10	9	7	2	1	1	1	1	2	6	7	9
200,000		10	9	7	2	1	1	1	1	2	6	7	9
20,000	25th	4	4	4	2	1	1	1	1	1	3	4	4
30,000		4	4	3	2	1	1	1	1	2	3	4	4
40,000		10	10	9	3	1	1	1	1	3	4	9	10
50,000		10	10	9	3	1	1	1	1	3	7	9	10
60,000		10	10	9	3	1	1	1	1	3	7	9	10
70,000		10	10	7	3	1	1	1	1	2	7	9	10
80,000		10	10	7	2	1	1	1	1	2	7	9	9
90,000		10	10	7	2	1	1	1	1	2	6	9	9
100,000		10	10	7	2	1	1	1	1	2	6	9	9
125,000		10	10	7	2	1	1	1	1	2	6	9	9
150,000		10	10	7	2	1	1	1	1	2	6	9	9
175,000		10	10	7	2	1	1	1	1	2	6	9	9
200,000		10	10	7	2	1	1	1	1	2	6	9	9

Event peak (ML/d)	Temperature percentile	January	February	March	April	May	June	July	August	September	October	November	December
20,000	50th	4	4	4	2	1	1	1	1	1	3	4	4
30,000		4	4	4	2	1	1	1	1	2	3	4	4
40,000		10	10	9	3	1	1	1	1	3	4	9	10
50,000		10	10	9	3	1	1	1	1	3	7	9	10
60,000		10	10	9	3	1	1	1	1	3	7	9	10
70,000		10	10	9	3	1	1	1	1	3	7	9	10
80,000		10	10	9	3	1	1	1	1	3	7	9	10
90,000		10	10	9	3	1	1	1	1	3	7	9	10
100,000		10	10	9	3	1	1	1	1	3	7	9	10
125,000		10	10	9	3	1	1	1	1	3	7	9	10
150,000		10	10	9	3	1	1	1	1	3	7	9	10
175,000		10	10	9	3	1	1	1	1	3	7	9	10
200,000		10	10	9	3	1	1	1	1	3	7	9	10
20,000	75th	4	4	4	2	1	1	1	1	1	3	4	4
30,000		4	4	4	2	1	1	1	1	2	3	4	4
40,000		10	10	9	3	1	1	1	1	3	4	9	10
50,000		10	10	9	3	1	1	1	1	3	7	9	10
60,000		10	10	9	3	1	1	1	1	3	7	9	10
70,000		10	10	9	3	1	1	1	1	3	7	9	10
80,000		10	10	9	3	1	1	1	1	3	7	9	10
90,000		10	10	9	3	1	1	1	1	3	7	9	10
100,000		10	10	9	3	1	1	1	1	3	7	9	10
125,000		10	10	9	3	1	1	1	1	3	7	9	10
150,000		10	10	9	3	1	1	1	1	3	7	9	10
175,000		10	10	9	3	1	1	1	1	3	7	9	10
200,000		10	10	9	3	1	1	1	1	3	7	9	10

Event peak (ML/d)	Temperature percentile	January	February	March	April	May	June	July	August	September	October	November	December
20,000	95th	4	4	4	2	1	1	1	1	1	3	4	4
30,000		4	4	4	3	1	1	1	1	2	3	4	4
40,000		10	10	9	3	1	1	1	2	3	4	9	10
50,000		10	10	9	6	1	1	1	2	3	9	9	10
60,000		10	10	9	6	1	1	1	2	6	9	10	10
70,000		10	10	9	6	1	1	1	2	6	9	9	10
80,000		10	10	9	6	1	1	1	2	6	9	9	10
90,000		10	10	9	6	1	1	1	2	6	9	9	10
100,000		10	10	9	6	1	1	1	2	6	9	9	10
125,000		10	10	9	6	1	1	1	2	6	9	9	10
150,000		10	10	9	6	1	1	1	2	6	9	9	10
175,000		10	10	9	6	1	1	1	2	6	9	9	10
200,000		10	10	9	6	1	1	1	2	6	9	9	10

Appendix C – Expert review notes for Murray project area

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
1	10/10/1906	1906–07	91,826	perc25_sm	October	Y15D25	7	7	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Cooler year, ongoing inundation of the lower floodplain starting in June. Decision: Likely hypoxia in Edward Wakool.	
1	10/10/1906	1906–07	91,837	perc25_sm	October	Y25D25	7	7		
1	10/10/1906	1906–07	91,834	perc25_sm	October	Y30D30	7	7		
1	10/10/1906	1906–07	91,845	perc25_sm	October	Y40D40	7	7		
1	10/10/1906	1906–07	91,835	perc25_sm	October	Y45D40	7	7		
2	9/08/1911	1911–12	25,305	perc50_sm	August	Y25D25	1	1	Description: Possible hypoxia for Y40D40 and Y45D40 scenarios. Mitigating factors: Average temperature year, flow option crosses step threshold in model, flow option brings flow peak into following month. Decision: Not hypoxic – difference driven by model artefacts. Re-evaluated to '5'.	
2	29/09/1911	1911–12	29,982	perc50_sm	September	Y30D30	2	2		
2	3/11/1911	1911–12	36,512	perc50_sm	November	Y40D40	9	5		
2	3/11/1911	1911–12	36,300	perc50_sm	November	Y45D40	9	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
3	30/09/1916	1916–17	56,901	perc25_sm	September	Y15D25	3	3	Description: Possible hypoxia in Y30D30 scenario. Long event with the higher peak in Y30D30 scenario shifted to December. Mitigating factors: Small amount of antecedent floodplain inundation, with the floodplain inundated from moderate-sized floods in July. Decision: Not hypoxic – difference driven by model artefacts. Re-evaluated to '5'.	
3	30/09/1916	1916–17	55,132	perc25_sm	September	Y25D25	3	3		
3	1/12/1916	1916–17	51,520	perc25_sm	December	Y30D30	10	5		
3	3/09/1916	1916–17	52,216	perc25_sm	September	Y40D40	3	3		
3	22/08/1916	1916–17	55,090	perc25_sm	August	Y45D40	1	1		
4	24/10/1917	1917–18	206,949	perc25_sm	October	Y15D25	7	5	Description: Possible hypoxia in all scenarios for Edward Wakool. Mitigating factors: Considerable priming events from July to mid-October. Decision: Not hypoxic due to antecedent conditions. Re-evaluated to '5'.	
4	24/10/1917	1917–18	206,947	perc25_sm	October	Y25D25	7	5		
4	24/10/1917	1917–18	206,953	perc25_sm	October	Y30D30	7	5		
4	24/10/1917	1917–18	206,944	perc25_sm	October	Y40D40	7	5		
4	24/10/1917	1917–18	206,942	perc25_sm	October	Y45D40	7	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
5	20/09/1920	1920–21	56,387	perc25_sm	September	Y15D25	3	3	Description: Possible hypoxia in Y45D40 scenario for Edward Wakool. Mitigating factors: Complex event with multiple peaks, the flow option shifts which peak is the highest, changing the evaluation date. Cooler year. Decision: Not hypoxic in Edward Wakool.	
5	19/09/1920	1920–21	58,305	perc25_sm	September	Y25D25	3	3		
5	13/09/1920	1920–21	44,718	perc25_sm	September	Y30D30	3	3		
5	13/09/1920	1920–21	44,553	perc50_sm	September	Y40D40	3	3		
5	25/10/1920	1920–21	45,094	perc25_sm	October	Y45D40	7	5		
6	18/06/1923	1923–24	31,102	perc25_sm	June	Y15D25	1	1	Description: Possible hypoxia in Y40D40 and Y45D40 scenarios for Edward Wakool. Peak size increases across flow options. Mitigating factors: Low peaks in the months before with ongoing flows above bankfull height. Cooler year. Decision: This is a very marginal assessment. Although hypoxia is possible under the higher flow option scenarios, these flows would not be delivered.	
6	18/10/1923	1923–24	34,657	perc25_sm	October	Y25D25	3	3		
6	18/10/1923	1923–24	40,982	perc25_sm	October	Y30D30	4	4		
6	18/10/1923	1923–24	49,144	perc25_sm	October	Y40D40	7	5		
6	17/10/1923	1923–24	53,369	perc25_sm	October	Y45D40	7	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
7	6/09/1926	1926–27	48,676	perc50_sm	September	Y15D25	3	3	Description: Possible hypoxia in Y45D40 scenario for Edward Wakool. Mitigating factors: Priming flows from early September, flow option changes the timing of the flow peak. Short duration event, completed by mid–late October. Average temperature year. Decision: Not hypoxic due to priming.	
7	6/09/1926	1926–27	48,505	perc50_sm	September	Y25D25	3	3		
7	6/09/1926	1926–27	45,062	perc50_sm	September	Y30D30	3	3		
7	6/09/1926	1926–27	44,274	perc50_sm	September	Y40D40	3	3		
7	1/10/1926	1926–27	45,075	perc50_sm	October	Y45D40	7	5		
8	31/10/1934	1934–35	128,706	perc25_sm	October	Y15D25	7	6	Description: Possible hypoxia across all scenarios for Edward Wakool. Possible hypoxia at Barmah for Y25D25 and Y40D40. Mitigating factors: Constraints shift timing of flow peak from late October to early November, increasing risk. Models using specific timing score all scenarios at ‘6’. Decision: Re-evaluated all scenarios to ‘6’, hypoxic in Edward Wakool but not Barmah.	0
8	2/11/1934	1934–35	99,303	perc25_sm	November	Y25D25	9	6		0
8	31/10/1934	1934–35	127,926	perc25_sm	October	Y30D30	7	6		0
8	3/11/1934	1934–35	83,398	perc25_sm	November	Y40D40	9	6		0
8	31/10/1934	1934–35	121,518	perc25_sm	October	Y45D40	7	6		0

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
9	12/10/1947	1947–48	46,009	perc25_sm	October	Y15D25	7	5	Description: Reduced likelihood for Y45D45 scenario. Possible hypoxia in Edward Wakool for all other scenarios and Y30D30 has possible hypoxia for Barmah. Mitigating factors: All scenarios preceded by a flow peak of commensurate size in August with continuous return flows in-between. Decision: Not hypoxic, re-evaluated to '5' for all.	
9	11/10/1947	1947–48	46,606	perc25_sm	October	Y25D25	7	5		
9	12/11/1947	1947–48	38,342	perc25_sm	November	Y30D30	9	5		
9	9/10/1947	1947–48	50,758	perc25_sm	October	Y40D40	7	5		
9	21/09/1947	1947–48	45,494	perc25_sm	September	Y45D40	3	3		
10	17/11/1948	1948–49	50,642	perc25_sm	November	Y15D25	9	9	Description: Reduced likelihood in Y25D25 scenario. Mitigating factors: Cooler year. Reduced flow peak in Y25D25 scenario because event is much reduced. Decision: The absence of any event in the Y25D25 scenario means this difference among flow options is likely.	17
10	22/11/1948	1948–49	26,658	perc25_sm	November	Y25D25	4	4		0
10	9/11/1948	1948–49	35,319	perc25_sm	November	Y30D30	9	9		17
10	8/11/1948	1948–49	43,350	perc25_sm	November	Y40D40	9	9		17
10	17/11/1948	1948–49	49,873	perc25_sm	November	Y45D40	9	9		17

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
11	10/11/1949	1949–50	44,157	perc25_sm	November	Y15D25	9	9	Description: Possible hypoxia in all scenarios for Edward Wakool, reduced likelihood in Barmah for Y30D30 and Y40D40 scenarios. Mitigating factors: Flow option changes date to one day earlier, reducing the risk in two scenarios. Borderline assessment. Cooler year. Decision: It is unlikely that a small change in date would substantially reduce hypoxia risk. Re-evaluated low-scoring scenarios to '8'.	12
11	1/11/1949	1949–50	42,921	perc25_sm	November	Y25D25	9	9		12
11	31/10/1949	1949–50	45,552	perc25_sm	October	Y30D30	7	8		12
11	31/10/1949	1949–50	53,016	perc25_sm	October	Y40D40	7	8		12
11	2/11/1949	1949–50	56,990	perc25_sm	November	Y45D40	9	9		12
12	6/11/1950	1950–51	36,476	perc50_sm	November	Y15D25	9	4	Description: Possible hypoxia in Y15D25 and Y25D25 scenarios for Barmah. Possible hypoxia in Y45D45 for Edward Wakool. Mitigating factors: Higher flow options result in slightly earlier flow peak with a cooler temperature. Y15D25 has some priming of the floodplain beginning in early October. All scenarios were re-run with bespoke timing. Decision: Adopted scores using specific timing. Y15D25 scenario preceded by flushing.	
12	6/11/1950	1950–51	35,358	perc50_sm	November	Y25D25	9	4		
12	24/10/1950	1950–51	32,808	perc25_sm	October	Y30D30	3	3		
12	24/10/1950	1950–51	43,728	perc25_sm	October	Y40D40	4	5		
12	29/10/1950	1950–51	45,291	perc25_sm	October	Y45D40	7	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
13	19/12/1954	1954–55	38,080	perc50_sm	December	Y15D25	10	5	Description: Reduced likelihood from Y15D25. Flow peak is higher in Y15D25, exceeding the 30K threshold and increasing risk. Mitigating factors: Fairly low flow to create hypoxia. It is possible that the flow options have reduced the risk of hypoxia in this case, but the assessment is marginal. Some pre-watering with continuous flows to the floodplain from August would reduce risk. Decision: Not hypoxic in Y15D25.	
13	20/12/1954	1954–55	28,809	perc50_sm	December	Y25D25	4	4		
13	9/12/1954	1954–55	24,605	perc50_sm	December	Y30D30	4	4		
13	9/12/1954	1954–55	25,767	perc50_sm	December	Y40D40	4	4		
13	9/12/1954	1954–55	24,386	perc50_sm	December	Y45D40	4	4		
14	19/10/1958	1958–59	76,128	perc25_sm	October	Y30D30	7	5	Description: Possible hypoxia in Y30D30, Y40D40 and Y45D40 scenarios for Edward Wakool. No event peaks detected in lowest two scenarios. Mitigating factors: Continuous event from July with two peaks. Flow scenarios shift which peak is evaluated. Decision: Not hypoxic – events are mitigated by preceding flows.	
14	19/10/1958	1958–59	76,181	perc25_sm	October	Y40D40	7	5		
14	19/10/1958	1958–59	76,280	perc25_sm	October	Y45D40	7	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
15	2/11/1959	1959–60	26,029	perc25_sm	November	Y15D25	4	4	Description: Possible hypoxia in Y40D40 and Y45D40 scenarios for Edward Wakool. Mitigating factors: Results indicate an increasing likelihood of hypoxia associated with delivered flows due to a shift in the timing of the flow peak. It is unlikely that a standalone event would be delivered at this flow rate and at this time of year. Decision: The assessment accurately predicts hypoxic blackwater but this flow is too high risk to have been a managed event.	
15	22/10/1959	1959–60	25,447	perc25_sm	October	Y25D25	3	3		
15	15/10/1959	1959–60	31,918	perc25_sm	October	Y30D30	3	3		
15	4/11/1959	1959–60	41,025	perc50_sm	November	Y40D40	9	5		
15	1/11/1959	1959–60	40,383	perc50_sm	November	Y45D40	9	5		
16	2/10/1960	1960–61	96,668	perc25_sm	October	Y15D25	7	7	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Not a hot year. Decision: Likely hypoxia in Edward Wakool.	0
16	2/10/1960	1960–61	96,337	perc25_sm	October	Y25D25	7	7		0
16	2/10/1960	1960–61	96,855	perc25_sm	October	Y30D30	7	7		0
16	2/10/1960	1960–61	97,111	perc25_sm	October	Y40D40	7	7		0
16	2/10/1960	1960–61	97,119	perc25_sm	October	Y45D40	7	7		0

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
17	15/10/1964	1964–65	94,406	perc25_sm	October	Y15D25	7	7	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Not a hot year. Decision: Likely hypoxia in Edward Wakool.	0
17	16/10/1964	1964–65	88,777	perc25_sm	October	Y25D25	7	7		0
17	16/10/1964	1964–65	88,178	perc25_sm	October	Y30D30	7	7		0
17	16/10/1964	1964–65	88,246	perc25_sm	October	Y40D40	7	7		0
17	16/10/1964	1964–65	88,309	perc25_sm	October	Y45D40	7	7		0
18	20/12/1966	1966–67	51,850	perc25_sm	December	Y15D25	10	3	Description: Possible hypoxia across all scenarios. Mitigating factors: Complex event with multiple flow peaks. The flow-splitting function has treated these as separate events because the flows fell below 10K for two weeks. Decision: Not hypoxic – flows inherit likelihood from event in late-September.	
18	20/12/1966	1966–67	35,242	perc25_sm	December	Y25D25	10	3		
18	20/12/1966	1966–67	36,842	perc50_sm	December	Y30D30	10	3		
18	20/12/1966	1966–67	36,779	perc50_sm	December	Y40D40	10	3		
18	20/12/1966	1966–67	36,920	perc50_sm	December	Y45D40	10	3		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
19	16/11/1971	1971–72	76,040	perc25_sm	November	Y15D25	9	9	Description: Possible hypoxia across all scenarios. Mitigating factors: Cooler year. Decision: Likely hypoxia. Substantial flow peaking in mid-November.	1
19	16/11/1971	1971–72	76,041	perc25_sm	November	Y25D25	9	9		1
19	16/11/1971	1971–72	74,907	perc25_sm	November	Y30D30	9	9		1
19	16/11/1971	1971–72	74,725	perc25_sm	November	Y40D40	9	9		1
19	16/11/1971	1971–72	74,421	perc25_sm	November	Y45D40	9	9		1
20	19/01/1974	1974–75	53,858	perc50_sm	January	Y15D25	10	5	Description: 50K event in mid-January, likely hypoxia across all scenarios. Mitigating factors: Substantial >100K event in September with another 70K event in October. The flow-splitting function treats as a separate event because flows reduce to below 10K for a small amount of time. Decision: Not hypoxic. Substantial pre-watering of the floodplain, likelihood score inherited from September peak.	
20	19/01/1974	1974–75	53,888	perc50_sm	January	Y25D25	10	5		
20	19/01/1974	1974–75	53,891	perc50_sm	January	Y30D30	10	5		
20	19/01/1974	1974–75	53,894	perc50_sm	January	Y40D40	10	5		
20	19/01/1974	1974–75	53,892	perc50_sm	January	Y45D40	10	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
21	22/10/1974	1974–75	152,173	perc25_sm	October	Y15D25	7	5	Description: Large October event, likely hypoxia in Edward Wakool across all scenarios. Mitigating factors: 140K event in late July with continuous return flows and smaller peaks. Cooler year. Decision: Not likely to create hypoxia because of antecedent watering. Re-evaluated score to ‘5’.	
21	22/10/1974	1974–75	152,181	perc25_sm	October	Y25D25	7	5		
21	22/10/1974	1974–75	152,178	perc25_sm	October	Y30D30	7	5		
21	22/10/1974	1974–75	152,196	perc25_sm	October	Y40D40	7	5		
21	22/10/1974	1974–75	152,194	perc25_sm	October	Y45D40	7	5		
22	30/10/1975	1975–76	183,671	perc50_sm	October	Y15D25	7	7	Description: 180K event in late October, hypoxia across all scenarios for Edward Wakool. Mitigating factors: Preceded by 130K event in September. Decision: Likely hypoxia in Edward Wakool. Late in the year for such a large event, a lot of dry floodplain inundated.	0
22	30/10/1975	1975–76	183,671	perc50_sm	October	Y25D25	7	7		0
22	30/10/1975	1975–76	183,671	perc50_sm	October	Y30D30	7	7		0
22	30/10/1975	1975–76	183,671	perc50_sm	October	Y40D40	7	7		0
22	30/10/1975	1975–76	183,670	perc50_sm	October	Y45D40	7	7		0

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
23	5/10/1978	1978–79	68,931	perc25_sm	October	Y15D25	7	5	Description: Reduced hypoxia in Y15D25 for Edward Wakool. Higher flow limit options deliver this peak much earlier and reduce its magnitude. Mitigating factors: Cooler year, preceded by a minor flow peak in August. Re-evaluation using specific dates reduced likelihood score to '6'. Decision: It is likely that in this case the use of environmental water has reduced the risk of hypoxia by delivering water earlier in the year, reducing the size of a subsequent event. However, for the analysis this flow will be regarded as not hypoxic. The low evaluation likelihood, cooler conditions and priming flows are expected to have mitigated hypoxia.	
23	14/08/1978	1978–79	56,789	perc25_sm	August	Y25D25	1	1		
23	15/08/1978	1978–79	59,733	perc25_sm	August	Y30D30	1	1		
23	14/08/1978	1978–79	66,742	perc25_sm	August	Y40D40	1	1		
23	14/08/1978	1978–79	69,909	perc25_sm	August	Y45D40	1	1		
24	4/10/1979	1979–80	65,804	perc50_sm	October	Y15D25	7	7	Description: 70+K event in early October creates likely hypoxia across all scenarios. Mitigating factors: Small priming flow of 40K in September. Short event completed by November.	0
24	4/10/1979	1979–80	70,432	perc50_sm	October	Y25D25	7	7		0
24	4/10/1979	1979–80	75,003	perc25_sm	October	Y30D30	7	7		0
24	4/10/1979	1979–80	76,958	perc25_sm	October	Y40D40	7	7		0

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
24	4/10/1979	1979–80	77,024	perc25_sm	October	Y45D40	7	7	Decision: Likely hypoxia in Edward Wakool. NB: this event was not evaluated as hypoxic for the fish assessment.	0

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
25	11/10/1984	1984–85	73,531	perc25_sm	October	Y15D25	7	5	Description: 70+K event in early October, hypoxic across all scenarios for Edward Wakool. Mitigating factors: Substantial volume of water delivered at lower flow rate from late-August. Event is short, completed by mid-October. Decision: Not likely to be hypoxic in any scenario.	0
25	11/10/1984	1984–85	73,538	perc25_sm	October	Y25D25	7	5		0
25	11/10/1984	1984–85	71,318	perc25_sm	October	Y30D30	7	5		0
25	11/10/1984	1984–85	71,181	perc25_sm	October	Y40D40	7	5		0
26	30/10/1986	1986–87	94,033	perc25_sm	October	Y15D25	7	5	Description: Possible hypoxia in Edward Wakool for Y15D25 and Y40D40 scenarios. Complex event with multiple peaks, flow options deliver water earlier, reducing the size of the subsequent peak in late November. Mitigating factors: Cooler year. In all scenarios there are multiple events prior to the peak in late October that has the highest	
26	10/07/1986	1986–87	74,680	perc25_sm	July	Y25D25	1	1		
26	10/07/1986	1986–87	74,442	perc25_sm	July	Y30D30	1	1		
26	29/10/1986	1986–87	76,950	perc25_sm	October	Y40D40	7	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
26	10/07/1986	1986–87	74,434	perc25_sm	July	Y45D40	1	1	likelihood. The Y15D25 scenario is the most likely to cause hypoxia in Edward Wakool. Decision: Not hypoxic. The antecedent flows and cooler temperatures reduce the likelihood of hypoxia. Note that the flow options in this case may be reducing hypoxia risk.	

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
27	6/09/1989	1989–90	56,030	perc25_sm	September	Y15D25	3	3	Description: Possible hypoxia in Edward Wakool for Y45D40 scenario. Complex event from July to November. Mitigating factors: Flows are above bankfull for several months prior to the flow peak, flow limit options slightly increase the relative height of the peak in November, changing which peak in the series is greatest. The peak in the Y45D40 scenario is preceded by a flow of commensurate size in early September. Decision: Not hypoxic. The peak is part of a complex series of flows with continuous flows to the floodplain.	
27	6/09/1989	1989–90	55,384	perc50_sm	September	Y25D25	3	3		
27	6/09/1989	1989–90	59,295	perc50_sm	September	Y30D30	3	3		
27	6/09/1989	1989–90	59,310	perc25_sm	September	Y40D40	3	3		
27	15/10/1989	1989–90	45,259	perc50_sm	October	Y45D40	7	3		
28	23/10/1992	1992–93	108,619	perc5_sm	October	Y15D25	6	6	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Cooler year. Large, isolated flow peak without priming flows late in the year. Decision: Hypoxia in Edward Wakool across all scenarios.	
28	23/10/1992	1992–93	107,990	perc5_sm	October	Y25D25	6	6		
28	23/10/1992	1992–93	108,027	perc5_sm	October	Y30D30	6	6		
28	23/10/1992	1992–93	107,984	perc5_sm	October	Y40D40	6	6		
28	23/10/1992	1992–93	108,028	perc5_sm	October	Y45D40	6	6		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
29	8/10/1993	1993–94	168,338	perc25_sm	October	Y15D25	7	7	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Cooler year. Large, isolated flow peak without priming flows late in the year. Event completed by November. Decision: Hypoxia in Edward Wakool across all scenarios.	0
29	8/10/1993	1993–94	168,339	perc25_sm	October	Y25D25	7	7		0
29	8/10/1993	1993–94	162,832	perc25_sm	October	Y30D30	7	7		0
29	8/10/1993	1993–94	162,810	perc25_sm	October	Y40D40	7	7		0
29	8/10/1993	1993–94	162,810	perc25_sm	October	Y45D40	7	7		0
30	31/12/1993	1993–94	38,026	perc25_sm	December	Y15D25	10	5	Description: Possible hypoxia in all scenarios for Barmah and Edward Wakool. 40K event in late December. Mitigating factors: Preceded by large event in October of the same year. Decision: Not hypoxic in Barmah.	
30	31/12/1993	1993–94	38,026	perc25_sm	December	Y25D25	10	5		
30	31/12/1993	1993–94	37,954	perc25_sm	December	Y30D30	10	5		
30	31/12/1993	1993–94	37,954	perc25_sm	December	Y40D40	10	5		
30	31/12/1993	1993–94	37,954	perc25_sm	December	Y45D40	10	5		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
31	6/10/1996	1996–97	146,612	perc25_sm	October	Y15D25	7	5	Description: Possible hypoxia in all scenarios for Edward Wakool. Large event in early October. Mitigating factors: Event has two peaks, the earlier in August. Decision: Not hypoxic. It isn't clear whether the second, larger peak will have inundated enough additional area in October to cause hypoxia.	
31	6/10/1996	1996–97	146,605	perc25_sm	October	Y25D25	7	5		
31	6/10/1996	1996–97	146,144	perc25_sm	October	Y30D30	7	5		
31	7/10/1996	1996–97	141,575	perc25_sm	October	Y40D40	7	5		
31	7/10/1996	1996–97	141,499	perc25_sm	October	Y45D40	7	5		
32	31/10/2000	2000–01	92,989	perc25_sm	October	Y15D25	7	9	Description: Possible hypoxia in Y30D30 and Y40D40 scenarios for Barmah, possible hypoxia in all scenarios for Edward Wakool. Bimodal flow event with peaks in October or early November. Mitigating factors: For the Y30D30 and Y40D40 scenarios, the timing of the second flow peak is pushed back by one day, and so the events are scored using the November risk, which is higher. Flow option also affects which of the two flow peaks is greater. Decision: Hypoxia in both areas across all scenarios. The Y15D25 scenario possibly has lower likelihood because of the peak in early September. Note also that this is a known hypoxic blackwater event in the Murray.	10
32	31/10/2000	2000–01	92,109	perc25_sm	October	Y25D25	7	9		10
32	1/11/2000	2000–01	86,417	perc25_sm	November	Y30D30	9	9		10
32	2/11/2000	2000–01	57,860	perc50_sm	November	Y40D40	9	9		10
32	15/09/2000	2000–01	50,718	perc50_sm	September	Y45D40	3	9		10

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
33	30/10/2001	2001–02	21,578	perc25_sm	October	Y15D25	1	1	Description: Possible hypoxia in Y40D40 scenario for Edward Wakool. Decision: Not hypoxic. Note that the size and timing of the flow peak in the Y40D40 scenario could possibly result in hypoxia because of the size and timing of the event; however, operations would not allow for this flow to be engineered. Mitigating factors: Flow options result in an increasing flow peak in late September that is greatest for the Y40D40 scenario.	
33	31/10/2001	2001–02	34,018	perc50_sm	October	Y25D25	3	3		
33	30/10/2001	2001–02	38,488	perc50_sm	October	Y30D30	4	4		
33	31/10/2001	2001–02	49,022	perc25_sm	October	Y40D40	7	5		
33	31/10/2001	2001–02	35,214	perc25_sm	October	Y45D40	4	4		
34	6/09/2005	2005–06	39,296	perc50_sm	September	Y15D25	3	3	Description: Possible hypoxia in both areas for Y30D30 scenario and in Edward Wakool for the Y45D40 scenario. Mitigating factors: For the Y30D30 scenario, flow options change which peak in the series is greater, and the higher-likelihood peak is preceded by a similar-sized peak in September with continuous flows to the floodplain. For the Y45D40 scenario, flows at the peak commence in September.	
34	18/09/2005	2005–06	38,041	perc50_sm	September	Y25D25	3	3		
34	4/11/2005	2005–06	37,212	perc50_sm	November	Y30D30	9	5		
34	6/09/2005	2005–06	36,877	perc50_sm	September	Y40D40	3	3		

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
34	6/10/2005	2005–06	48,202	perc50_sm	October	Y45D40	7	5	Decision: Not hypoxic. Note that the size and timing of the flow peak in the Y45D40 scenario could possibly result in hypoxia in the Edward Wakool because of the size and timing of the event; however, operations would not allow for this flow to be engineered.	

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
35	15/12/2010	2010–11	87,828	perc25_sm	December	Y15D25	10	10	Description: Possible hypoxia across all scenarios. Large event with peak in mid-December. Mitigating factors: Cooler year. Decision: Hypoxia. This is a known hypoxic blackwater event with recorded low DO in the Edward Wakool in September 2010.	29
35	15/12/2010	2010–11	87,786	perc25_sm	December	Y25D25	10	10		29
35	15/12/2010	2010–11	88,147	perc25_sm	December	Y30D30	10	10		29
35	15/12/2010	2010–11	81,862	perc25_sm	December	Y40D40	10	10		29
35	15/12/2010	2010–11	87,961	perc25_sm	December	Y45D40	10	10		29
36	9/03/2012	2012–13	48,904	perc25_sm	March	Y15D25	9	9	Description: Possible hypoxia across all scenarios. Large event with peak in mid-December. Mitigating factors: Cooler period. Decision: Hypoxia. This is a known hypoxic blackwater event.	9
36	9/03/2012	2012–13	48,253	perc25_sm	March	Y25D25	9	9		9
36	9/03/2012	2012–13	49,047	perc25_sm	March	Y30D30	9	9		9
36	9/03/2012	2012–13	47,266	perc25_sm	March	Y40D40	9	9		9
36	9/03/2012	2012–13	48,820	perc25_sm	March	Y45D40	9	9		9

Event ID	Date of flow peak	Water year	Flow peak (ML/d)	Temperature percentile range	Month	Flow option scenario	Initial likelihood	Reviewed likelihood	Review notes	Severity index
37	8/10/2016	2016–17	169,350	perc25_sm	October	Y15D25	7	7	Description: Possible hypoxia in Edward Wakool across all scenarios. Mitigating factors: Some priming of the lower floodplain in August. Decision: Hypoxia in Edward Wakool. This is a known hypoxic blackwater event in the Edward Wakool.	0
37	8/10/2016	2016–17	169,254	perc25_sm	October	Y25D25	7	7		0
37	8/10/2016	2016–17	168,453	perc25_sm	October	Y30D30	7	7		0
37	9/10/2016	2016–17	101,586	perc25_sm	October	Y40D40	7	7		0
37	11/10/2016	2016–17	103,812	perc25_sm	October	Y45D40	7	7		0

Appendix D – Expert review notes for the Murrumbidgee project area

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
24/10/1906	1906–07	45,056	W22	9				
25/10/1906	1906–07	44,671	W32	9				
24/10/1906	1906–07	36,143	W36	0				
23/10/1906	1906–07	36,113	W40	0				
24/10/1906	**1906–07**	**40,945**	**Median**	**9**	**9**	**Particularly dry in the years prior.**		**30**
27/10/1916	1916–17	56,960	W22	9				52
27/10/1916	1916–17	56,960	W32	9				49
27/10/1916	1916–17	56,960	W36	9				39
27/10/1916	1916–17	56,960	W40	9				39
27/10/1916	**1916–17**	**56,960**	**Median**	**9**	**9**	**Substantial flow peak in September could mitigate hypoxia during October peak.**		**39**

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
11/09/1917	1917–18	46,377	W22	10				
11/09/1917	1917–18	46,377	W32	10				
12/09/1917	1917–18	46,087	W36	10				
12/09/1917	1917–18	46,087	W40	10				
11/09/1917	**1917–18**	**46,377**	**Median**	**10**	**NA**	**Event begins earlier, providing 2–3 months of inundation prior to the flow peak.**		
16/11/1934	1934–35	46,377	W22	10				35
16/11/1934	1934–35	46,377	W32	10				35
16/11/1934	1934–35	46,377	W36	10				35
16/11/1934	1934–35	46,377	W40	10				35
16/11/1934	**1934–35**	**46,377**	**Median**	**10**	**10**	**Substantial peak in August could mitigate hypoxia; however, the larger peak in November is high-risk.**		**35**
13/09/1939	1939–40	44,900	W22	8				
13/09/1939	1939–40	44,827	W32	8				
13/09/1939	1939–40	44,900	W36	8				
14/09/1939	1939–40	45,056	W40	8				
13/09/1939	**1939–40**	**44,900**	**Median**	**8**	**NA**	**Possibly some localised hypoxia but not expected to cause fish kill.**		

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
16/04/1950	1949–50	66,959	W22	8				9
16/04/1950	1949–50	66,959	W32	8				9
16/04/1950	1949–50	66,959	W36	8				9
16/04/1950	1949–50	66,959	W40	8				9
16/04/1950	**1949–50**	**66,959**	**Median**	**8**		April is very late for a hypoxic event to occur. Could possibly cause hypoxia if there were a large litter load.		**9**
13/11/1950	1950–51	51,595	W22	10				38
13/11/1950	1950–51	51,595	W32	10				38
13/11/1950	1950–51	51,595	W36	10				38
13/11/1950	1950–51	51,595	W40	10				38
13/11/1950	**1950–51**	**51,595**	**Median**	**10**	10	Although there is a larger event in the previous year, there has been a period of drying on the floodplain that would have allowed litter to accumulate.		**38**
10/07/1952	1952–53	64,971	W22	10				
10/07/1952	1952–53	64,971	W32	10				
10/07/1952	1952–53	59,205	W36	10				
9/07/1952	1952–53	62,216	W40	10				
10/07/1952	**1952–53**	**62,216**	**Median**	**10**	NA	Continuous event beginning in July, floodplain has been consistently wet before the flow peak.		

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
14/09/1955	1955–56	50,353	W22	9				
14/09/1955	1955–56	49,305	W32	9				
15/09/1955	1955–56	47,244	W36	9				
15/09/1955	1955–56	47,244	W40	9				
14/09/1955	**1955–56**	**48,291**	**Median**	**9**	NA	A long, low-level, flood that begins in late August and continues until mid-September with a flow peak of ~48,000. Floodplain has been consistently wet before the flow peak in September.		
26/07/1956	1956–57	66,959	W22	10				
27/07/1956	1956–57	66,959	W32	10				
29/07/1956	1956–57	66,959	W36	10				
31/07/1956	1956–57	66,959	W40	10				
27/07/1956	**1956–57**	**66,959**	**Median**	**10**	NA	Large flow event that continues for several months. Floodplain has been consistently wet before the high-risk period later in the year.		
17/10/1960	1960–61	53,337	W22	9				
17/10/1960	1960–61	53,337	W32	9				
17/10/1960	1960–61	53,337	W36	9				
17/10/1960	1960–61	53,337	W40	9				
17/10/1960	**1960–61**	**53,337**	**Median**	**9**	NA	Continuous event, floodplain has been consistently wet before the flow peak in October.		

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
28/10/1964	1964–65	39,390	W22	10				33
28/10/1964	1964–65	39,775	W32	10				33
28/10/1964	1964–65	39,775	W36	10				33
28/10/1964	1964–65	39,949	W40	10				33
28/10/1964	**1964–65**	**39,775**	**Median**	**10**	10	Flow peak in late October is poor timing for an event of this size; however, there is a large amount of water entering the floodplain from August. While this event is likely to trigger some localised hypoxia, it is not expected to cause a large fish kill.		**33**
19/10/1970	1970–71	56,359	W22	9				32
17/10/1970	1970–71	53,337	W32	9				32
17/10/1970	1970–71	56,359	W36	9				32
17/10/1970	1970–71	56,359	W40	9				32
17/10/1970	**1970–71**	**56,359**	**Median**	**9**	9	The floodplain has been dry for several years prior to this event. The litter load on the floodplain is expected to be high.		**32**
24/09/1974	1974–75	66,959	W22	10				
24/09/1974	1974–75	66,959	W32	10				
24/09/1974	1974–75	66,959	W36	10				
24/09/1974	1974–75	66,959	W40	10				
24/09/1974	**1974–75**	**66,959**	**Median**	**10**	NA	Not a hypoxic event. This event is during a very wet period, the floodplain has been consistently wet prior to the flow peak in September.		

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
18/11/1975	1975–76	56,359	W22	10				42
18/11/1975	1975–76	56,359	W32	10				42
18/11/1975	1975–76	56,359	W36	10				42
18/11/1975	1975–76	56,359	W40	10				42
18/11/1975	**1975–76**	**56,359**	**Median**	**10**	10	Large flow event that peaks in mid-late November is poor timing for an event of this size. Some wetting of the floodplain since August may have mitigated the severity of the event.		**42**
1/10/1978	1978–79	46,377	W22	9				
1/10/1978	1978–79	46,377	W32	9				
30/09/1978	1978–79	45,056	W36	9				
30/09/1978	1978–79	45,229	W40	9				
30/09/1978	**1978–79**	**46,377**	**Median**	**9**	NA	Flow peak in late September is preceded by flows a month earlier that will have mitigated the return of carbon from the floodplain during the flow peak. This event may cause some localised hypoxia but is not expected to cause fish kills.		
26/10/1993	1993–94	41,372	W22	10				32
26/10/1993	1993–94	41,306	W32	10				32
26/10/1993	1993–94	41,372	W36	10				32
26/10/1993	1993–94	41,372	W40	10				32
26/10/1993	**1993–94**	**41,372**	**Median**	**10**	10	Flow peak in late October is very late in the year for an event of this size.		**31**

Date of flow peak	Water year	Flow peak at Downstream Hay Weir (ML/d)	Flow option scenario	Maximum likelihood	Reviewed likelihood	Review notes	Severity index	Hypoxia days
26/12/2010	2010–11	53,073	W22	10				37
26/12/2010	2010–11	53,073	W32	10				37
26/12/2010	2010–11	53,073	W36	10				37
26/12/2010	2010–11	53,073	W40	10				37
26/12/2010	**2010–11**	**53,073**	**Median**	**10**	**10**	**This is a known hypoxic blackwater event.**		**37**
25/03/2012	2011–12	66,959	W22	9				20
25/03/2012	2011–12	66,959	W32	9				20
25/03/2012	2011–12	66,959	W36	9				20
25/03/2012	2011–12	66,959	W40	9				20
25/03/2012	**2011–12**	**66,959**	**Median**	**9**	**10**	**This is a known hypoxic blackwater event.**		**20**
23/10/2016	2016–17	55,130	W22	10				40
23/10/2016	2016–17	55,130	W32	10				40
23/10/2016	2016–17	56,359	W36	10				39
23/10/2016	2016–17	56,359	W40	10				39
23/10/2016	**2016–17**	**55,130**	**Median**	**10**	**10**	**This is a known hypoxic blackwater event.**		**40**