Blackwater Review

Environmental water used to moderate low dissolved oxygen levels in the southern Murray Darling Basin during 2016/17

Australian Government

Commonwealth Environmental Water Office

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Leopold (1949) wrote about the importance of 'thinking like a mountain," of recognising that 'a thing is right when it tends to preserve the integrity, stability and beauty of the biotic community" (Leopold 1949, in Laferrière & Stoett, 1999)

Front cover: Edward escape refuge flow into the Edward River (schematised)

Inset below: Panoramic of oxygenated environmental water (left) used to create fish refuge during the 2016 hypoxic event in the Edward - Wakool

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Executive Summary

The major goal of the Commonwealth Environmental Water Holder is to improve flow-stressed rivers and streams, using environmental water to protect and restore rivers, wetlands and floodplains (including water dependent native flora and fauna) of the Murray-Darling Basin (MDB). This report considers the environmental watering interventions used to limit the harmful impact of low oxygen conditions during 2016/17 within the regulated Edward-Wakool, Murrumbidgee, Lachlan, Goulburn Broken and Murray River (below Lake Victoria).

September 2016 was the wettest on record for the Murray Darling Basin (MDB) as the area-averaged rain totalled 118.5 mm, which was 249% above the long-term monthly mean, and well above the previous record set back in 1906. Extreme events such as the 2016 flood have a low frequency of occurrence, but when they do occur, they tend to have major consequences for water quality in rivers and water storages. The 1 in 30 year flood occurrence was characterised by two significant flood pulses, and to offer some perspective, the second peak was equal to 50% of the discharge recorded during the 1955 flood event at Deniliquin. The widespread inundation mobilised organic material from floodplain soils and vegetation that was returned to the river channel thereby promoting high rates of bacterial production. Adverse water quality problems followed; in particular, a plume of low oxygen water extended along major tributaries of the southern MDB from late October to December. When dissolved oxygen levels dropped below 2 mg L^{-1} (likely fish kill threshold) water holders and stakeholders formulated discrete environmental watering responses designed to create refuge and protect freshwater biota.

The MDB is recognised as one of the world's most variable regions in terms of stream flows and precipitation and while the 2016 flood event was atypical, dams and storages have had profound influences on the connections between lowland rivers and their floodplains, particularly for the small to medium flood events. River regulation and abstraction has interrupted the extent, frequency, duration and timing of floodplain inundation appreciably. Discharging environmental water for the purpose of diluting low dissolved oxygen levels or generating fish refuge during a large flood event is beset with inherent complexity and ambiguity. For example, there are human resource restraints, tensions within the Australian federal and state systems, complexities coordinating the network of water-related agencies with responsibilities in the MDB, as well as, social, cultural and economic barriers. These factors in one form or another influenced the delivery of environmental water during 2016.

The key recommendations arising from the report include:

1. *Develop a Blackwater Response Plan*

Greater clarity regarding the management and governance of poor water quality events in the Murray Darling Basin is required. Importantly, an inter-jurisdictional process needs to be facilitated and agreement reached for the management of hypoxic blackwater events. This approach was advocated following the 2011 hypoxic blackwater event, yet in 2016 water holders and water resource managers found they were operating in isolation, as no clear strategic framework regarding risk management, emergency response interventions, coordination, data requirements, likely 'hot spots' or innovative approaches to improve ecological outcomes existed. A southern MDB Blackwater Response Plan would articulate important information particularly the prioritisation of management interventions and protection efforts (Figure 74).

2. *Identify new and novel approaches to manage environmental water during low oxygen conditions*

Generally, the management responses implemented in 2016 were found to be adaptive, and collaborative, using science-based understanding, and various forms of feedback from the environment in a 'learning by doing' approach. Nonetheless, the Commonwealth Environmental Water Holder's (CEWH) good neighbour policy of 'no third party impacts' required some interpretation in consultation with community representatives. This policy may benefit from greater elucidation regarding the delivery of environmental water under different flood scenarios. Without exception environmental water was delivered on the falling limb of the hydrograph, in an effort to avoid flood afflux, however this approach fails to adequately address the requirement to manage the first flush, which has been shown to carry higher concentrations of dissolved organic carbon and nutrients. Future responses could consider in consultation with the community the acceptable afflux under a range of flood events applicable to the rising limb, peak and falling limb for each category of flooding.

A measure is needed to manage the nutrient loads on floodplains for better water quality outcomes. It may be possible through stakeholder engagement and collaboration to revisit social and cultural narrows that currently constrain the delivery of environmental water during hypoxic blackwater events, and to also invest in complementary measures that would close or limit nutrient pathways.

Consideration therefore needs to be given to the various natural inundation patterns of floodplain ecosystems, and commensurate with flow levels and river height. Spatial data that identifies barriers to fish passage would assist water holders to understand the limitations and also locations where water can be released for optimum benefit. Reflecting on the natural, pre-regulation rate of inundation could be used to qualify the effects of small amounts of environmental water. Importantly an increase in the frequency of small to medium floodplain inundation events would lower the nutrient load returned to rivers in the major flood event, whilst building important in-stream productivity necessary to build resilient aquatic ecosystems. (see Table 1 below).

3. *Fish tracking and identifying valuable habitats that may provide protection for aquatic biota*

Following the 2011 hypoxic blackwater event Whitworth et al (2011) noted that not all native fish had been killed, and called for a more thorough understanding of the sub-lethal effects of hypoxia and elevated DOC. In the past five years our understanding of the triggers that initiate fish movement during a flood event has advanced. Importantly, fish tracking data from the Edward –Wakool show the exodus in 2016 occurred prior to the arrival of the low oxygen pulse, and on the rising limb of the hydrograph. Similar to 2011, the fish tracking data indicates native fish were not completely annihilated, even though re-colonisation was significantly reduced. These findings suggest native fish have unique tolerances and adaptive capacity that supports at least some of the cohort.

Corresponding to the period of poor water quality in the Murray and its tributaries, a massive Murray cod-spawning event occurred in the lower Darling River in late 2016. The provision of an environmental flow in the Darling River may have provided refuge for fish to escape hypoxic water in the River Murray. This is one example, but further consideration needs to be given to prioritising sites that offer protection and aquatic ecological refuges. Locating river reaches with good water quality during hypoxic blackwater events is equally as important as understanding where low dissolved oxygen sites exit, because they offer the chance for in-situ persistence for vulnerable species.

4. *Identify hot spots and assessing vulnerability and risk*

Adoption of remote sensing to monitor events or transient events that affect water delivery and water quality could greatly reduce labour costs involved in field based water-sampling, sensor maintenance and instrument servicing. High frequency surveillance and spatial coverage is now available, and could be adopted by water resource managers to guide planning, monitoring of key processes and for reporting. Spatial data can be correlated with real-time measurements of temperature, conductance and turbidity and other important water-quality properties, such as bacteria, that tend to be more costly and difficult to monitor and analyse. This information could also support the development of a basin scale network to adequately represent key ecological assets as well as threats such as hypoxic blackwater events.

5. *Strategic water quality monitoring network*

A strategic and real time dissolved oxygen monitoring network is needed for all major rivers in the central and southern MDB. Understanding dissolved oxygen levels in lowland rivers requires monitoring to observe water quality issues prior to an event, rather than event based monitoring that tends to occur once a problem has been detected. Continuous monitoring could improve the understanding of diel fluctuations (hourly/daily time frame), and dissolved oxygen monitoring using submersible sensors at telemetered gauging stations offers spatial and temporal integration at relatively low cost.

Measuring dissolved organic carbon using in situ optical measurements with field-deployable fluorometers and spectrophotomers would provide another line of evidence to complement the dissolved oxygen data. This type of monitoring was previously logistically difficult or impossible, but it is now a quick, precise, and relatively inexpensive measure when compared to collecting discrete water samples in the field and later completing chemical C analyses (Ruhala and Zarnetske 2017).

6. *River metabolism, and dissolved organic carbon and macronutrient inputs*

Despite the current understanding of hypoxic blackwater events, further research is needed to address overall river metabolism, and the thresholds (concentrations or loads of dissolved organic carbon and co-limiting nutrients) needed to support biodiversity and ecosystem functioning. Despite their ubiquity we have limited knowledge of the ecological roles of algae, heterotrophic bacteria or photoautotrophic bacteria, and yet these biota are critical to ecological processes. We need better understanding of the genetic structure of representative aquatic species. Investigations need to also consider the quantification of terrestrial carbon stocks from riparian or terrestrial vegetation on adjacent riverine floodplains, dissolved organic carbon contribution from modified landscapes and soils of the riverine floodplains.

7. *Modelling*

A suite of hydrodynamic, hydrologic and floodplain models are available to support decision-making regarding environmental water during hypoxic events. As there are gaps in modelling of carbon inputs from different sources including the relative magnitude of allochthonous verses autochthonous carbon and macronutrients inputs, further research investigations are warranted. The blackwater computer models that now exist have been developed for river red gum-dominated floodplains, but could be modified to account for other vegetation types. These models are useful for scenario testing, risk management and understanding appropriate timing of floodplain inundation. However, modelling was found to have certain limitations in 2016, due to the scale of the event, and current calibration may only be applicable for localised or small to medium flood events.

8. *Implementing climate adaptation actions*

The long term effects of climate change could be better linked within the current environmental watering discourse, as rapid rates of change, particularly, season, temperature and rainfall patterns are likely to increase the pressure on freshwater aquatic ecosystems in the future. The intense rainfall that occurred during September 2016 was unexpected, and winter temperatures were above the long-term average. While hypoxic conditions occurred when temperatures were below those previously described as high risk (that is >20 °C), the warm and wet winter along with floodplain organic material were conducive to the onset of the blackwater event. Further consideration of a temperature gradient, and the environmental conditions known to accelerate the decomposition of organic material may provide a more meaningful guide for water resource managers who need to work within a risk based framework.

9. *Engaging indigenous groups, local communities and industry (pastoralism and tourism) with environmental watering actions and monitoring*

Training and equipment is needed to support the management and monitoring of lowland rivers by people who live and work in these regions. A dedicated program is needed to facilitate community and industry engagement to better share knowledge of key drivers.

10. *Risk Framework*

A risk framework is recommended and based on water scenario indices, shown in Table 1. The ecosystem condition can be forecast from flow history and site monitoring data. The assessment of whether environmental water can be released is therefore dependent on whether or not there would be an improvement in ecosystem condition, particularly fish populations beyond a 'do nothing scenario'. The release of environmental water would be supported if there were a capacity to move from a higher risk setting towards a low or medium risk condition. For example, the framework could be applied to low-lying floodplain areas that are in a 'dry' condition due to the lack of inundation in the last ten years. A meteorological prediction of an intense rain event would give a scenario classification of 'protect', and this would trigger the release of environmental flows (fresh or water delivered to critical sites) as a fish refuge, to generate a shift toward the 'improve' status. The water scenarios can also be coupled to a blackwater intervention model.

Table 1 Blackwater management in relation of ecosystem condition and three water scenarios (dry, median, wet) (adapted from Overton et al. 2011)

		Ecosystem Condition		
Water Scenario	Average Recurrence Interval (ARI)	**Dry**	**Median**	**Wet**
Cease to flow (tribs)		Avoid	Avoid	Avoid
Base Flow	<1:1	Avoid	Maintain	Maintain
Freshes	1:1	Maintain	Maintain	Maintain
Bankfull	1:1 to 1:2	Maintain	Improve	Improve
Low flood	1:3 to 1:5	Protect	Improve	Improve
High flood	>1:5	Avoid	Protect	Avoid

Management actions in relation to future blackwater events and ecosystem condition for scenarios (dry, median and wet)

DO Trigger	<4 mg/L	<5mg/L	>5mg/L	>5mg/L
Objectives	Avoid damage/sustain populations	Ensure capacity for recovery	Maintain health	Improve ecological health
Actions	Refuge/dilution flows	Freshes	Promote low lying floodplain connectivity	Increase floodplain (lateral) connectivity
	Water areas likely to attract aquatic species	Water critical sites	Build resilience	Increase longitudinal connectivity

Antecedent hydrology, Monitoring (DOC and DO), Evaluation, Reporting, Stakeholder Engagement and Communication

Introduction

The Commonwealth Environmental Water Holder (CEWH) provides water allocations for flow-stressed rivers and streams to protect and restore rivers, wetlands and floodplains (including water dependent native flora and fauna) of the Murray-Darling Basin (MDB). The CEWH is governed by the Water Act (2007) and the Basin Plan (2012), and therefore complies with the requirements of Commonwealth legal, policy and environmental legislation and frameworks.

During 2016/17, environmental water holders were presented with an unexpected challenge, as many lowland rivers in the southern and central regions of the MDB were subject to low oxygen conditions following widespread natural flooding. The management responses were adaptive, and collaborative, using science-based understanding, and various forms of feedback from the environment in a 'learning by doing' approach. Environmental water flows were directed toward mitigation of poor water quality rather than enhancement of ecological assets. This review was commissioned by the CEWH to examine the environmental watering interventions used to limit low oxygen conditions during 2016/17 within the regulated Edward-Wakool, Murrumbidgee, Lachlan, Goulburn Broken and Murray River (below Lake Victoria).

Context

Rainfall and environmental water planning

September 2016 was the Murray-Darling Basin's (MDB) wettest September on record. According to the Bureau of Meteorology, the area-averaged rain totalled 118.5 mm, which was 249% above the long-term monthly mean, and well above the previous record set back in 1906 (BOM 2017). The very wet September followed several months of above average rain stretching back to May when considerable areas of the central and southern basin catchments shifted from dry conditions to flood. The MDBAs 2016 annual environmental watering priorities were distanced from the high rainfall events or the potential of any follow-on water quality risk. For example, a dry outlook scenario underpinned the 2016 MDBA priorities; with some consideration for moderate conditions should water availability improve. A mid-year update described a number of priorities to capitalise on the change to wetter conditions, and as a consequence environmental water priorities were shifted toward freshening groundwater, reducing soil salinity and improving the health of mature native trees (REF). The extremely wet conditions exceeded the 2016 climate outlook negating the need for environmental water to be directed toward key ecological assets. Where possible, the updated advice suggested environmental watering actions could be used to exploit the unpredicted wet conditions. The focus then turned toward sustaining waterbird breeding in the Lachlan, Macquarie and Murray catchments. Outwardly the high rainfall would appear to be an anomaly, however the MDB is recognised as one of the world's most variable regions in terms of stream flows and precipitation (Grafton et al. 2017). Thus, extremely variable climate conditions demands greater flexibility within the annual planning cycle to ensure planning for environmental watering includes climate variability (both wet and dry).

Low dissolved oxygen

When many rivers and tributaries across the southern and central basin were found to have low dissolved oxygen (DO) concentrations (<5 mg L^{-1}) at the peak of the flood event, environmental water holders worked together with stakeholders to develop watering actions that would improve the low oxygen concentrations, and diminish the threat posed to native biota. Oversight of environmental water during the 2016 flood events was a considerable undertaking across different regions where DO concentrations dropped below the likely fish kill level (<2 mg L^{-1}) and in many rivers remained below this critical threshold for several weeks.

Cross agency and/or stakeholder collaboration

The management of the low oxygen conditions across the southern basin had resource implications, as the rapid decline in water quality required emergency response efforts, and adjustment to the scheduled environmental flows. In the Edward-Wakool an established network known as the Murray Dissolved Oxygen Group (MDOG) existed as an artefact of the 2010/11 hypoxic blackwater events. This group, (comprising agency and community representatives) was facilitated by the Murray Local Land Services (MLLS) and re-formed quickly as water quality deteriorated. In other river valleys, advisory groups were less structured, and informal. Whether or not these advisory groups were all-inclusive and representative (e.g. scientific, water managers and community) is unclear. Ambiguity exists regarding the oversight of poor water quality events, especially hypoxic blackwater in the basin. This gap has possibly arisen as water managers have responsibilities for particular components or functions related to water resources, but there is no framework or single body entrusted with the overall management of poor water quality that often occurs following high or low flow conditions.

Tools to guide environmental flows

The tools available to support decision-making during hypoxic events were considered, and these were either applied in 2016 or have the potential for adoption in the future. For example, the risk assessment and dilution flow models (Baldwin et al. 2012) developed following the 2010/11 hypoxic blackwater events lacked evaluation under different flow scenarios. Also, data acquired from satellite imagery has been distanced from environmental water management, despite its wide adoption by emergency services during extreme events. The potential exists to improve the delivery of environmental flows using remote sensing as repeated views of a region of interest can be acquired and compared with in situ measurements that tend to be limited by low frequency spatial or temporal resolution (i.e. grab sample). Unmanned Aerial Vehicles (UAVs) are capable of collecting high-resolution imagery at sites where by low-oxygen conditions are indicated. Despite being an emerging technology, UAVs are now used in remote locations to monitor, document and process optical and spectral water quality data to help determine and forecast water quality parameters. Several software packages are available this purpose, such as: MATLAB, ENVI and Geomatica.

Methods that identify deterioration in water quality prior to DO reaching sub lethal conditions are desirable to support decision-making. The dissolved oxygen sensors currently deployed at gauging stations within the Edward-Wakool and Murrumbidgee Rivers measure diel fluctuations, and the effect of stream metabolism that results from allochthonous (or autochthonous) derived dissolved oxygen carbon (DOC) concentrations following floods.

While resource managers are interested in obtaining information from a range of sources to strengthen assessments, the benchmark often applied comprises reliable, cost-effective and applicable at different scales. Enthusiasm for the adoption of technological solutions and standardised protocols between research groups and environmental regulators is required to establish a cohesive data-sharing network. In situ optical instruments for example, are likely to become a strategic tool for measuring river responses in a timely manner compared to the current approach. There is possibly a need to revisit water quality sampling design in the basin and move toward more cost effective, reliable and consistent monitoring measures. Particularly in view of the shift in sampling frequency (weekly to monthly) to measure the complex grouping of molecules, dissolved organic carbon (Biswas and Lawrence 2013).

Approach

Attempting to capture the influence of the 2016 floods, and low oxygen conditions at the scale reported poses a daunting challenge. To do so requires an understanding of complex ecosystem processes (biological, geochemical and physical), and how river regulation, land use, climate and local stressors influenced water quality and low oxygen conditions. The review is part of continuous improvement ethos that aims to inform adaptive environmental management in the future. The approach involved accessing three main sources of information:

- published and unpublished reports and data;
- multispectral Landsat 8 and Sentinel 2 satellite imagery; and
- personal communication with relevant persons.

From stakeholder input, and in consideration of adaptive learning observance the following questions guided the direction of the review:

- Were the environmental watering objectives achieved or do they need to be adjusted?
- Was monitoring adequate?
- Were predicted outcomes correct?
- Were the selected actions delivered appropriate?

Along with the associated literature, the individual environmental watering actions delivered during 2016/17 were examined. Environmental watering in the basin is a contemporary phenomenon, and consequently the current understanding of the relationships that exist between flows and ecological outcomes is experimental and incomplete. Obtaining data for each river affected was problematic as there are different methodologies applied across the basin, and a dissolved oxygen-monitoring network is one of the major deficiencies.

DO data

The data sources utilised within the review include long-term, fixed-station, mid channel and event based surface monitoring. While no universally accepted water quality monitoring method is applied across the basin, spot grab data was included despite a lack of temporal frequency where no other data existed. It is acknowledged dissolved oxygen concentrations fluctuate on a diel cycle, and therefore the raw data represented ambient conditions at a given time. Descriptive statistics were used to obtain measures of central tendency. Where more than one DO measurement was taken the 7-day mean values were reported. In addition, a dissolved oxygen alert schema was developed to graphically represent dissolved oxygen concentrations over time and overlaid on flood inundation patterns.

Spatial analysis and water mapping

Water mapping was acquired for the review as it is expected near real time satellite imagery will, in the future be utilised for planning, monitoring and reporting environmental flows. Research has shown data acquired from satellites can be a unique source of information to support aquatic ecosystem conservation, and emergency response during flood events where large areas of the landscape are inundated (Crétaux et al. 2011). Water mapping therefore is useful for analysing the changing distribution of water across large areas. The assimilation of space based hydrological information for water-management (e.g. measurement of environmental water flows) also has enormous potential for the advancement of eco-hydrological models both, forecasting and hindcasting (Crétaux et al. 2011).

The information for the water maps was obtained from satellite image bands that detect reflected light from the earth's surface in the mid-infrared wavelength. Radiation in this region is mostly absorbed by water; consequently images show well-defined contrast between the high reflectance in the landscape, and the very low reflectance of water. Layers were derived from Landsat 8 and Sentinel 2A multispectral imagery (top of atmosphere reflectance) downloaded from the USGS and AWS archives. Water detection was performed using the Open Water Likelihood algorithm, and cloud masking of satellite images was undertaken using the Landsat Collection 1 Level-1 Quality Assessment (QA) and Level-1C processing that applies masks computation: cloud and land/water. Water in the landscape was detected by isolating the pixels within the image that have a very low reflectance value, indicating that the light was absorbed and not reflected (for band 4) (see, Gouweleeuw et al. 2011).

Composite Water Mapping provided by NSW OEH for the period July 2016 to April 2017 was included. The semi-automated approach to map inundation uses an integrated spectral response to water and vegetation (Fisher et al. 2016). From cloud-free Landsat 7 satellite imagery, the water index and vegetation index (NDVI) was derived, and a threshold classification technique applied to determine inundation classes for water, mixed use and vegetation. The water index inundation is classified as water (open water) and mixed (water mixed with vegetation and soil cover types), and the vegetation index is classified as vegetation (inundated vegetation that has dense cover which obscures water detection). Previous case study validation was undertaken of inundated areas from aerial oblique photos captured at the same time as the Landsat satellite observation date. Multi spectral 30 m resolution imagery from Landsat satellites is captured every 16 days.

Background

Here the basic and applied scientific literature from Australia and overseas relating to hypoxic blackwater is summarised.

Low dissolved oxygen environments occur in a broad range of aquatic ecosystems, varying in temporal occurrence, patterns and persistence. There has been an observed rise in the frequency and magnitude of hypoxic events from the 1980s to the present time. Diaz (2009) states the number of systems globally reporting low oxygen conditions or more specifically, hypoxia has increased from less than 50 to approximately 400, and the future status of hypoxia is dependent on altered patterns of precipitation, temperature and land use (Morrongiello et al 2011; Van and Cooke 2011). Despite weaknesses often attributed to long range climate forecasting (synoptic, statistical and average characteristics estimation), intense rainfall events increase runoff, and conditional upon catchment conditions can result in overbank flooding and floodplain inundation. Vegetation assemblages that dominate the floodplain, particularly those that are largely intolerant of inundation provide abundant labile dissolved organic carbon substrate for decomposition following flooding. Decomposition of this labile carbon pool consumes oxygen in the overlying floodwaters when DOC concentrations are elevated, flooding is prolonged, and water temperatures are conducive to bacterial growth of DOC (Ning et al. 2015). Precipitation is therefore an important determinant of river dissolved organic carbon (DOC) (Mullholland 2003). In the River Murray and its tributaries hypoxia is considered to be an aperiodic feature, for example, six events have been recorded downstream of Barmah-Millewa Forest since 1990 (i.e. 1992, 2001, 2005, 2010/11, 2012 and 2016) (McCarthy et al. 2014).

Research and monitoring suggests that once a system develops hypoxia it is likely to become a prominent and characteristic feature going forward (Diaz 2009). The rivers of the Murray-Darling Basin that are typified by highly variable flow regimes, and occasional floodplain inundation are especially prone to hypoxic conditions due to flood pulses that return flows containing high concentrations of DOC. Due to the disruption of natural flow regimes following damming and abstraction of water from rivers, the frequency of small to medium floods in the southern Murray Darling Basin has decreased (Robertson et al. 2001). While the amount of carbon liberated during flooding is largely dependent on the characteristics of the substrate (Howitt and Watts 2016), labile C pools alongside warmer conditions are key to the promotion of C mineralisation (Kim et al. 2015).

Sources of stream and river DOC can be regarded as a function of terrestrial accumulation transfer to the channel and in-stream processing; this lotic DOC is regulated by terrestrial sources (Stanley et al. 2012). Transfer is largely hydrologic, although riparian vegetation can make important seasonal contributions to dissolved organic carbon. DOC pools in streams in catchments developed for agriculture differ from historic conditions, and include more labile material and almost certainly a variety of compounds, such as pesticides or antibiotics (Stanley et al. 2012). There is a deficit in the current research literature regarding DOC contributions from agricultural streams, yet the associated ecological consequences are likely to be widespread. Agro-ecological practices such as rice cultivation represents a major DOC source, and these systems contribute significant C exports to adjacent water bodies with important implications for water quality and agricultural catchment C budgets (Said-Pullicino et al. 2016). DOC concentrations within streams relate to the source, transfer and processing, and effectively dictate the quantity and quality of loads (Stanley et al. 2012). Importantly, hypoxic blackwater cannot be attributed to a single factor rather permutations of hydrologic, geomorphological, and ecological processes, a warmer climate and anthropogenic modifications influence water quality.

Floods provide the physical linkages between floodplain habitats and adjacent river channels (Robertson et al. 2001). Flooding creates pools and runners across the floodplain where high rates of microbial decomposition occur, and this process tends to be ubiquitous during the warmer months (Ryan et al. 2013). Many Lowland Rivers are net heterotrophic, as the respiration of carbon from the floodplains provides sustenance or 'energy' for aquatic food webs (Kerr et al. 2013). According to Baldwin (nd) *the functioning of lowland river floodplain ecosystems depends on the two-way exchange of water, nutrients and energy during flood events*. When significant carbon loads are mobilised during flood events, heterotrophic bacteria consume DOC, and they can use the available oxygen in the water at a faster rate than it can be replenished (Ning et al. 2014) (Figure 1).

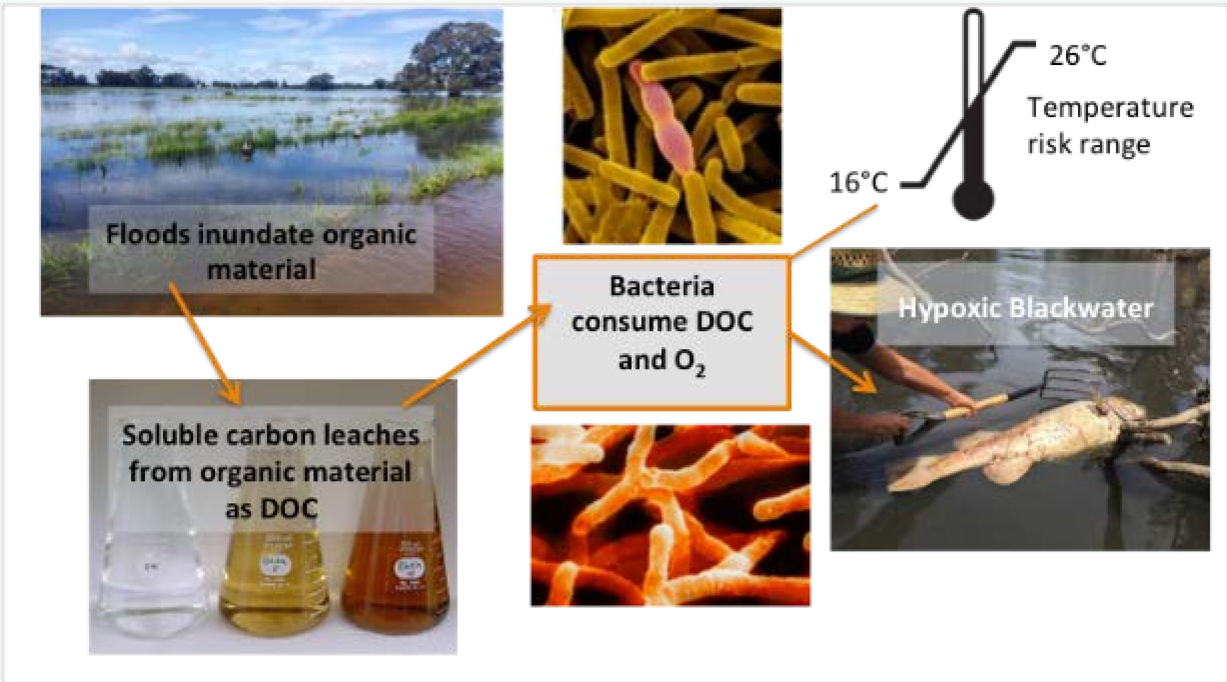


Figure 1 Graphical representation showing carbon metabolism processes leading to hypoxic conditions in 2016 (adapted from Kerr et al. 2013)

Our understanding and ability to readily measure the sources of dissolved organic carbon (DOC) transported to the river channel during flood events, including its influence on aquatic ecosystems is deficient. Currently, there is little known about the contribution of pasture vegetation to DOC upon inundation, and further research is required to understand DOC contributions from agricultural zones, particularly, riverine soil types (e.g. vertosols and sodosols) under different cropping regimes (Whitworth et al. 2011). In heterogeneous landscapes numerous biotic and abiotic factors control the temporal and spatial variations in DOC quantity and quality in soils subjected to alternating redox conditions. Rates of decomposition of organic matter for example may occur at a greater rate when conditions alternate between aerobic and anaerobic periods (Reddy and Patrick 1975). Baldwin and Mitchell (2000) argue the inundation of floodplain soils will lead to increased productivity, a potential decrease in oxygen, and the onset of anaerobic conditions, yet we have a limited understanding of the mechanisms underlying these effects.

Research has shown the decomposition rates of river red gum (*Eucalyptus camaldulensis*) forest litter to DOC occurs more rapidly from leaves than twigs or bark, with significant differences in microbial communities under different oxygen availability [(Brookes et al. 2009). *E. camaldulensis* leaves flushed from the floodplain to the river during flood events contain leachates that produce an additional chemical stressor from plant secondary metabolites known as polyphenols, and these may be lethal to aquatic biota (Small et al. 2014). Experimentally, polyphenols have been found to influence the survival of Golden perch (*M. ambigua*), as the leachate in combination with low DO influenced behaviour, gill structure and survival rate. Juveniles exposed to wood leachates for 30 minutes suffered 97% mortality (Gehrke et al.1993). Gehrke et al. (1993) concluded the presence of toxic leachates and low oxygen availability in flooded river red gum forests may render these habitats unsuitable as nursery areas for certain native fish species. Even so native fish have a high resistance to blackwater events, as McMaster and Bond (2007) found no significant effects were detected when small-bodied native fish were exposed to DOC concentrations of 20 mg L^{-1} for 92 h. The native fish examined were unable to tolerate the strong toxic effects of extreme concentrations (~80 mgL^{-1}) from *E. camaldulensis* leaf leachate, thereby establishing lethal threshold concentrations (McMaster and Bond 2007). The experimental species examined were the southern pygmy perch, (*Nannoperca australis*), mountain galaxias, (*Galaxias olidus*) and western carp gudgeon, (*Hypseleotris klunzingeri*), and these small-bodied fish (<10 cm), may have high tolerance to low DO because of the habitats they naturally occupy.

The species-specific differences in hypoxia tolerance appear to be aligned to known life-history strategies as, *M. peelii* may be especially sensitive to hypoxia. Their susceptibility may not be entirely due to physiology, being a large-bodied species, rather, an evolved life history utilising lotic oxygenated river environments (Small et al. 2014). Low oxygen conditions can stimulate extraordinary adaptations in native fish, as increased haemoglobin concentration provides a unique survival mechanism that increases oxygen carrying capacity (Wu 2002). Improving our current understanding of aquatic fauna to various low oxygen conditions is considered to be important for developing hypoxic mitigation guidelines (Small et al. 2014).

Whitworth et al. (2011) found limited evidence existed to directly attribute low-oxygen water or indeed any other causal factor to a number of fish kills that occurred previously in Australia. Data collated for Victorian fish kills covering the period 1998 to 2007 shows that only 10% of fish mortalities could be directly linked to hypoxic blackwater, while 47% of deaths remained unexplained (Victorian EPA 2007). Similarly, in NSW no identifiable cause was established for 38% of the fish kills over a forty year period (1970-2010), and overall, low dissolved oxygen was found to be the main cause of fish deaths in 18% of the cases examined (Koehn and Todd 2012). These findings may in part be as a result of the lag time that occurs between agencies receiving notification of a fish kill, the time taken to collect field samples and laboratory analysis. In particular, diagnostic assessment to attribute a definitive cause of a fish kill to low-oxygen concentration is problematic unless water quality parameters are monitored concurrently. Fish may have delayed reactions or carry-over effects to a particular stressor that occurred weeks or even months prior to their demise [(Van and Cooke 2011). While there are weaknesses associated with integrating water quality monitoring and field sampling of fish kills in Australia, research from other parts of the world such as United States also shows weak linkages to low dissolved oxygen impacts, and attribution was therefore <6% (Small et al. 2014).

Blackwater events span the ecological, socioeconomic and political spectrum. Notably, ecological consequences from protracted hypoxia can be profound, as aquatic fauna need to extract oxygen dissolved in water to breathe (with the exception of some microorganisms) (Whitworth et al. 2011). The loss of threatened and iconic species that can result from hypoxia, especially Murray cod (*M. peelii*) ignites passionate responses within the broad community. Media coverage from the 2016 event demonstrates the community sentiment that is aroused when fish kills occur (Appendix 2). The loss of a range of native fish species in 2002, 2003 and 2004 in the Murray Darling Basin (MDB) had an economic value between AUS $4 – 5.6 million (~3000 fish deaths per event) (Van and Cooke 2011). Not only were population recovery times expected to take up to 52 years, recreational fisheries, food web dynamics, and aquatic ecosystems were considerably diminished as a result of the low oxygen conditions that caused the fish kills (Koehn 2005; Koehn and Todd 2012).

In 2010/11 an unseasonal flood event followed five years of low flows, and this generated a plume of hypoxic blackwater for over 1800 km in the southern MDB system (King et al. 2011; Whitworth et al. 2011). Fish kills were reported, especially Murray cod (*M. peelii*), and there were large numbers of Murray crayfish (*Euastacus armatus*) emerging from the water exposed and vulnerable to dehydration (King et al. 2011). The 2010/11 hypoxic blackwater event was positively strengthened by the effects of river regulation, high summer temperatures, and the disturbance of reactive sulfidic sediments during stock and domestic releases (Baldwin et al. 2011). Investigations following the 2010/11 blackwater event showed the sources of soluble organic carbon contributing to hypoxia originated from river red gum forested areas, and also from agricultural floodplains (Whitworth et al. 2011).

From research undertaken during and post the 2010/11 hypoxic blackwater events, recommendations for water managers were suggested, and these include:

- Recognition that there is a higher risk of hypoxic blackwater following extended drought
- Strategies are required to manage the first ‘flush’ from the floodplain in a flood event
- Allowing floods to occur in winter when temperatures are cooler is preferable
- Preventing water from pooling on the floodplain for prolonged periods during warmer weather decreases the severity of the problem
- An investigation of how water (both rate and pattern) is returned to the river channel from the floodplain during flood events is required
- In the future, when another blackwater event occurs increase the spatiotemporal scale of research investigations (King et al. 2012).

While oxygen-limited regions are thought to be expanding globally, patterns of microbial communities associated with dissolved oxygen gradients are not particularly well understood, and this constitutes an important knowledge gap. Dissolved organic carbon (DOC) in aquatic systems originates from two discrete sources; autochthonous primary production within the system, and allochthonous terrestrial organic matter carried into the system from the floodplain (Cole et al., 2002). Westhorpe et al. (2010) argue that when allochthonous labile DOC is available, bacterioplankton production can be many times higher than production from, and coupled to, autochthonous DOC release. Aquatic heterotrophic bacterial communities have been found to contain an almost full quota of carbon processing functional groups, and therefore they are able to utilise different carbon sources rapidly (Westhorpe et al. 2010). Restoration and management-relevant efforts rarely incorporate DOC as a major management criterion let alone consider bacterial assemblages. Sinsabaugh and Findlay (2003) argue we now have an expanding ability to deconstruct the “black boxes” due to analytical chemistry and molecular biology thus enabling the determination of particular guilds of bacteria relative to input labile DOC. The key recommendation arising from a study of the Namoi River, NSW (northern tablelands and north west slopes) suggested environmental flows ought to increase the duration of allochthonously driven heterotrophic dominance during the summer months, and replicate natural flow conditions for greater periods (Westhorpe et al. 2010). However, this flow regime is mismatched with patterns that once naturally occurred in the southern and central rivers of the MDB. It is therefore important for environmental flows and management activities to be carefully targeted and harmonised to the interplay between the external, large-scale processes and the internal small-scale processes that regulate microbial community structure.

The water quality parameter - dissolved oxygen

Oxygen is arguably the single most important ambient water quality parameter, particularly as low oxygen is a ubiquitous stressor for aquatic fauna. In slow flowing rivers, wetlands and impoundments dissolved oxygen concentrations fluctuate daily. Typically, DO concentrations in the photic zone (i.e. the water column that receives sufficient sunlight for photosynthesis to occur) rise sharply during daylight hours, and then gradually fall during the night (Butler and Burrows 2007). The intensity of these diel fluctuations, varies through the water column, and can reach maximum levels around submerged aquatic plants. Ice-cold water can hold double the amount of oxygen as warm water (Wetzel 2001). Depending on temperature and salinity, water contains 20-40 times less oxygen by volume and diffuses 10,000 times more slowly through water than air (Graham 1990). Water temperature determines the 100% saturation point for oxygen in the water (i.e. DO (100%) = 11.3 mg L^{-1} at 10°C, 8.3 mg L^{-1} at 25°C and 6.4 at 40°C). It is the relatively low solubility and diffusion of oxygen in water combined with two key principle factors, i.e. the density stratification and decomposition of organic matter that consumes dissolved oxygen and leads to the development of hypoxia. Oxygen levels also depend on whether water is flowing or not, and aeration occurs through mixing by wind, and inflows. The surface water interface with sufficient light for photosynthesis is generally saturated or supersaturated with oxygen. Yet, in freshwater lakes oxygen is generally low at the hypolimnion; being at depth, it is isolated from surface wind-mixing during summer, and usually receives insufficient irradiance for photosynthesis to occur.

New South Wales rainfall 2016

In 2016, New South Wales recorded its wettest year since 2011, with rainfall well above average across most of the inland and southern regions of NSW (Figures 2 and 3). Importantly, 2016 was the wettest May to September period on record. The heavy rain during winter and early spring caused widespread flooding across much of inland NSW including the Edward/Wakool, Lachlan, Murrumbidgee as well as rivers in northeast Victoria.

Despite the above average rainfall and cloud cover, record-warm nights were recorded in 2016. It was the sixth-warmest year on record, as the mean temperature was 1.08 °C above the average, and the minimum temperature was 1.24 °C above average. Daytime temperatures cooled in inland regions during the second half of the year, associated with the above average rainfall. In particular, the spring average temperatures were the coolest since 1993. The maximum temperatures recorded for September were 0.2°C below average, whereas December recorded the second warmest on record (BOM 2017).

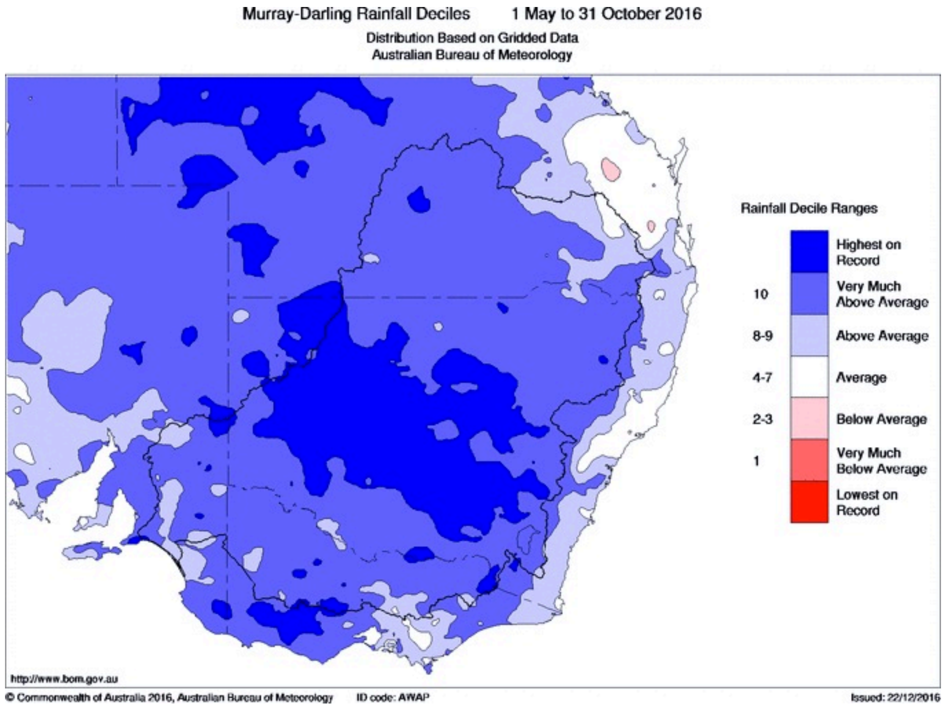


Figure 2 Murray Darling Basin Rainfall deciles May to October 2016

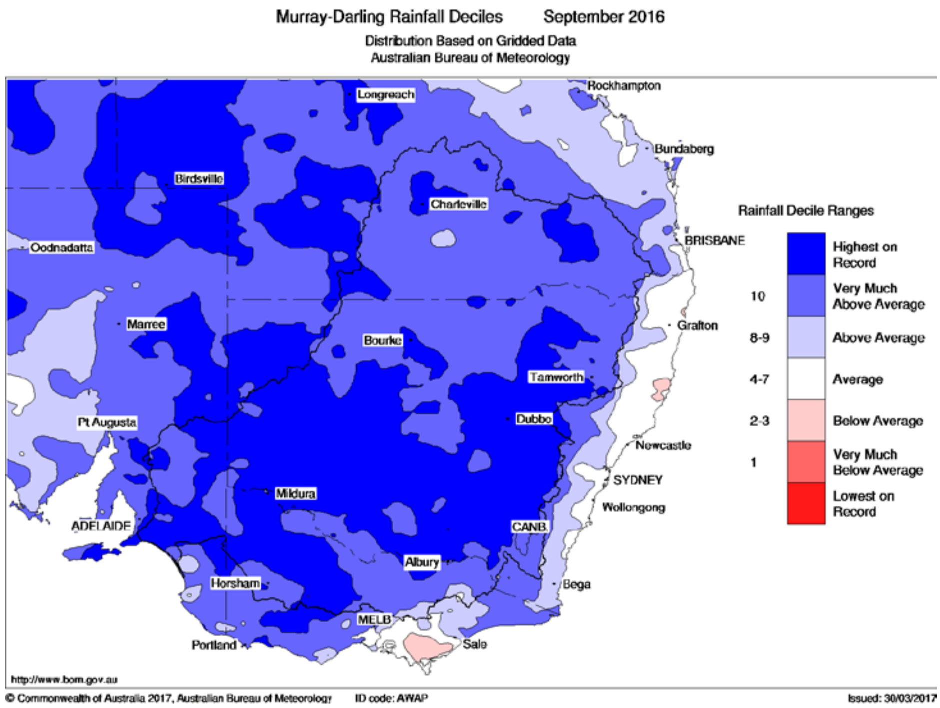


Figure 3 Murray Darling Rainfall deciles (September 2016) Source: Bureau of Meteorology

Victoria rainfall 2016

During December, areas of above average rainfall were recorded in the Goulburn region. In particular, storms in late December resulted in some of the highest rain rates ever recorded in Victoria. The low-pressure system interacted with a frontal system in the Bight, forming a slow moving complex low-pressure system. Figure 4 shows the area impacted by the intense high rainfall event in upper reaches of the Goulburn catchment.

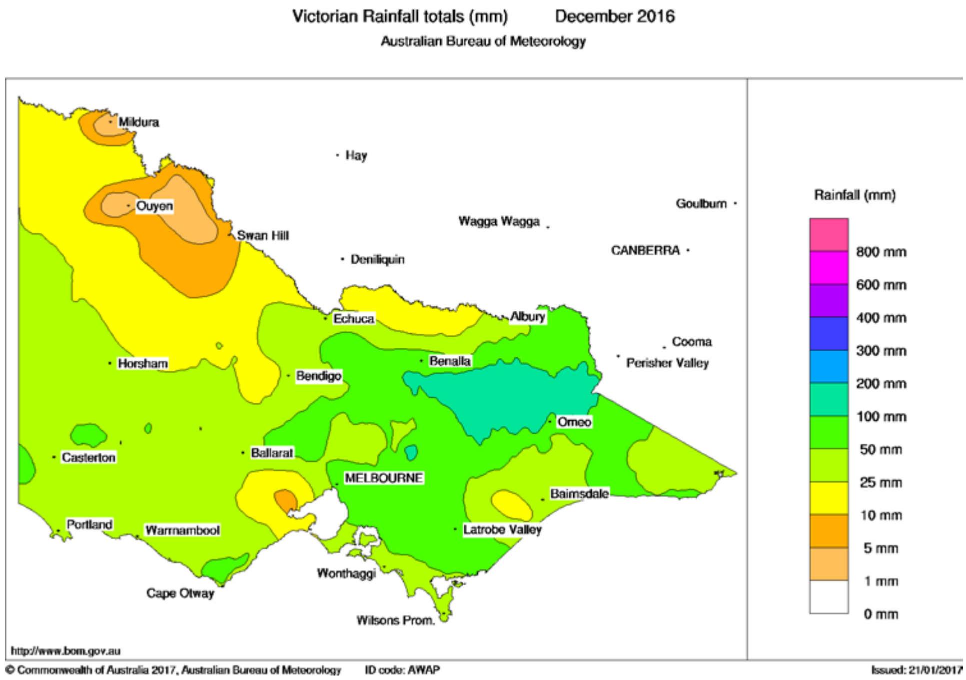


Figure 4 Rainfall totals for Victoria with >100mm recorded in the Upper Goulburn Catchment

The maximum temperatures in late December were between 27 and 30 °C.

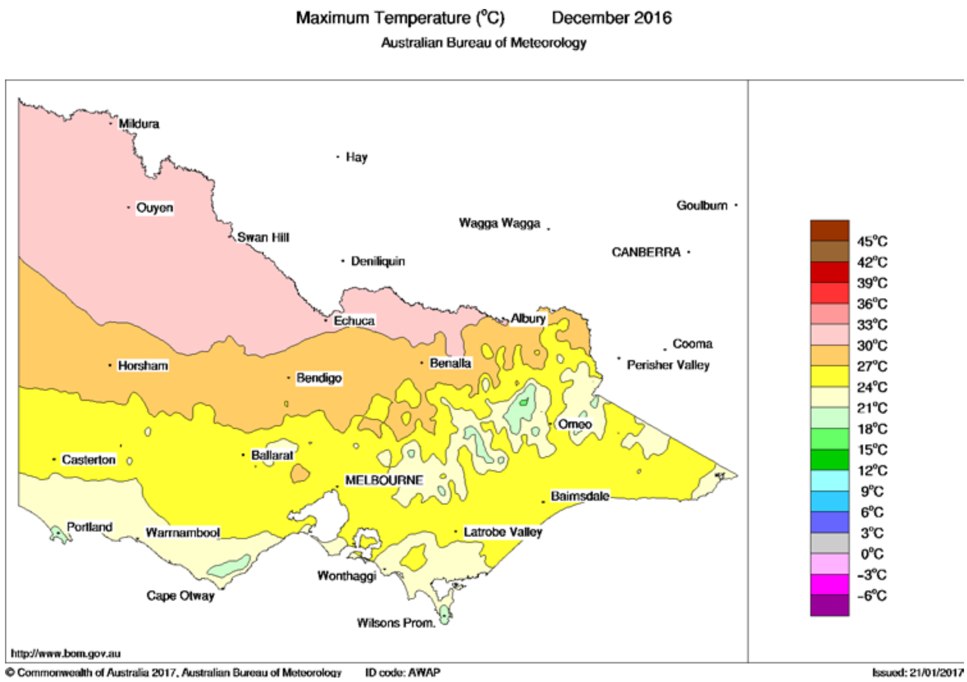


Figure 5 Maximum temperatures recorded in Victoria during December 2016

Flood patterns

Extreme events such as major floods have a low frequency of occurrence, but when they do occur, they can have major consequences for water quality in rivers and water storages (Sinclair Knight Merz, 2010). Flood events in the rivers of the southern Murray-Darling Basin tend to occur during the spring and winter seasons. Grootemaat (2008) demonstrated out of 38 floods, ten occurred in September, seven in October, while June, July and August recorded four, five, and four respectively (Figure 6). Heavy summer rainfall events that influence the Murray River downstream of Mulwala pose significant water quality threats, particularly flows that would otherwise be diverted for irrigation, as they remain in the river and cause a small 'rain rejection' flood. Chong and Ladson (2003) showed forest flooding in the Barmah-Millewa has increased from 15.5% of days to 36.5% of days between December and April using pre and post regulation data. The economic analysis suggested there would be a net benefit of at least Aus$1.4 million per year by creating airspace in Lake Mulwala during summer (Chong and Ladson 2003). River operators are alert to short term weather forecasts especially summer rain events, and where possible adjust releases to limit rain rejection flows.

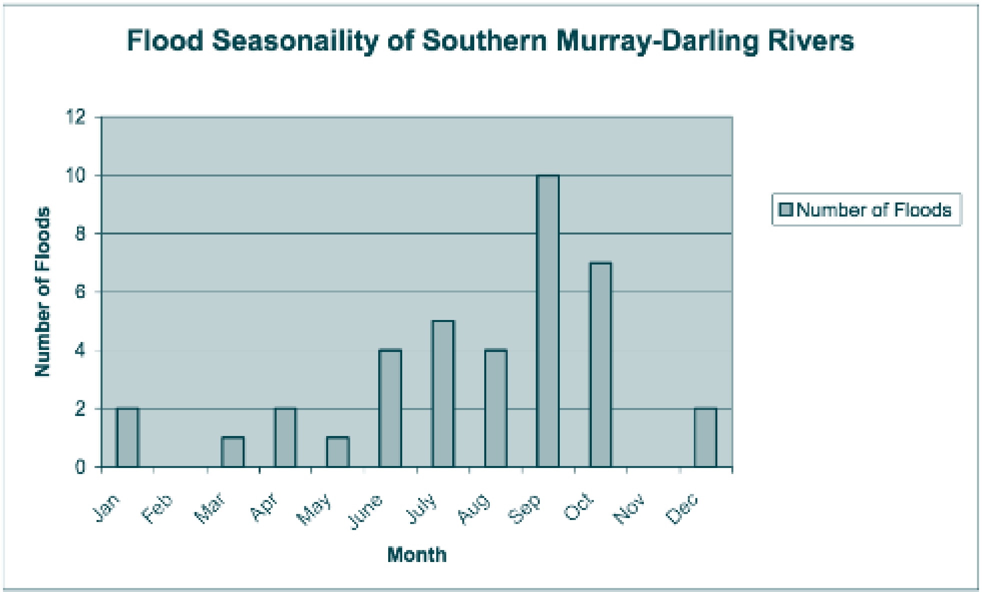


Figure 6 Flood seasonality for 38 floods in the southern MDB (Murray, Lachlan, Murrumbidgee, Avoca and Broken rivers) (source: Grootemaat (2008, p.113)

The Basin Plan

Under the Basin Plan (2012), the Commonwealth Environmental Water Holder (CEWH) must have regard to the following dissolved oxygen target value as set out in the water quality and salinity management plan (Chapter 9.14), when making decisions about the use of environmental water. Specifically, the plan contains the target, *to maintain dissolved oxygen at a target value of at least 50% saturation.* This equates to approximately 50% oxygen saturation at 25°C and 1 atmosphere of pressure or approximately an oxygen concentration of 4 mg L^{-1}. The CEWH, holders of environmental water and managers of planned environmental water must have regard to the targets in subsection (5) when making decisions about the use of environmental water.

Risk Management

As new information becomes available updating and amending existing protocols, especially risk planning is a remit of a continuous improvement process. The current Risk Management Guide for the use of Commonwealth Environmental Water (2014) reflects an understanding of previous low oxygen conditions, especially the blackwater events that occurred in the southern MDB in 2010/11. However, there were different climatic drivers influencing the 2016 event the risk approach may need to be amended given the guide currently states: *With temperature being the predominant driver of oxygen levels, inundation occurring between November and March is more likely to produce blackwater events with low DO levels,* and, *An increased likelihood of a blackwater event can be associated with prolonged periods of drought, as the litter has accumulated in large amount".* The 2016 hypoxic events commenced in late September and early October and did not follow a prolonged period of drought, as the central basin had received significant inflows in 2015. The bias toward temperature (>20 °C) during certain months of the year (summer to early autumn), and overbank flooding following a drought is not consistent with the hypoxic blackwater events that occurred in 2016. Low oxygen values were recorded in the Edward-Wakool, Lachlan and Murrumbidgee (September to October) when air temperatures were 2 °C below average.

The Basin Plan (2012) includes guiding principles in sections 8.33 and 8.34, and briefly summarised, environmental watering is to be undertaken in a way that has regard to social and economic outcomes; and the variability of the natural flow regime, by mitigating or avoiding seasonal inversion of flows is to be considered; and strategies to deal with a variable and changing climate are to be incorporated.

DO trigger values

The ANZECC (2000) guidelines for slightly or moderately disturbed freshwater ecosystems (i.e. moderately cleared catchments and/or disturbed systems including rural streams receiving runoff from grazing or pastoralism) state dissolved oxygen should not normally be permitted to fall below 5 mg L^{-1}, which a aberration from the Basin Plan target. One approach adapted from the ANZECC (2000) guidelines to establish trigger values for the key stressor; dissolved oxygen is shown in Figure 7.

1. **Select key indicator and management target**
    - Dissolved oxygen concentration >60% saturation for 9 in 10 years
2. **Identify key stressor and key performance indicator**
    - Key stressor/s (DOC, temperature and flow)
    - Key performance indicator such as DOC loading
3. **Determine trigger value for key stressor**
    - Develop models relating DOC loading and DO concentration
    - Validate model relationships using local reference and impacted sites for which data are available
    - Use models to determine trigger values (sustainable loads) for key

Figure 7 Recommended approach for determining trigger values for the protection of Aquatic Ecosystems at the Catchment Scale (adapted from ANZECC 2000)

The ANZECC (2000) guidelines are based on the principle of long term ecological monitoring and catchment assessment. Adaptive management (AM), a key resource management concept, involves monitoring to assess the consequences of management actions. AM therefore provides a linkage between process-based ecosystem decision support, and ecosystem process-based monitoring—the emphasis of which is on temporal patterns of indicator change rather than comparisons between static indicators.

To capture spatial heterogeneity, longitudinal monitoring of inland rivers is required to characterise processes of the river and the floodplain ecosystems. Lovett et al. (2007) for example argue, solutions for environmental challenges can be expensive and technically challenging, but what is often overlooked is the cost of well-designed monitoring programmes, which tend to be much less than either the cost of policy implementation, or the monetary benefits associated with the environmental improvement.

For practicality, the DO data considered in this report aligns to the trigger values recommended by MDBA (2011), and a traffic light (Green, Amber and Red) structure was applied (Table 1). The trigger values cited in the review are similar to those developed following previous hypoxic events (Whitworth et al. 2011), and adapted from a risk based Alert Level Framework for freshwater cyanobacteria. In the future, an order of levels based upon the detection of DO trigger values could trigger an incremental escalation of management actions.

Table 2 Proposed alert level framework for dissolved oxygen

Dissolved Oxygen Trigger Values		
Alert Levels	**Description**	**mg L^{-1}**
	Acceptable	>5
	Stressed	>4 to <5
	Very Stressed	>2 to <4
	Fish Kill Likely	<2

The table shows alert trigger values to be adopted by the CEWH and other stakeholders for reporting during and following a hypoxic blackwater event. The trigger values were developed in consideration of the effects of prolonged or even periodic exposure to sub lethal hypoxia. The output can be linked to visualisation and modelling systems (i.e. remote sensing and GIS) consistent with a trend that is increasingly applied by water resource managers for ecological management. These are notional DO concentrations; below which fish may be forced to adopt high-risk survival tactics.

When conditions drop below <2 mg L^{-1} large bodied fish have very few options at their disposal, as they are often seen on the surface of the water on their sides if they are too large to access oxygenated micro-habitats. More comprehensive water quality guidelines regarding particular faunal tolerance to low DO may be refined over time, but for the purpose of this review the trigger values are a direct measure of deviations from ideal conditions, and can therefore be used to inform the relative risk.

The Edward-Wakool River System

The Edward–Wakool River system consists of a mosaic of rivers, streams, wetlands and floodplains, and covers an area of more than 1,000 km^2 between the Murray and Edward Rivers (Figure 8). Diverging from the Murray River below the Barmah-Millewa forest, the Edward River receives water from the Gulpa Creek offtakes near the Barmah Choke in the Barmah-Millewa Forest. (BM) The regulated flows travel along the Edward River, and also flows may be added from the Mulwala Canal upstream of Deniliquin. Water enters the Wakool River via the Merran Creek. The confluence of the Edward and Wakool Rivers is approximately 30 km upstream from where the Edward River returns to the Murray River (MDBA 2012).

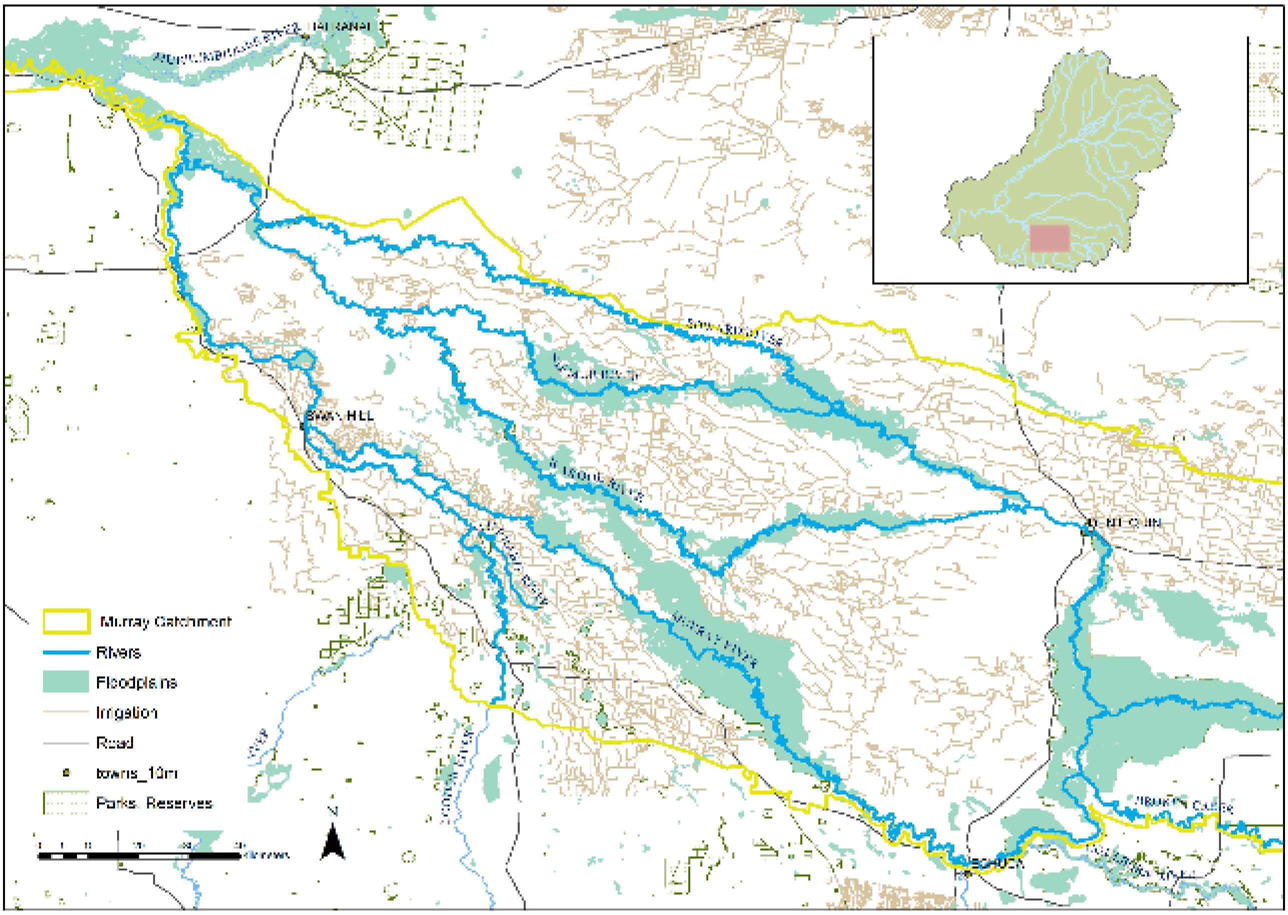


Figure 8 Location of the Edward–Wakool River System

In very high flow events, the volume of Murray River water passing through the Edward-Wakool system can be in the order of five times greater than that passing through the main stem of the Murray River immediately downstream of the BM forest (Ecological Associates and SKM 2011). Therefore, the flooding regime in Barmah-Millewa forest dictates the inflow regime of the Edward-Wakool system.

Water flows and water quality in the Edward/Wakool mirrors the condition of the Murray River Catchment upstream. Also, pollutants mobilised from within the Edward-Wakool system have the potential to impact the Murray River downstream of the Murray-Wakool Junction (Baldwin 2009). A number of stressors are thought to be advancing ecological deterioration in the Edward-Wakool among which is increased carbon loading within channels, and Baldwin (2009) suggests this allochthonous carbon source has the potential to trigger to blackwater events. Changes in flow as a direct result of river regulation, climate change and, zones of high salinity, low dissolved oxygen and high concentrations of dissolved toxicants (sulfide, ammonia and metals and metalloids at the bottom of deep pools) and eutrophication reduce water quality within the Edward-Wakool system (Baldwin 2009).

Hydrology

On 29 September as high inflows arrived at Yarrawonga Weir, releases were steadily increased from 51,000 ML/day to a peak of 180,000 ML/day by 7 October, representing the highest discharge at the weir since 1993 (MDBA 2016). In 2016 the northern gates on the Yarrawonga weir were opened as discharge increased beyond 80,000 ML/day, and as a consequence significant stream bank erosion downstream and widespread flooding of the native forest area immediately downstream of the weir occurred (pers.comm. Tony Beamish, Goulburn Murray Water, 11 July 2017) (Figure 9). Water is diverted from Lake Mulwala via the Mulwala Canal and the Yarrawonga Main Channel, and it is therefore the location where the greatest diversion point from the River Murray occurs. In 2010/11 the Mulwala Canal irrigation infrastructure was used to deliver environmental flows during low oxygen conditions.

The 1 in 30 year flood occurrence in the Edward-Wakool was characterised by two significant flood pulses, with the peak ~50% of the discharge recorded during the 1955 flood at Deniliquin. In 2016, the first rising and falling limb lasted for 30 days, and reached a peak discharge of ~89,000 ML/d at Tocumwal (25 km upstream of the Barmah-Millewa Forest). This event would have inundated large areas of the Barmah-Millewa Forest floodplain, as the Barmah Choke has limited capacity, when discharge exceeds 10,600 ML/d. Also, when flows are above 10,600 ML/d, effluent creeks into the Barmah-Millewa forest commence to flow over the forest regulators (Cook et al. 2015). While the Murray River channel in the Tocumwal region is more deeply incised, floodplain connection above the Barmah-Millewa Forest occurred as flows exceeded channel capacity (~29,900 ML/d).

The floodplain between Yarrawonga and Tocumwal is confined to a corridor approximately 1.5 kilometres wide and contains both native river red gum (*Eucalyptus camaldulensis*) forest as well as highly modified agricultural environments. As a consequence of floodplain inundation significant allochthonous terrestrial organic matter would have been carried into the system from the floodplain from the first overbank flood pulse. Furthermore, the second significant flood pulse that occurred over 30 days with a peak discharge at Tocumwal of 177,122 ML/d on 8 October 2016 would have extended floodplain inundation. The areas where the lateral connectivity occurred upstream of Edward-Wakool, included Tocumwal, Albury, Corowa, Yarrawonga, Torrumbarry and Barham, as well as the Edward River at Stevens Weir and Moulamein. Minor flooding was also reported at Deniliquin in late September and early October. Local media reports suggested up to 90 per cent of the 2016 harvest on properties located in Tuppal Creek, and west of Tocumwal were lost due to inundation (Border Mail, October 2016). Consequently, organic material from native forests (e.g. Koondrook Perricoota) and agricultural sites (e.g. cropping) would have contributed to the DOC levels within the Edward-Wakool system.

Figure 9 D/S Yarrawonga weir, (northern view) showing extensive overbank flooding of the river red gum floodplain during 2016

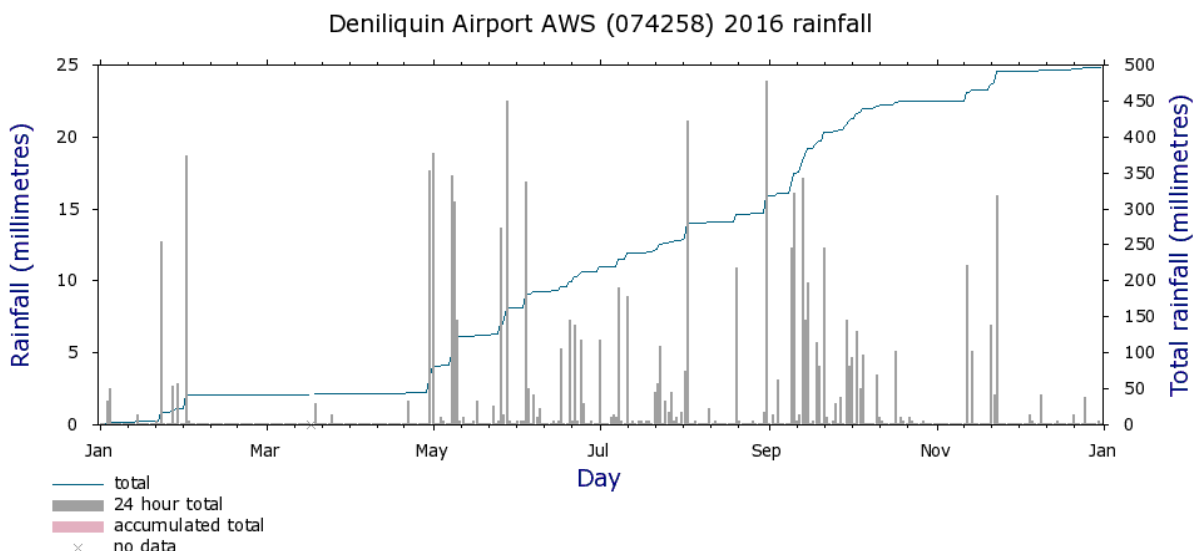


Figure 10 Deniliquin airport rainfall with monthly on the left y axis and total rainfall on the right y axis (Jan-Dec 2016) (Source Climate Data – Bureau of Meteorology 2017)

The BOM summary statistics for the Deniliquin Airport AWS shows the highest monthly rainfall recorded for the 1997 to 2016 period occurred in May and September of 2016 (Figure 10).

Edward-Wakool dissolved oxygen concentrations

At Deniliquin (gauging station number 409003) the continuous loggers showed dissolved oxygen concentrations dropped below the fish kill threshold of <2 mg L^{-1} around 23/10/2016. The low DO concentrations continued mostly unchanged until 06/11/2016 (21-days), followed by a slow return to acceptable levels > 5 mg L^{-1} by 25/11/2016 (Figure 11). On 25/12/2016 DO concentrations dropped at Deniliquin below the acceptable level, but remained within the stressed level (4 - 5 mg L^{-1}) for 7 days. Oxygen concentrations were slightly higher at Deniliquin compared to the other sites considered during the event.

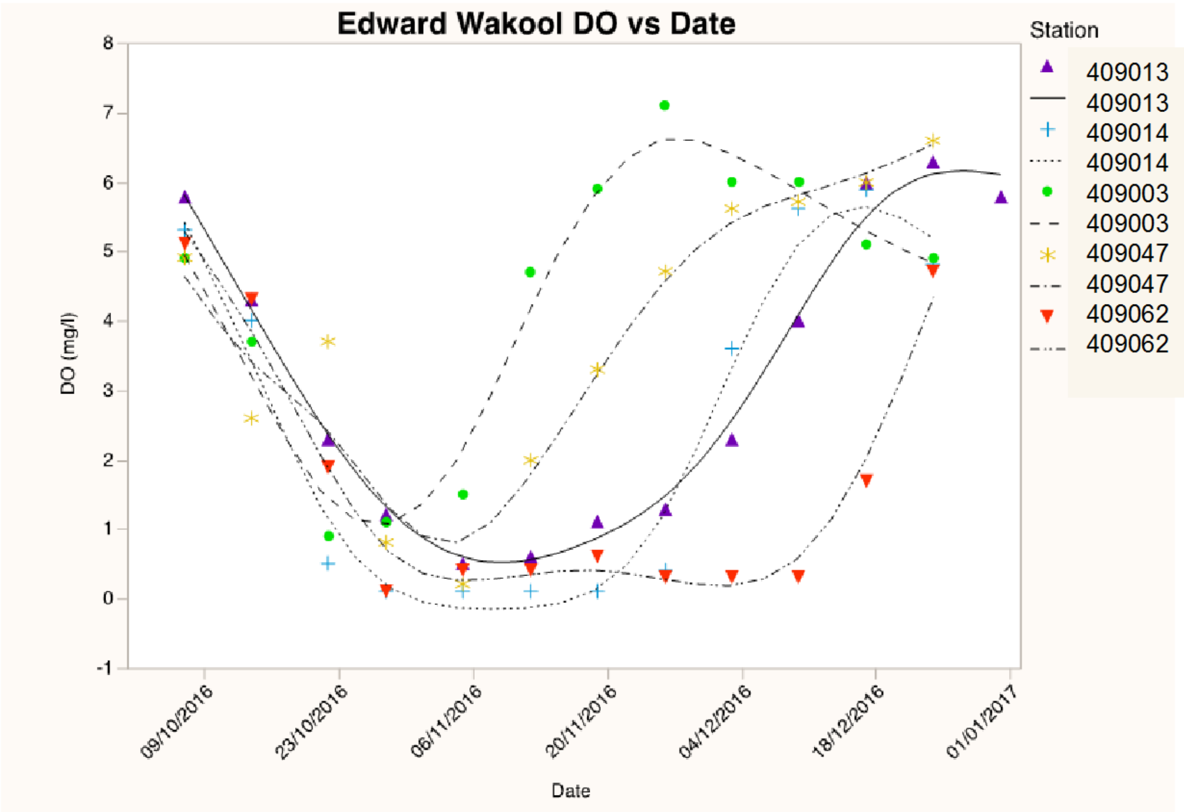


Figure 11 Daily Mean DO data for Edward-Wakool (1July 2017 to 30 December 2016)(Source NSW DPI Office of Water)

On 17/10/2016 the Deniliquin gauge (409003) showed the water level had reached 8.58 m, the discharge was 75,541 ML/d, temperature 17.7 °C, and DO was <2 mg L^{-1} (fish kill range). The gauging station Edward R @ Toonalook (409047) reached a maximum level of 8.0 m on 28/10/2016, and exceeded levels recorded in 1979.

Table 3 Edward-Wakool Gauging Station Details

Site no.	Maximum gauged level (metres)
409003	9.3
409047	8.0

Water chemistry

Dissolved organic carbon (DOC) is monitored on a monthly basis at Kyalite downstream from the confluence of the Edward-Wakool Rivers. DOC concentrations for this site showed a steady increase to a maximum concentration of 19 mg L^{-1} six days after the peak discharge of 83,433 ML/d (* there is no flow data at Kyalite, therefore discharge was calculated from the Wakool at Stoney Crossing and the Edward River at Liewah). The DOC data corresponds to the period of overbank flooding, however the low frequency monthly spot sampling data limits an accurate temporal determination, preventing extrapolation beyond, DOC concentrations were well above average on the rising, peak and falling limb (Figure 12).

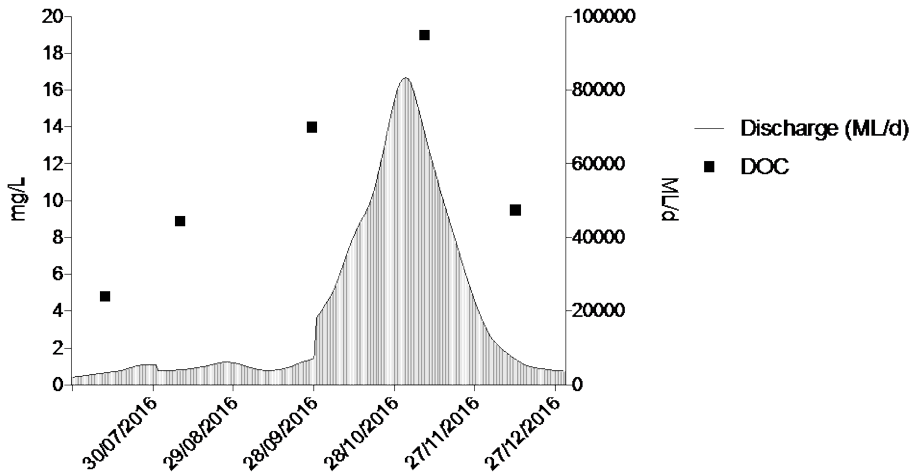


Figure 12 Monthly surface water sampling for DOC @ Kyalite, shows combined discharge for Edward-Wakool (Source: Murray Darling Basin Commission Water Quality and NSW Water)

The minimum DOC concentration of 4.5 mg L^{-1} was recorded in July, and the maximum was 51% above the mean value of the pre and post peak flood values. By 12/12/2016 the DOC concentration had dropped commensurate with the steep falling limb of the hydrograph. DOC in streams and rivers is influenced by precipitation and landform (Mullholland 2003), therefore these factors are important determinants of river DOC. Meybeck (1988) reported the typical DOC concentration for arid and semi-arid regions falls within a 1-3 mg L^{-1} range, therefore DOC was three to six fold greater than these characteristic values during the August to November period. From two years of water quality data for the Wakool River the monthly DOC values observed ranged between 2.5 to < 7.5 mg L^{-1}, excluding a spike (~12.5 mg L^{-1}) that paralleled a cyanobacteria bloom that occurred in late summer and early autumn of 2016 (Watts et al. 2016).

The factors that potentially influenced elevated DOC during the 2016 flood relate to the morphology (flat lowland landscape) of the Edward-Wakool, anthropogenic sources, and the flow path of water across the landscape in contact with organic-rich soil horizons, forest floor debris and wetlands within the catchment.

For a detailed DOC analysis refer to the Edward-Wakool 2016-17 LTIM annual report where DOC monitoring occurred primarily within the Wakool River. However, early results tend to suggest the highest DOC concentrations occurred within the Wakool at the Gee Gee Bridge site. The raw data (Figure 13) denotes replicate samples for some sites, yet there is no DOC data for the Edward River. Not dissimilar to the MDB grab sampling, frequency of sampling is a weakness. Even so, the concentrations were consistent with the Kyalite site where the highest DOC value was measured close to the peak discharge. The data (~6 samples) for the Mulwala canal (Figure 13), in

October and November shows concentrations < 6 mg L-1, and this serves to strengthen the rationale for using the irrigation infrastructure to deliver refuge flows.

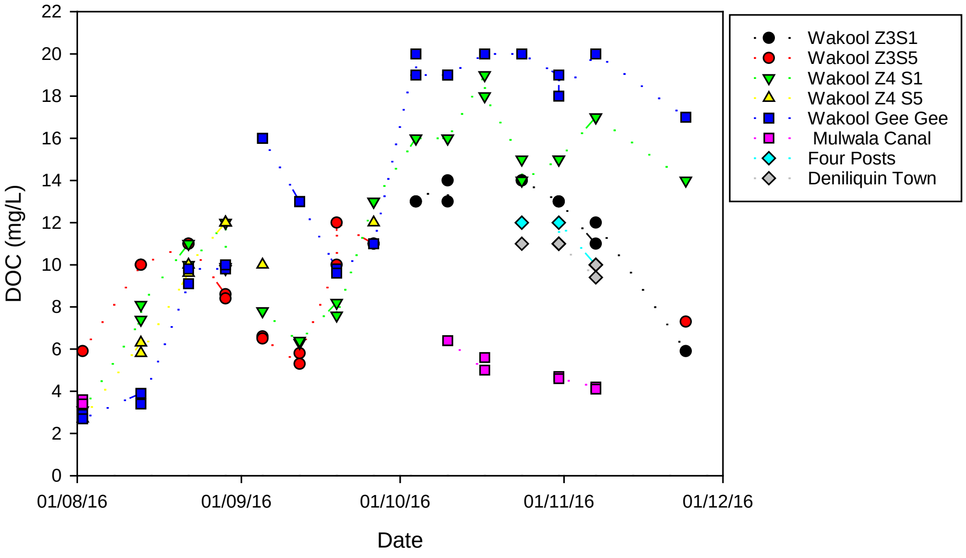
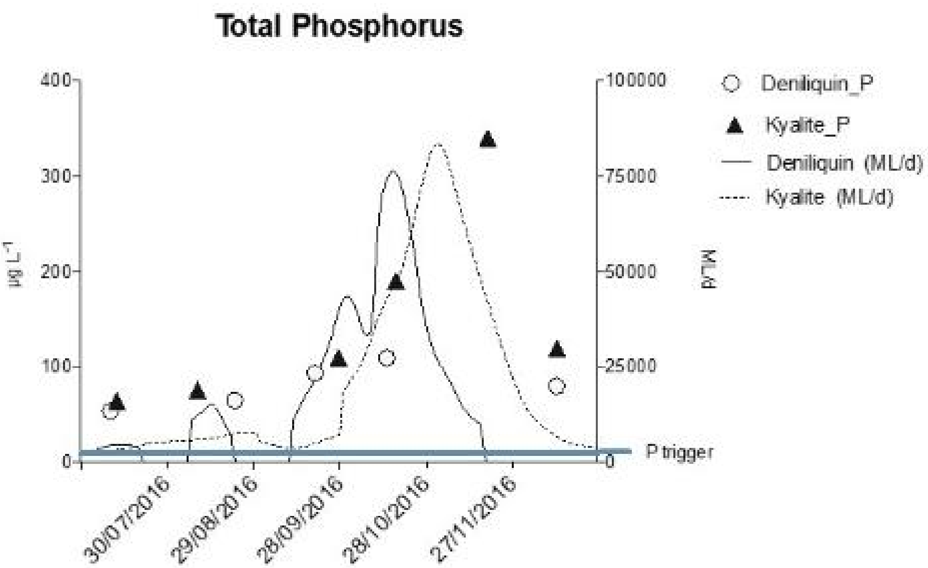


Figure 13 LTIM DOC preliminary data for the Wakool (source: Watts et al. 2016)

Total N and Total P exceeded the ANZECC (2000) guidelines for all months (modified aquatic ecosystems), and the point data shows both TN and TP values were highest when the discharge reached 76,417 ML/d on 19/10/2016 at Deniliquin (Figure 14). The Kyalite data (end of system) also shows TN and TP increased as flows increased. Due to the low sampling frequency it is difficult to ascertain whether or not maximum TN or TP concentrations were attained pre or post the peak discharge. The other surface (0.25 - 0.3 m) water quality parameters measured at Kyalite and Deniliquin were pH, turbidity, electrical conductivity, temperature, filterable reactive phosphorus and silica (data not shown).



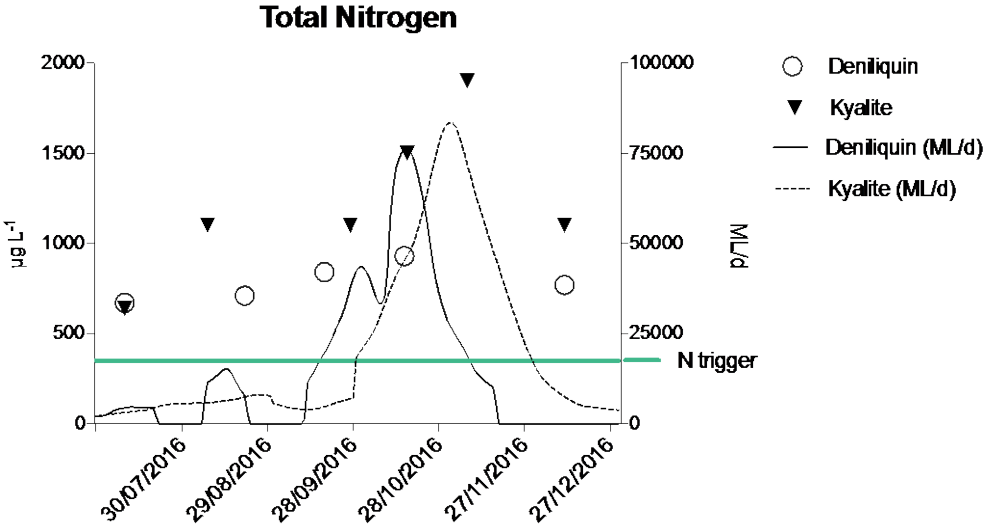


Figure 14 Total N and total P concentrations recorded monthly at Deniliquin and Kyalite

Agriculture has been identified as a major nutrient contributor to receiving waters, and excessive P loads delivered to neighbouring waterways can trigger undesirable phenomena, such as eutrophication and hypoxia. The consequences of the excessive nutrient loads to surface waters have regional impacts that may affect downstream freshwater ecosystems thousands of kilometres from the source (Carpenter 1998). For example, the formation and development of the hypoxia zone in the Gulf of Mexico has been attributed in part to excessive amounts of P delivered from agricultural sites in the upper Mississippi Basin.

Water mapping and DO time series

The inundated area estimated from the Landsat 8 and Sentinel 2a satellite imagery shows its shape was influenced by the topography: in low-lying areas it extends further inland and flooded areas link up with permanent water bodies in depressions (see, time series maps). The dissolved oxygen data from the in situ loggers was processed to produce daily average values and the 14-day mean shown.

The time series spatial data and average DO concentrations shows the locations within the Edward-Wakool, the inundation pattern, and the dissolved oxygen data compilation classified by the DO threshold values shown in Table 1 (acceptable = grey, stressed = green, highly stressed = orange and fish kill likely =red). The DO point data shows the fortnightly mean for each site. The resultant maps for the Edward-Wakool are shown in Figures 15 – 18.

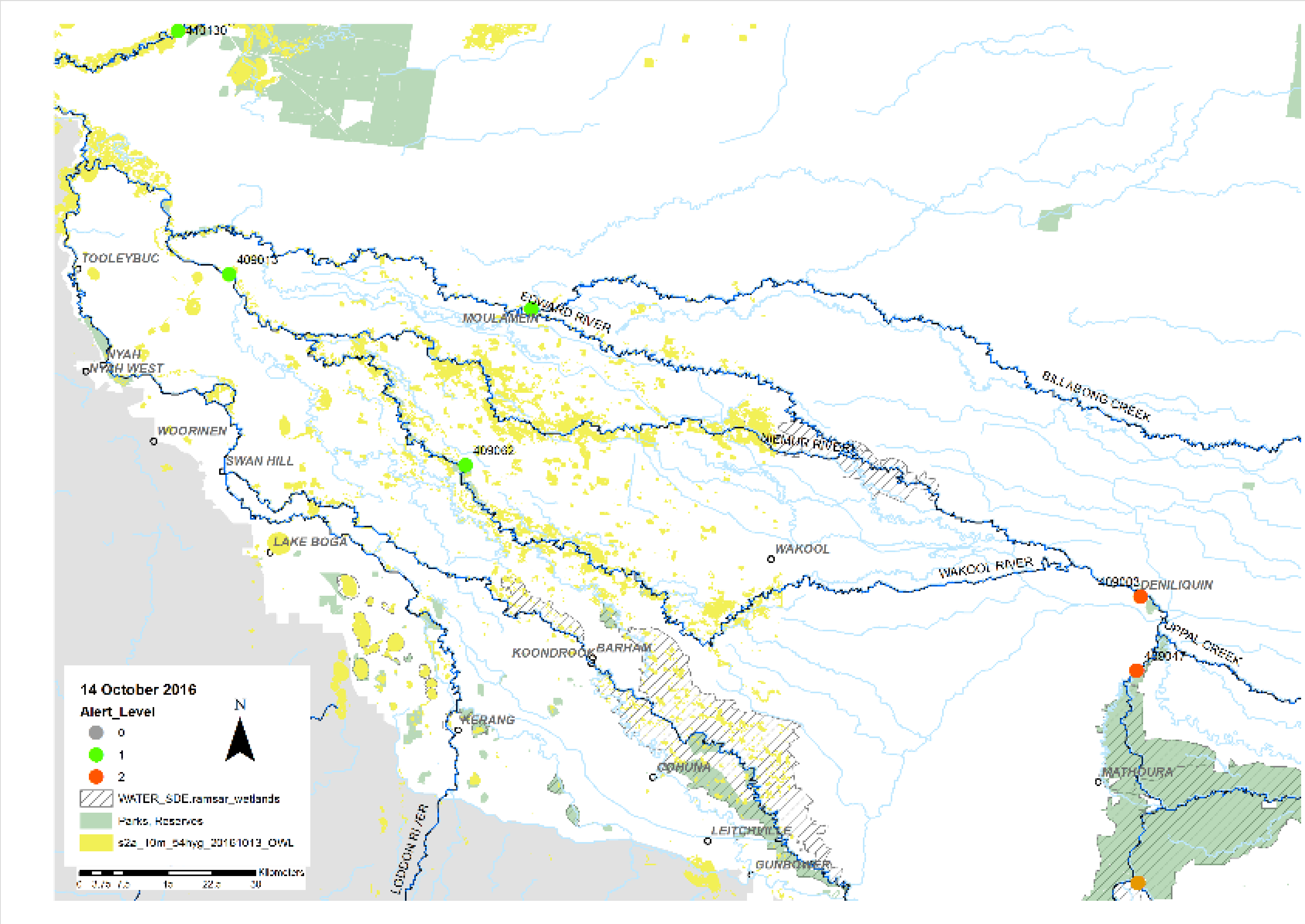


Figure 15 Average dissolved oxygen for sites in the Edward-Wakool showing the DO collation (1-14 October 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

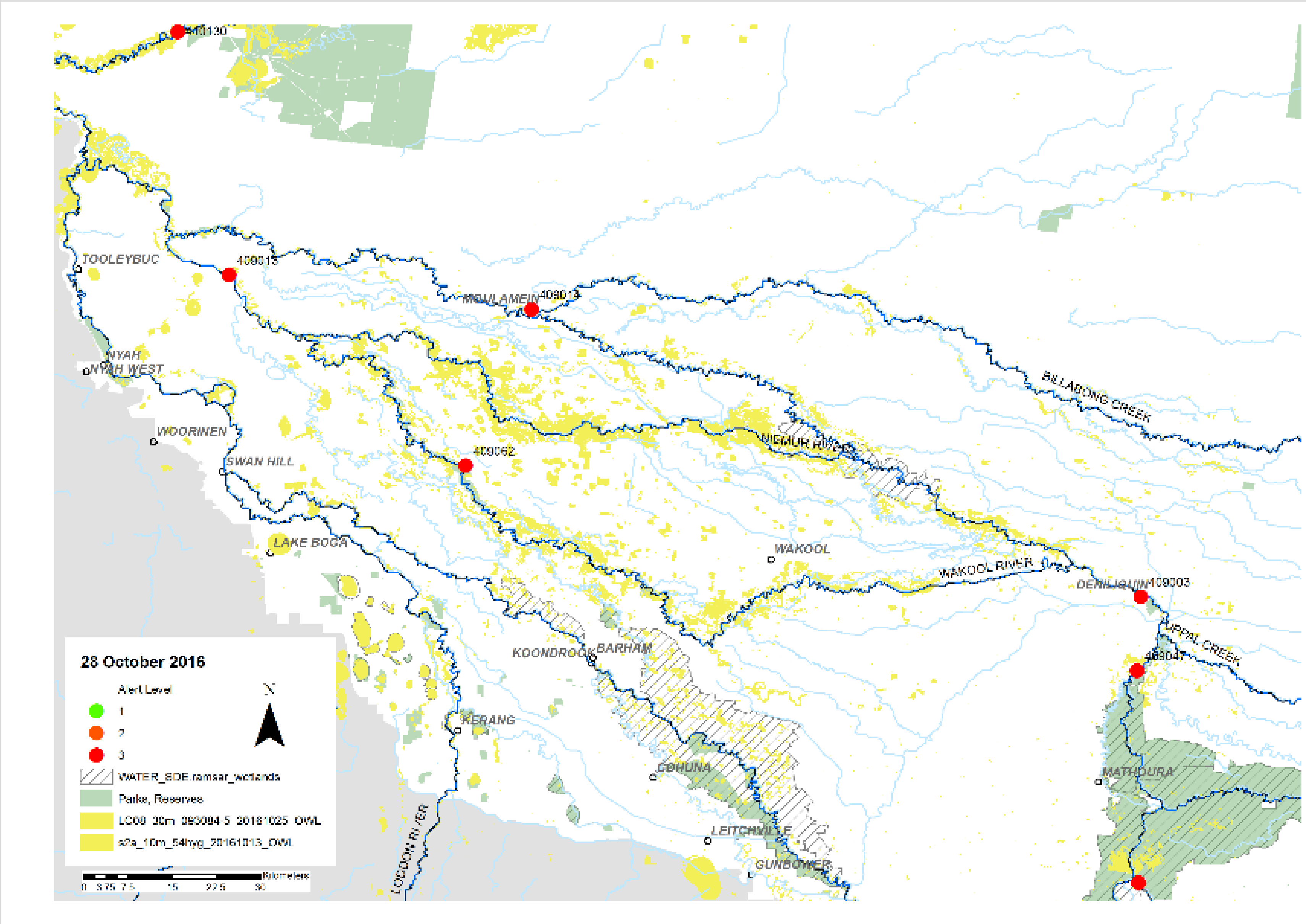


Figure 16 Average dissolved oxygen for sites in the Edward-Wakool showing the DO collation (l5-28 October 2016), and water inundation derived from Sentinel 2a and Landsat imagery (yellow)

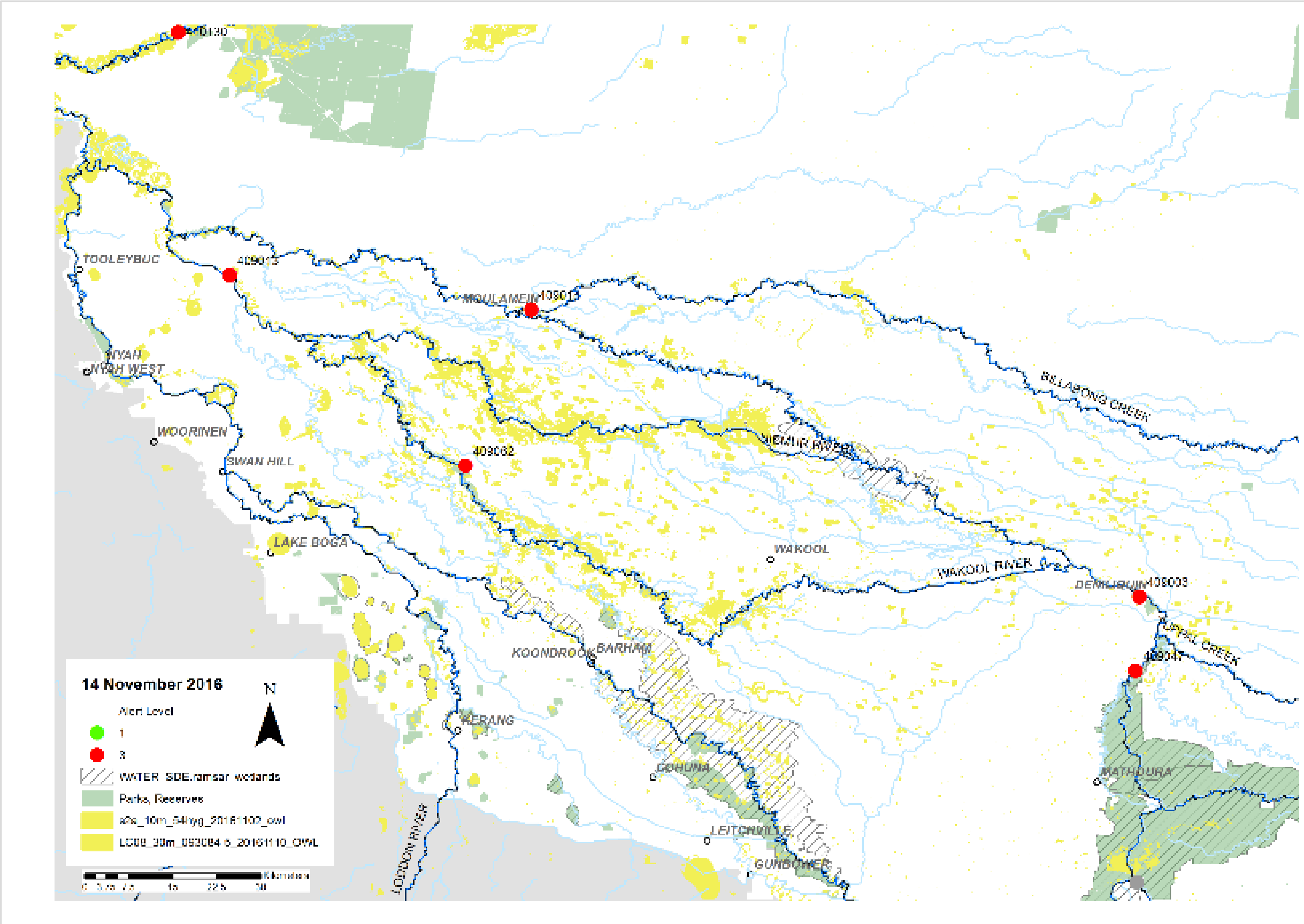


Figure 17 Average dissolved oxygen for sites in the Edward-Wakool showing the DO collation (1-14 November 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

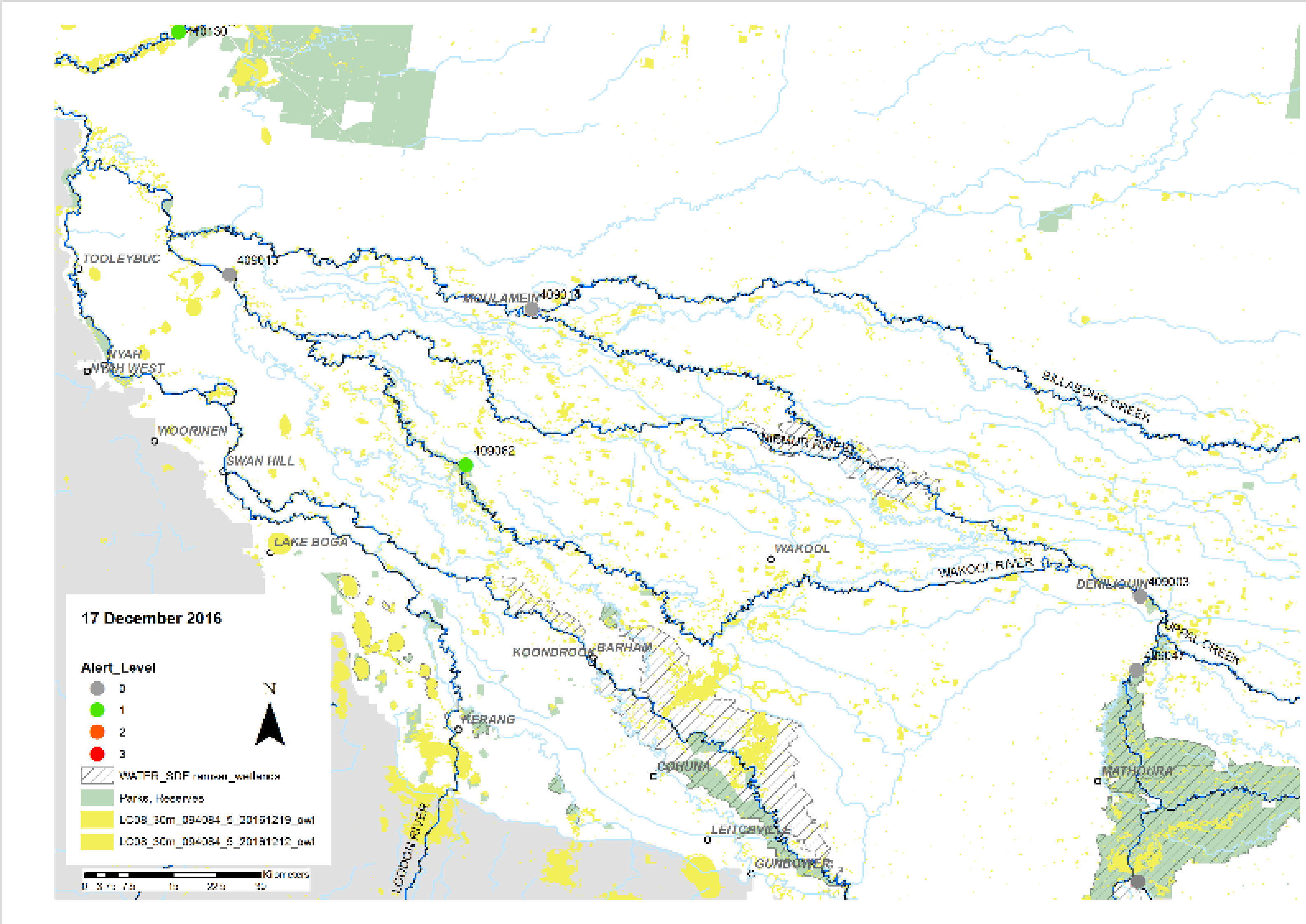


Figure 18 Average dissolved oxygen for sites in the Edward-Wakool showing the DO collation (1-17 December 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

Impact to aquatic species

The locations of fish kills reported to NSW DPI Fisheries are shown in Figure 20. The earliest report of a fish kill was 20 October 2016, with 20 Silver perch found floating downstream of Deniliquin. At the same location, Murray crayfish were emerging from the water, and a number of shrimp had perished. On 23/10/2016, a fish kill was reported at Merribit Creek, and the sizes of *M. peelii* (Murray cod) that succumbed to the conditions varied from small to large bodied fish (120 to 1000 mm). In the following weeks there were several reports of fish kills in the Edward-Wakool River system and its tributaries. *M. peelii* (Murray cod) was the dominant native species affected however, other native species also perished including; Bony bream, Silver perch, Golden perch, Catfish, Smelt and Flathead gudgeon.

The detection of 100s of dead and decaying *M. peelii* (Murray cod) in late December in the Edward-Wakool exemplifies the difficulty entailed in determining where and when a fish kill actually occurs during widespread flooding, particularly as access may be impracticable. The precise number of native species that perished in the low oxygen conditions could not be verified, however both large bodied and smaller native fish species were affected (pers. comm. Luke Pearce, 23 May 2017). The LTIM fish-tracking data shows fish movement began as early as September 2016. Not all species however responded to the conditions in the same way, for example, golden perch exited the Edward-Wakool system into the Murray River, and one travelled to Kyalite and back, while others (*n*=6) travelled further downstream to Glenbar, in search of refuge from the poor water quality. Similarly, silver perch (*n*=3) exited the Edward-Wakool, and one sought refuge at the Edward-Wakool confluence at Kyalite. Interestingly the movement of Murray cod differed from the perch as they (*n*=5) travelled upstream to Stevens Weir in early October, and then returned to the Edward River at Moulamein in November (Watts 2017). Movement by golden perch has previously been found to commence early in flow events when the water level was increasing (Marshall et al. 2016), however the Edward-Wakool data for fish tagging is yet to yield longitudinal results. Other observations from the Edward-Wakool LTIM project showed the flood resulted in high productivity, despite hypoxic conditions. For example, chironomid larvae (commonly known as bloodworms) are a food source for native fish, and they were abundant within the Edward-Wakool, and other river systems during the peak of the flood in 2016 (Figure 19). These larvae tolerate anoxia due to a unique survival mechanism, as they possess haemoglobin, which stores oxygen (Hoback and Stanley 2001).

Figure 19 Field monitoring in the Edward-Wakool following the floods where abundant populations of bloodworms were found (Source: Watts et al. 2017)

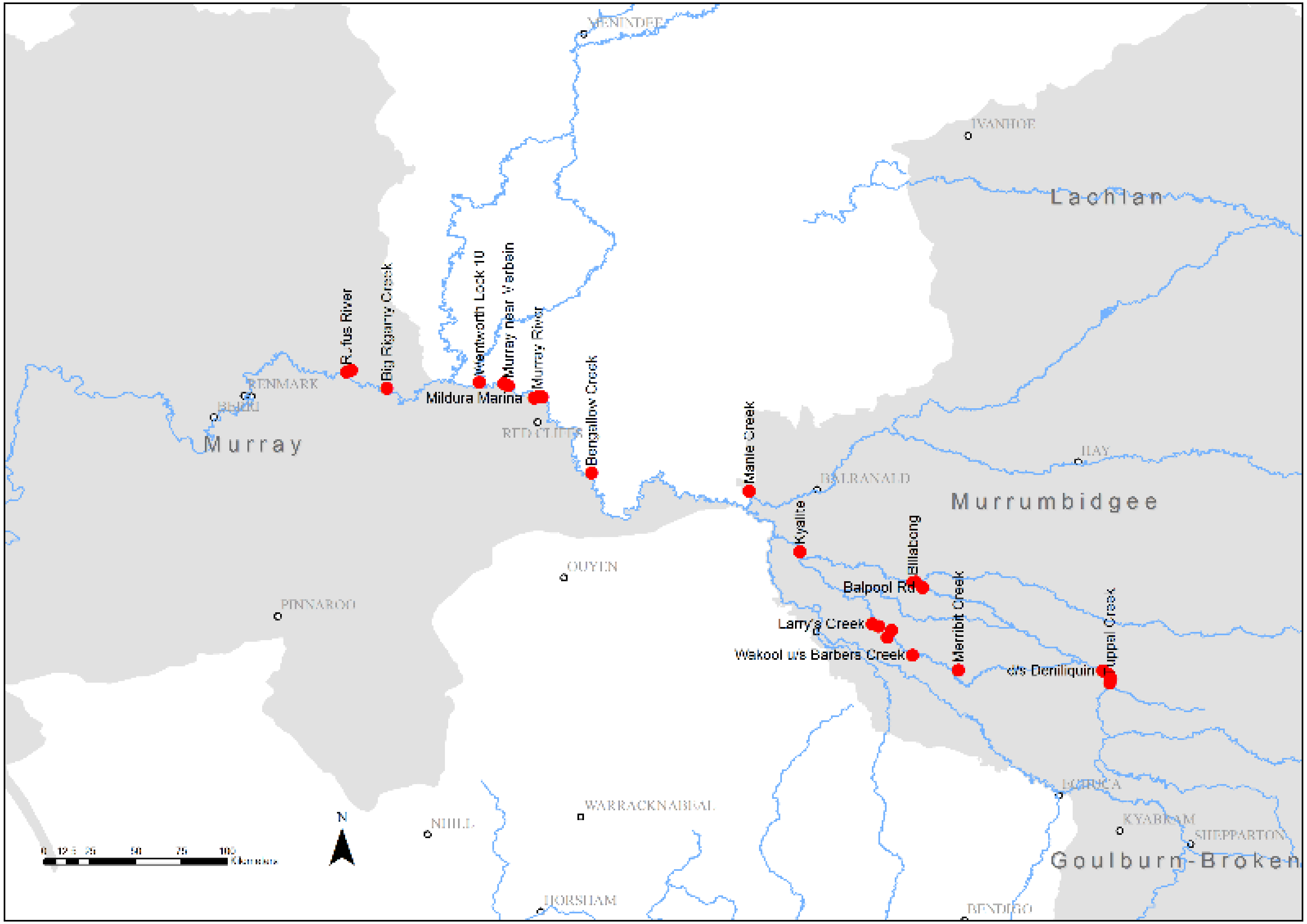


Figure 20 Fish kills identified in the Murray River 2016 (Source: NSW DPI Fisheries)

Following the hypoxic blackwater event the recovery or recolonisation of native species was considered as a one facet of the LTIM routine monitoring in May 2017. The data for one site at the Wakool Reserve - Bookit Island showed that there had been a 95% loss (recolonisation) of the *M. peelii* (Murray) cod population, and a 78% loss of Golden perch compared to 2016 data (Table 3). The Silver perch data is not statistically representative of a population, due to sample size, albeit only two species were caught in the routine sampling. Consequently hypoxic blackwater had a deleterious impact on native fish populations despite the ample food source available once they had recovered if at all.

Table 4 Numbers of native fish observed at the Wakool Reserve (source Jason Thiem, NSW Department of Primary Industries)

Species	2015	2016	2017
Golden perch	107	116	14
Murray cod	210	334	18
Silver perch	5	5	2

Environmental flows

The CEWH made a volume of up to 170,000 ML available for use in the Edward-Wakool River system from July 2016 to June 2017. Within the annual environmental water plan for the Edward-Wakool (2016/17) watering objectives were articulated, including a requirement to maintain water quality and provide fish refuge habitat from adverse water quality events including hypoxic blackwater. The Edward-Wakool annual plan specified the need to consolidate past environmental flows, and broadly, watering actions were developed to support the recovery and resilience of native fish populations, recruitment of riparian and aquatic native vegetation, and maintain water dependent aquatic ecosystems. These objectives and proposed actions were consistent with the MDBA forward outlook and watering priorities. As the wet spring unfolded variations were made to CEWH's internal Water Use Minutes (WUV10054-01 to WUV100 54-03), as low oxygen levels dictated a change to the proposed water use recommendations. An early estimate of 40,000 ML of Commonwealth environmental water was deemed adequate to generate refuge flows but ultimately insufficient to meet ecological needs, and an additional 80,000 ML using Murray Irrigation escapes at a flow rate of ~2500-3500 ML/day was approved (see examples, Figures 21 and 22).

In total, the CEWH approved the use of up to 120,000 ML in the Edward-Wakool, and refuge flows were managed with due consideration of natural flows, and the requirement to share channel capacity with irrigation demand in December. The refuge flows designed to protect native fish populations in the Edward-Wakool commenced on 25/10/16, and by 31/12/16, 107,370 ML of Commonwealth environmental water had been released through Murray Irrigation infrastructure to generate native fish refuge. The total NSW OEH environmental water volume delivered during the hypoxic event was 2,578 ML (Table 3).

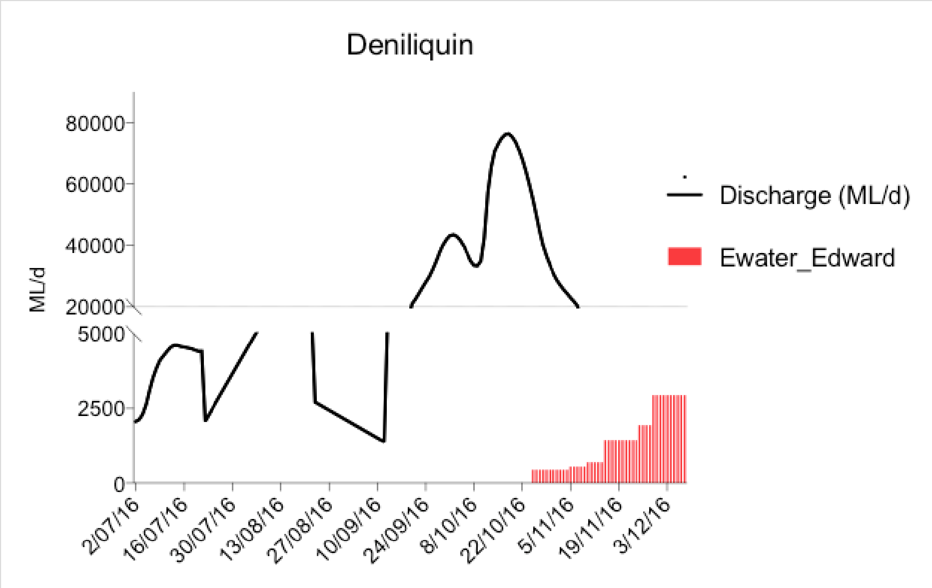


Figure 21 Plot showing the y axis (separate break) show the peak discharge at Deniliquin in mid-October, and the environmental water delivered via the Edward escape (red) from 25 October 2016 (River discharge data: NSW Water)

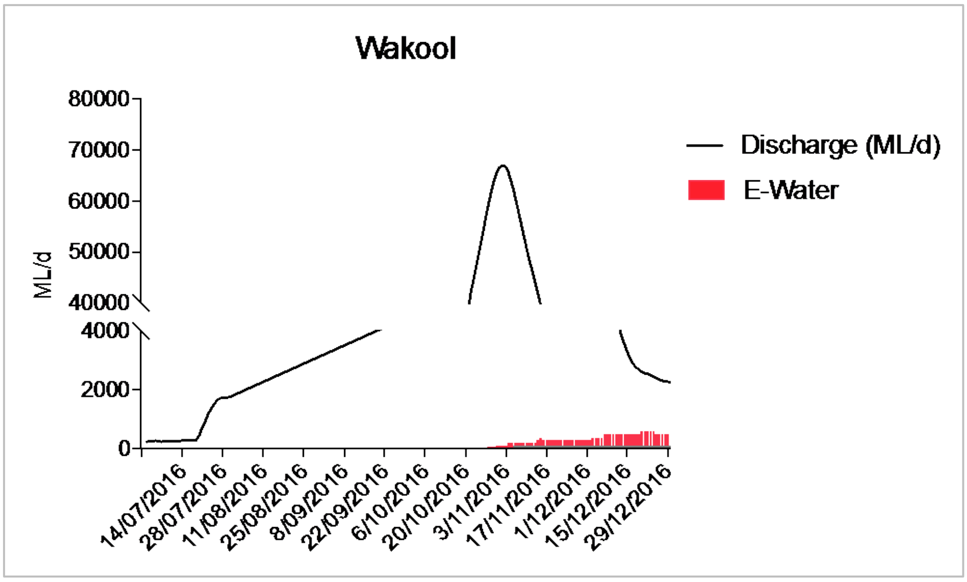


Figure 22 Plot showing the y axis break (different units), with the peak discharge in the Wakool River occurring on 2 November 2016, and the environmental water delivered via the Wakool escape (red) that commenced 29 October 2016 (River discharge data: NSW Water)

Table 5 Blackwater environmental flows (source: NSW OEH)

Escape	NSW Water	Commonwealth Water	Days	Starting Date	Finish Date
Edward	-	63,951.00	44	25/10/2016	8/12/2016
Wakool	-	22,447.00	63	29/10/2016	31/12/2016
Niemur	-	1,726.00	28	17/11/2016	15/12/2016
Jimaringle 1	-	171.00	29	22/11/2016	21/12/2016
Thule	718.00	1,278.00	49	4/11/2016	23/12/2016
Jimaringle 3B	72.00	311.00	29	22/11/2016	21/12/2016
Northern 3	214.00	103.00	16	8/12/2016	24/12/2016
Yallakool	268.50	259.50	18	5/12/2016	23/12/2016
Bunnaloo	124.40	502.90	35	18/11/2016	23/12/2016
Yarraman 8	61.50	198.80	30	23/11/2016	23/12/2016
Yarraman Ext	86.00	260.00	34	19/11/2016	23/12/2016
Bunnaloo 5	136.00	385.00	35	18/11/2016	23/12/2016
Southern 27	178.00	176.00	18	5/12/2016	23/12/2016
Wakool Town	345.00	-	7	7/12/2016	14/12/2016
Total (ML)	**2,578.0**	**107,370.0**			

Blackwater intervention tool

The Blackwater Intervention Assessment Tool (BIAT) (Whitworth et al. 2013) was examined for the Edward-Wakool using October 2016 data (DPI real time, ratings tables and field data). However, Watts et al. (2016 unpub.) suggested only a small improvement in local DO in the Edward River, and minimal change in Thule Creek would occur until the discharge was reduced to 1000 ML/day or less. Consequently, the model could not be adopted during the high flows. The downstream effects of dilution flows were also difficult to predict due to the assumptions in the time series component of the BIAT model (Watts et al. unpub. 2016). A lack of data for the model, i.e., DOC concentration, water temperature, biological activity, type of carbon or channel configuration also limited the modelled outputs. The preliminary findings indicated DO concentrations would not reduce after the point of mixing unless water temperatures rose above 20 °C, and in the absence of additional downstream carbon inputs (Watts et al. unpub. 2016).

Stakeholder engagement

Previous experience gained during the 2010/11 hypoxic blackwater event in the Edward -Wakool provided the basis for a coordinated response, and therefore response efforts were progressed quickly in comparison to other river ecosystems affected by low dissolved oxygen conditions. A Draft Terms of Reference (ToR) dated September 2016, for the Murray Dissolved Oxygen Group (MDOG), and circulated to key stakeholders stated the purpose of the group was “Minimising (where possible) the detrimental influence of hypoxic black water within the Murray and Edward-Wakool system to improve native fish refuge”. The ToR specified the rivers in the mid Murray that is, the Edward-Wakool Colligen, Neimur, Yallakool, Millewa, Werai and Koondrook- Perricoota. As one of the members of the group the CEWO understands the ToR remains in draft format. Still the TOR provided a governance and operational framework, and described the need to develop a coordinated response to low oxygen conditions in the Edward-Wakool. The Murray Local Land Services (MLLS) facilitated the MDOG meetings as needed, however following the 2016 event the LLS will step down and therefore the role will need to be filled by another agency.

A number of media reports released during the 2016 blackwater event had reference to the Edward-Wakool system, and some contained statements contrary to the information being released by agencies (see, example CEWH’s, E-water to provide fish refuge in the Edward River). Speculations made regarding the 2016 natural flood event especially that environmental flows were responsible for the hypoxic blackwater event (see, Appendix 2) distorted the evidence. Not only does incorrect media reporting confuse the broader community, this also places undue stress on agency and stakeholders operating in an emergency response environment. In retrospect, the community may have benefited from a more frequent stream of information that was prepared well in advance.

The efforts and commitment of local landholders in the Edward-Wakool was commendable as many with properties adjacent to the river deployed mechanical aerators *in situ*. The purpose of the aerators was to provide fish refuge benefits and re-oxygenate water locally. Many of these aerators had been trialled as management interventions in 2011, with findings suggesting sustained mechanical aeration had localised benefit, but they were costly due to 24hours/day operation and fuel cost (Whitworth et al. 2011). In 2016, native fish were observed gathering around the aerators, and this is consistent with the findings of 2011. The scale of the blackwater event in 2016 impacted the entire Edward-Wakool system, and therefore aerators provided localised improvement.

Figure 23 Aerator used during 2016 in the Edward- Wakool (source: Western murray tueloga-aerator)

Summary

The CEWH’s annual watering plan for the Edward-Wakool identified poor water quality (including hypoxia) as a potential risk. The ability to provide dilution flows to mitigate hypoxia at a broad scale was highlighted as a potential challenge, as it was understood (1) the Commonwealth has insufficient water holdings to undertake dilution flows in the Edward-Wakool, and (2) during a flood, dilution flows could exacerbate overbank flooding and therefore this approach was unlikely to be used as a mitigation measure. For effective dilution of blackwater, the flow must comprise 30% of the downstream discharge (Whitworth et al 2011), and complement the floodplain returns. The use of Murray Irrigation Ltd (MIL) canals, via Tuppal Creek, and the Wakool-Yallakool escapes to generate fish refuge was cited as a potential water delivery option if and when a hypoxic blackwater event occurred in the 2016 Edward-Wakool.

Consistent with actions delivered during the 2011 hypoxic event, environmental water was released via the irrigation infrastructure in 2016. Given the delivery limitations imposed by the 1:30 year flood occurrence, the escapes proved to be an effective measure for the delivery of oxygenated water for native species (Watts, unpub 2017). In particular, the environmental flows were found to have lower DOC concentrations, and re-aeration of water flowing over the escapes generated fish refuge, as fish were observed congregating around the escapes.

For environmental flows to be used effectively as a mitigation measure water holders require real time spatial and temporal information to support decision making. Access to water quality data, particularly the key parameters dissolved oxygen, dissolved organic carbon and nutrient data is essential alongside remote sensing data. The in situ DO data from deployed instruments within the Edward-Wakool proved to be invaluable for quantifying the rapid drop in this parameter. However, the current monthly spot grab monitoring approach adopted for the end of system (e.g. Kyalite) for the Edward-Wakool lacks spatio- temporal coverage, and it is unsuitable for risk based decision-making and scant data exists for many consituents. Emerging technological solutions are available for water quality monitoring (i.e. DOC spectrophotometry) and these tools could provide water resource managers with important data in real time during flood events. The adoption of technological advancements has cost benefits in comparison to traditional grab sampling, as DOC sensors can be programmed to log data at the required temporal scale, and sensors can be deployed at telemetered gauging stations. Approaches that improve the way in which water quality information is collected and conveyed can guide the timely delivery of environmental water during hypoxic blackwater events.

Research undertaken following 2010/11 blackwater showed the flood conditions had a negative impact on native fish in the Barmah-Millewa region, which made any assessment of the resilience of the fish community difficult to measure (King et al. 2011). Data showed high levels of dissolved organic carbon (DOC) and nutrients (total nitrogen and total phosphrous) were released from the floodplain into aquatic habitats during flooding. The scale of the event, a 1:30 year occurrence meant that vast areas of the natural and modified landscape were inundated for prolonged periods, particularly low-lying areas that had not been flooded for up to 30 years. The data shows high levels of DOC and nutrients were released from the floodplain, however no research was undertaken to describe the complex compounds or sources.

NSW Fisheries received notification that there had been a fish kill in the Edward-Wakool around 20 October 2016, yet, due to the time taken to coordinate mitigation measures, environmental water was not released until five days later. The initial fish kill occurred 3-7 days earlier when river discharge was almost at the peak, and corresponding to the rapid drop in dissolved oxygen in early October. In effect dissolved oxygen began to drop 10 days prior to the release of environmental water, and the first poor water quality pulse or ‘shock’ occurred on the rising limb.

The collaborative approach (community, agency and scientists) implemented for the management of blackwater in the Edward-Wakool was important for decision-making, communications and community engagement. Therefore the model has the potential to be replicated within other rivers systems. Moreover, the approach could be expanded to address the basin scale, as the flood event in 2016, demonstrates the connectedness of rivers in the southern basin, and therefore inter-valley collaboration would be constructive moving forward.

The principles of emergency management that is, mitigation, preparedness, response and recovery, used for preventing, avoiding or minimising disasters are integral to hypoxic blackwater management, and sustaining resilient fish populations. Planning and risk management therefore needs to be undertaken in the intervening period, and inter-jurisdictional collaboration would be fundamental. It is envisaged, a blackwater response plan would align with existing SES flood plans. The NSW State Flood Plan can be found at the following location (https://www.emergency.nsw.gov.au/publications/plans/sub-plans/flood.html).

A planned and prepared communication response could also assist with the management of these aperiodic events in the future as communications in 2016 were developed as the event unfolded and this was far from ideal.

Overall, the environmental watering outcomes were acceptable for the Edward-Wakool, especially in view of the scant water quality data that exists, and the unexpectedness of a hypoxic blackwater event that occured when temperatures were below those previously described as high risk, that is >20 °C (Whitworth et al. 2011).

The Murrumbidgee River

The Murrumbidgee River begins in the Snowy Mountains at 1600 m elevation, and it is 1485 km in length. On the western edge of the Great Dividing Range, the Murrumbidgee leaves the uplands and emerges as a broad river valley through rolling hills that have effectively been cleared of native woodlands for agricultural purposes. The river leaves the western slopes and enters the lowlands, continuing in a gentle descent to join the Murray River west of Balranald at 60 metres elevation. Murrumbidgee water is used to support an extensive irrigation network, with over 10,000 kilometres of channels served by weirs at Berembed, Yanco, Gogeldrie, Hay, Maude and Redbank (Figure 24).

The Murrumbidgee catchment has a diversity of wetland and riverine habitats including the Lowbidgee wetlands and Tuckerbill and Fivebough Swamps that are listed under the Ramsar Convention for international ecological importance. The catchment also contains numerous wetlands of national and regional environmental importance.

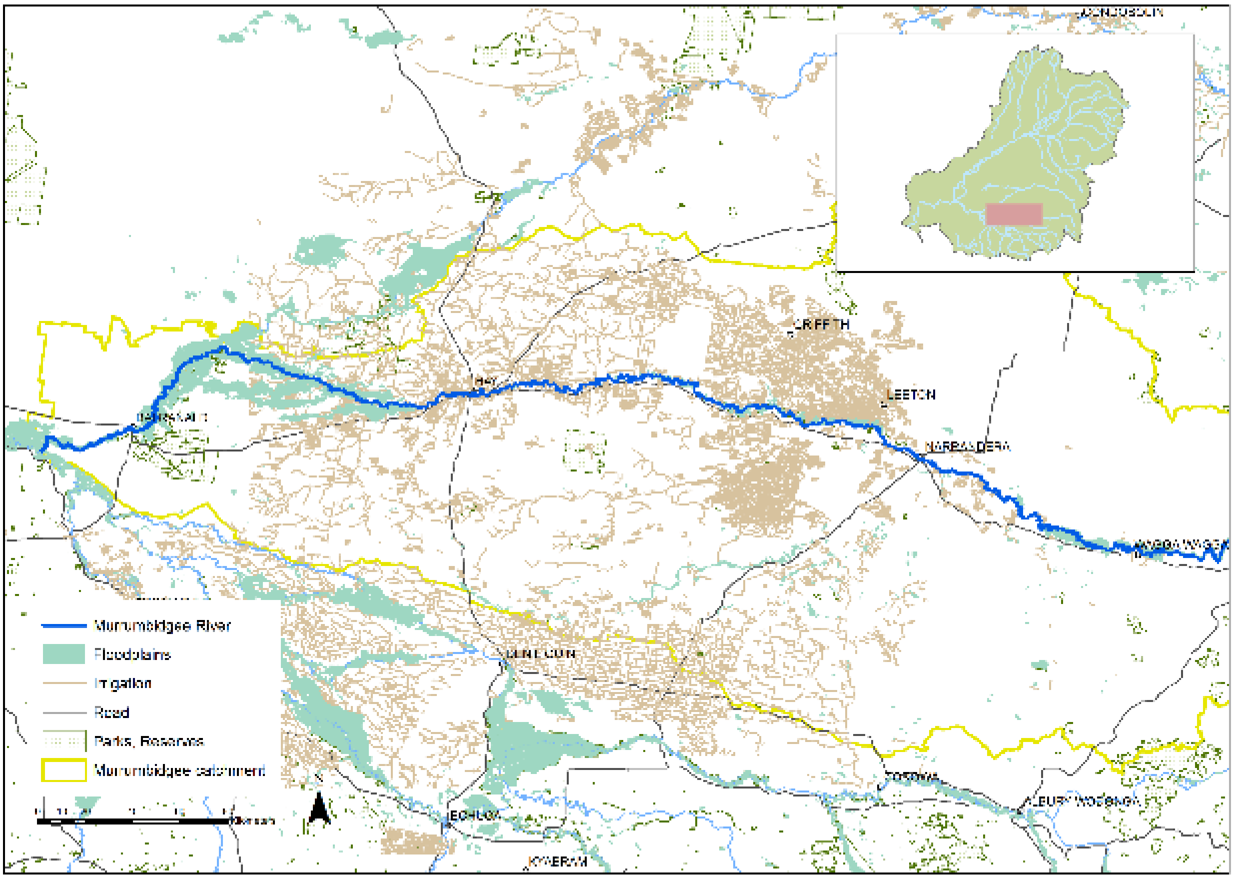


Figure 24 The location of the mid to lower reach of the Murrumbidgee River

Hydrology

During winter and spring 2016, high rainfall (see NSW climate overview) resulted in widespread natural inundation, and this produced moderate flood levels along the mid and lower reaches of the Murrumbidgee system. On 4 October 2016, the discharge hydrograph for the Wagga Wagga gauging station showed a maximum of 91, 000 ML/d, more than sufficient to overtop the river bank to fill the floodplain and many wetlands. Flood events of this size typically carry a significant sediment concentration equivalent to ~400 mg L^{-1} (Olive and Olley 1997). The

2016 flood extent downstream from Hay, was greater than the flood extent recorded during 2012 (EWAG minutes, 1 December 2016).

The BOM summary statistics for the Wagga Wagga AMO shows September 2016 recorded the highest monthly rainfall (171 mm) for the period 1941 to 2016.

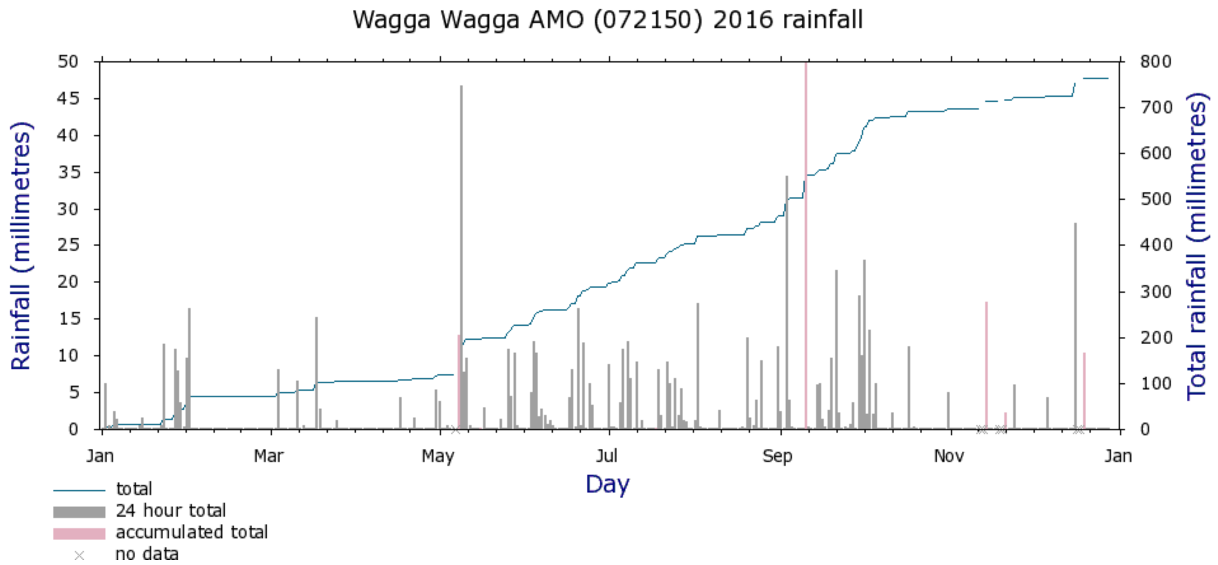


Figure 25 Wagga Wagga rainfall with monthly on the left y axis and total rainfall on the right y axis (Jan-Dec 2016) (Source Climate Data – Bureau of Meteorology 2017)

Flood warnings were issued along regional centres located on the Murrumbidgee River during 2016, including Gundagai and Wagga Wagga, and at Narrandera, where the river peaked on 09/10/16 at 8.00 metres. Major flooding also occurred at Hay.

Murrumbidgee dissolved oxygen concentrations

Dissolved oxygen (DO) values from the Maude Weir gauging station (410040) indicated conditions (daily average of 2.2 mg L^{-1}) were at the highly stressed range for ~30 days. Whereas DO levels in the lower reaches of the Murrumbidgee River dropped to the fish kill range of (<2 mg L^{-1}) from late October to early December 2016 (Figure 26). Downstream of Maude Weir dissolved oxygen began to steadily decrease from mid-September, and by 15 October, values dropped when the river discharge approached 23,000 ML/day and the water temperature was 17 °C. From 1 November 2016, the water temperature had increased to 19 °C, and at this time a recovery in DO values was measured, although low DO persisted in the highly stressed range (> 2 and < 4 mg L^{-1}) for a further 7 days. At Redbank (410041), dissolved oxygen began to decrease from mid-September and levels dropped to the likely fish kill range < 2 mg L^{-1} on 18/10/2016, as river discharge reached 10,000 ML/d. At Balranald Weir (410130) low DO was protracted, and values remained below the fish kill threshold until late December 2016.

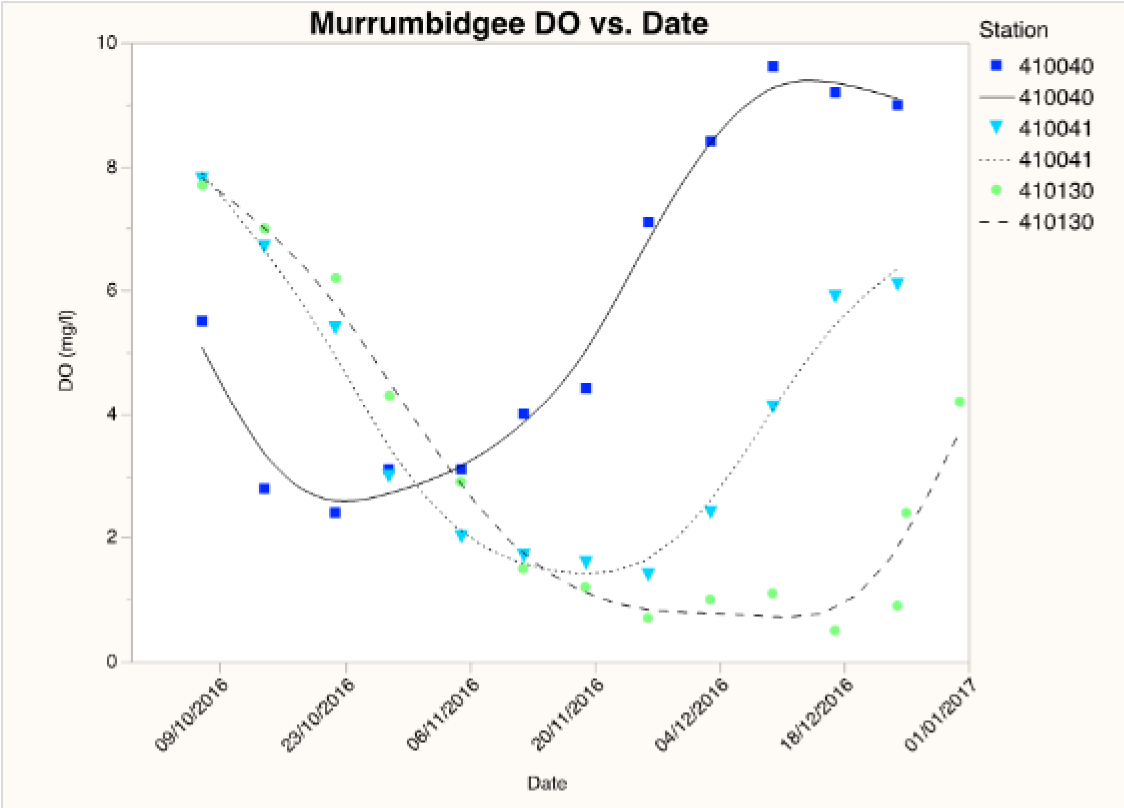


Figure 26 Daily dissolved oxygen showing the 7-day average for gauging stations located in the lower Murrumbidgee River (source DPI Water) (Gauging stations 410040=D/S Maude, 410041=D/S Redbank and 410130=D/S Balranald)

Water Chemistry

Ambient water quality monitoring undertaken by Water NSW for the parameter dissolved organic carbon at the Balranald gauging station in 2016 from the four spot grab samples shows the median DO concentration in the months of July, August and December was 11 mg L^{-1}, and data shows the maximum value of 19 mg L^{-1} occurred on 18/10/2016 coinciding with the rising limb of the hydrograph. The peak discharge of 31,222 ML/d was logged at Balranald on 10/11/2016. The scant DOC data does not permit detailed analysis, and it is unclear if the maximum DOC concentration was reached on the rising, peak or falling limb of the hydrograph. The point data however, indicates the DOC concentration on 18 October was 53% greater than the other sampling results for the July to December 2016 period (Figure 27).

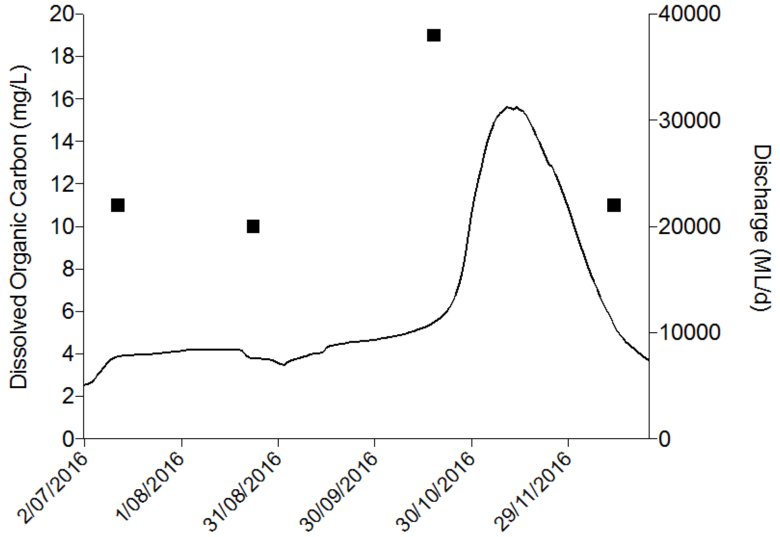


Figure 27 Dissolved organic carbon concentration from monthly (excluding September) grab sampling, and discharge recorded at Balranald gauging station (410130).

At Balranald the ambient water temperature data (2 replicates, 8 sampling events for the 6-month period) show the minimum was 10.4 ºC in July and the maximum was 25.0 ºC in late December, and the median value was 16.0 ºC. The maximum turbidity of 180 NTUs was recorded on 12/07/2016, and a decrease recorded for each subsequent measurement to the minimum of 15 NTUs in mid-November (no sampling data for December). The median value was 46 NTUs for the July to December 2016 period.

Total N and P exceeded the ANZECC (2000) guidelines for lowland aquatic ecosystems in all months (Figure 28). The point data shows the maximum concentration for total nitrogen occurred in October, prior to the peak discharge of 31,222 ML/d on 09/11 /2016 at Balranald. Interestingly, the maximum value for total phosphorus was measured on 23/08/2016. This tends to suggest P absorbed by soil particles (e.g., sediment-bound P) was released along with the eroded soil particles and delivered to the adjacent river through surface runoff as the maximum turbidity value was observed in July 2016. During wet years, soil erosion and surface runoff are the main P release and transport mechanisms. Typically floodplains act as a sink for P, but under high flow conditions and floods, erosion may occur, where soil particles along with the attached P are removed from the topsoil. Moustakidis (2016) found minor flood events (2, 5 and 10-year occurrence) act as a sink, while larger flood events release fine sediment and total P from the floodplain, which becomes part of the in-stream load.

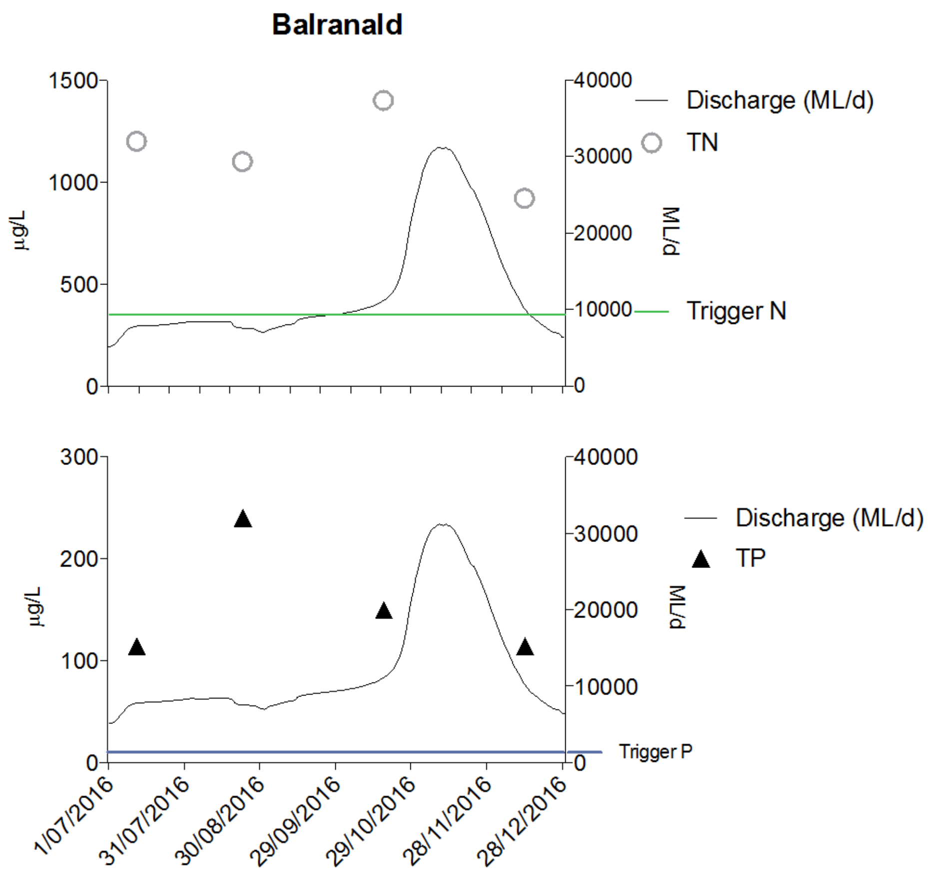


Figure 28 The spot sampling macronutrient data for the lower Murrumbidgee (total nitrogen and total phosphorus) for the period July to December 2016

Water maps and DO time series

The lower Murrumbidgee inundation map shows DO levels that began to decrease in October 2016, when river discharge was above 20,000 ML/day downstream of Maude Weir. Improvements in DO levels occurred by December at all sites excluding Balranald (Figure 32). The quality of environmental water from up stream of Yanga National Park from 25/11/2016 was 9.0 mg/L. The dilution flows of oxygenated water from Maude Weir would have accelerated recovery in the reach between Maude Weir and Balranald. The inundation pattern, and the dissolved oxygen values were classified according to the DO threshold values shown in Table 1 (acceptable = grey, stressed = green, highly stressed = orange and fish kill likely =red). The resultant maps for the Murrumbidgee River are shown in Figures 29-32.

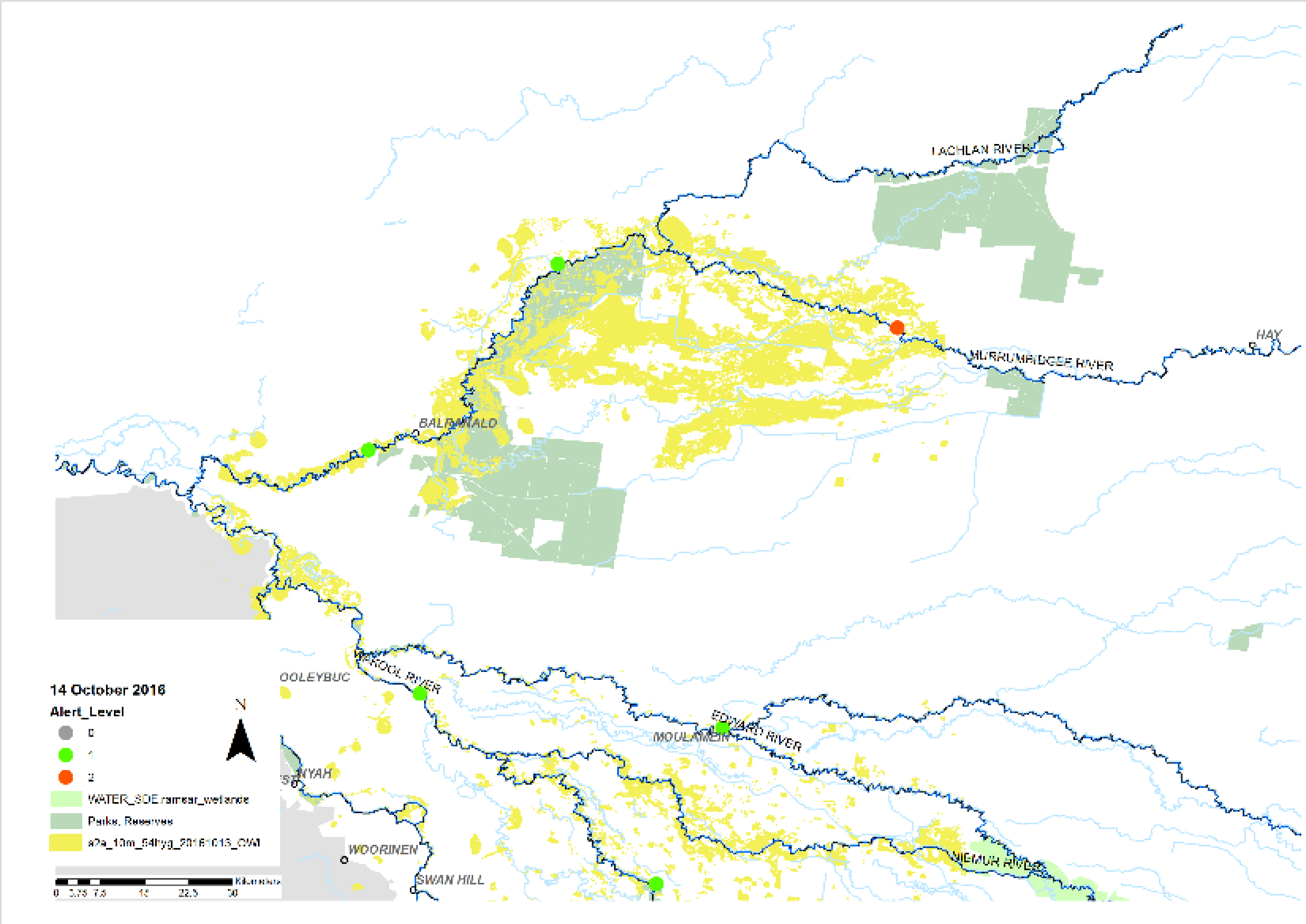


Figure 29 Average dissolved oxygen for sites in the lower Murrumbidgee showing the DO collation (1- 14 October 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

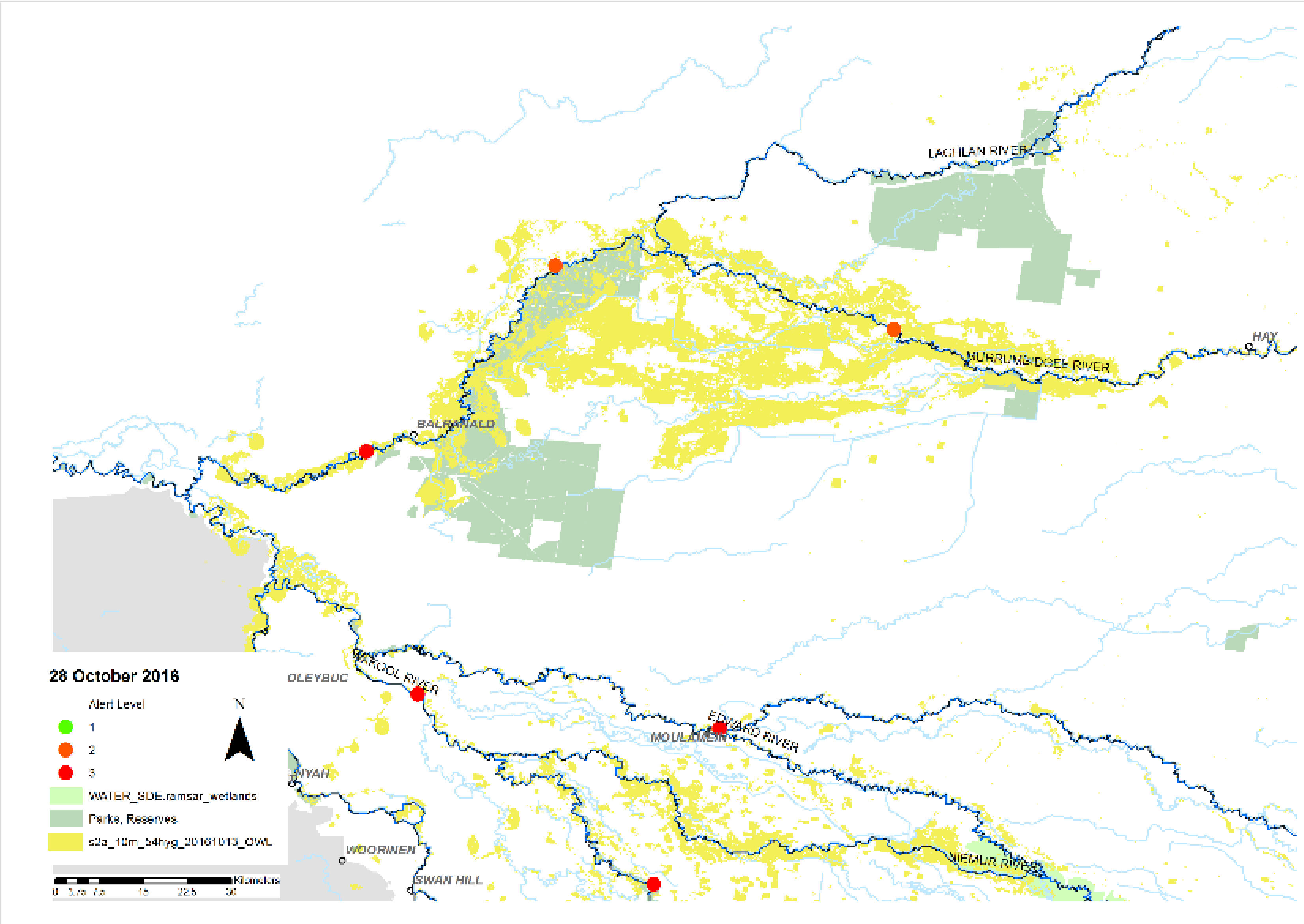


Figure 30 Average dissolved oxygen for sites in the lower Murrumbidgee River showing the DO collation (I5-28 October 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

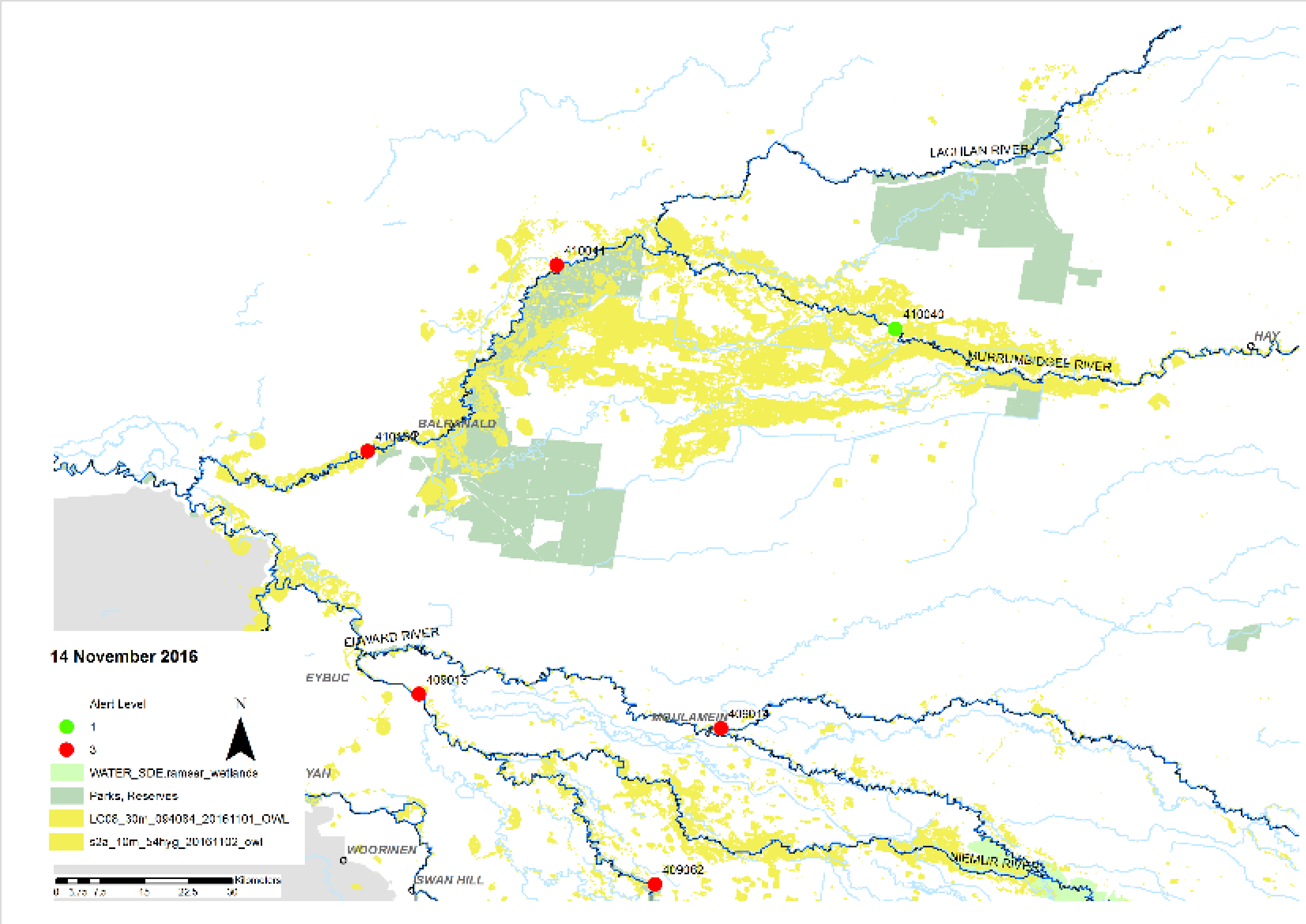


Figure 31 Average dissolved oxygen for sites in the lower Murrumbidgee River showing the DO collation (1-14 November 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

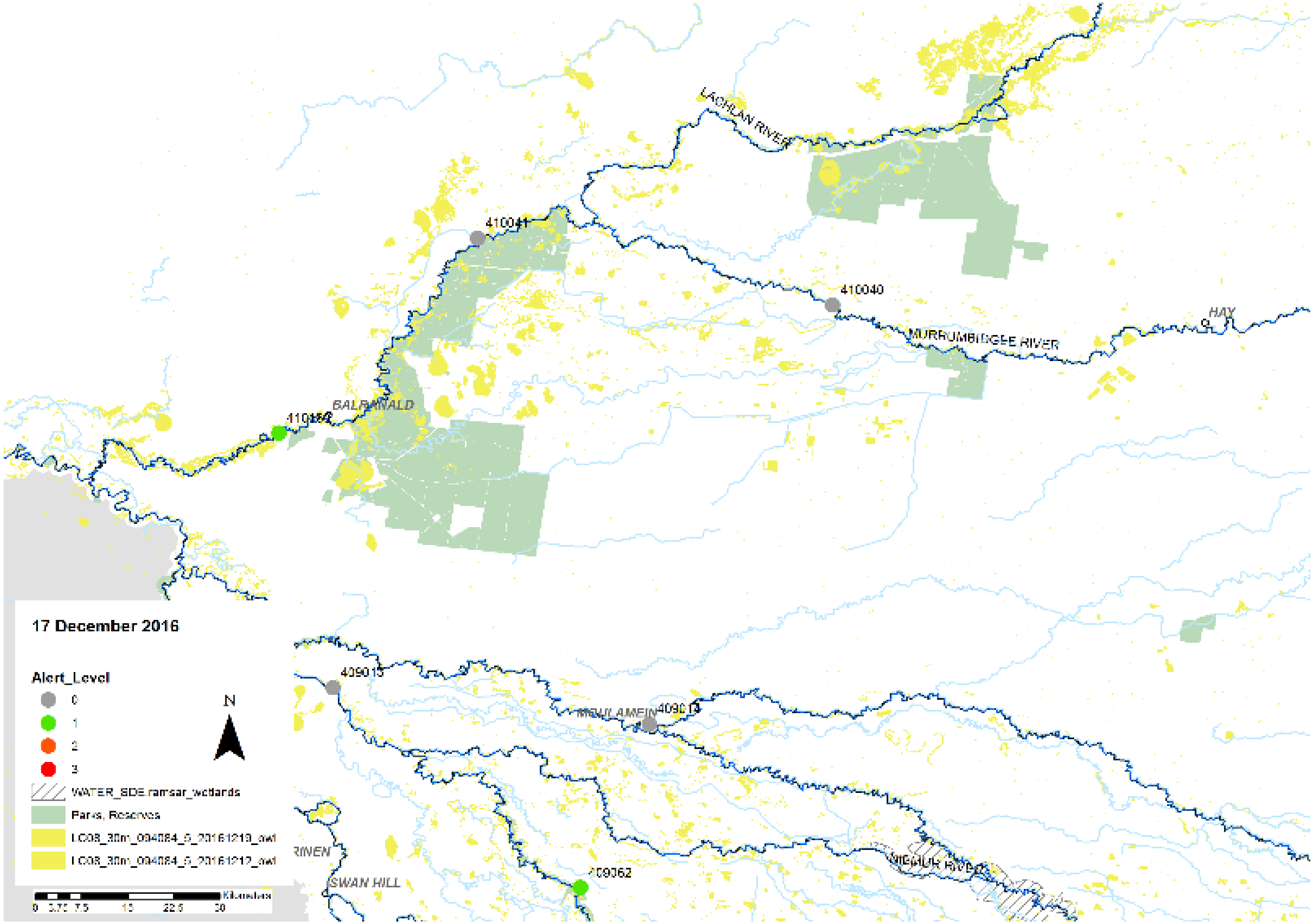


Figure 32 Average dissolved oxygen for sites in the lower Murrumbidgee River showing the DO collation (1 – 17 December 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow)

Impact to aquatic species

The June 2017 Murrumbidgee LTIM Progress Report suggested the dilution flows were successful in preventing fish mortality, and there were no major adverse effects of hypoxic blackwater on native fish recorded in the Carrathool reach, and array in terms of size in the Murray cod population had prevailed (Wassens et al. 2017). Although not monitored under the LTIM program, it was thought no fish kills had been reported to NSW DPI fisheries downstream of Carrathool. However, a fish kill was reported downstream of Balranald Weir, and details provided by a landholder with a property adjacent to the river estimated there were 100s of Murray cod as well as golden perch (lower numbers than Murray cod) floating down a 20 km stretch of the river below the Balranald Weir, on two separate occasions (late October to early November) (pers. comm. Peter Morton 27 August 2017). The 2016 fish kill observed was thought to be of similar magnitude as the fish kill that occurred during the 2011 hypoxic blackwater event. The Manie Creek (Figure 33) was reported to have had a fish kill and this site was influenced by floodplain return flows for the Murrumbidgee and Murray rivers (Fig. 33).

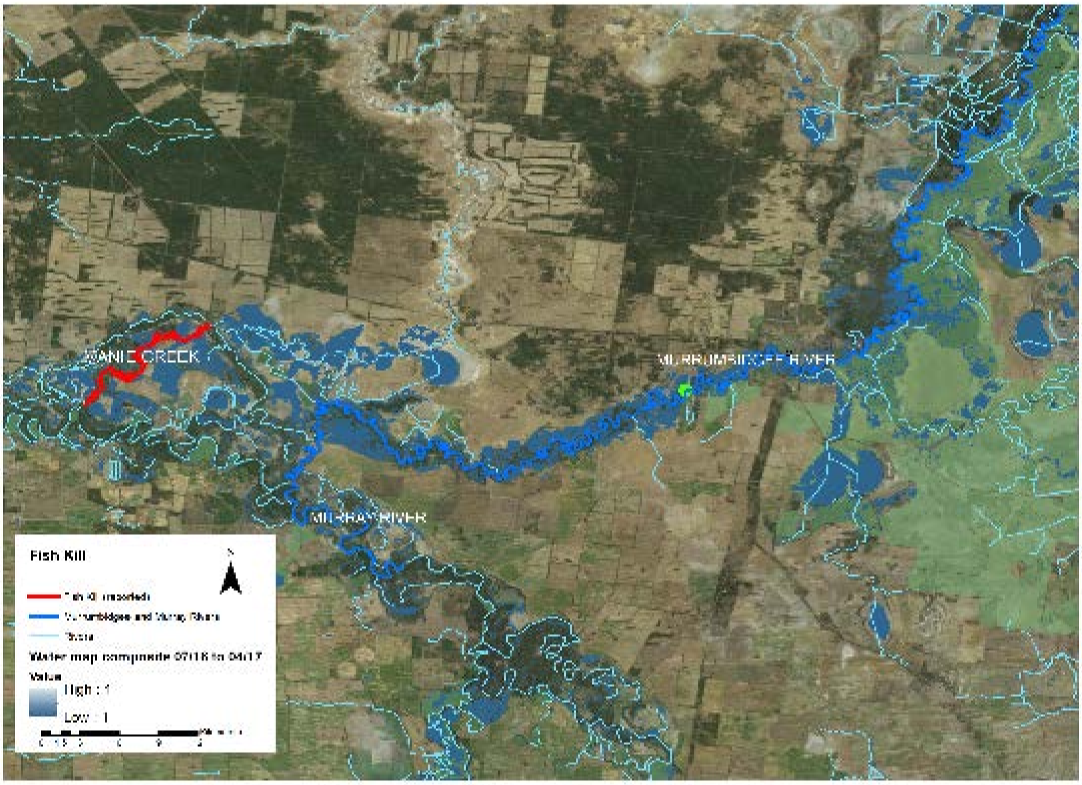


Figure 33 Location of the Fish kill reported in the Manie Creek (red) below the confluence of the Murrumbidgee and Murray Rivers (2016).

Environmental flows

The sources of environmental water used during the 2016 hypoxic event in the Murrumbidgee comprised 150,978 ML of regulated Commonwealth environmental water, 134,861 ML of the NSW Environmental Water Allowance and 85,000 ML of the Living Murray allocation, and a total of 370,839 ML.

The CEWH's environmental flows were delivered to the mid and lower reaches of the Murrumbidgee where continuous data from the Integrated Telemetry System showed low dissolved oxygen conditions existed (WUM

10052 Variation). A water use recommendation, titled *Flood Recession and Dissolved Oxygen Management in the Murrumbidgee Catchment* (4 November 2016) included objectives for the release of environmental water as follows: (1) to steadily decrease flows to extend the duration of connection between the river and floodplain wetlands; (2) to provide the opportunity for native fish and other aquatic species to move from the floodplain to the river channel and minimise/prevent stranding; and (3) to provide refuge for native fish from low DO conditions.

Modelled outputs from the Murrumbidgee Blackwater project as part of the LTIM guided the environmental flows released during the 2016 hypoxic blackwater in the Murrumbidgee River. While longer-term deliverables were included within the scope of work undertaken, the Blackwater Intervention Tool (Whitworth and Baldwin 2013) informed the environmental watering actions and measured the potential benefit of flows from D/S Maude Weir (Wolfendon unpub). Modelled DO results were compared to establish various dilution flow discharges aligned with a base flow of 200 ML/day. The final results will be published in the 2016/17 Murrumbidgee LTIM report, and it is expected the report will include modelled scenarios for the dependent variables, dissolved oxygen and the independent variables, water temperature, carbon concentration and river discharge at the Balranald gauging station.

From 29/10/2016 to 5/01/2017 dilution flows were released consistent with the modelled scenario (moderate) for the mid and lower reaches of the Murrumbidgee River. The first action (29 October to 8 November 2016) began using NSW Environmental Water Allocation (EWA) (accounting point Wagga), at a discharge rate of ~11 000 ML/d, and the total volume used was 125,070 ML (Figure 34). The EWA exceeded the conservative modelled dilution flow rate of 8000 ML/d, and was therefore likely to accelerate recovery at Balranald than would be anticipated from a 'do nothing' scenario (Wolfenden et al. unpub). The second action (13 November to 19 November 2016) was Commonwealth environmental water (CEW), from D/S Gogeldrie, with a target flow rate also of 8000 ML/d (total = 56,978 ML) (Figure 35). The final dilution flows commenced seven days later (27 November 2016 to 5 January 2017), and used a combination of environmental water allocations that were ordered from D/S Maude Weir. Given modelling predicted ongoing hypoxia (<2 mg L^{-1}) in the Balranald reach until early December, the third action was sustained for 40 days and comprised 94 000 ML of CEW, 85,000 LM and 9791 of EWA, and totalled 188,791 ML (Figure 36).

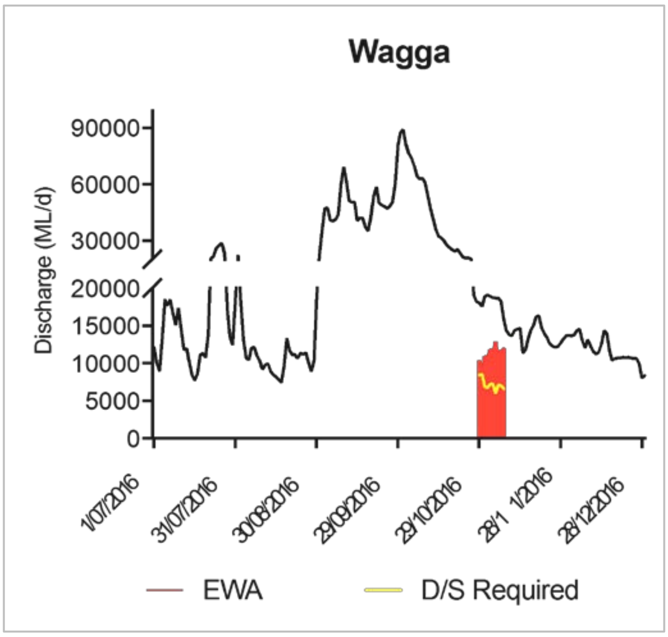


Figure 34 Action 1 with the y axis break (different intervals) as the two separate axes show the peak discharge at Wagga from July to December 2016,and the e-water (red) from 29 October 2016. Yellow line represents the required flow downstream (River discharge data: NSW Water)

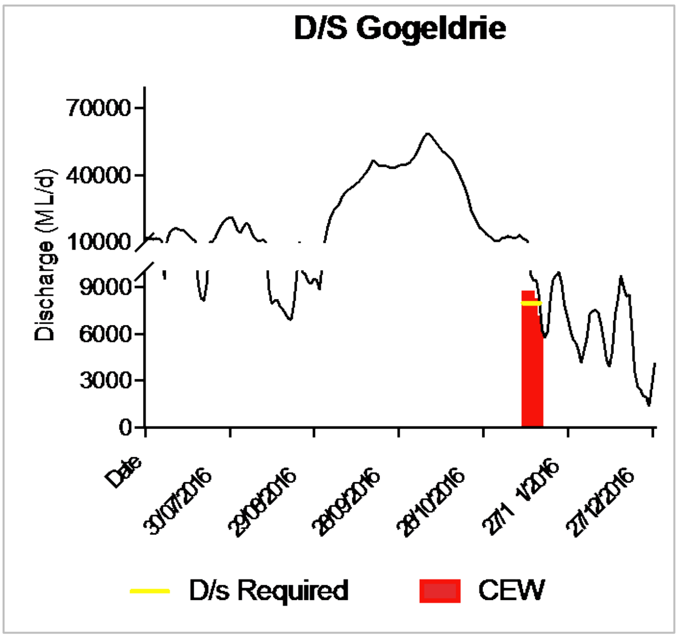


Figure 35 Plot showing the y axis break (different intervals) as the two separate axes show the peak discharge at Gogeldrie Weir, and the 7-day e-water intervention (red) from 13 November to 7 November 2016. Yellow line represents the required flow downstream (River discharge data: NSW Water)

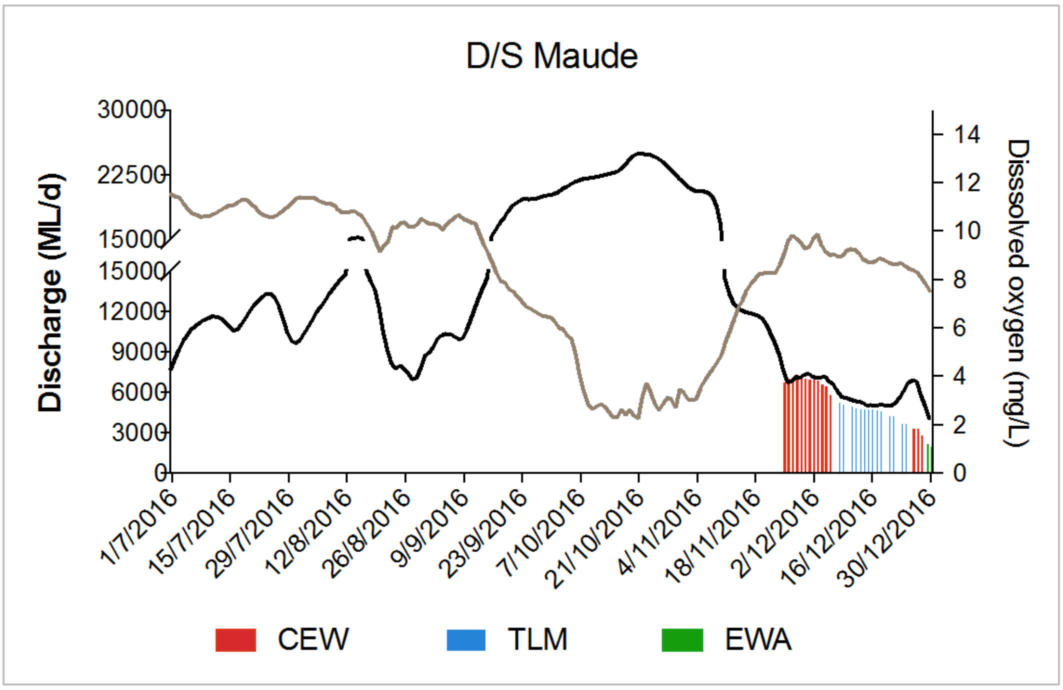


Figure 36 Plot showing the y axis break (different intervals) as the two separate axes show the peak discharge at D/S Maude Weir, and the 40-day combined dilution flows from 27 November to 1 January 2017, with discharge (ML/d() on the y right axis and dissolved oxygen on the right y axis, River discharge data: NSW Water

Charges associated with the delivery of environmental water

The cost of fees associated with the delivery of environmental water in the Murrumbidgee River in 2016 to mitigate low dissolved oxygen for the CEWH was $ 782,066.04.

Communications

An interagency and collaborative approach was adopted for the management of environmental flows to minimise the influence of hypoxic blackwater in the lower Murrumbidgee River. CEWO personnel met regularly with stakeholders to discuss environmental flows during the 2016 hypoxic blackwater event. NSW OEH convened the technical advisory group meetings, and the Riverina LLS engaged with the broad community, disseminating information on blackwater, and the environmental flows being used to reduce the any lethal effect of low DO to native fish.

During the event two media releases were distributed to the media. The first from the LLS (18 /10/2016) was titled *Lower Murrumbidgee River Low Dissolved Oxygen levels* and contained three key messages, (1) dissolved oxygen levels were being monitored daily by a multi-agency group, (2) environmental water was allocated for use in the Murrumbidgee River system to minimise impacts to native fish and, (3) environmental water may reduce the severity and duration of hypoxia and assist in the recovery of stressed native fish. The MDBA's media release (22/12/ 2016) titled, *The Benefits of Bidgee Environmental Water* contained a number of messages including; (1) monitoring shows that diluting areas of blackwater is helping to sustain some of the local fish population in the lower part of the river, (2) water managers waited until the floods began to recede before releasing the environmental water to avoid exacerbating the inundation on floodplain properties and, (3) it was encouraging to see evidence of golden perch spawning in the Murrumbidgee upstream of the affected blackwater areas in response to environmental flows. Regrettably an inter-agency media statement did not reach a position of solidarity for the 2016 event.

The CEWO media team developed a fact sheet and web page relating to hypoxia, its causes, and impacts titled, *Hypoxia Blackwater*, and located at [Hypoxic blackwater].

Summary

The hydrograph (Figure 36) shows environmental water actions met the stated objectives for the Maude site that is, releases occurred on the falling limb, slowing the rate of recession, while not escalating overbank flooding, and therefore e-water flows were below the gauged level at the station 410040 (Table 6). Anecdotal evidence suggests *Macquaria ambigua* (Golden perch) and *Maccullochella peelii* (Murray cod) spawned on the dilution flow, and Tala Lake served as fish refugia (James Dyer pers comm. 1 December 2016).

Table 6 Gauging station levels for the low Murrumbidgee River

Site no.	Maximum gauged level	Catchment area Sq. km
410041	6.914	No data
410040	7.354	57700
410130	6.875	166000

The modelled output indicated dilution flows would promote an earlier recovery in DO compared to the 'do nothing' scenario. Thus, recovery to acceptable DO levels with the 'no dilution flow' scenario was not predicted to occur until early-mid December (Wolfendon 2016, unpub). While this was achieved for the majority of the lowland gauged sites, data show the downstream reach at Balranald weir did not return to acceptable levels > 5 mg L^{-1} until late-December. Initially the input data used to generate the dilution model such as the return flow volumes were based on the 2012 flood event. Due to flat topography and differential flow rates in the river and floodplain, and the large returns of floodplain water that continued for four months, as well as connected flows from the lower Lachlan, the model output miscalculated the rate of recovery. Subsequent, hindcasting of the intervention model using the estimated 2016 flood return rates produced an output that was reported to more accurately represent the rate of recovery. The Murrumbidgee River was the only lowland system to adopt the dilution model during the hypoxic blackwater event in 2016.

Following the blackwater event that occurred during the summer of 2010 in the Murrumbidgee valley the NSW Office of Water commissioned a study to consider a number of physical and chemical parameters, and subsequently highlighted options that could lead to improvements in event based monitoring in the future. Among the key recommendations were, better approaches to forecast and manage hypoxic events in the lower Murrumbidgee River, a monitoring plan to capture data ahead of any anticipated hypoxic event, better hydrological knowledge of Lowbidgee floodplain return rates, more comprehensive dissolved oxygen time series monitoring, comprehensive dissolved organic carbon monitoring before, during and following events, and increased use of existing blackwater models to enable better validation and enhance prediction (Ryan et al. 2013). Negligible information was found to assess how these recommendations were progressed since 2013. The key elements such as a water quality monitoring plan pre and post hypoxic events, estimates of floodplain return rates, and increased time series of dissolved oxygen have seemingly not progressed, however, the Blackwater Intervention model was adopted and used to inform environmental flows and predict recovery rates in 2016.

The Lachlan River

The Lachlan River is 1,339 km in length, and it often is described as a terminal system due to infrequent joining with the Murrumbidgee River. The Lachlan runs from the Great Dividing Range in central New South Wales, westwards through sloping country in the central catchment, and then across lowland riverine plains. During high flow events water travels southwards through the Great Cumbung Swamp and reconnects with the Murrumbidgee River (Figure 37).

The lower Lachlan floodplain has 9 nationally important wetlands, including Lake Brewster, the Booligal Wetlands and the Great Cumbung Swamp. In particular, the Cumbung Swamp has one of the largest stands of river red gums in New South Wales, and it is recognised as a significant waterbird-breeding area in eastern Australia. Accordingly, the Lachlan River and its floodplains provide a wide range of aquatic habitats such as pools, backwaters and billabongs, in-stream woody habitat and aquatic plants. In 2016 environmental flows were used to limit the impact of low dissolved oxygen in the mid reach of the Lachlan River.

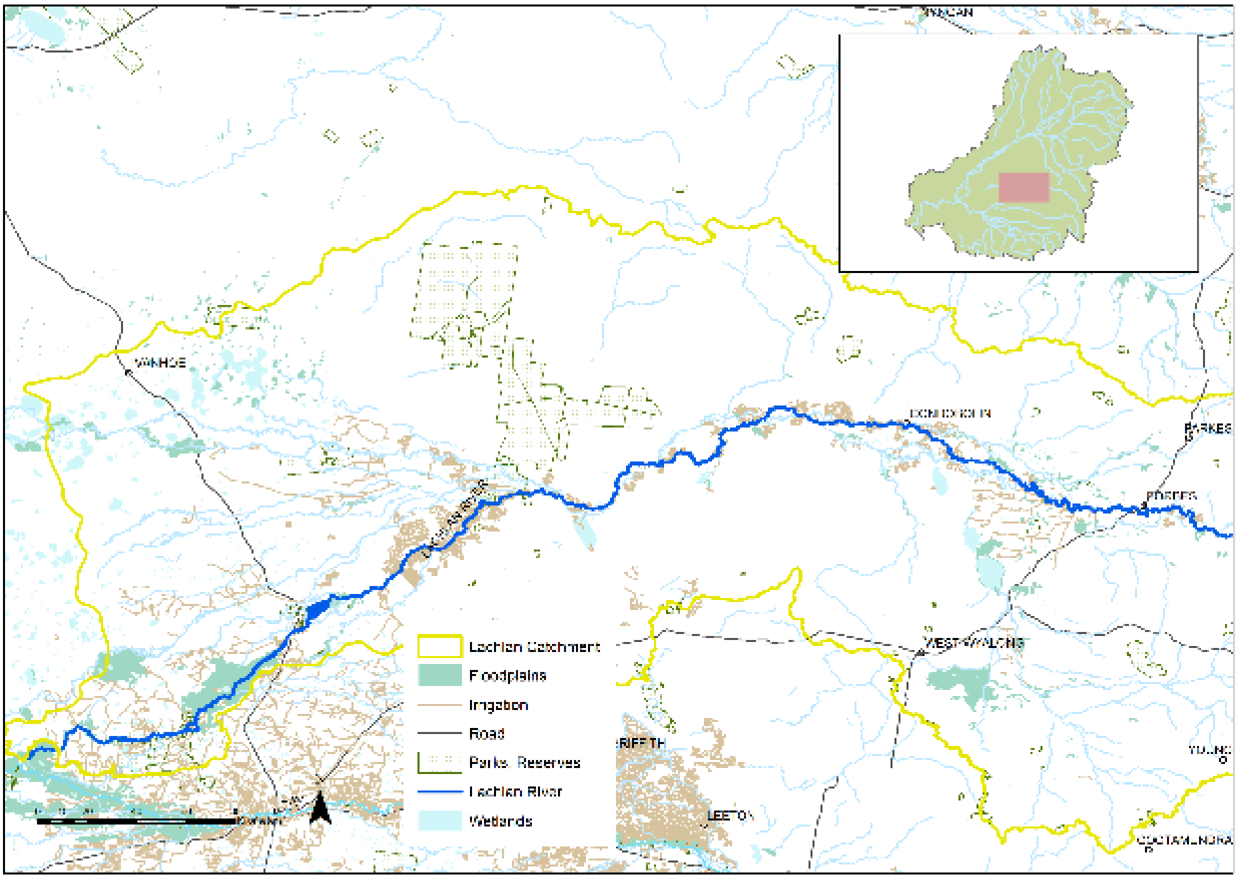


Figure 37 The mid and lower reach of the Lachlan River affected by low oxygen concentrations during 2016/17

Hydrology

The high rainfall in central NSW generated widespread inundation with major to moderate flood warnings issued for the mid to lower Lachlan catchment in 2016. A total of 152 flood warnings were issued for the Lachlan, with the final published for the lower Lachlan at Booligal on 26 /12/2016. The BOM rainfall statistics for the Forbes

Airport AWS shows January, May and September 2016 recorded the highest monthly rainfall, 81.4 mm, 78.4 mm and 119.8 mm respectively for the period 1995 to 2016. The total annual rainfall exceeded the median in 2016, equivalent to the 95th percentile (Figure 37).

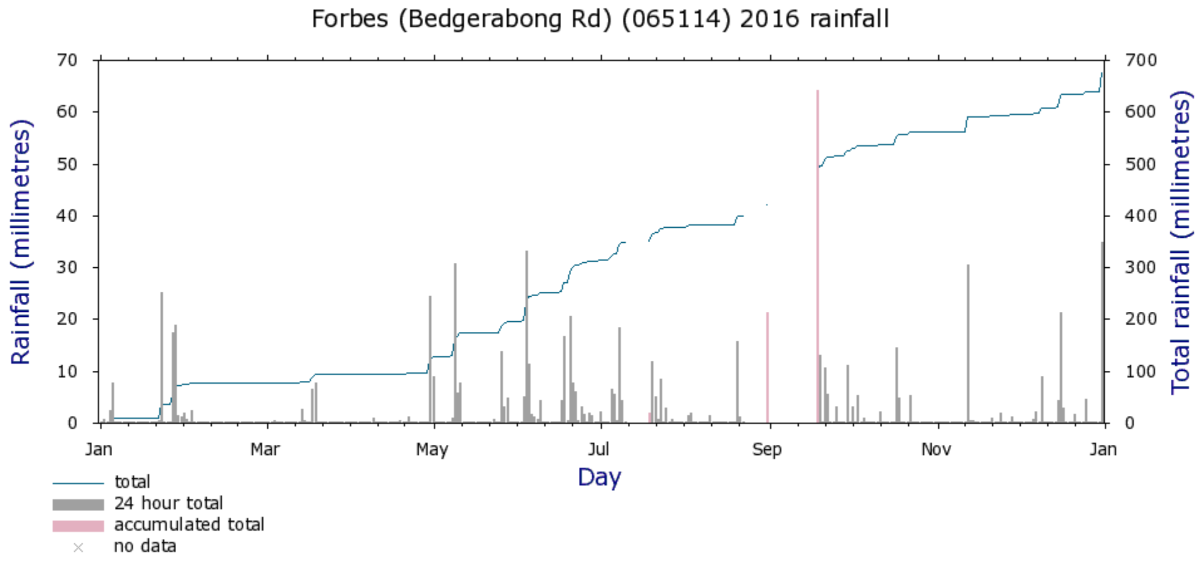


Figure 38 Forbes daily rainfall (January2016 to January 2017) (source: BOM 2017)

Figure 39 Widespread flooding at Forbes, 25 September 2016, Image Retrieved from https://watchers.news/data/uploads/forbes-nsw-australia-flooding-25-september-2016-4-credit-NSW-SES.jpg

With significant inflows to Wyangala Dam, the environmental flow rules under the Water Sharing Plan for the Lachlan Regulated River Source (2016) were triggered. The translucent flows commenced in July 2016, providing a more natural flow regime within the river system by permitting some of the natural dam inflows to pass down the river for environmental benefit. The flow rules state translucent flows must be released from Wyangala Dam, during the period, 15 May to 15 November, in any given year, and when the inflows to Wyangala Dam since 1 January of that calendar year have been greater than 250,000 mega litres (ML).

From 09/07/2016 the hydrograph for D/S Wyangala Dam shows the translucent flows were released as pulse flows, and reached a maximum of 20,000 ML/d, returning to 1319 ML/d by 24/08/2016. On 30/08/2016, following further high rainfall and inflows to the storage, the hydrograph shows discharge being increased from 10,000 ML/d to 44,600 ML/d within four days. A stepped and temporary reduction in discharge to 7,500 ML/d followed, but as rainfall continued to fall in the upper catchment during September, releases were increased, and a peak discharge of 50,500 ML/d was recorded on 23 /09/2016.

Downstream at Forbes, a peak discharge of 49,070 ML/d was recorded 6 days later on 29/09/2016. The hydrograph shows the first flood pulse and rising limb on 30/08/216, with discharge at 3647 ML/d and a steady increase 8 days later to 31,847 ML/d. These high river flows produced overbank flooding, and surpassed the major flood level at the Forbes gauge in September and October (Figure 41).

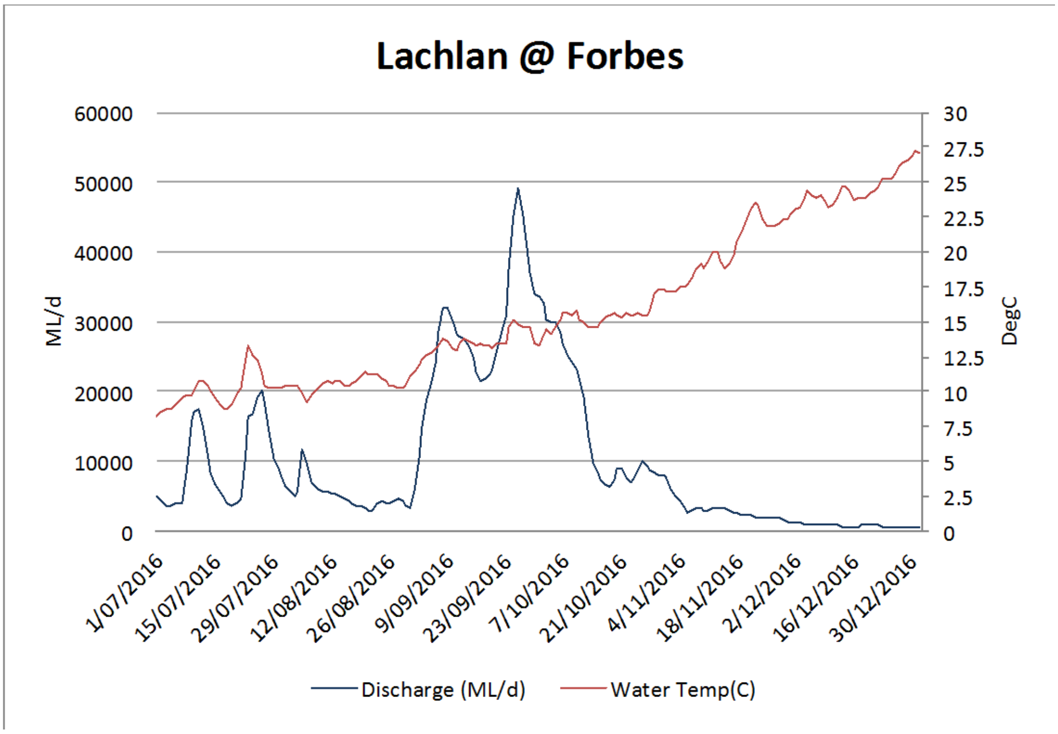


Figure 40 Forbes discharge and temperature data for the period July – December 2016

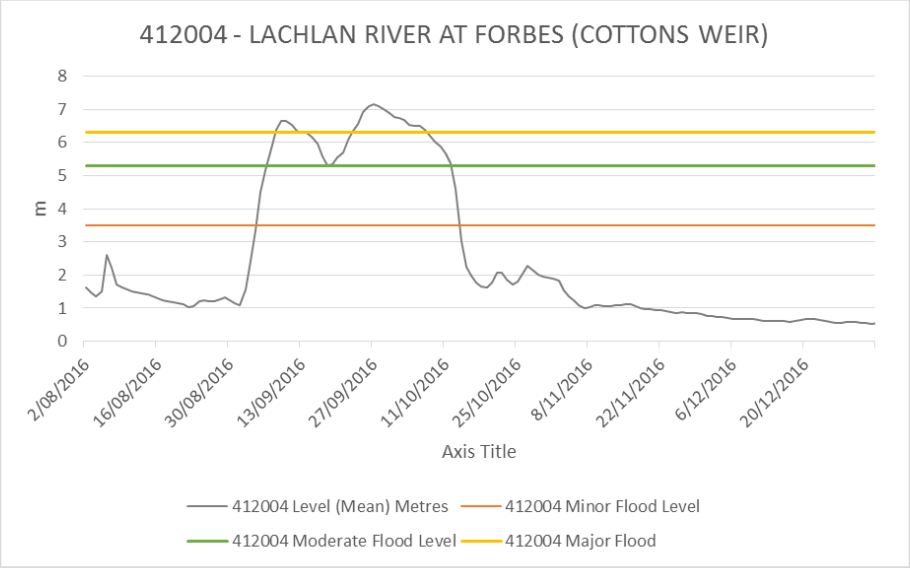


Figure 41 Daily river heights showing the duration of flooding at Forbes (05 September to 15 October 2016) (source: Office of Water NSW)

Lachlan dissolved oxygen concentrations

Historically, the Lachlan River has had fragmentary water quality monitoring conducted for key analytic parameters. However, spot sampling undertaken as part of the selected area lower Lachlan LTIM project in late October 2016, showed dissolved oxygen had dropped to the highly stressed or likely fish kill level. The spot sampling indicated dissolved oxygen values had dropped to 0.9 to 2.9 mg L^{-1} in the main river channel near Hillston.

In response to the flooding and suspected poor water quality, event based spot monitoring was commenced by Water NSW at key locations in the mid reach of the Lachlan in late October. The sampling frequency was increased from the routine monthly to weekly in the mid and lower reach of the Lachlan River. The monitoring commenced on 26/10/2016 at various sites (*n*=10), to measure longitudinal condition. The field monitoring confirmed dissolved oxygen values had dropped at multiple locations. The field monitoring showed values were below the acceptable level (<5 mg L^{-1}) at numerous sites along the river, and extremely hypoxic water persisted in streams located D/S from Lake Cowal in the Walaroi, Wallamundry and Bogandillon Creeks. By mid-November a recovery in dissolved oxygen in the lower reach of the Lachlan River was observed, as values were within the stressed to acceptable range (3.5 – 6 mg L^{-1}) (Figures 42 and 43).

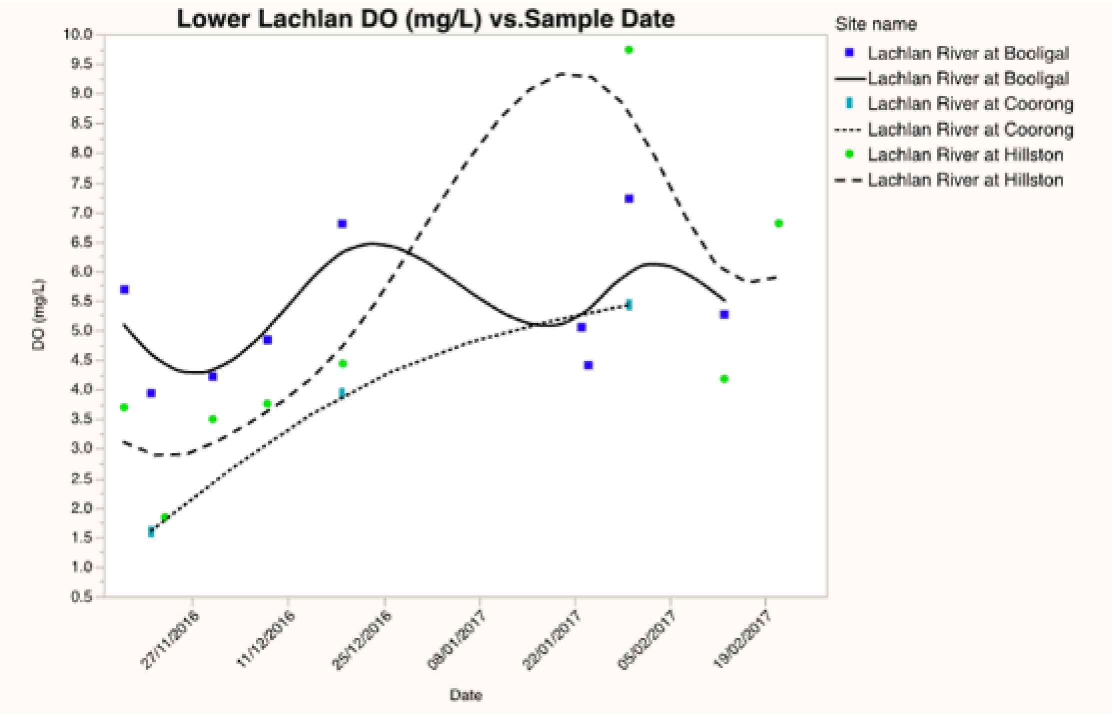


Figure 42 The lower Lachlan dissolved oxygen concentrations from spot sampling at three sites, Data: NSW Office of Water

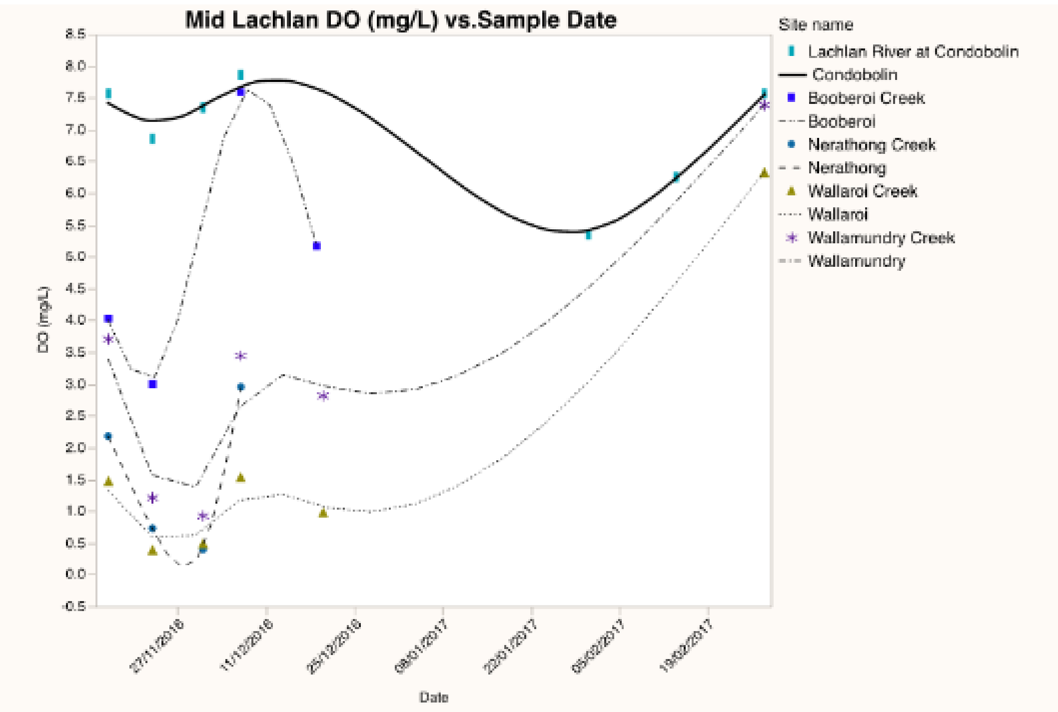


Figure 43 Dissolved oxygen concentrations in the mid Lachlan reach at Condobolin and streams in the Lake Cowal area

Water temperatures increased during late spring and early summer in the lower reaches of the Lachlan. The fish kill that reported to NSW Fisheries in early November occurred around the peak of the flood, and when the surface water temperature was an average of 21 °C (7-days, prior to the incident).

Table 7 Surface water monthly mean temperatures for Hillston Weir (Source: NSW DPI Water)

Month (2016)	Surface water temperature (°C)
July	11.0
August	12.3
September	15.2
October	19.3
November	24.0
December	25.9

Figure 44 Image showing blackwater pulse from the lower Lachlan entering the Redbank canal in the Murrumbidgee Catchment

Water Chemistry

Water quality monitoring such as spot grab sampling is modest in the Lachlan River and there are not in situ loggers at gauging stations to measure temperature or dissolved oxygen. In consideration of the conditions experienced in 2016, Water NSW commenced weekly event based spot sampling at nine sites, over a four-week period, and commenced in mid-November. The monitoring sites were located in the mid and lower reaches of the Lachlan River and its tributaries. The physicochemical parameters considered included; dissolved oxygen, temperature, electrical conductivity, turbidity and nutrients (TN, TP, NOx, FRP, TC, TOC and TIC).

At Condobolin, DOC concentrations were below those recorded for the lower reach sites. Extrapolating any tendency from the data is problematic, as the first sampling date was 35-days after the peak, and clearly on the falling limb (Figure 45). In the lower reaches (Corrong and Oxley) DOC concentrations were 23 to 28 mg L^{-1} in November, and 30 mg L^{-1} in December. The flattened hydrograph for the Lachlan River Corrong gauge (412045) shows the peak discharge of 1919 ML/day occurred on 21/12/2016, whereas upstream at Booligal (412005) the peak discharge of 3867 ML/day occurred 27-days earlier on the 25/11/2016, and corresponds to the highest DOC concentration of 23 mg L^{-1} at this site. The DOC concentrations exceeded the global average for temperate rivers at all sites, however to better inform understand flood behaviour and contaminant mobilisation and load event based monitoring needs to occur occurred on the rising and falling limb.

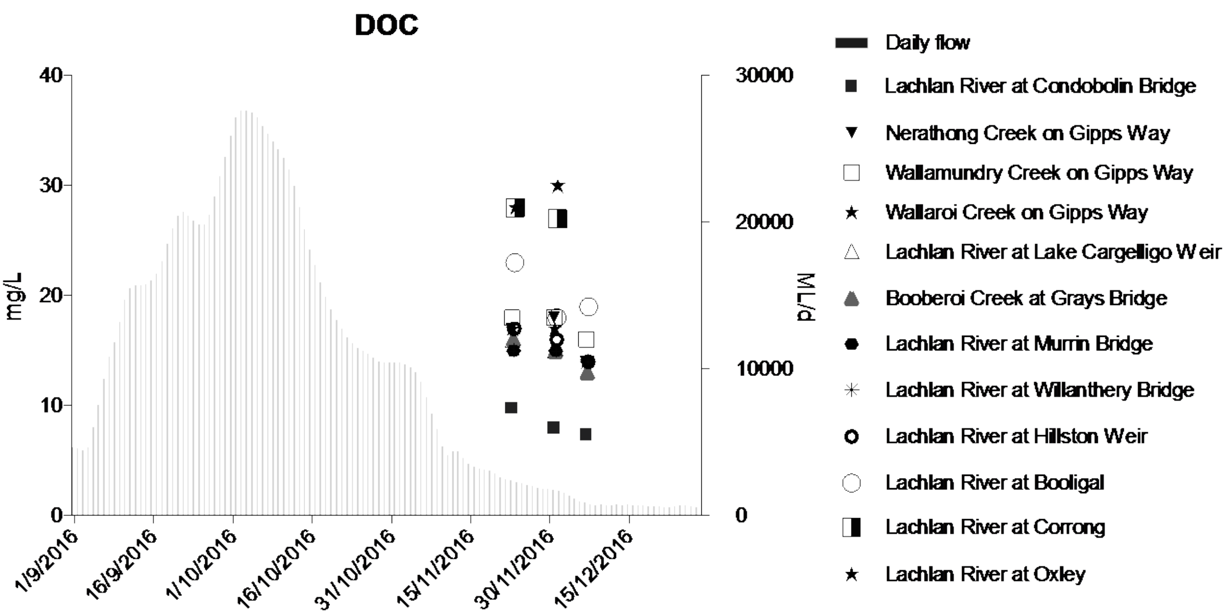


Figure 45 DOC weekly spot sampling data from the Lachlan River (Source: Murray Darling Basin Commission Water Quality)

Nutrient enrichment (up to 8% of the yearly average) can occur within the first 5 to 10 days of a flood event, and the addition of nutrients can lead to significantly higher bioavailable DOC that is likely to increase bacterial development (Fouilland et al. 2012; Hitchcock and Mitrovic 2015). Figure 46 shows the box and whisker plot for the combined macronutrient data, and the median values for TN (2500 µg L^{-1}) and TP (380 µg L^{-1}) exceeded the ANZECC guidelines at all sites.

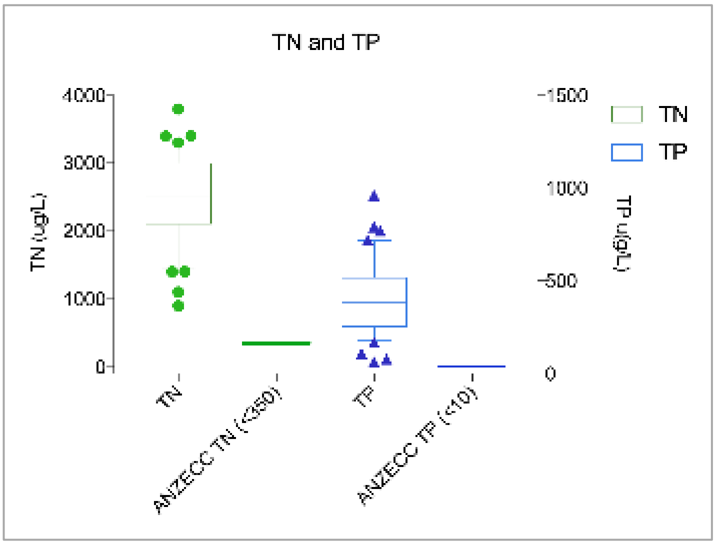


Figure 46 Box and whisker (10-90 percentile) plot showing macronutrient data for TN on the left y axis and TP on the right y axis with the ANZECC guidelines for lowland ecosystems (moderately disturbed) shown (*n*=42)

Water maps and DO time series

The inundation mapping for the Lachlan River is focussed on the mid reach where environmental flows were directed in 2016 and is vector data derived from Landsat 8 and Sentinel 2a satellite imagery. The DO concentrations shown for the Lachlan were derived from weekly spot sampling and represent the average for sites where monitoring was undertaken. The inundation pattern, and the dissolved oxygen values were classified according to the DO threshold values shown in Table 1 (acceptable = grey, stressed = green, highly stressed = orange and fish kill likely =red). The resultant maps for the Lachlan River are shown in Figures 47-50. Figure 49 shows open water in the catchment, as imagery was captured directly following a significant rain event in December.

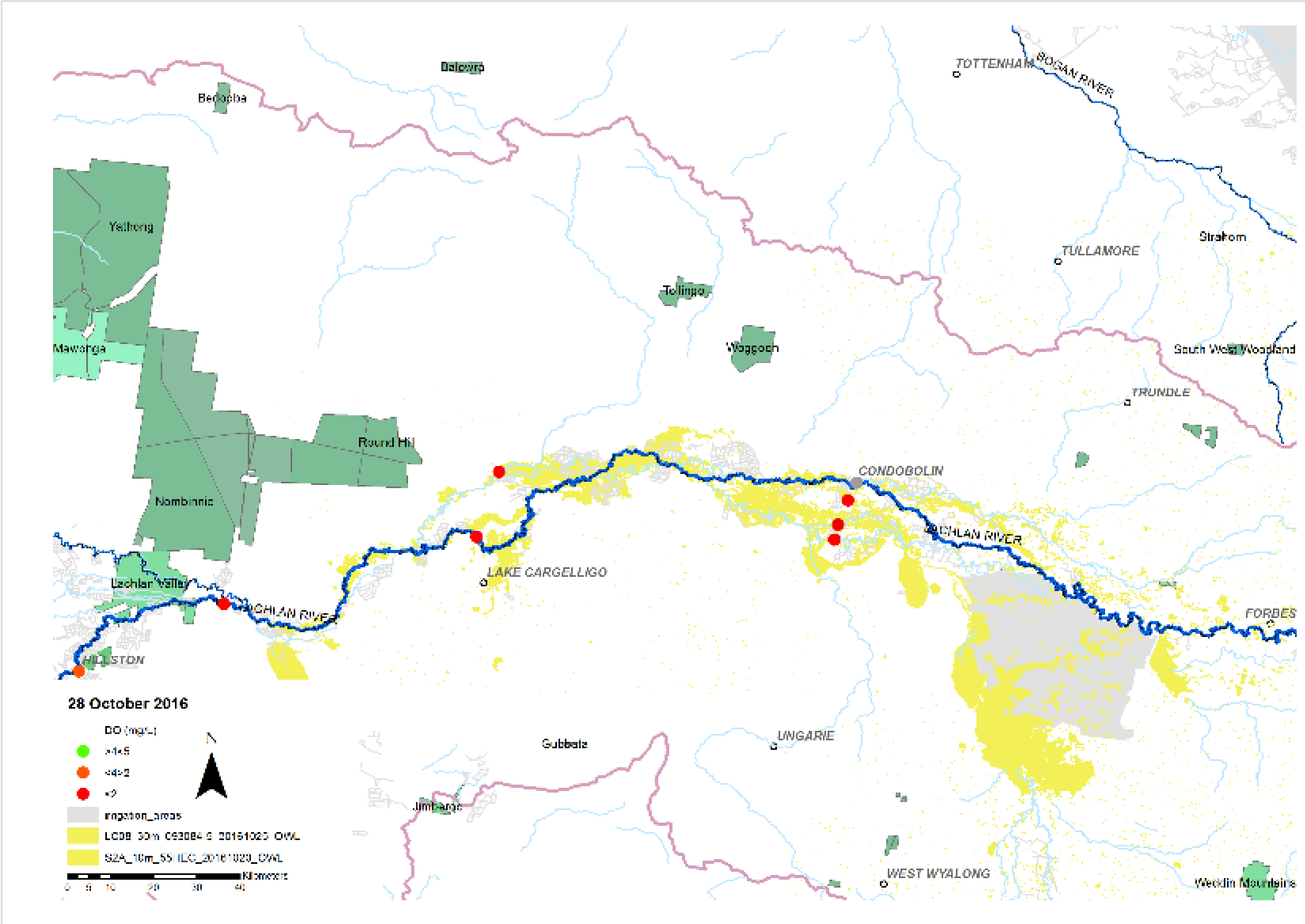


Figure 47 Average dissolved oxygen for sites in the mid Lachlan River (and case study area at Lake Cowal) (October 2016), and inundation from Sentinel 2 and Landsat imagery (yellow Inundation)

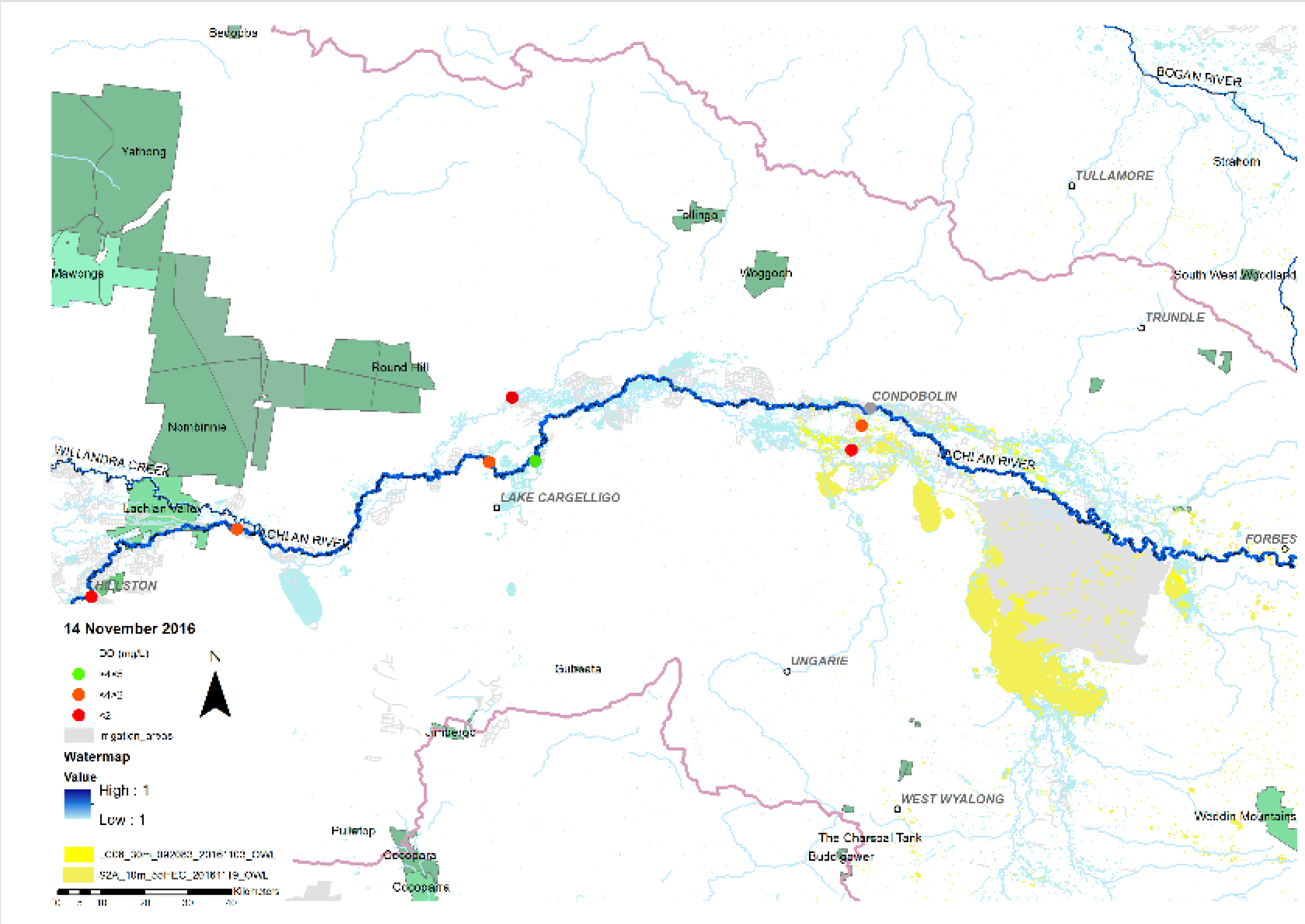


Figure 48 Average dissolved oxygen for sites in the mid Lachlan River (Lake Cowal) (1-14 November 2016), and data derived from Sentinel 2 and Landsat imagery (yellow Inundation mapping). NSW OEH composite water map shows area where inundation occurred in landscape the period July 2016- April 2017) in pale blue

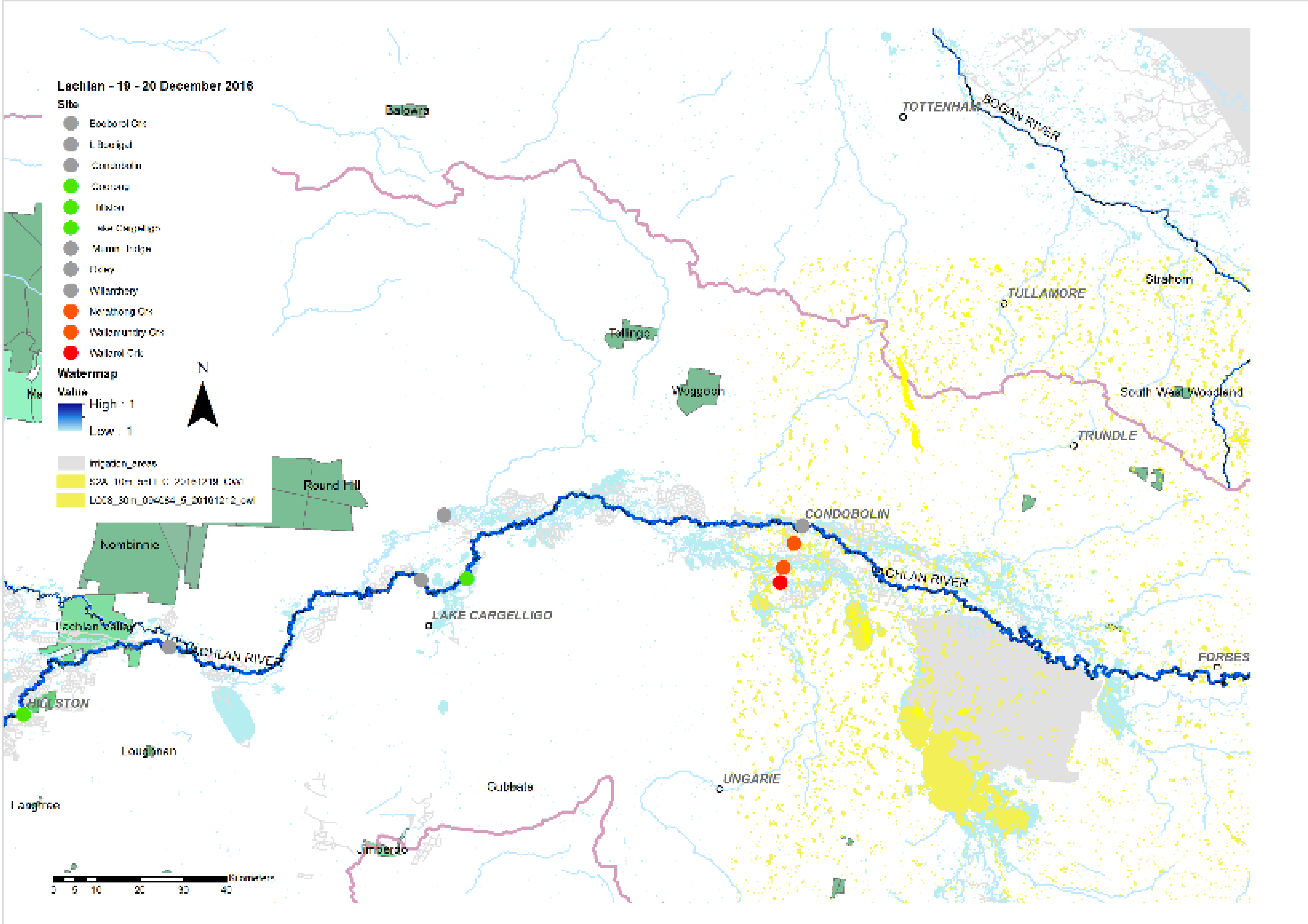


Figure 49 Average dissolved oxygen for sites in the mid Lachlan River (Lake Cowal) (1December 2016), and water inundation derived from Sentinel 2 and Landsat imagery (yellow Inundation mapping). NSW OEH water composite water map data shown in blue.

Impact to aquatic species

A local landholder reported a fish kill upstream from Hillston on 08/11/2016 to NSW Fisheries. The report indicated 100s Murray cod ranging in size from 60 to 90 cm were observed floating on the surface of the water. The fish kill was estimated to over a 14 km reach within the Lachlan River. Physical characteristics were also described that is, a strong odour and a dark tea colouration of the water. The fish were bloated which tends to suggest they perished a number of days earlier, but exactly when the sub lethal conditions were reached was not determined. Decomposition rates of Australian native fish are relatively unknown.

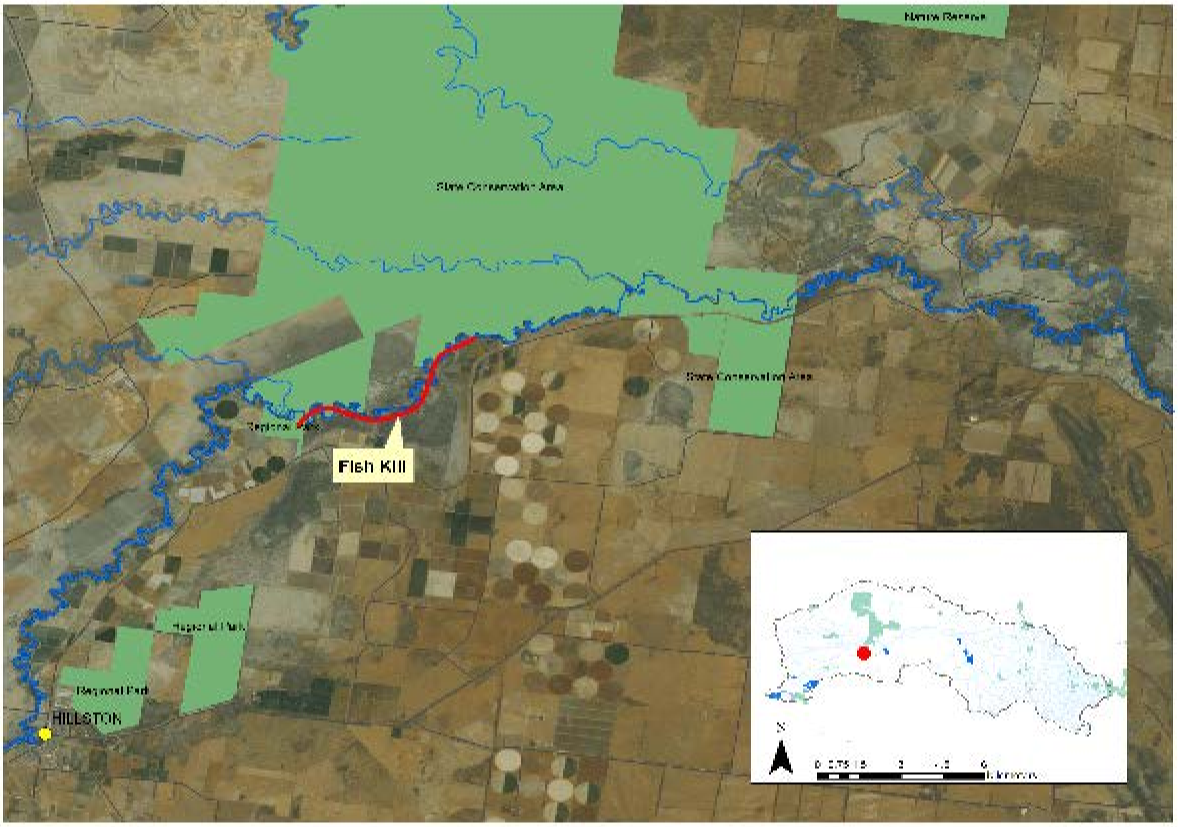


Figure 50 Location of the Fish Kill reported in the lower Lachlan D/S from Hillston (October or early November 2016)

The University of Canberra researchers responsible for Long Term Intervention Monitoring (LTIM) in the lower Lachlan did not detect any native fish, larval fish or fish eggs at replicate sites during site visits in October or December 2016. The low dissolved oxygen concentration (< 2 mg L^{-1}) from the sampling undertaken during the high flows was considered to be a factor preventing native fish spawning (Dyer et al. 2016). Native aquatic species have adaptive capacity or physiological mechanisms and are adapted to variable conditions and short-term low oxygen conditions. In particular, they may employ respiratory responses, and cease feeding or breeding. Importantly there will be a large variation among taxa in response to hypoxia. For example, the low Lachlan LTIM drift net catches consisted largely of Chironomids (bloodworms) and micro-crustaceans (predominantly Cladocera, commonly known as water fleas).

Environmental flows

The rational to release environmental water in the Lachlan River was based on field observations, that is, the grab sampling data provided by research partners from the lower Lachlan, and the subsequent event monitoring (weekly) undertaken by NSW DPI Water and NSW OEH for the mid and lower reach of the Lachlan River. Based on advice provided by NSW OEH regarding the mid Lachlan where poor water quality inflows had previously impacted the river during flood events, this reach was viewed as a priority. It was feasible to release environmental flows to target low dissolved oxygen in the mid reach whereas widespread flooding prevented any releases at the end of the system.

The NSW Water Quality Allowance (WQA) that was originally for salinity and harmful algal bloom mitigation, was released at a rate of 2,000 ML/day for approximately five days from Wyangala Dam, and commenced on 05/11/2016. Given the environmental conditions a cyanobacteria bloom occurrence was rated as low risk in 2016/17, however 10,000 ML was withheld for a contingency. The WQA achieved a target flow rate of 3,000 ML/day downstream at Forbes over 5 days. This was followed by a shared action (75:25) to maintain refuge flows using Commonwealth Held Environmental Water and NSW OEH allocation (Figure 51). The total volume of CEW and NSW OEH water used to generate fish refuge was 29,918 ML and 11,161 ML respectively. Also, the within channel watering action was implemented as a transition flow as dam releases were scheduled to be reduced to minimum flows.

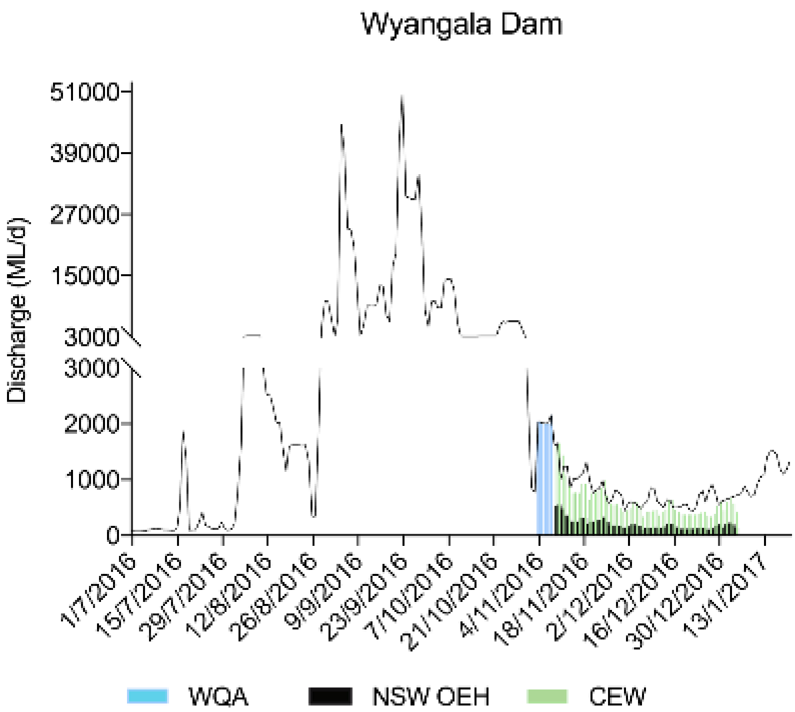


Figure 51 Environmental flows released on the falling limb of the hydrograph from D/S Wyangala Dam from November 2016 to 4 January 2017 (shaded areas = water holders contributions)

The staged recession from 2000 to 500 ML/day was based on Water NSW ratings tables, to ensure flooding at Hillston was not exacerbated. The environmental water flows were longitudinal, and given the lag in travel time due to widespread flooding and slow return rate, the environmental water flows were commensurate with the CEWH's ‘no third party impact’ policy. The main objective cited in the Water Use Recommendation (CEWO, November 2016) was; *to minimise the potential influence of hypoxia—the subsequent depletion of dissolved oxygen (DO) in the Lachlan River in order to provide refuge for freshwater aquatic communities*. The environmental water targeted the mid reaches of the Lachlan River at Forbes, as there were few if any options available to mitigate hypoxia in the lower reaches. The flattened hydrograph at Hillston Weir exemplifies the magnitude of the 2016 event, with the peak on /10/2016 at 3.1 metres, which was close to the 1956 maximum level of 3.3 metres recorded at Hillston.

Charges associated with the delivery of environmental water

The cost of fees associated with the Commonwealth’s environmental flows in the Lachlan River was $728,157.48.

Communication

An interagency Technical Advisory Group (TAG) (OEH, DPI Water, DPI Fisheries, Local Land Services and the CEWO) was established once low oxygen conditions were identified in the Lachlan River. The TAG was facilitated by OEH, and the group met weekly to discuss flows, field data and environmental flows. Formal minutes were recorded for each meeting, up until December 2016.

The Water Use Recommendation – Lachlan dated 05/11/2016 was developed to manage hypoxic blackwater and included the following objective: Provision of a designed event to minimise the potential influence of hypoxic Blackwater —the subsequent depletion of dissolved oxygen (DO) in the Lachlan River in order to provide refuge for freshwater aquatic species. Therefore, dilution was not considered as an option given the flow rate.

The rationale to undertake the proposed action and target the mid Lachlan reach was based on learnings from previous events where flood return water from the Lake Cowal area was found to contain pollutants (DOC). This together with anecdotal observations provided by community members that water in the general area (upstream of Jemalong and Wolaroi) had a putrid smell and dark (tea stained) colour was indicative of blackwater (as it is known to have an unpleasant smell) (pers. comm. Paul Packard, OEH, Sam Davis, DPI Fisheries, 2 November 2016).

There were two media releases published for the Lachlan. The first titled *Lachlan River Low Dissolved Oxygen Levels* dated 11/11/2016 was published under the Local Land Services logo. The second, titled *Flows underway to reduce the impact of low dissolved oxygen levels in the Lachlan* dated 01/12/2016 was released by the CEWO. The key points in the second media release related to the creation of fish refuges in the Lachlan River and informing the community of the environmental flows targeting the Lachlan River downstream of Forbes.

Summary

The environmental flows met the objective in the water use recommendation for the Lachlan River as no fish kills were reported in the mid reach. Due to the extent of flooding in the lower reaches there was no capacity to deliver environmental water, and the fish kill that was observed happened on the initial pulse in late October or early November.

The Lachlan is often referred to as a terminal system, and yet the large flood event (1: 30 year) demonstrates it is very much a connected system, with a direct influence on the hydrology and water quality of the lower Murrumbidgee. The environmental water intended to create fish refugia, was released on the falling limb of the hydrograph. The environmental water was a precautionary measure to circumvent any potential risk associated with low dissolved oxygen in the mid reach of the Lachlan.

The fish kill in the lower Lachlan was detected when a landholder contacted NSW DPI Fisheries, and is another demonstration of valuable community input. The anecdotal data was a valuable source of information, regarding the identification of the species impacted, and the spatial extent of the fish kill. Yet, it was not possible to accurately verify the point in time when the fish kill occurred, as decomposition rates of the native species lacks a complete understanding. Parmenter and Lamarra (1991) for example showed rainbow trout (*Oncorhynchus mykiss*) had only a slight tendency to bloat in the first few days following their demise. The fish kill in the Lachlan may have occurred a number of days prior to the landholder witnessing large bodied Murray cod floating on the surface.

Sustaining populations of higher order consumers (fish) tends to be the priority when managing low oxygen events. Yet, an important ecological response arising from the 2016 low oxygen conditions was the emergence of Chironomids. Known as non-biting midges, the larvae (bloodworms) were seen in many rivers in parallel with low oxygen concentrations. They were abundant and reproduced quickly due to the increased load of organic material. Bloodworms have the capacity to clean up the environment by feeding on bacteria and algae. Their bright red adaptation shows the presence of haemoglobin – similar to that in human blood, which allows the storage of oxygen. With an ability to survive in extreme conditions of temperature, pH, salinity, organic pollution, and heavy metal loads (Laviad and Halpern 2016), bloodworms have potential to be useful biotic indicator of poor water quality. The larvae and pupae are food for both insects and fish.

The frequency of the water quality data used to inform environmental water flows in the Lachlan was insufficient. Different equipment was used to measure DO, and calibration or maintenance of these instruments was unknown. Furthermore, in the lower Lachlan (and elsewhere in the basin) submersible DO sensors are deployed as part of the LTIM metabolism program. The high frequency data (logged every 10 minutes) is an important source of information yet retrieving data from the loggers was not possible in real time due to the extent of flooding.

To manage hypoxic blackwater events effectively, water managers require access to real time data that has temporal frequency. Standardised methods throughout the MDB would better inform the delivery of environmental water flows during poor water quality events and flood events that often have a detrimental impact on water quality. Due a deficient network of DO probes, the actions implemented by water resource managers in 2016 were reactive rather than responsive. When adequate resources are allocated to water quality monitoring, research has shown the cost of amelioration is greatly reduced. Table 7 provides an estimate of the cost associated with the installation and maintenance of D-Opto Optical instruments for monitoring the parameters temperature and dissolved oxygen. Ideally in the Lachlan DO and temperature loggers would be installed in the mid and lower reach of the Lachlan River (Condobolin and Hillston) where low oxygen conditions were found in 2011 and 2016.

Table 8 Estimate of cost to install and maintain dissolved oxygen sensors at telemetered gauging stations

Item	Cost ($)
The installation of two DO probes (Including upgrade to infrastructure and labour)	10946
DO probe (2 instruments)	8530
Annual maintenance	9100
Total (exclusive GST)	**28576**

The unplanned approach adopted to respond to the low dissolved oxygen concentrations in the Lachlan was not ideal. To improve the management of blackwater events in the future early intervention, preparedness and advanced communications are essential. The Lachlan Technical Advisory Group was reliant on local knowledge to guide decision making, and while the approach provide to be acceptable, access to real-time spatial and stream water quality data from selected gauging stations may have served to alert water managers of the approaching drop in dissolved oxygen, accurately tracked the pulse of hypoxic blackwater as it moved through the system and measured recovery explicitly. Also, as it is understood the initial flood pulse triggers fish movement, and therefore data from sites where dissolved oxygen is above the acceptable threshold is also required to inform environmental releases. This applies to the Lachlan and other sites where In situ water quality monitoring is absent, and discussion with other water holders and the community is recommended.

An understanding of aquatic native species response to low oxygen events was identified as a key knowledge gap in the Lachlan. Consequently, investment in long term monitoring to measure fish movement pre and post low oxygen conditions, including response behaviours, the time taken for fish to re-establish at sites that were impacted and the factors driving productivity.

Goulburn Broken

The Goulburn River flows primarily through cleared agricultural land, and via a narrow (<150 m) forested river red gum floodplain along the lower reaches, upstream of Shepparton to its confluence with the Murray River at Echuca. The river is largely regulated with major storages particularly Lake Eildon and Lake Nagambie.

Hydrology

On 29 and 30 December 2016 an intense rain event (>100mm) produced localised stream responses in the upper reaches of the Seven Creek (Goulburn River) catchment. The high rainfall event influenced flows within the Stony Creek, as discharge increased from 3 ML/d to a peak of 8051 ML/d within 24 hours, analogous to the peak recorded in on 5 August 2016. Figure 52 shows the daily mean at the Stony Creek gauging station 405247. The rainfall in the upper Goulburn catchment produced some of the highest rain rates ever recorded in Victoria. A low-pressure system interacted with a frontal system in the Bight, forming a slow moving complex low-pressure system.

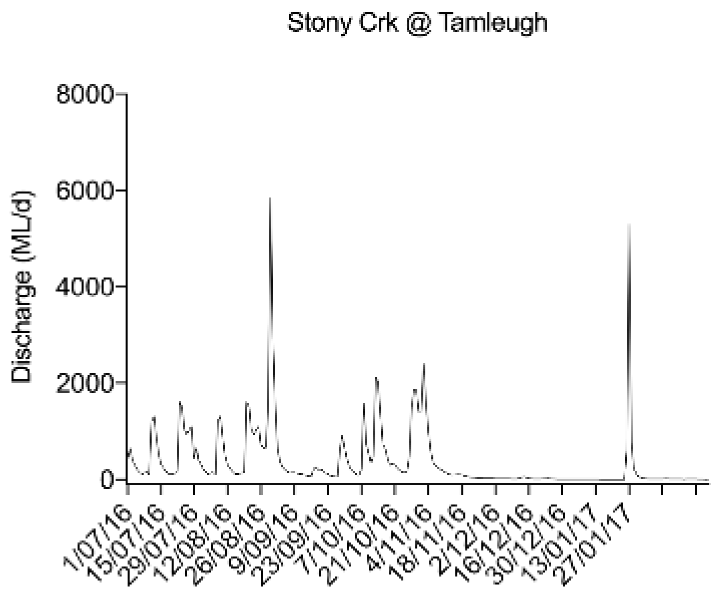


Figure 52 Site 405247 Stony Creek Discharge (daily mean) July 2016 to February 2017

The hourly flow data for Stony Creek in late December 2016 and early January 2017 is represented in Figure 53. The hydrograph shows a steep gradient rising limb to a peak of 8051 ML/d, consistent with a rapid increase in rainfall and surface run off. The falling limb was a gentler gradient than the rising limb as overland flow had been discharged.

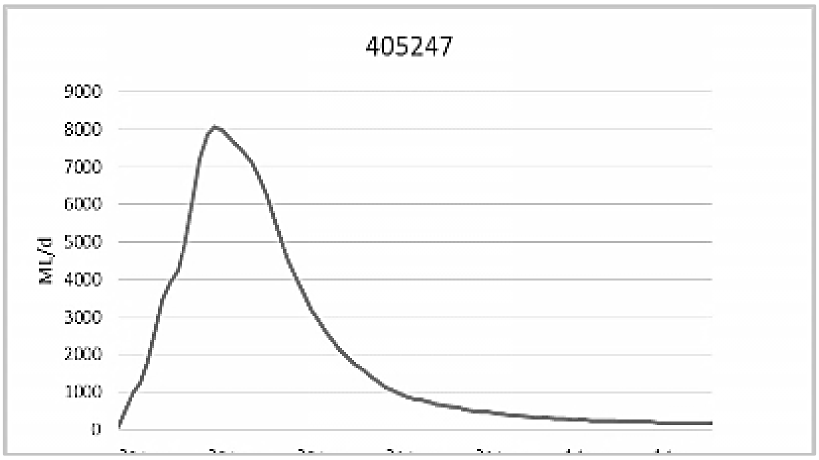


Figure 53 Site 405247 showing the peak of 8051 ML/day over 3 days

At the same time the Kialla West discharge was 4,300 ML/d, and the Broken Creek discharge was 2,000 ML/d (see details for the Broken Creek below). The peak discharge in the Goulburn River at Shepparton was 5,500 ML/d on 1 January 2017, and decreased to ~1,500 ML/d by mid-January 2017 (Lovell 2017).

Goulburn River dissolved oxygen concentrations

The dissolved oxygen concentrations at the Shepparton gauging station 4052718 dropped below the fish kill threshold to 1.4 mg L^{-1} on 02/01/2017. The hypoxic blackwater event was not protracted in the Goulburn River, and despite the plume of poor water quality recovery to acceptable dissolved oxygen levels >5 mg L^{-1} occurred within 7-days. Further downstream from Shepparton at McCoy's Bridge, the impact of the pulse of hypoxic water resulted in dissolved oxygen concentrations dropping to the likely fish kill range, of 1.2 mg L^{-1} on 04/01/2017. Similar to values recorded upstream at Shepparton dissolved oxygen remained below the acceptable trigger value of 5 mg L^{-1} for approximately 6 days. The low oxygen conditions in Goulburn River reach returned to acceptable levels by Friday 06/01/2017, and there were no further reports of hypoxia after this date.

Impact to aquatic species

On 31/12/2016 there were reports of dart coloured water in the Goulburn during the afternoon and recreational users reported stressed shrimp and spiny crays at Mooroopna (Lovell 2017). DO levels dropped to 4.3 mg/L at Shepparton golf club, but then subsequently rose in the afternoon. At the time it was thought the levels were above those that would cause impacts to aquatic species. On 02/01/2017 the Victorian DPI Fisheries reported a fish kill and estimated that approximately 200 native fish had perished. The fish kill appeared from the confluence of the Goulburn River and Seven Creeks, up to Undera. A small number of crustaceans (shrimp and spiny cray) were showing obvious signs of stress, as they were emerging from water. By 04/01/2017, the extent of the fish kill became apparent as ~ 1,000 native fish, predominantly *M. peelii* (Murray cod) of all sizes had perished. The other native species affected were *Macquaria ambigua* (Richardson, 1845) *and Bidyanus bidyanus (*Mitchell, 1838) (Golden and Silver perch). NSW Fisheries advised fish kills are more likely to occur in the early morning when dissolved oxygen is at its lowest in the diel cycle. (pers. comm. Iain Ellis 18 May 2017

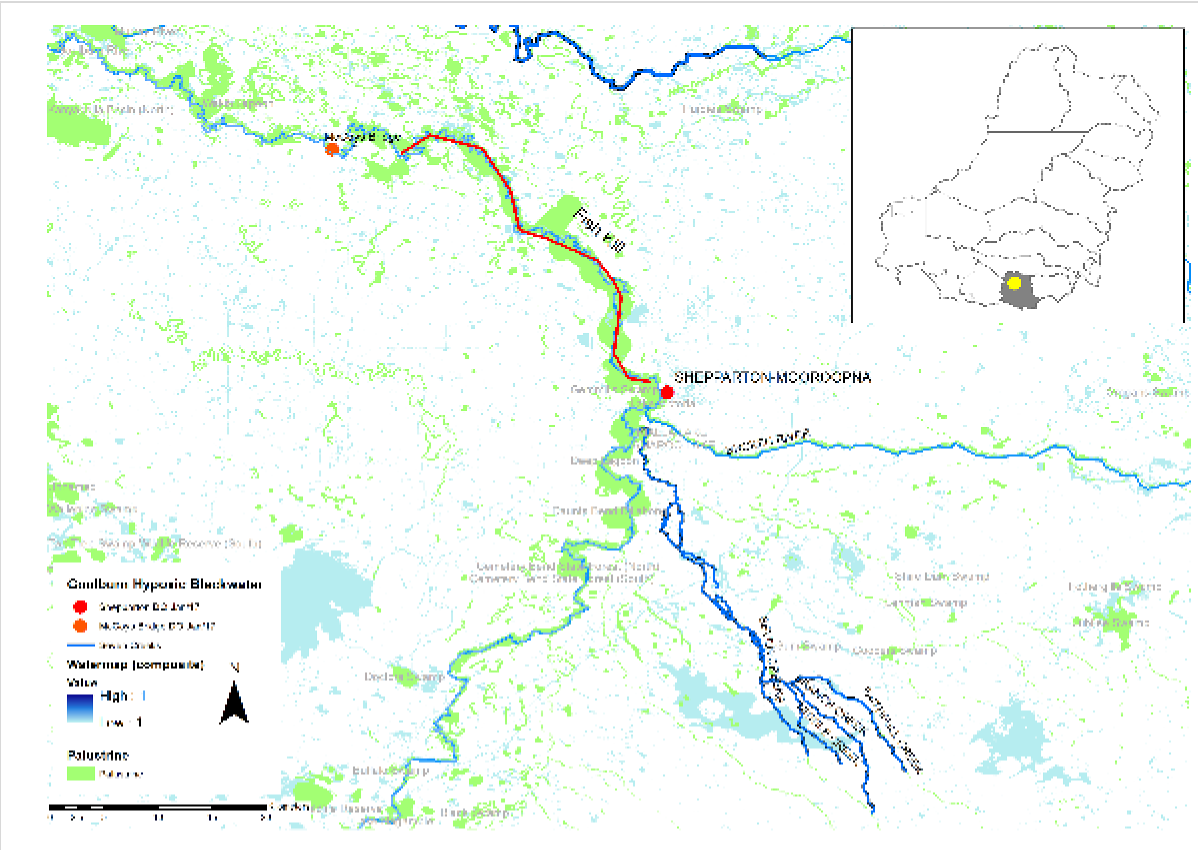


Figure 54 The Seven Creeks influence by the intense rain event in 29 December 2016, and Goulburn River reach D/S from Shepparton (red) where the fish kill from 2 to 4 January 2017 occurred

Environmental flows used to improve low dissolved oxygen

Eildon releases (Goulburn Water Quality Reserve) commenced on 02/01/2017, and passed Goulburn Weir two days later (04/01/2017). Releases from Lake Eildon started at a flow rate of 800 ML/d, then 2,000 ML/d and aimed to reach 5,000 ML/d to enable the delivery of sufficient water to generate refuge flows downstream of Goulburn Weir. Travel time from Lake Eildon to the Goulburn Weir takes 2.5 days. Therefore, the Goulburn Murray Irrigation distribution channel outfalls were used where possible to accelerate the delivery of environmental water. Flows at McCoy's Bridge D/S from Shepparton reached 4,000 ML/d before receding to 2,800 ML/d in mid-January 2017. The Goulburn weir peak was 3,000 ML/d and reduced according to a planned recession. However, the travel time from the accounting point at Eildon delayed the delivery of oxygenated water downstream of Goulburn weir, and regrettably was delivered after the significant fish kill had occurred. The flows nonetheless would still have provided refuge for species that survived the initial pulse 'shock'.

The management of this hypoxic blackwater event was limited by the time required to order and deliver the volumes of environmental water required to generate refuge and/or dilution. Quite simply there is often insufficient water in the system to meet all demands in the summer, and it takes time for water released from Lake Eildon to reach the Lower Goulburn.

The combined environmental water (IVT and CEWH) refuge flows that totalled 29,174 ML and released during late December 2016 and January 2017 are shown in Figure 55 and Table 9. The Commonwealth's contribution to the refuge flow intervention in the Goulburn River was 8,199 ML.

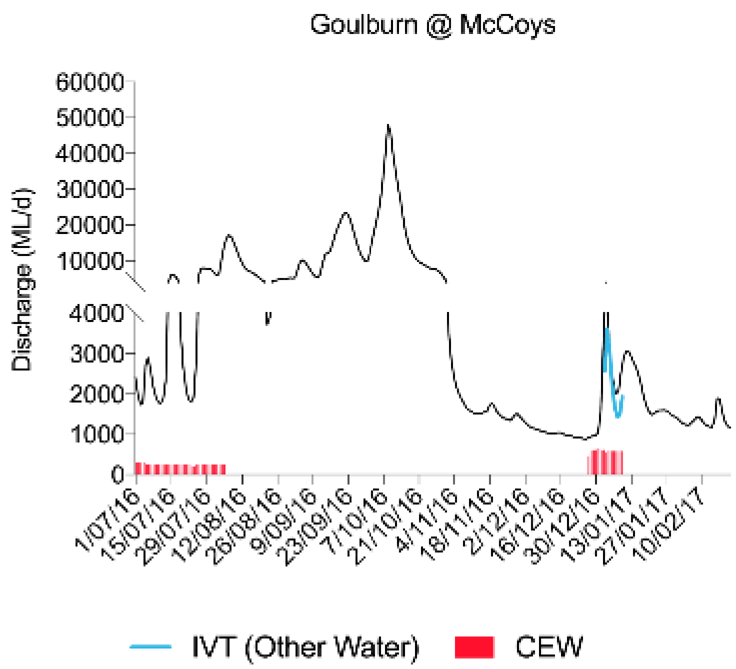


Figure 55 Hydrograph at McCoy's Bridge and the environmental water releases targeting low dissolved oxygen D/S Shepparton from 27 December to 10 January 2017

Table 9 Refuge flows (ML/d) for the Goulburn at McCoy's bridge – 27 December 2016 to 9 January 2017

	Eflow and IVT	CEWH Environmental Release	Total
December	1907	2932	4840
January	19067	5267	24334

A low flow rate environmental flow (~300 ML/day) was released in July 2016 for 35 days. With significant rainfall and high inflows during August this flow was discontinued, and any decision regarding environmental flows such as the planned fresh for golden perch spawning fresh in September was held in abeyance. Outside of the irrigation season 8,500 ML/d is the maximum rate for the delivery of environmental water. The planned late spring fresh action was cancelled due to concern that any further inundation of vegetation on the lower banks, could result in overwatering of floodplain vegetation, and bank slumping was identified as a potential risk as the soil profile was saturated. The Eildon releases for the irrigation season also commenced at the beginning of November 2016.

Collaboration and Decision Process

The Goulburn Broken Catchment Management Authority (GB CMA) convened the Lower Goulburn River Blackwater Event Workshop in February 2017. Water holders, water resource managers and key stakeholders considered the actions that led up to the hypoxic blackwater event, the current gaps in understanding, and the watering actions delivered. The workshop was designed to identify opportunities to improve responses to low oxygen conditions in the future. The GB CMA sought to consult with partners, clarify responsibilities of the water agencies, identify irrigation infrastructure that could be used for dilution and refuge flows and develop a blackwater risk assessment tool. A report titled the *January 2017 Goulburn River Blackwater Event Summary and Actions*, made a number of recommendations including:

- The need for a Blackwater Response Plan
- Longer term water quality monitoring
- Fish population monitoring (tracking)
- Soil analysis to investigate water chemistry
- Environmental water constraints, that is, flows >3000ML/d requires 4 weeks' prior notice during the irrigation season, whereas orders of up to 8500ML/d may be delivered outside of the demand period.

Summary

Observations from previous studies of hypoxic blackwater events shows it is possible to re-oxygenate low oxygen water using in-channel regulatory structures and that there are measurable localised improvements (Whitworth et al. 2013). The oxygenated water delivered in the Goulburn River using in river and irrigation infrastructure would have mixed with the river water as it moved downstream, and provided refuge for native fish, especially large bodied species with limited capacity to move from the affected reach. The hypoxic blackwater event in the Goulburn River was not classified as a prolonged incident, and in many respects contrasts the low oxygen conditions that occurred in other parts of the basin during the spring of 2016.

The impact of the low oxygen pulse in the Goulburn River D/S from Shepparton was pronounced, and the conditions proved fatal for ~1000 native fish, whereas the invasive carp were able to withstand the poor water quality conditions, due to their resilient physiology. The volume and rate of environmental water released in the Goulburn River was insufficient to satisfy the recommended dilution flow ratio, and therefore adoption of the Blackwater Intervention Model in the future may serve to improve decision-making relating to the rate and volume of water required. The environmental flows were delivered on the falling limb of the hydrograph, and travel time from the water storage to the target reach delayed the recovery outcome.

The hypoxic event was characterised by an intense storm event that was unprecedented in Victoria's history, and this in combination with above average temperatures recorded in December exacerbated the decline in dissolved oxygen levels. Both climate and catchment condition, such as increased productivity following the above average rainfall during the winter were significant factors underlying the hypoxic event. It is evident from the spatial data that the localised rain event in the Seven Creeks catchment fell on a highly modified landscape with scant wetlands or riparian native vegetation remaining. Thus, the intense rain event flushed organic matter from the adjacent farmland to the upland streams triggering a consequent downstream ‘shock’.

Monitoring to determine DOC or any other potential stressors such as macro nutrients from the catchment was undertaken on the falling limb, and therefore critical pre event data was not collected. This data gap limits the ability to accurately measure load or other potential contaminants that may have also been present. The monitoring of key constituents in the upper reach is deficient, and consequently early warning of the flood event or threat posed to aquatic species was not measured until the pulse reached Shepparton.

It is difficult to ascertain from the available data if the release of environmental flows into the Goulburn diluted low dissolved oxygen (DO) and positively abated DO concentrations. In particular, the event occurred as a rapid pulse, DO entering the river was not measured at the source in the Stoney Creek, and therefore the ability to conduct a detailed analysis is limited. Hypothetically, the pulse of low oxygen water may have simply dissipated as it moved through the system. It is clear however the hypoxia was stimulated by the intense storm event in the upper reaches of the catchment when air temperatures were ideal for microbial decomposition of material. Elevated summer temperatures can positively promote microbial decomposition of dissolved organic carbon (DOC). There were aspects of the Goulburn River hypoxic event that were reminiscent of the summer blackwater incidents that occurred in the Murray River during 201/11. The event however contrasts 2011 in other respects, as the catchment in the upper reach where the intense storm event occurred is highly modified.

Broken Creek

The Broken Creek diverges from the Broken River west of Lake Mokoan and flows north-west to the Murray River. Most of the Broken River catchment has been cleared of native vegetation, and a large part of the northern section is situated within the Murray Valley irrigation district where intensive horticultural, dairy and livestock activities occur. The Barmah-Millewa, a RAMSAR Wetland Forest spans the NSW Victorian border – and it is directly influenced by the Broken Creek.

Figure 56 Barmah Forest (RAMSAR Wetland) at the confluence of the Broken Creek and River Murray (Source Goulburn Broken Regional River Health Strategy 2005-2015)

Hydrology

Flows within the Broken Creek in 2016 were associated with the high rainfall conditions experienced in the inland region of NSW during winter and spring. Data from downstream Rice's weir gauging station 404214 shows high flows occurred in August, September and early October. The upper Broken Creek tends to have relatively low flows all year round, and is ephemeral between Waggarandal Weir and Katamatite (GBCMA, nd).

In early September the unregulated flows in the Broken Creek were above the anticipated base flow for spring, at around 2,000 ML/day, following high rainfall in the catchment, and flows at Rices Weir were the highest in the last four years. Figure 58 shows the rising limb of the hydrograph as a gradual slope, and reflective of a prolonged rain event, to the peak discharge of 4810 ML/d that occurred 16 October 2016 at Rice's Weir.

Broken Creek dissolved oxygen concentrations

Dissolved oxygen concentrations dropped on the rising limb of the hydrograph at Rices Weir to the fish kill threshold of 1.39 mg L^{-1} on 27 October 2016. The median water temperature from 1 September to 11 November when DO began to recover was 16.0 °C. In early January 2017, DO concentrations dropped below the highly stressed range but these low values were not sustained (Figure 57).

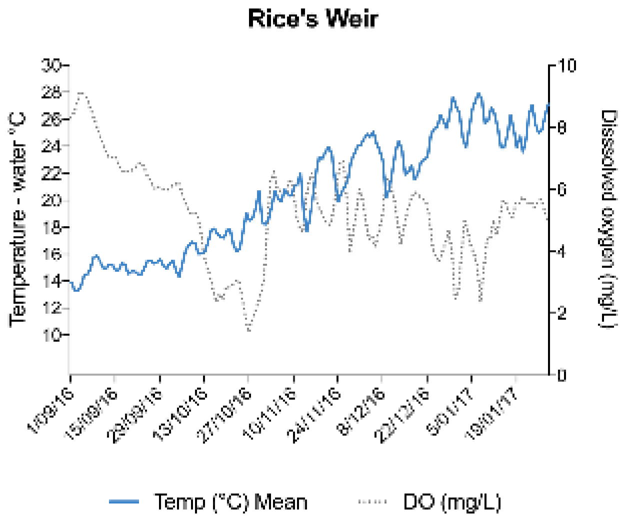


Figure 57 Dissolved oxygen concentrations at Rice's weir on the Broken Creek (Data: Vic data.gov)

Environmental water used to limit the impact of low DO

The Broken Creek WUM10041 (2015 to 2018) shows approval for the use of up to 40,000 ML of water per year in accordance with the partnership agreement between the CEWH and the VEWH. The schedule for water use over the three year period discusses a number of environmental objectives, including the requirement to maintain dissolved oxygen >5mgL $^{-1}$ at Rice's Weir. An original planned environmental release in the Broken Creek at a rate of 40 ML/day was due to commence 15 August and cease on 30/09/2016. However, this action was postponed due to high inflows, and indeed the follow up action was also held in abeyance due to high inflows.

When dissolved oxygen levels dropped below the critical threshold environmental water was released on the falling limb of the hydrograph as shown in Figure 58.

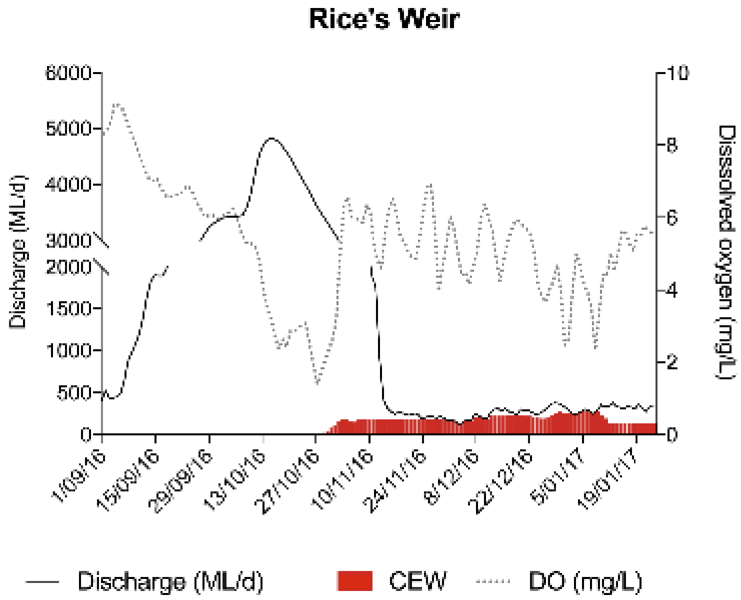


Figure 58 Broken Creek at Rice's Weir and the CEW environmental water released early November to January 2017. Figure shows dissolved oxygen concentrations and total discharge (ML/d).

Water map and dissolved oxygen

The inundation pattern, and the dissolved oxygen values were classified according to the DO threshold values shown in Table 1 (acceptable = grey, stressed = green, highly stressed = orange and fish kill likely =red). The resultant maps for the Broken Creek are shown in Figures 59-60.

Summary

In 2015 when the WUM10041 for the Broken Creek was developed the risk of a hypoxic blackwater event was rated as low, and similar to other environmental watering plans (southern basin), it was suggested a fish kill was more likely to occur during the summer to autumn period. The 2016 event shows that a large natural flood event occurring spring can also produce a hypoxic blackwater event. Thus, amendment is required to the existing planning framework, and the risk factors to be included comprise; the influence of high intensity rain events, different flood scenarios, seasonality and an indicative temperature gradient (see, Blackwater management, Table 1).

There was a rapid recovery in dissolved oxygen levels at the Broken Creek site corresponding to the steep falling limb of the hydrograph, and the environmental flows would have had a positive influence for downstream native biota in the Barmah-Millewa area. Sustaining the environmental watering action beyond the initial recover proved to be advantageous, when temperatures increased to 28°C in December, particularly as dissolved oxygen levels dropped for a second time.

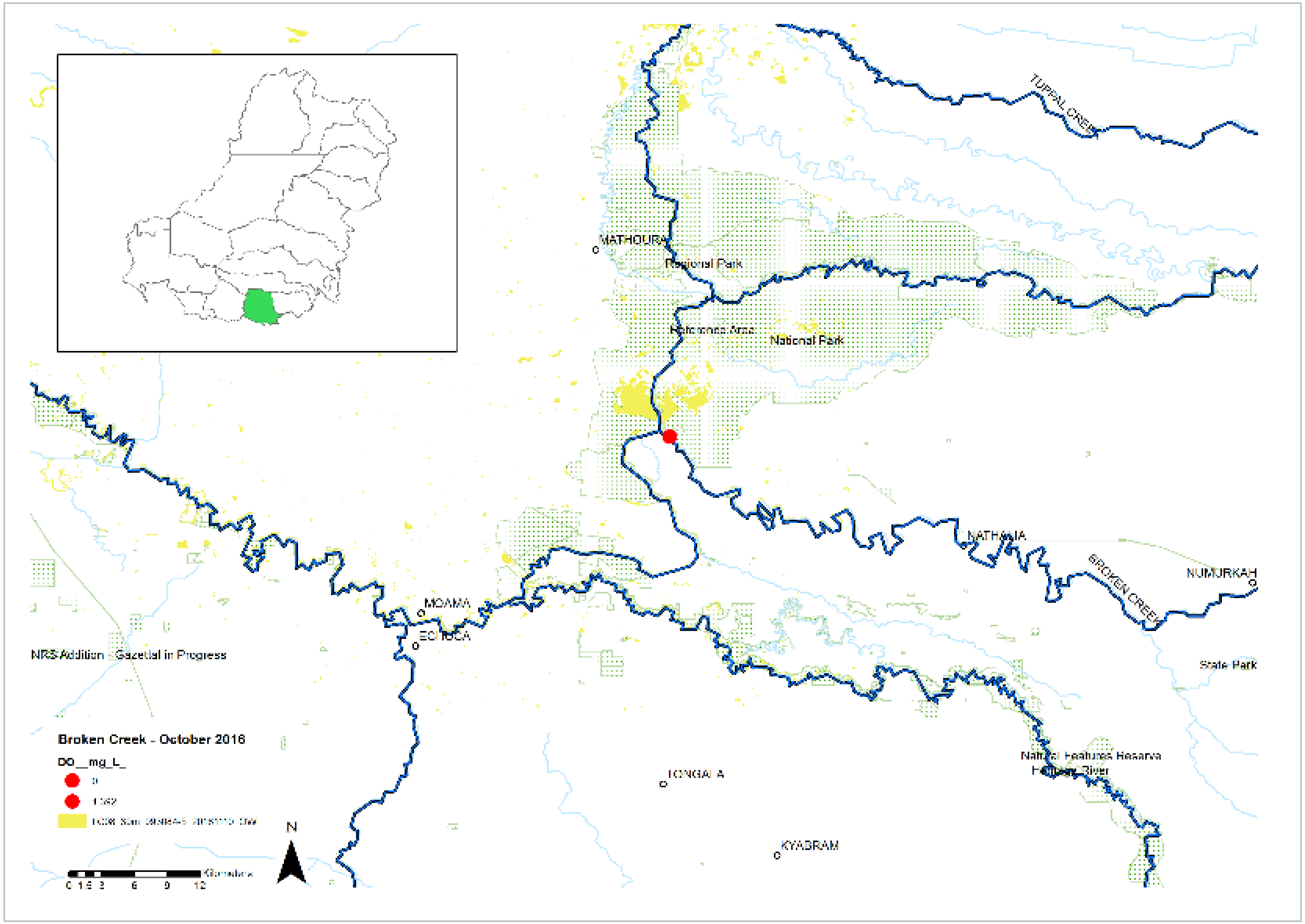


Figure 59 Rices Weir on the Broken Creek, where continuous data showed DO was at highly stressed and reached a likely fish kill level during October 2016 (Yellow = inundation mapping derived from Landsat (source: DO data from DELWP)

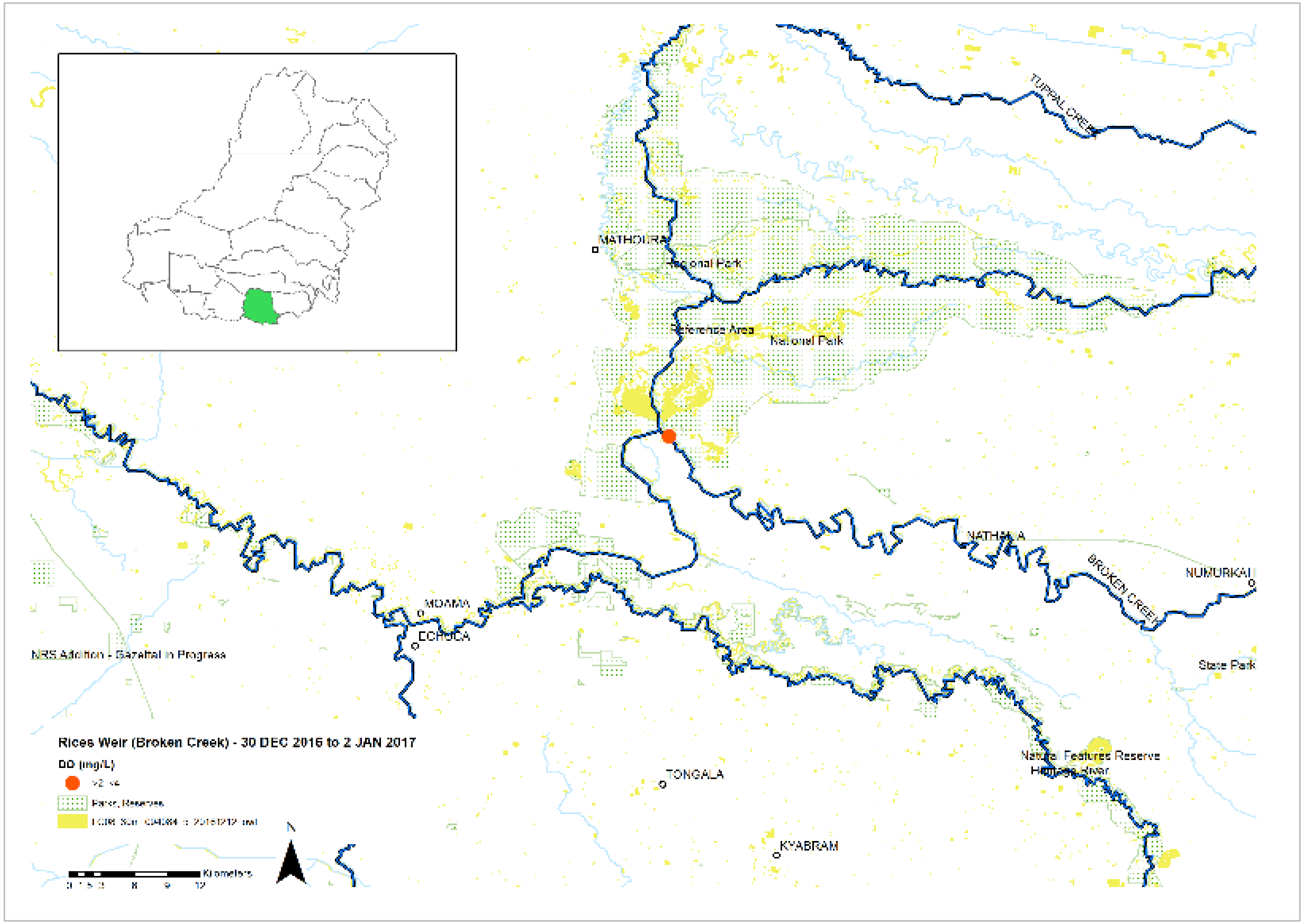


Figure 60 Broken Creek at Rices Weir, where continuous data showed DO was at amber alert (30 Dec 2016 to 2 Jan 2017) Yellow = inundation mapping derived from Landsat (source: DO data from DELWP)

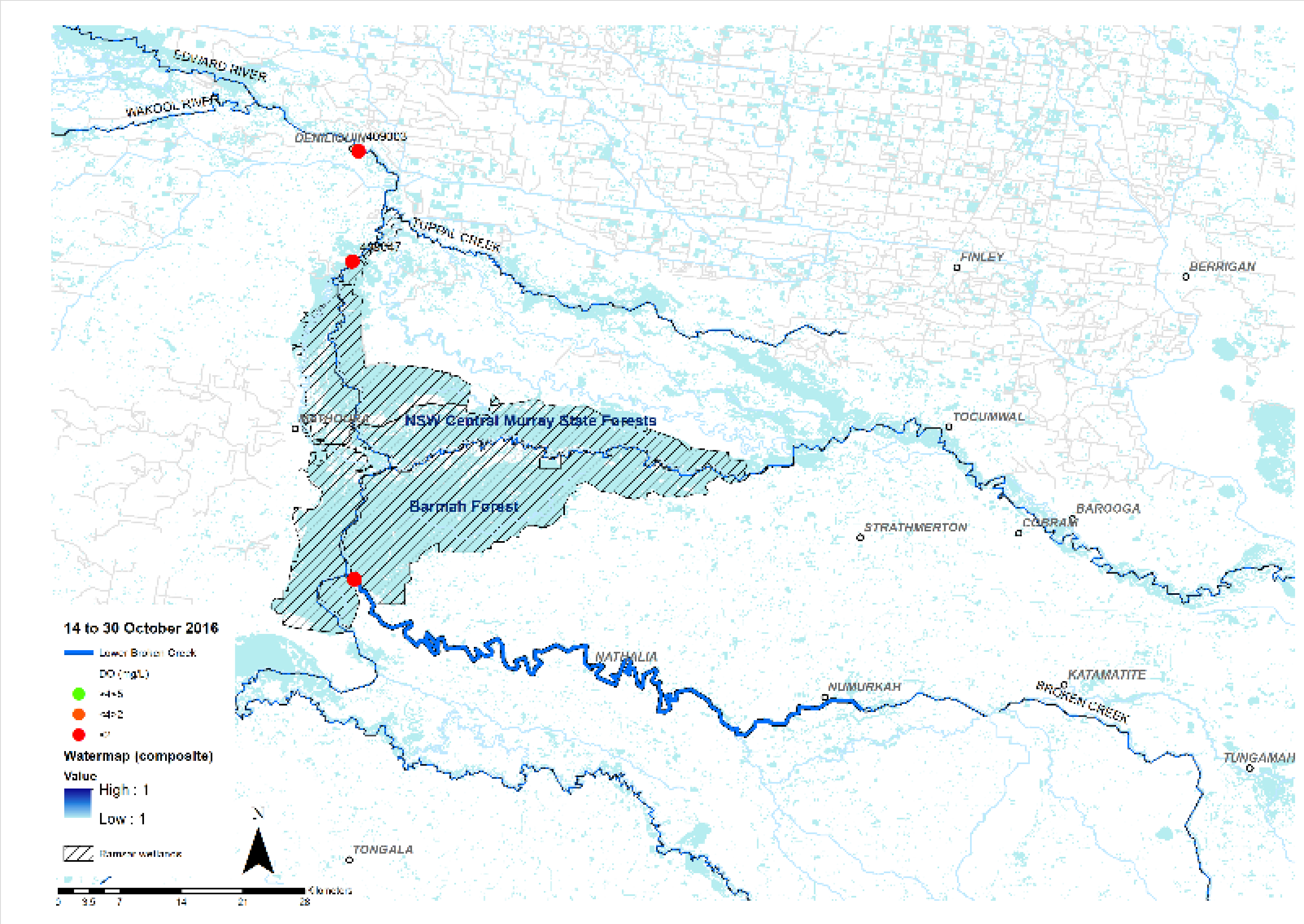


Figure 61 Lower Broken Creek and NSW OEH composite water map (light blue denotes water in the landscape (July 2016 to April 2017)

Lake Victoria

Lake Victoria is a naturally occurring shallow freshwater lake, (capacity 677 GL; area ~ 120 km^2; mean depth at FSL is 5.6m). The lake is approximately 60 kilometres downstream of the Murray-Darling Junction in southwestern New South Wales, and in a low topographic relief, semi-arid region of the Murray Darling Basin. Without a local catchment of significance inflows to Lake Victoria are dependent on diversions from the River Murray. Of the total 677 GL capacity of Lake Victoria ~85% is active storage (AS) (equal to 577 GL). The active storage is maintained at relatively high levels (~75% of AS). Frenchman's Creek diverges from the Murray River and flows into Lake Victoria. Regulators (sluice gates) allow control of the flow from the Murray into Frenchman's Creek, and outflows from Lake Victoria are returned to the Murray via an outlet regulator on the Rufus River. Wind speed at the lake averages 10 km h^{-1} during summer. Lake Victoria has an important role in moderating small-to-moderate floods to the lower Murray floodplain; however, in high floods MDBA river operations fill the lake to FSL prior to the release of environmental water. At the beginning of August 2016, Lake Victoria's AS was at 89% capacity, and reached 99.4% capacity by mid December 2016.

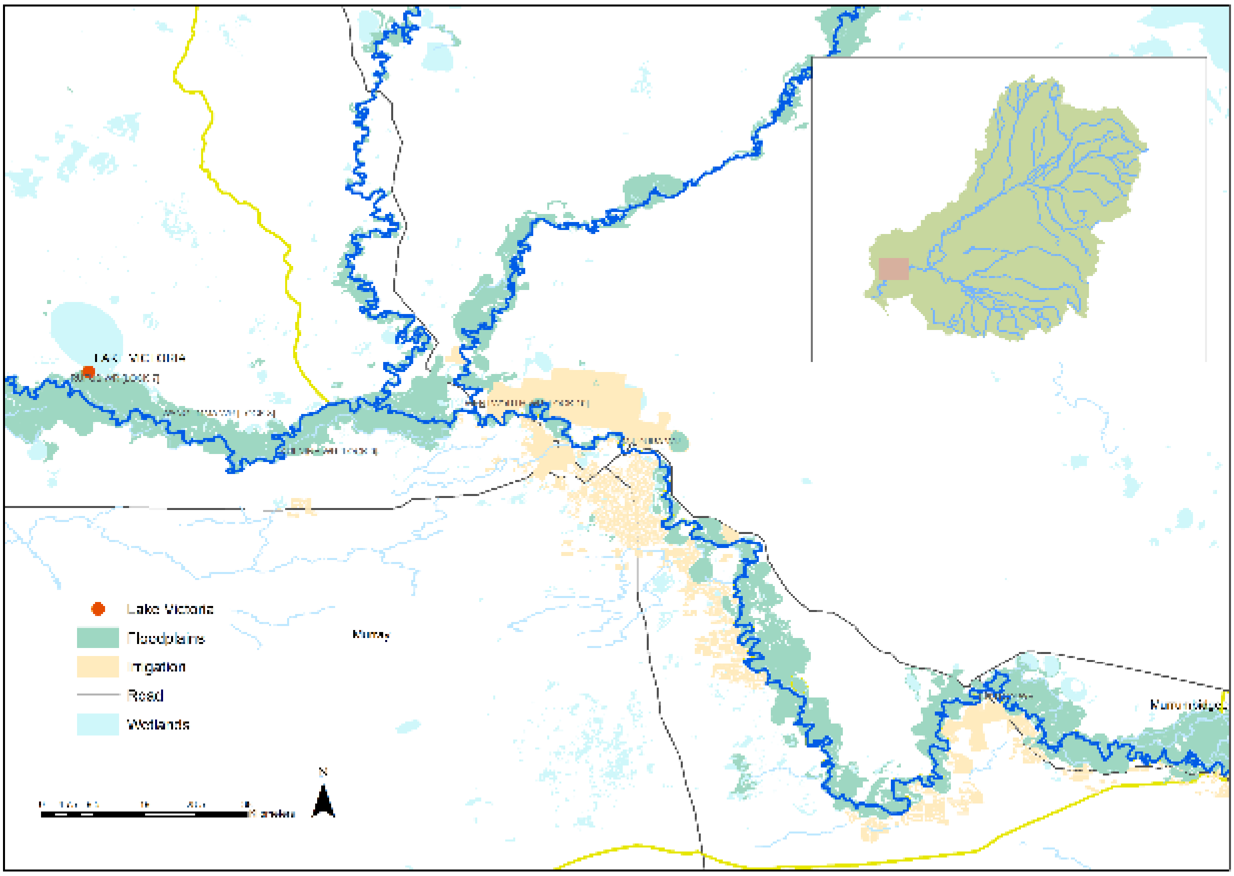


Figure 62 Location of Lake Victoria (centre left)

Lake Victoria received inflows of extreme hypoxic blackwater in November 2016, and the South Australian section of the River Murray was affected over a period of weeks in 2016/17, following high river inflows, and the pulse of low oxygen water from rivers in NSW and Victoria (see, blackwater plume Figure 62).

Figure 63 Blackwater entering Lake Victoria, in NSW. The image is from drone footage taken in early November 2016 (source:http://www.abc.net.au/news/2016-12-01/river-murray-blackwater/8079984)

Temperature

At Lake Victoria the median air temperature recorded during November and December was 19.4 and 24.3 °C respectively.

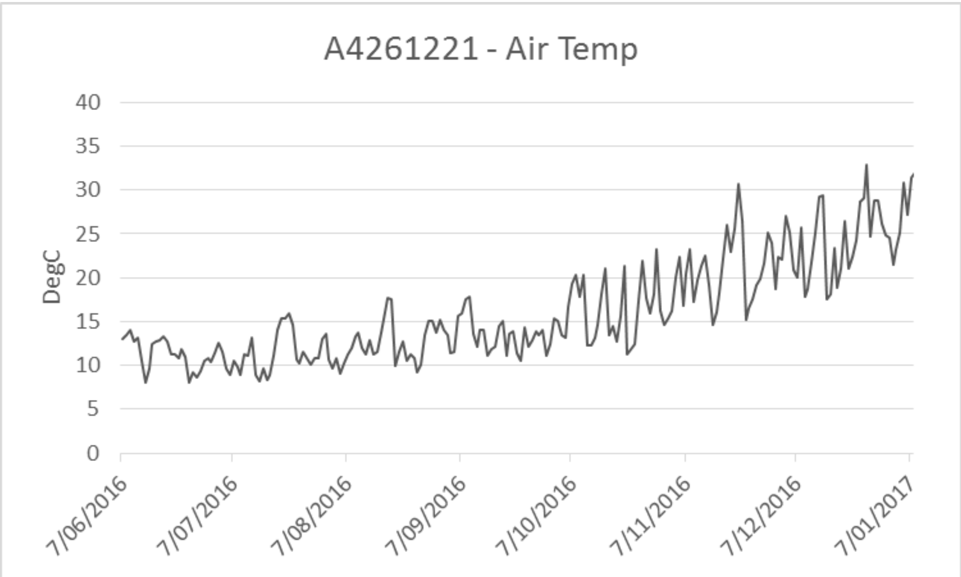


Figure 64 Air temperature from Lake Victoria weather station A4261221) 1 July 2016 to 1 January 2017 (source Water connect)

Lake Victoria dissolved oxygen concentrations

Field monitoring of dissolved oxygen concentrations upstream of Lake Victoria, at Lock 9 commenced on 09/11/2016. The water quality field monitoring was undertaken by SA Water personnel and dissolved oxygen data collected using hand held dissolved oxygen meters. No information was provided regarding the number of discrete measurements or the time of day sampling was undertaken. Additional site surveillance using drone imagery, aerial photography, and satellite data was undertaken. The low DO water diverted to Lake Victoria on 09/11/2016 was found to be at the red alert level (<2 mg L^{-1}). Subsequently, MDBA commissioned event based monitoring at 18 sites to assess water quality at the inflow and outflow channels, and spot sampling undertaken by SA water commenced on 15/11/2016.

Spatial map and dissolved oxygen time series

Time series satellite imagery was not considered, and outside the scope of the current project. The dissolved oxygen values for Lake Victoria were classified according to the DO threshold values shown in Table 1 (acceptable = grey, stressed = green, highly stressed = orange and fish kill likely =red). The resultant maps for Lake Victoria are shown in Figures 64-66.

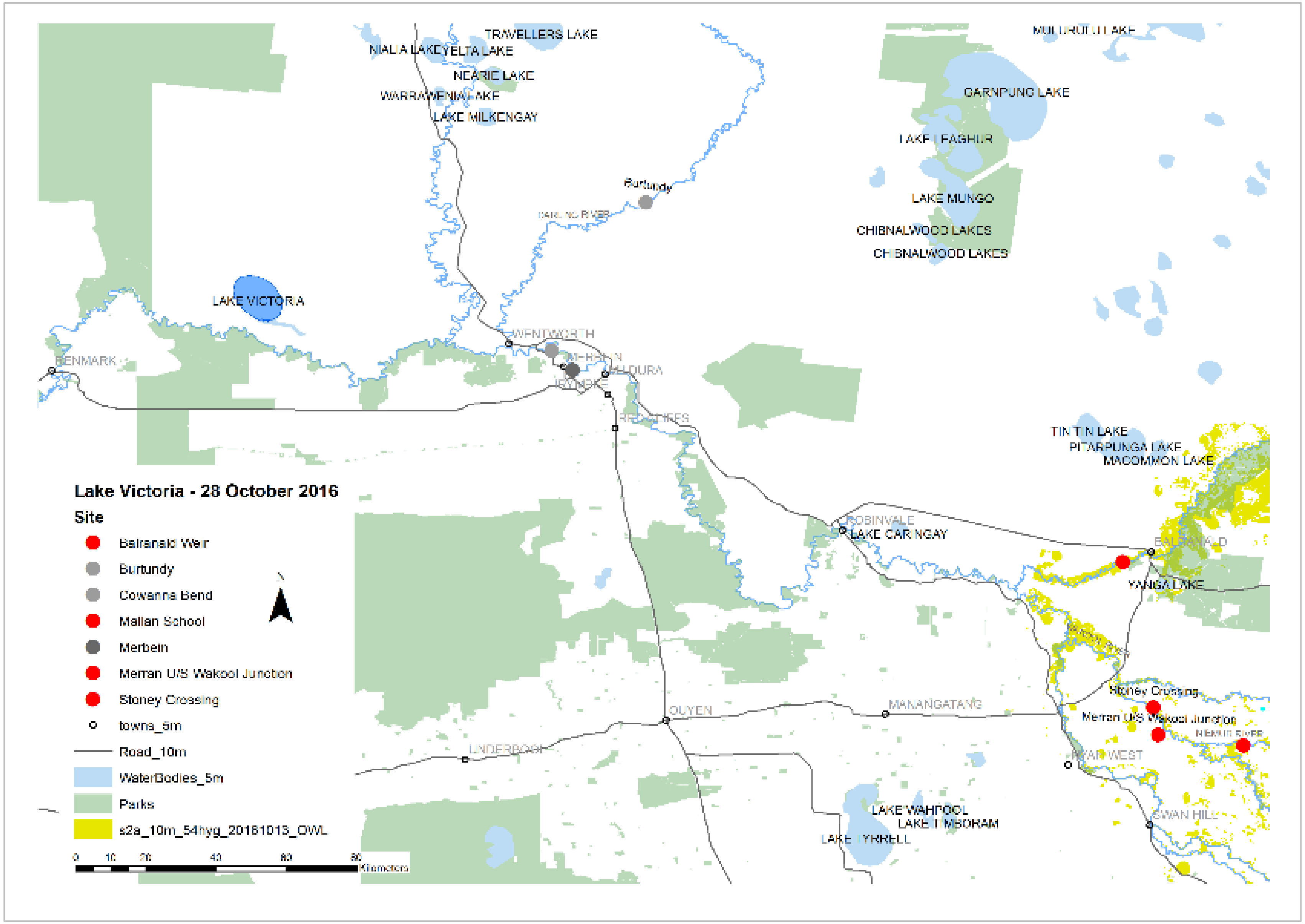


Figure 65 Average dissolved oxygen levels at Lake Victoria showing the spot sampling for October (spot sampling). The right of the map shows inundation extent from Sentinel 2a

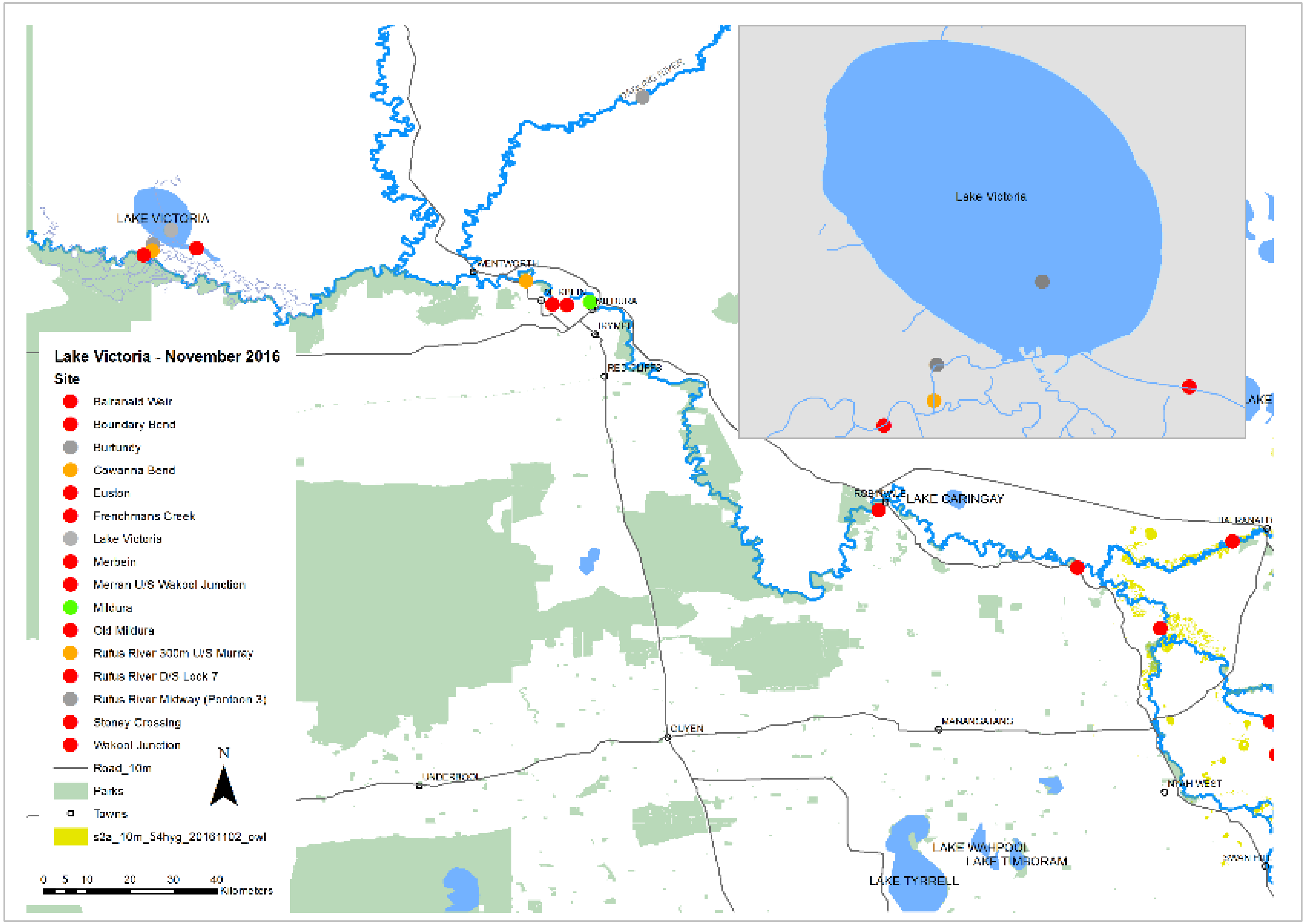


Figure 66 Average dissolved oxygen levels during November 2016 at Lake Victoria and upstream (spot sampling)

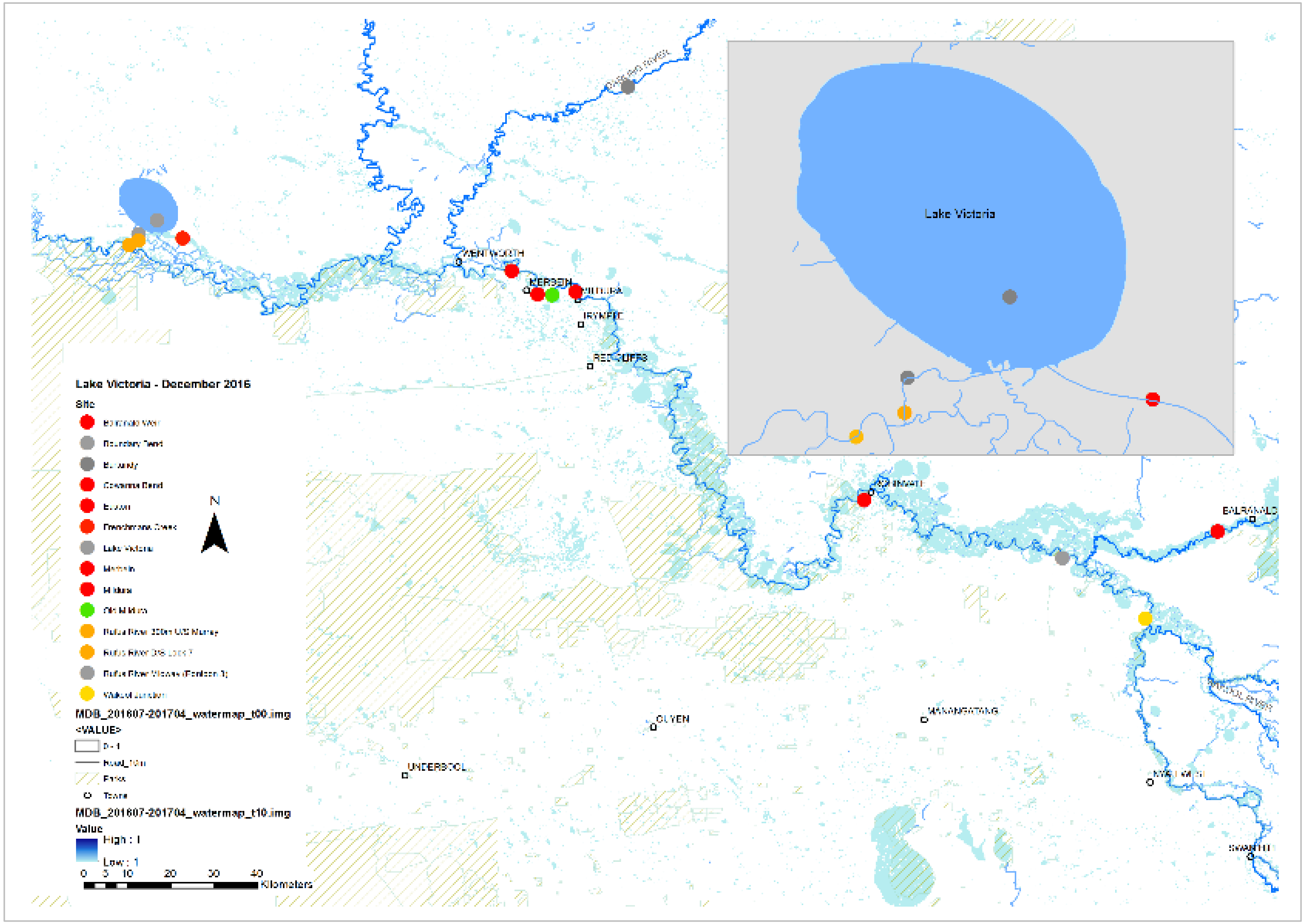


Figure 67 Average dissolved oxygen levels during the blackwater monitoring period (December 2016) NSW OEH composite (July 2016 to April 2017) water map showing overbank flooding extent along the Murray River

Impact to aquatic species

The first report of a fish kill in Rufus River occurred on 07/11/2016, and futher numbers of dead and dying fish were observed in the Rufus River near the Lake Victoria outlet 5 days later (12/11/ 2016). The release of oxygenated water from Lake Victoria that measured 8.71 mg L^{-1} did not prevent the loss of a large number of *M. peelii* (Murray cod) (Commens 2017). NSW DPI Fisheries estimated hundreds of large bodied *M. peelii* (Murray cod) had perished in the Rufus River; and this was attributed to fish movement (from the Murray River), and physical damage (fish passage barriers). It is likely native fish were responding to the low oxygen conditions downstream in the Murray River, and they sought refuge in the Rufus River (Iain Ellis pers. comm. 18 May 2017). As the pulse of the floodwaters increased native species effectively became trapped in hypoxic blackwater, and the oxygenated water releases were not sufficient for dilution or recovery.

Environmental water used to limit the impact of low DO

River operations were modified at Lake Victoria via the Lake Victoria Outlet Regulator, and releases were increased above minimum flows (500 ML/day) from around 10 November 2016, and these were gradually increased to 5,000 ML/day, due to the fish kill that occurred in the Rufus River. The gradual increase of environmental flows to ~ 5,000 ML/day ceased 16 November. A total volume of 59,148 ML of environmental water was released for the purpose of generating fish refuge in the Rufus River (Figure 68), and the combined action was a 50:50 shared release (29,574 ML of CEW and 29,574 ML of TLM).

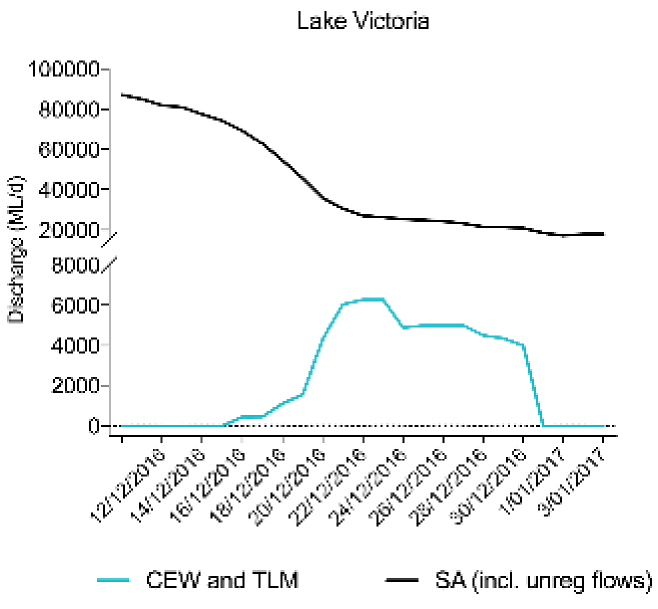


Figure 68 Environmental releases from Lake Victoria and the main river discharge?

Communications

The key stakeholders (Murray Darling Basin Authority, the Department of Environment, Water and Natural Resources, New South Wales Department of Primary Industries (DPI), Primary Industries and Regional South Australia, Commonwealth Environmental Water Office, and SA Health worked collaboratively to manage was the hypoxic blackwater event at Lake Victoria in 2016.

A paper (Draft) prepared by MDBA and Draft was provided for background on the timing and actions undertaken at Lake Victoria. A description of dissolved oxygen concentrations at the inflow, within the storage and the outflow site, the actions implemented by the river operator, and proposed adaptive management measures were all documented. In particular, the authority cited the approach to event based water quality monitoring data, the use of spatial data, drone footage, the fish kill, and included an outline of the releases made from Lake Victoria to generate fish refuge. Information was made available to the wider community in various formats, using print and online media. A dedicated blackwater web page describes the benefits and problems associated with Blackwater, and drone footage of hypoxic blackwater from the inlet can be located at Lake Victoria Drone footage.

There were a number of key recommendations arising from the MDBA internal review. For example, potential approaches to improved dissolved oxygen during a hypoxic blackwater events may require the inflows at Frenchman's creek to be ceased or minimised during high flood events, and releases from the storage increased to maximum permissible rates for dilution (Commens 2016). Additional complementary measures were proposed, i.e. the construction of a fish passage at Frenchman's Creek and also at the outlet regulator on the Rufus River.

SA water managed the blackwater event by amending water treatment processes to deal with the increased organic matter. Water was disinfected with chlorine to destroy any microorganisms and ensure compliance with the Australian Drinking Water Guidelines. This placed additional cost on water treatment. In South Australia the national media coverage reported domestic impacts of Blackwater. For example, on 1 December 2016 households reliant on untreated River Murray supply were struggling as the odour of the water was described as being similar to that of sewage (from http://www.abc.net.au/news/2016-12-01).

Lake Victoria and the lower Darling River were two sources of water with acceptable DO concentrations during the hypoxic event. An environmental flow released in the Darling River may have provided important refuge for native species, but this was not presented as a coherent proposal due to perceived community risk at the time.

Summary

Environmental flows were released from Lake Victoria following the initial fish kill. It is possible, had the watering interventions (volume and rate) been implemented earlier, when upstream hypoxia in the major tributaries was identified (October) the scale of fish kills downstream may have been reduced. Importantly, however the extent of the 2016 flood event had significant implications for river operators, and due to the magnitude of river flows and overbank-flooding throughout the entire southern basin releases were limited to the permissible volumes. In the future, environmental water flows may be guided by a set of options appropriate to different flood scenarios (low to high), and thereby water holders would have greater certainty of the flows that may be released during hypoxic blackwater events.

The event based water quality monitoring at Lake Victoria was a considerable undertaking for the field personnel from SA Water, yet the approach was not without its shortcomings. The spot monitoring approach lacked a clear design, and therefore spatial and temporal variability had not been considered prior to the event. Water quality data tend to have non-normal distributions and contain a significant amount of variability; consequently, the median or the middle measurement is often used to describe the data set. It was unclear from the information provided if the values described the mean, median or raw data. Data sharing more generally is problematic across agencies, and a single repository with QA and QC would alleviate some of the issues associated with data acquisition and data sharing. Statistically valid methods for spatial and temporal monitoring could be considered for any future water quality program (see, de Gruijter et al. 2006). A monitoring program that addresses changes over time and space, and a deeper understanding of native fish responses to low oxygen conditions is important to improving the delivery of environmental flows during poor water quality events.

Real time continuous dissolved oxygen monitoring is not available at Lake Victoria. Having access to daily data especially at the inflow and outflows from Lake Victoria could prove to be a more efficient and effective monitoring approach in the longer term. It is evident water quality monitoring programs could better align and consideration for strategic sites to measure the key water quality parameters within the MDB probably made a priority as both quantity and quality are important for sustaining ecological systems. Not only is this important for the management of aquatic ecosystems but also to underpin the decisions for investment in environmental flows that rely on robust scientific evidence as well as adaptive management.

A sound-planning framework developed in advance rather than implementing measures when dissolved oxygen levels drop below the desirable threshold (<5 mg L^{-1}) is worthy of deeper consideration.

Management issues

The unforeseen aspects of the 2016 hypoxic blackwater events were the timing and duration. The spring flooding produced a plume of hypoxic water that extended along all major tributaries of the lowland regions of the MDB. DOC was up to 10 times higher than the average around the peak of the flood, and the factors contributing to high carbon and nutrient export from the floodplain requires further study. Carbon exported from inundated river red gum forests has been identified as a key factor contributing to hypoxic blackwater events, and indeed carbon flushed from native forests has received considerable research attention previously (e.g. Howitt et al. 2007; Baldwin et al. 2000). In 2016, elevated DOC and low DO concentrations were associated with landscapes characterised as highly modified floodplains in the Lachlan, and upper reaches of the Goulburn catchment. Thus, in 2016 pasture and cropping systems also contributed to hypoxic blackwater. To better understand the potential water quality impacts that are likely to occur from agricultural landscapes further research to compare both modified and native systems is required.

Using environmental water to limit the impact of hypoxic blackwater is beset with inherent complexity and ambiguity. For example, there are human resource restraints, tensions within the Australian federal and state systems, complexities coordinating the network of water-related agencies with responsibilities in the Murray-Darling Basin, as well as social, economic, and environmental limitations that restrict water delivery and implementation of mitigation actions (Connell and Grafton 2011). These in one form or another influenced operations and delivery of environmental water during the 2016 hypoxic events. The Commonwealth Environmental Water Holder's (CEWH) good neighbour policy of 'no third party impacts' could be expounded to reflect different social, economic and ecological factors that tend to govern water management under different flood scenarios. In 2016 the environmental watering interventions were delivered on the falling limb of the hydrograph, but this approach does not adequately address the requirement to manage the first flush of key constituents that enter the river during the initial flood pulse.

The CEWO has a pivotal role in cultivating opportunities that will improve inter-agency collaboration so that access to the best-available data, models, knowledge and expertise is shared and contributes to the common goal of improved outcomes for aquatic ecosystems. During the preparation of the Blackwater Review many water managers including personnel at the CEWO, and key stakeholders lacked an awareness of their roles and responsibilities in regard to the overall governance of hypoxic events. To improve water management during poor water quality events in the southern basin, the strengthening of regional partnerships, an emergency response protocol for the delivery of environmental water, alongside an agreed communication strategy appears warranted. The NSW Regional Algal Coordinating Committee provides an example of an enduring and successful model for inter-jurisdictional governance and collaboration that is underpinned by the best available science and a multimedia communication strategy. The lead agency has not been determined, but presumably MDBA with governance for the entire basin would be ideally positioned to coordinate a Blackwater Response Plan.

Some commentary published in the media during 2016 suggested environmental water was the catalyst for hypoxic events, and also that blackwater events were a recent phenomenon. It is important moving forward that scientists and agencies work toward expanding and sharing knowledge of the factors triggering hypoxic conditions in the southern MDB. It is clear these events are driven by a number of factors, including river regulation, especially the reduction of small to medium flood events. Anthropogenic activities related primarily to organic and nutrient enrichment have led to increases in hypoxia in freshwater ecosystems worldwide, and the rapid rise in hypoxic systems has lagged about 20 years behind the increased use of industrial fertiliser (Diaz and Brietburg 2009). Interestingly the expansion of irrigation development in the MDB from the 1950s to 1980s parallels other systems that have reported increased hypoxia (from <50 in 1960 to about 400 at present) (Diaz and Rosenberg, 2008). With investment in complementary measures nutrient or carbon inputs to rivers and streams can be regulated. Thus, better management of the floodplain using innovative measures such as bioreactors could reduce macronutrient loads and greatly improve river health. The future ubiquity of hypoxia in all freshwater ecosystems will depend on climate driven events and land management factors. As changes in rainfall patterns are predicted (IPCC 2007), increased runoff due to intense rain events as experienced during 2016 can be anticipated. Observations from other large basins globally shows that increased nutrient loads leads exacerbates oxygen depletion, particularly when floodplain management programs are not activated, and bio diverse vegetation is absent from riparian and floodplain zones.

Consequently, mimicking the natural, pre-regulation rate of inundation could be used as a guide for environmental water management, to allow for lateral floodplain connectivity of the small to medium flood events with greater frequency than is currently the case. Greater percentage of floodplain inundation would lower the nutrient loading whilst building important in stream productivity. Diaz and Brietburg (2009) argue increased storm intensity and higher temperatures may lead to more hypoxia but this will depend on nutrient stores on the floodplain, vegetation cover and run off rates (Figure 69).

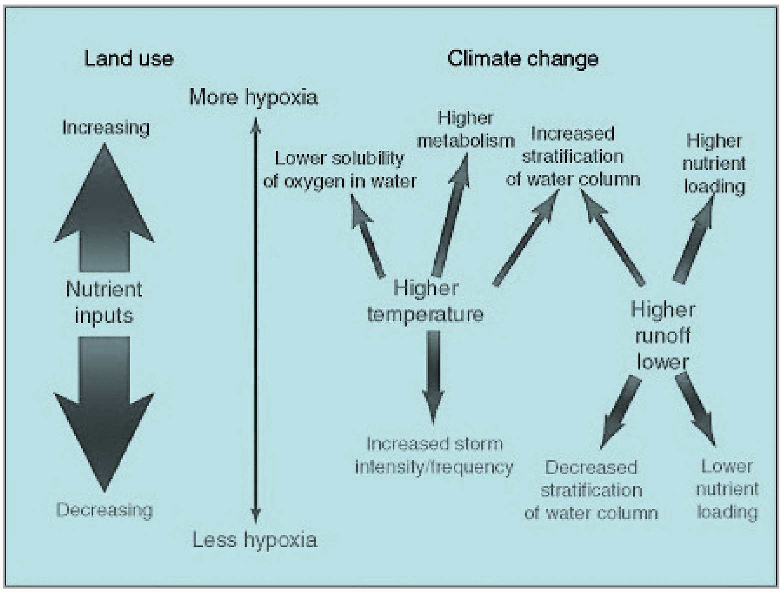


Figure 69 The relative contribution of global climate change and land use to future hypoxia. Thickness of the arrows indicates the magnitude of effect (Source: Diaz and Brietburg 2009)

The hypoxic blackwater triggered different physiological responses in native and non-native aquatic species during 2016, with fish kills (all native species) symbolic of stressors present. Where native fish monitoring is undertaken as part of the LTIM project (e.g. Lachlan), native fish (larval or adults) were not detected during the low oxygen conditions and data following the event shows nominal recovery rates or re-colonisation in many of the monitored rivers in the central and southern basin. Following the 2011 hypoxic blackwater event Whitworth et al (2011) noted that not all native fish had been obliterated, and argued for a more thorough understanding of the sub-lethal effects of hypoxia and elevated DOC. Since 2011 ongoing fish monitoring research efforts in the MDB has led to an improvement in our understanding of fish movement, especially monitoring of the exodus in the Edward-Wakool that was triggered by the rising limb of the hydrograph and poor water quality. The 2016/17 fish tracking data within selected areas shows native fish were not completely annihilated from the affected waterways. This finding suggests native fish have particular tolerances and adaptive capacity to support their survival during low oxygen events. While a massive Murray cod-spawning event also occurred in the lower Darling River that was not impacted by low DO in late 2016, additional environmental flows in the Darling were needed to assist distressed fish escape poor water from the Murray River (pers. comm. Iain Ellis, 10 February 2017). Unfortunately, the poor water quality conditions that occurred in 2016 were conducive to carp recruitment, and low DO had negligible impact on carp survival.

The concept of community respiration, mainly by bacteria leading to reduced oxygen concentrations is widely accepted. In general, the warmer the water and the greater the supply of labile organic carbon, the faster oxygen concentrations are reduced. However, risk gradients may need to be expanded and tested more comprehensively as the hypoxic conditions during 2016 occurred at lower water temperatures than previously considered to be high-risk. The 2016 floods were larger than those following the millennial drought in 2010/11, and consequently water spread further out on the floodplains to areas that perhaps had not been inundated for over 30 years.

Risk Framework

A risk framework is proposed based on water scenario indices, shown in Table 10. The ecosystem condition can be forecast from flow history and site monitoring data. The assessment of whether environmental water should be released is dependent on whether the released water would improve the ecosystem condition, particularly fish populations beyond a ‘do nothing scenario’. The rationale for the use of environmental water during flood events and potential blackwater hypoxic events can be supported if there is a capacity to move from a detrimental range towards an improved or median condition. For example, the framework could be applied to low-lying floodplain areas that are in a ‘dry’ condition due to the lack of 1 low flood in the last ten years. A climate prediction of an intense rain event would give a scenario classification of ‘protect’, and this would trigger the release of environmental flows (fresh or water delivered to critical sites) as a fish refuge, to generate a shift toward the ‘improve’ status.

Table 10 Blackwater management in relation of ecosystem condition and three water scenarios (dry, median, wet) (adapted from Overton et al. 2011)

		Ecosystem Condition		
Water Scenario	Average Recurrence Interval (ARI)	**Dry**	**Median**	**Wet**
Cease to flow (tribs)		Avoid	Avoid	Avoid
Base Flow	<1:1	Avoid	Maintain	Maintain
Freshes	1:1	Maintain	Maintain	Maintain
Bankfull	1:1 to 1:2	Maintain	Improve	Improve
Low flood	1:3 to 1:5	Protect	Improve	Improve
High flood	>1:5	Avoid	Protect	Avoid

Management actions in relation to future blackwater events and ecosystem condition for scenarios (dry, median and wet)

DO Trigger	<4 mg/L	<5mg/L	>5mg/L	>5mg/L
Objectives	Avoid damage/sustain populations	Ensure capacity for recovery	Maintain health	Improve ecological health
Actions	Refuge/dilution flows	Freshes	Promote low lying floodplain connectivity	Increase floodplain (lateral) connectivity
	Water areas likely to attract aquatic species	Water critical sites	Build resilience	Increase longitudinal connectivity

Antecedent hydrology, Monitoring (DOC and DO), Evaluation, Reporting, Stakeholder Engagement and Communication

Recommendations

The key recommendations arising from the report include:

The key recommendations arising from the report include:

1. *Develop a Blackwater Response Plan*

Greater clarity regarding the management and governance of poor water quality events in the Murray Darling Basin is required. Importantly, an inter-jurisdictional process needs to be facilitated and agreement reached for the management of hypoxic blackwater events. This approach was advocated following the 2011 hypoxic blackwater event, yet in 2016 water holders and water resource managers found they were operating in isolation, as no clear strategic framework regarding risk management, emergency response interventions, coordination, data requirements, likely 'hot spots' or innovative approaches to improve ecological outcomes existed. A southern MDB Blackwater Response Plan would articulate important information particularly the prioritisation of management interventions and protection efforts (Figure 74).

2. *Identify new and novel approaches to manage environmental water during low oxygen conditions*

Generally, the management responses implemented in 2016 were found to be adaptive, and collaborative, using science-based understanding, and various forms of feedback from the environment in a 'learning by doing' approach. Nonetheless, the Commonwealth Environmental Water Holder's (CEWH) good neighbour policy of 'no third party impacts' required some interpretation in consultation with community representatives. This policy may benefit from greater elucidation regarding the delivery of environmental water under different flood scenarios. Without exception environmental water was delivered on the falling limb of the hydrograph, in an effort to avoid flood afflux, however this approach fails to adequately address the requirement to manage the first flush, which has been shown to carry higher concentrations of dissolved organic carbon and nutrients. Future responses could consider in consultation with the community the acceptable afflux under a range of flood events applicable to the rising limb, peak and falling limb for each category of flooding.

A measure is needed to manage the nutrient loads on floodplains for better water quality outcomes. It may be possible through stakeholder engagement and collaboration to revisit social and cultural narrows that currently constrain the delivery of environmental water during hypoxic blackwater events, and to also invest in complementary measures that would close or limit nutrient pathways.

Consideration therefore needs to be given to the various natural inundation patterns of floodplain ecosystems, and commensurate with flow levels and river height. Spatial data that identifies barriers to fish passage would assist water holders to understand the limitations and also locations where water can be released for optimum benefit. Reflecting on the natural, pre-regulation rate of inundation could be used to quailfy the efffects of small amounts of environmental water. Importantly an increase in the frequency of small to medium floodplain inundation events would lower the nutrient load returned to rivers in the major flood event, whilst building important in-stream productivity necessary to build reslient aquatic ecosystems. (see Table 1 below).

3. *Fish tracking and identifying valuable habitats that may provide protection for aquatic biota*

Following the 2011 hypoxic blackwater event Whitworth et al (2011) noted that not all native fish had been killed, and called for a more thorough understanding of the sub-lethal effects of hypoxia and elevated DOC. In the past five years our understanding of the triggers that initiate fish movement during a flood event has advanced. Importantly, fish tracking data from the Edward –Wakool show the exodus in 2016 occurred prior to the arrival of the low oxygen pulse, and on the rising limb of the hydrograph. Similar to 2011, the fish tracking data indicates native fish were not completely annihilated, even though re-colonisation was significantly reduced. These findings suggest native fish have unique tolerances and adaptive capacity that supports at least some of the cohort.

Corresponding to the period of poor water quality in the Murray and its tributaries, a massive Murray cod-spawning event occurred in the lower Darling River in late 2016. The provision of an environmental flow in the Darling River may have provided refuge for fish to escape hypoxic water in the River Murray. This is one example, but further consideration needs to be given to prioritising sites that offer protection and aquatic ecological refuges. Locating river reaches with good water quality during hypoxic blackwater events is equally as important as understanding where low dissolved oxygen sites exit, because they offer the chance for in-situ persistence for vulnerable species.

4. *Identify hot spots and assessing vulnerability and risk*

Adoption of remote sensing to monitor events or transient events that affect water delivery and water quality could greatly reduce labour costs involved in field based water-sampling, sensor maintenance and instrument servicing. High frequency surveillance and spatial coverage is now available, and could be adopted by water resource managers to guide planning, monitoring of key processes and for reporting. Spatial data can be correlated with real-time measurements of temperature, conductance and turbidity and other important water-quality properties, such as bacteria, that tend to be more costly and difficult to monitor and analyse. This information could also support the development of a basin scale network to adequately represent key ecological assets as well as threats such as hypoxic blackwater events.

5. *Strategic water quality monitoring network*

A strategic and real time dissolved oxygen monitoring network is needed for all major rivers in the central and southern MDB. Understanding dissolved oxygen levels in lowland rivers requires monitoring to observe water quality issues prior to an event, rather than event based monitoring that tends to occur once a problem has been detected. Continuous monitoring could improve the understanding of diel fluctuations (hourly/daily time frame), and dissolved oxygen monitoring using submersible sensors at telemetered gauging stations offers spatial and temporal integration at relatively low cost.

Measuring dissolved organic carbon using in situ optical measurements with field-deployable fluorometers and spectrophotomers would provide another line of evidence to complement the dissolved oxygen data. This type of monitoring was previously logistically difficult or impossible, but it is now a quick, precise, and relatively inexpensive measure when compared to collecting discrete water samples in the field and later completing chemical C analyses (Ruhala and Zarnetske 2017).

6. *River metabolism, and dissolved organic carbon and macronutrient inputs*

Despite the current understanding of hypoxic blackwater events, further research is needed to address overall river metabolism, and the thresholds (concentrations or loads of dissolved organic carbon and co-limiting nutrients) needed to support biodiversity and ecosystem functioning. Despite their ubiquity we have limited knowledge of the ecological roles of algae, heterotrophic bacteria or photoautotrophic bacteria, and yet these biota are critical to ecological processes. We need better understanding of the genetic structure of representative aquatic species. Investigations need to also consider the quantification of terrestrial carbon stocks from riparian or terrestrial vegetation on adjacent riverine floodplains, dissolved organic carbon contribution from modified landscapes and soils of the riverine floodplains.

7. *Modelling*

A suite of hydrodynamic, hydrologic and floodplain models are available to support decision-making regarding environmental water during hypoxic events. As there are gaps in modelling of carbon inputs from different sources including the relative magnitude of allochthonous verses autochthonous carbon and macronutrients inputs, further research investigations are warranted. The blackwater computer models that now exist have been developed for river red gum-dominated floodplains, but could be modified to account for other vegetation types. These models are useful for scenario testing, risk management and understanding appropriate timing of floodplain inundation. However, modelling was found to have certain limitations in 2016, due to the scale of the event, and current calibration may only be applicable for localised or small to medium flood events.

8. *Implementing climate adaptation actions*

The long term effects of climate change could be better linked within the current environmental watering discourse, as rapid rates of change, particularly, season, temperature and rainfall patterns are likely to increase the pressure on freshwater aquatic ecosystems in the future. The intense rainfall that occurred during September 2016 was unexpected, and winter temperatures were above the long-term average. While hypoxic conditions occurred when temperatures were below those previously described as high risk, that is >20 °C, the warm and wet winter along with floodplain organic material were conducive to the onset of the blackwater event. Further consideration of a temperature gradient, and the environmental conditions known to accelerate the decomposition of organic material may provide a more meaningful guide for water resource managers who need to work within a risk based framework.

9. *Engaging indigenous groups, local communities and industry (pastoralism and tourism) with environmental watering actions and monitoring*

Training and equipment is needed to support the management and monitoring of lowland rivers by people who live and work in these regions. A dedicated program is needed to facilitate community and industry engagement to better share knowledge of key drivers.

10. *Risk Framework*

A risk framework is recommended and based on water scenario indices, shown in Table 1. The ecosystem condition can be forecast from flow history and site monitoring data. The assessment of whether environmental water can be released is therefore dependent on whether or not there would be an improvement in ecosystem condition, particularly fish populations beyond a ‘do nothing scenario’. The release of environmental water would be supported if there were a capacity to move from a higher risk setting towards a low or median risk condition. For example, the framework could be applied to low-lying floodplain areas that are in a ‘dry’ condition due to the lack of inundation in the last ten years. A meteorological prediction of an intense rain event would give a scenario classification of ‘protect’, and this would trigger the release of environmental flows (fresh or water delivered to critical sites) as a fish refuge, to generate a shift toward the ‘improve’ status. The water scenarios can also be coupled to a blackwater intervention model.

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Appendices

Appendix 1 - Best Practice Communications

A sample of the media reports published during the 2016/17 (following) demonstrates the concern expressed by community and how information can be misconstrued during the hypoxic blackwater events. A key issue related to the loss of iconic native fish, as large bodied native fish were observed floating down the river or washed on up on riverbanks. Hypoxic blackwater and the drivers of these events continue to be a key concern to regional communities.

The two common themes reported in the media that reverberated were the sense of frustration, and that the government's response was insufficient. Also, there was a perception that there is a "quick test" that will yield a definitive answer regarding the triggers, and causes contributing to a rapid decline in dissolved oxygen, and any subsequent fish kill. While somewhat misguided, this tends to suggest the communication approach could be improved. Some members of the community have elected to disregard the information provided at public forums, media releases and/or web pages developed by agencies. Novel approaches to engage with the affected communities may assist them to grasp the complex and interacting factors that trigger hypoxic blackwater events.

It is important to provide the community with information that clearly explains the actions environmental water holders propose, what is understood, and what is not during emergency situations. Any fish kill investigation will take time, and there are protocols in place for the collection of water and tissue samples. While it unclear if any tissue samples from native fish were collected or analysed from the 2016 fish kills, examination in the laboratory, and analysis and results are not immediate. Generally, it can take two weeks from sample submission to the release of the results, and this lag time means there is a communication void. Standard laboratory water analysis similarly has a considerable lag time from the point of field collection to data analysis.

The best practice guidelines to ensure public concerns are either allayed or addressed as quickly as possible comprise:

- a multimedia and coordinated communication approach through local newspapers, websites and electronic pamphlets and direct face to face meetings in the community
- increased media coverage of blackwater events, and imagery of the sites where fish kills are likely to occur or have occurred
- a description of the actions or investigations being undertaken by agencies including mitigation measures such as environmental watering to limit the impact of hypoxic water.

Appendix 2 - Media reports from the 2016 blackwater event

Murray fish deaths: Blackwater event kills hundreds of cod

Author: DALE WEBSTER, the Weekly Times December 2, 2016 4:31pm

ABOUT 200 dead and dying Murray cod have been found in an 8km stretch of water near Lake Victoria, where they had made their way looking for oxygen after being caught in a blackwater event. Rod Mackenzie, of Manangatang, said most had suffered too much by the time they got there to survive. Mr Mackenzie said he had only once before seen a blackwater event of this scale, in 2010-2011, which also killed large numbers of Murray cod, crayfish and yabbies over a 700-800km stretch of the river. Mr Mackenzie has shot footage of the huge dead cod in the Darling River at Wentworth and the Rufus River, fish that he believes left the main Murray River in their doomed quest for fresh water.

Angry at the losses, he wants to challenge the Murray Darling Basin Authority on how the management of environmental water may have caused events of this scale. “We know from spending our lives on the river that what is happening isn’t right,” he said. “You have natural blackwater events — no one is disputing that — but generally they are small and localised.”

Mr Mackenzie believes environmental water stored for extended periods in forests then picked up by natural floods when the river breaks its banks could be behind the scale of the blackwater events. “Never before in history has this happened,” he said. “The only link to this is environmental flooding into the bush — did this flood pick up a payload of toxic environmental water that had been held in the Yamba Forest since last summer and drag it down the river? “If it’s true what the locals say, and that water has been sitting in 40 degrees in the bush for six months, how much oxygen would it have left in it?”

Mr Mackenzie is asking the MDBA to reveal where and how much environmental water was being held for extended periods in forests in the flood-impacted areas, and wants an open discussion whether that could have contributed to the scale of the fish deaths. “We don’t want anyone’s head on a chopping block but until they stop just saying this is a natural event and take some sort of responsibility for this they can continue to do this forever — and that’s the scary thing,” he said. “If the last two floods have been like this, is the one after this going to be the same and then the one after that? We’ll end up with no fish left in the river.”

MDBA environmental management executive director Carl Binning has said previously that the blackwater event had no links to its management of environmental flows and was instead due to the amount of debris that had been washed into the river from plains that had not been flooded for 25 years.

“One thing that’s clear is that environmental watering and works programs on the Murray did not give rise to the backwater we’re now seeing,” he said.

Posted 6 Dec 2016, 6:24pmTue 6 Dec 2016, 6:24pm

Figure 70 These dead fish have been pulled out of the Wakool River. (ABC Rural: Emma Brown)

With widespread flooding occurring along the Murray, Murrumbidgee, Edward and Wakool Rivers, it may be hard to believe there is not enough healthy water in the southern Murray-Darling Basin system for native fish.

But as the water has spread along flood plains and forests, carbon matter has been swept up and is breaking down, causing a blackwater event.

Oxygen levels are dropping, leading to hypoxic events and fish kills.

But along the Wakool River, farmers and anglers are desperately working to save as many fish as they can by pumping oxygen into the dark, flooded river.

Farmer Tim Betts, who lives near Moulamein in southern New South Wales, said it may be a hopeless cause, but he felt he must try to protect native fish from suffocating in the blackwater.

Figure 71 Water that has inundated trees near the Wakool River quickly turns dark. (ABC Rural: Emma Brown)

"It looks like one great big bottle of Cola going past. In reality it is black and horrible," he said

"I've designed a series of pretty rough aerators to try and put some oxygen back into the water, just to make a micro environment or a small area where the fish can take refuge.

"I don't know if it's going to work or not, but I just figure that if one female fish lays hundreds of thousands of eggs and I can save one, I've saved basically maybe 5,000 or 10,000 future fish.

"So if I save one fish I'll be happy. Maybe I'm clutching at straws, but I've got to do something. My conscience doesn't allow me to just sit here and do nothing."

Figure 72 Tim Betts moves an improvised aerator in an effort to put more oxygen in the river. (ABC Rural: Emma Brown)

It is not the first time Mr Betts has seen a hypoxic event in his stretch of the Wakool River.

He said the current flood in his area was not doing as much damage as previous events, but he had concerns that would change as more floodwater filled with decomposing leaf matter and tannins returned to the main river.

"The first time that I was faced with a blackwater event, we had probably total sterilisation of the river where we lost all the fish in the river," he said.

"It sounds like I'm exaggerating, but you could literally walk across the surface of the water on dead fish.

"So there were tens and tens of thousands of dead fish.

"This time it's not as bad as that, but I think this is only the start of it, because when the river gets back in its banks and the water starts running in off the country that's been flooded, then the oxygen levels will decrease even more.

"Then god knows what we might see."

YouTube: Tim Betts uses an aerator to put more oxygen into the river

Causes must be examined

Mr Betts said he was worried about the future of the fish population and what was behind the widespread fish kills.

He said blackwater was an important part of the river's functions, but the extent of the deoxygenation was a concern.

YouTube: The fish aerator in action at Moulamein

"It'd terribly challenging because we see this once every 20 years or once every 50 years, so we don't really know how to deal with it," he said.

"We've got to work in with the environment. We can't work against it.

"All I know is that we must be doing something wrong because we haven't had dead fish in the past every time we have a high water event.

"I've spoken to older guys that were professional fishermen in their day, and they've fished through these events in the past.

"They've never seen dead fish and blackwater like this. We have to go back to the start, find out what we are doing wrong and fix it."

Figure 73 The flooded Wakool River from Tim Betts's backyard, with the fish aerator bubbles in the front left. (ABC Rural: Emma Brown)

There's a downside to all that water in the Murray: Lolicato

*(*the only comments to this post were from individuals who strongly disagreed with the views presented in the following and they offered alternative views*)

by Riverine Herald January 27, 2017

Wakool Rivers Association chairman John Lolicato wants to know why is there a propensity to spruik about environmental positives along the Murray River system from increased flows but ignore all the negatives?

He said for many years Basin communities have questioned the apparent 'just add water' philosophy used by the Murray-Darling Basin Authority in its implementation of the Basin Plan. He said recent high-level scientific advice has strongly supported these concerns and indicated extra flows are not the way to achieve the best environmental outcomes in the system, however it is being ignored by governments and organisations including the MDBA.

Mr Lolicato said the environmental benefits from last year's flooding continue to be publicly highlighted, but again the damage is ignored.

"For example, a South Australian Department of Environment spokesperson said recent high flows meant many parts of the river system were 'showing their strongest health since before the drought' and 'provided excellent breeding conditions for a range of species such as fish, frogs and waterbirds'," Mr Lolicato said.

He said it was interesting "we again do not get any mention of the flood damage, the fish kills, the river bank slumping and the explosion in carp breeding".

"No-one questions there have been environmental benefits from widespread rain across the Basin in spring," he said.

"But isn't it time we had a balanced debate and accepted if we pour huge volumes of water down the system, a consequence will also be significant environmental damage, not to mention the devastating social and economic consequences?"

Mr Lolicato said while those trying to justify huge flow volumes are happy to talk about native fish and bird breeding, they conveniently elect not to mention the thousands of dead Murray cod from a hypoxic blackwater event caused by these flows. Or mention the millions of carp that are breeding, quoting the National Carp Control Project co-ordinator Matt Barwick who told ABC News, "what we are seeing now is 5-10cm fish (carp) in their millions, and that is a big concern".

Mr Lolicato said the environmental damage caused by carp is well documented.

"We cannot stop a breeding explosion during a natural flood, but we can reduce unnatural flows and therefore limit the carp damage," he said.

"If the Murray-Darling Basin Plan is specifically designed to improve the river's environment, it's time we looked at solutions other than 'just add water'.

"The only winners if we implement a plan that delivers 3200 gig litres to South Australia will be South Australia, especially those who enjoy waterfront housing and lower lakes recreation.

"A smart solution would be improved operation and management of the lower lakes and the Coorong, acknowledging that the wasteful use of vast quantities of fresh water is too important in trying to overcome some of South Australia's self-made problems, for example the south-east drainage scheme which has added to the hyper salinity of the southern Coorong."

Mr Lolicato said "we don't want more flooding events that ruin crops and livelihoods, but that's what we will get if the approach to the Basin Plan is not changed.

“Nor do we want to see any more of these hypoxic blackwater events that kill native fish, birds and other animals that drink the deadly water.

“It’s time to stop kidding ourselves and start acknowledging environmental flows in the Murray system are important, but they’re not the ‘be all and end all’.”

Environmental water leads to more kills: Chair

By Zoe McMaugh, October 28, 2016

Environmental watering is exacerbating the hypoxic blackwater event in the Edward River, according to Barham’s John Lolicato.

The Wakool Rivers Association chairman said cod and yellow belly are being found dead in large numbers, some floating in the water and others washed ashore. It is the result of severely low dissolved oxygen levels in the Wakool River and Neimur Creek from floodwaters.

Mr Lolicato said while blackwater events always follow a flood they have not always resulted in fish kills. But he said each flood of the last six years has ended that way.

He said the only connection he can make with the increased fish kill events is the greater focus on controlled environmental watering programs.

‘‘Every flood is followed by a blackwater event, but history shows us they were not all hypoxic,’’ Mr Lolicato said.

‘‘But with every flood now we’re getting hit hard. The only difference I can see between now and previous blackwater events is the over watering of the forests.

‘‘The Barmah-Millewa is being watered every year, and so you can’t say that more environmental water will fix everything. In this case it seems to be making it worse.’’

Mr Lolicato says it all comes down to balance; something landholders have been demanding since the first draft of the Murray-Darling Basin Plan — which sets out a plan for environmental watering — in 2009.

‘‘You would think this hypoxic event would be caused by the Koondrook-Perricoota which has not been watered for some time, but it’s all coming out of Deniliquin and the Barmah-Millewa,’’ Mr Lolicato said.

‘‘It is essential for the red gums forests to have a drying out phase, and this gives us another reason as to why this should happen.’’

Mr Lolicato said while the Commonwealth Environmental Water Holder’s plans to provide flows to create fish refuges is commendable, it would only be a ‘‘drop in the ocean’’ in rectifying the issue.

He said authorities should be doing what they can to relocate affected fish to healthier water sources.

‘‘In our clean-up of dead fish the other day we found one that was still alive; just,’’ Mr Lolicato said.

‘‘We moved him and he bobbed around a little, and then he was off, swimming away.’’

Australian Government
Commonwealth Environmental Water Office

Flows underway to reduce the impact of low dissolved oxygen levels in the Lachlan

1 December 2016

Fish refuges are being created in the Lachlan River to reduce the severity and duration of poor water quality including low dissolved oxygen levels being experienced in local waterways. Up to 21 gigalitres of water held by the Commonwealth Environmental Water Holder and NSW Office of Environment and Heritage is being delivered to create fish refuges in the Lachlan River. This is additional to the 15 gigalitres made available in early November for areas downstream of Forbes from the Water Quality Allowance (WQA) under the Water Sharing Plan.

Low dissolved oxygen levels in creeks, rivers, and wetlands cause stress (and eventually death) to fish and other aquatic animals. It is a widespread issue throughout the Basin currently, due to large amounts of organic matter being mobilised from the floodplains. This organic matter is now decaying, resulting in extremely low oxygen levels. Whilst the use of environmental water cannot prevent this naturally occurring process, some local refuges of better quality water will assist native fish in the vicinity.

Recent scientific monitoring undertaken along the river and creeks between Jemalong and Kiacatooby NSW Office of Environment and Heritage indicates there are a number of low dissolved oxygen level hotspots (also known as hypoxic blackwater) associated with poor quality water draining from the floodplain into the river following the recent natural flooding. Following the 15GL of WQA, from 10 November a combination of Commonwealth and NSW environmental water has been used to support fish populations and other aquatic animals. These flows have remained in channel and have provided oxygenated water in the river for fish to move into.

Commonwealth Environmental Water Holder David Papps said “collaborative effort amongst agencies and local water managers, including our State delivery partner the NSW Office of Environment and Heritage together with Water NSW, NSW Department of Primary Industries (Fisheries), NSW Department of Primary Industries (Water), Local Land Services and others, was critical to developing strategies based on latest information and scientific knowledge”. NSW Department of Primary Industries (Fisheries) Senior Fisheries Manager Sam Davis said “we are working to maximise the benefit from the available water and doing all we can with the information that is available”.

For facts about blackwater: http://www.environment.gov.au/water/cewo/publications/factsheethypoxic-blackwater-events-and-water-quality

Members of the public are requested to notify NSW DPI Fisheries if they observe any stressed or dead fish in the region.

Fishers Watch Hotline 1800 043 536

Senior Fisheries Manager – Western 0408 663 338

Appendix 4 - Emergency Management

Emergency management planning has 4 phases: mitigation, preparedness, response and recovery, otherwise known as the emergency management cycle. This approach is frequently used in preventing, avoiding or minimising disasters. An outline is provided on how each stage relates to vulnerability, and potential risk, and is a general guide only, and therefore should not be read as an emergency response strategy.

No effort

When no planning is done, the potential for disaster is at its highest risk. Ignoring basic management practices means that every hypoxic blackwater event can become a potential disaster.

Mitigation

Mitigation is an attempt to keep hazards from turning into disasters, or to reduce the effects of disasters when they occur. Mitigation efforts focus on taking long-term actions to reduce or remove the risk. Examples of mitigation efforts could include:

- Land-use planning and legislation (likely impacted areas can be designated)
- An updated weather forecasting service to warn when floods may occur (frequency of data)

The best approach to protect against the potential threat of poor water quality is to become informed. If there is no awareness of a possible threat, there is no reason to do anything to prepare.

Preparedness

Preparedness includes developing specific action plans to be followed when the threat such as a flood event is imminent. There may be particular actions required if low oxygen conditions or other water quality triggers occur. Thus, prior to the occurrence of a hypoxic blackwater event:

- Responsible personnel can be provided with a deeper understanding of hypoxic blackwater and how these events pose a risk to aquatic ecosystems
- Endeavour to build a more resilient system, and one that is less vulnerable to hypoxic events
- Develop an emergency plan – Ensure everyone knows what to do, where to go and how to stay connected to information sources.
- Information sources – Make sure accurate (best available) science and on ground information is available.

Preparedness can include the following:

- Developing a clear communication plan
- Developing and practicing multi-agency emergency cooperation

- Developing and exercising emergency public warning procedures
- Determining the emergency operations centre (lead agency), that is well-supported by policy and practice.

Response

Response includes ensuring a well-coordinated effort is in place for an efficient and successful response so that plans may be activated as and when required. Being proactive rather than reactive can help reduce certain losses.

Examples of response efforts just prior to and during an event:

- Issuing specific information to the public

Recovery

Recovery attempts to restore the affected area and bring the system back to acceptable condition. The recovery phase begins once the threat has dissipated. An example of recovery efforts may include the following:

- Cleaning up areas where dead fish were observed (using NSW fisheries or EPA Vic guidelines)
- Rebuilding vulnerable fish populations

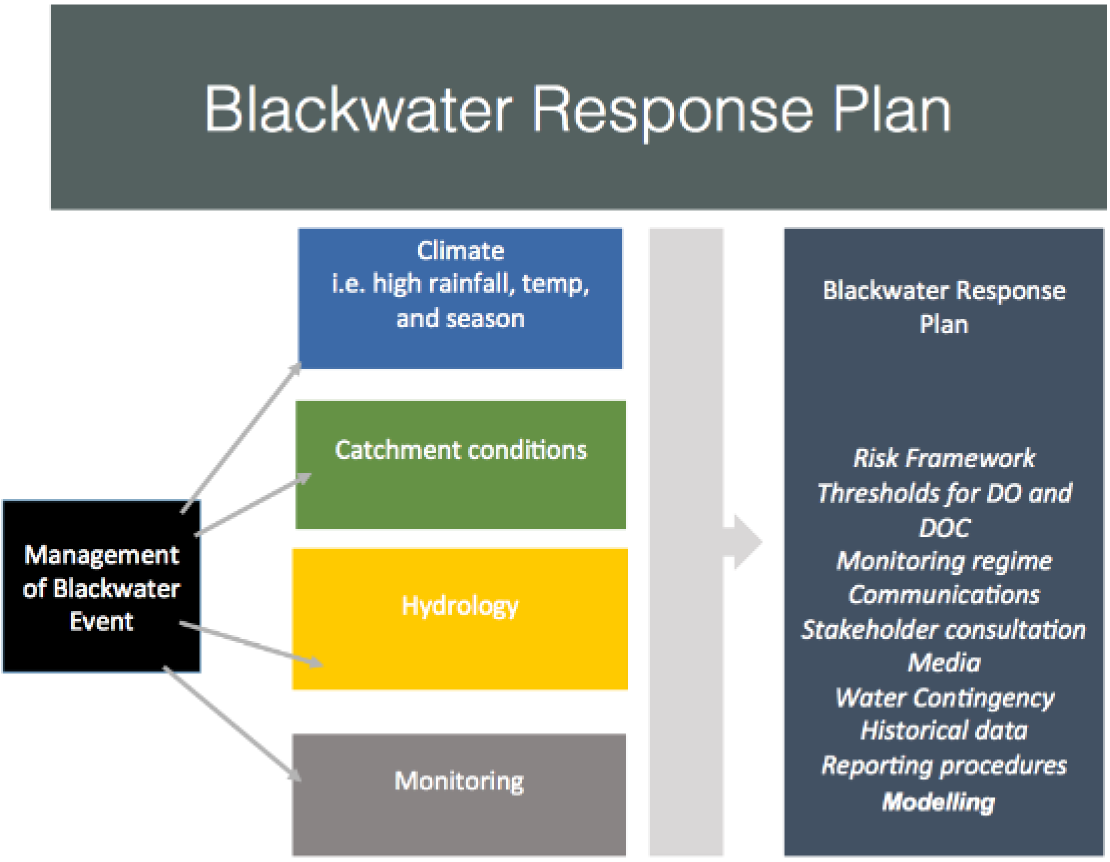

Figure 74 Graphic overview of a Blackwater Response Plan

Appendix 5 - Stakeholder Analysis

Stakeholder group	Reason	Degree of influence on project	Expectations	Participation level *
General community	Observations and concerns expressed	Medium	Ongoing	Consult and involve
CEWO Internal				
Lachlan	CEWO Delivery Team	High	✓ 2016 environmental watering actions ✓ Document the area impacted ✓ Consider the need for annual planning to include a water quality contingency	Consult, involve, collaborate and empower
Edward/Wakool	CEWO Delivery Team	High	✓ Establish and clarify agency responsibilities ✓ Communication approach ✓ Emergency response ✓ Clarification regarding source of low oxygen ✓ Staff management and resourcing (including staff wellbeing and identifying needs early) ✓ Communications and perception/expectation management (external) ✓ Availability of data and technical/research resources ✓ Financial cost of responding to blackwater events and demonstrating value for money	Consult, involve, collaborate and empower

			✓ CEWO Hypoxic Event Response and Communications Plan	
Murrumbidgee	CEWO Delivery Team	High	Complete ✓ Communication approach ✓ Clarification regarding source of low oxygen ✓ Availability of data and technical/research resources ✓ Financial cost of responding to blackwater events and demonstrating value for money	Consult, involve, collaborate and empower
Murray	CEWO Delivery Team	High	Complete ✓ Communication approach ✓ Clarification regarding low oxygen ✓ Availability of data and technical/research resources ✓	Consult, involve, collaborate and empower
Victoria				
Victorian EPA		Low		
Goulburn Broken CMA	Lead agency	Medium	✓ Develop a coordinated approach ✓ Document the 2016 event, site, landscape condition, no's of fish kills and streams impacted ✓ Better understand the triggers,, how to respond and manage an event early ✓ Work with partners to develop water delivery approaches ✓ Test (hind cast) dilution flow model ✓ Ensure the communication message is consistent, targeted and uses multimedia approach.	Consult and involve

Goulburn Murray Water	River operator	Low	Through GB CMA workshop	Inform
Goulburn Valley Water		Low	Through GB CMA workshop	Inform
Commonwealth Partners				
MDBA and River Murray Water	Regulatory – WQ within the Basin Plan	Medium	Meetings and ongoing discussions	Consult, involve
NSW Agency				
OEH	Reps on all Advisory Groups Key Water Delivery partner in NSW actions	Medium	Ongoing	Consult, involve and collaborate
DPI (Fisheries)	Regulatory - Fisheries Management Act (1994)	Medium	EWAG	Consult, involve and collaborate
Local Land Services	Community networks	Medium	EWAG	Consult, involve and collaborate
Murray Irrigation		Advisory	EWAG	Consult, involve and collaborate
Murrumbidgee Irrigation			EWAG	
NSW Water			Ongoing	Consult, involve and collaborate
Other Agencies (e.g. Emergency Services)				Consult, involve and collaborate
SA Water	Collection of WQ Data below Lake Victoria	Advisory	Attended Basin state WQ meeting	Consult, involve and collaborate
Research Partners				
Charles Sturt University	Research expertise in Blackwater	Medium	Ongoing	
Murray Darling Freshwater Research Centre	Research expertise in Blackwater	Medium	Ongoing	
University of Canberra	Freshwater Ecology	Medium	Ongoing	

- Inform—the stakeholder will be provided with balanced and objective information to assist them in understanding the problem, alternatives and solutions.
- Consult—the stakeholder will be able to provide feedback on analysis, alternatives and/or decisions, and be advised how their input subsequently influenced the final decision.
- Involve—the stakeholder will be able participate throughout the project to ensure their requirements and concerns are consistently understood and considered and are directly reflected in the final decision.
- Collaborate—the stakeholder will provide advice and innovation in each aspect of the project, including development of alternatives and identification of the preferred option. Their advice and recommendations will be incorporated into the decisions to the maximum extent possible.
- Empower—the stakeholder will make the final decision on what will or will not be implement

Appendix 6 - Glossary

Adaptive management - a working explanation is scientists and managers coming together to document existing knowledge, identify uncertainties, consider multiple possible management options, evaluate these options using ecological models, monitor (i.e. by treating policy implementation and management actions as experiments), and adapt management on the basis of newly gained information.

Discharge is another term for streamflow; it is the measured volume of water that moves past a point in the river in a given amount of time. Discharge is usually expressed in Megalitres per day or cubic metres per second.

Emergency management (EM) is disaster management or disaster risk reduction is the act of avoiding, and dealing with risks. It involves making efforts before, during and after a disaster happens. In general, emergency management is a nonstop process in which all individuals, groups and communities manage hazards in a collective effort to avoid or reduce the impact of the hazards.

Floodplains are a characteristic of Australian lowland rivers, associated with a wide range of river forms dominated by sinuous anabranching and distributary systems. Floodplain regions contain complex geomorphic features with a diverse array of physical habitats, including anabranches, backwaters, cutoffs, shallow floodways and flat plains. Those features that retain water for any period of time have been termed 'wetlands' (Williams, 2000). Wetlands in Australia have high biodiversity and an important function as they are sites for the feeding, breeding and refuge of water and migratory birds (Kingsford, 1999), fish and other animals.

Flood (standard definition from GeoSciences Australia) refers to the covering of normally dry land by water that has escaped or released from the normal confines of: any lake, river, creek or other natural watercourse, whether or not altered or modified; or any reservoir, canal, or dam.

Fish kill is defined if the mortality event is (1) not part of the fishes' natural life cycle (e.g., mass mortality following spawning activity); (2) if a minimum of 25 dead fish are found in one square kilometre (lentic) or river kilometre (lotic) and within a 48-hr period, and (3) if mortality was not caused by predation, including by humans (i.e., harvest) (Van and Cooke 2011)

Hydrograph is a graph that shows changes in discharge or river stage over time. The time scale may be in minutes, hours, days, months, years, or decades.

Hypoxic blackwater is a phenomenon connected to the decomposition of organic matter, inundation and temperature [4]. The characteristics attributed to blackwater include; elevated organic carbon (DOC), low dissolved oxygen, dark (tea or black) colouration of water, and an unpleasant odour due to ecosystem metabolism that is, respiration of organic carbon (Kerr et al. 2013).

Ramsar Wetlands are representative, rare or unique in terms of their ecological, botanical, zoological, limnological or hydrological importance (MDBA 2012). The Ramsar Convention on Wetlands of International Importance (the Ramsar Convention) is an international treaty with the broad aim of halting the worldwide loss of wetlands, and conserve, those that remain.

Appendix 7 - Responsibilities

- Department of Agriculture and Water Resources, – National Health and Medical Research Council
- Murray Darling Basin Authority -
- Commonwealth Environmental Water Holder – refer to the Basin Plan (as for all water holders)
- Victorian Water Holders - refer to the Basin Plan (as for all water holders)
- DPI (Fisheries) is the lead agency responsible for coordinating investigations of fish kill incidents in NSW. The Department has fish kill response kits located at many regional Fisheries offices which include water quality testing and fish sampling equipment to allow for a rapid response to fish kill events.
- Environment Protection Authority (Vic) (As above)
- NSW Office of Environment and Heritage - refer to the Basin Plan (as for all water holders)
- NSW Office of Water - refer to the Basin Plan (as for all water holders)
- Victorian Catchment Management Authorities - refer to the Basin Plan (as for all water holders)
- NSW Local Land Services – Community Consultation
- Local Government - Community Consultation
- South Australia Water - refer to the Basin Plan (as for all water holders)
- Water Utilities -
- Emergency Services –

Appendix 8 - Legislation (and regulations)

Commonwealth

Water Act 2007

The objects of this Act are to:

(a) enable the Commonwealth, in conjunction with the Basin States, to manage the Basin water resources in the national interest

(b) give effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources) and, in particular, to provide for special measures, in accordance with those agreements, to address the threats to the Basin water resources; and

(c) in giving effect to those agreements, to promote the use and management of the Basin water resources in a way that optimises economic, social and environmental outcomes; and protect, restore and provide for the ecological values and ecosystem services of the Murray-Darling Basin and provide for the collection, collation, analysis and dissemination of information about Australia's water resources; and the use and management of water in Australia

Under Part 7 of the Water Act 2007, the Bureau of Meteorology is required to collect, hold, manage, interpret and disseminate Australia's water information. Section 126 of the Act places an obligation on persons specified in the Regulations to give certain water information to the Bureau.

Basin Plan 2012

Chapters 1 – 13

In particular: Part 2—Risks and strategies to address consequential risks including:

(1) water being of a quality unsuitable for use; and poor health of water-dependent ecosystems.

Strategies to manage, or address, identified risks including but not limited to:

- promote a risk-based approach to water resource planning and management;
- ensure effective monitoring and evaluation of the implementation of the Basin Plan;
- the impact of climate change on water requirements;
- the causes of water quality degradation and the effects of water quality on environmental assets and ecosystem functions.

See The Basin Plan

National Health and Medical Research Council Act 1992

The NHMRC contributes to the ongoing development of the National Water Quality Management Strategy, a joint national approach to improving water quality in Australian and New Zealand waterways., managed by the

New South Wales

Fisheries Management Act 1994

Section 5 – Definition (1) In this Act, "fish" means marine, estuarine or freshwater fish or other aquatic animal life at any stage of their life history (whether alive or dead).

The objects of this Act are to conserve and:

(4) promote ecologically sustainable development, including the conservation of biological diversity.

Threatened Species Conservation Act 1995

*Relationship between this Act and Part 7A of the Fisheries Management Act 1994

The objects of this TSC Act are to:

a) conserve biological diversity and promote ecologically sustainable development, and

(b) prevent the extinction and promote the recovery of threatened species, populations and ecological communities, and

(c) protect the critical habitat of those threatened species, populations and ecological communities that are endangered, and

d) eliminate or manage certain processes that threaten the survival or evolutionary development of threatened species, populations and ecological communities, and

(e) ensure that the impact of any action affecting threatened species, populations and ecological communities is properly assessed, and

(f) encourage the conservation of threatened species, populations and ecological communities by the adoption of measures involving co-operative management.

Victoria

Environment Protection Act 1970

The purpose of this Act is to create a legislative framework for the protection of the environment in Victoria having regard to the principles of environment protection.

Water Act 1989

Under the Act, CMAs have management powers over regional waterways, floodplains, drainage and environmental water.

Environment Protection and Biodiversity Conservation Act 1999

(1) The objects of this Act include to:

- provide for the protection of the environment, especially those aspects of the environment that are matters of national environmental significance;
- promote ecologically sustainable development through the conservation and ecologically sustainable use of natural resources; and
- to recognise the role of indigenous people in the conservation and ecologically sustainable use of Australia's biodiversity.

South Australia

Natural Resources Management Act 2004

This Act includes the approach to achieve ecologically sustainable development in the State by establishing an integrated scheme to promote the use and management of natural resources in a manner that—

(a) recognises and protects the intrinsic values of natural resources; and

(b) seeks to protect biological diversity and, insofar as is reasonably practicable, to support and encourage the restoration or rehabilitation of ecological systems and processes that have been lost or degraded; and

(c) provides for the protection and management of catchments and the sustainable use of land and water resources.