Assessment and mitigation options of blackwater risk in the River Murray system

Klaus Joehnk[1], Ashmita Sengupta[1], Tapas K Biswas[1], Luke Mosley[2] and Gavin Rees[1]

[1] CSIRO Land & Water

[2]School of Biological Sciences, University of Adelaide

A final report to the Murray-Darling Basin Authority for the project (MD004151)

Citation

Joehnk, K, Sengupta, A, Biswas, TK, Mosley, L. and Rees, G (2020). Assessment and mitigation options of blackwater risk in the River Murray system. pp 60. CSIRO Land and Water, Canberra ACT 2601, Australia.

Joint Report Disclaimer

Published by the Murray–Darling Basin Authority on behalf of Basin governments.
ISBN (online): 978-1-922396-19-8

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Basin governments pay respect to the Traditional Owners and their Nations of the Murray−Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

The guidance and support received from the Murray Lower Darling Rivers Indigenous Nations, the Northern Basin Aboriginal Nations and our many Traditional Owner friends and colleagues is very much valued and appreciated.

Aboriginal people should be aware that this publication may contain images, names or quotations of deceased persons.

Acknowledgments:

This project was funded by the MDBA Water Quality Monitoring Program, a joint initiative funded by the New South Wales, Victorian, South Australian, Australian Capital Territory and Commonwealth Governments, coordinated by the MDBA.

We acknowledge historical water quality data and reports provided by the MDBA. Authors thank Alistair Korn, MDBA and Matt Gibbs, SA-DEWNR for their help with eWater Source^{TM} model and blackwater plug-in respectively. Thanks are due to Jimmy Parascos, a CSIRO-Australian National University Honours student for providing field data and BRAT modelling works from his thesis. We thank Bern and John Stanton for access to their property *Erialta,* Victoria*.*

Thanks are also due to Rob Kingham and Craig Hardge (MDBA) for the management of the project and the members of the Water Quality Advisory Panel for their comments.

Cover Image: Blackwater plumes in South Australia (Photo courtesy: ABC, 2016)

Table of Contents

Executive Summary

Flooding contributes to major improvements in the long-term health of the Murray–Darling Basin and dissolved organic carbon-rich water (blackwater) can result via natural processes. Carbon enters the food web, increasing the zooplankton and macroinvertebrate communities, which in turn act as food sources for fish.

However, if dissolved oxygen is consumed faster than it is resupplied, hypoxic blackwater (low to no dissolved oxygen) can result. The short-term effects of a hypoxic blackwater event can be quite severe, for example massive fish kills occurred in 2010-2012 and 2016-17, and this severity should be mitigated wherever practical. Influences on hypoxic blackwater generation include many factors such as temperature, leaf litter load, inundation frequency and area, and dilution flow. While only some of these factors can be controlled, many can be factored into water management decisions.

The MDBA commissioned CSIRO to develop scenario modelling tools that improve the potential for water managers to mitigate blackwater events using flow management. In particular they wanted tools that have a more generic capacity than the current models and can be translated to other sites and other river systems. Event mitigation using flow management may also complement other Basin initiatives that allow for more frequent delivery of environmental water onto the lower floodplain, thus reducing the build-up of organic matter and helping mitigate the severity and frequency of blackwater events.

This project's overall aim is to develop recommendations for flow management to minimize the risk of future blackwater events in the River Murray system based on historical observations, new field data and scenario modelling. The project spanning over a two-year period has focussed on harnessing expert knowledge, identifying key study areas, collecting field data, testing the blackwater plug-in model at selected sites, and developing scenarios under different flow regimes. An expert workshop held in Canberra in January 2018 identified Barmah and the Gunbower-Koondrook-Perricoota systems as potential test sites. These systems have experienced recurring blackwater events over the past two decades.

This report synthesises and provides a comprehensive overview of relevant literature and data while highlighting the processes that contribute to hypoxic blackwater events in the River Murray system. It highlights the consequences of inundation and carbon leaching from pasture lands adjacent to the study sites. It applies the functionality of the new blackwater plug-in to Source™ modelling platform, which is the default hydrological and decision support modelling framework used in the Murray-Darling Basin (MDB). The model tests sensitivity of Dissolved Organic Carbon (DOC) and Dissolved Oxygen (DO) responses to changing temperature and upstream DO/DOC fluxes.

The novel blackwater plug-in for eWater Source model allows a regional scale assessment of blackwater events. In this study, a total of 21 flow scenarios were tested using the plug-in model, with flows released at Tocumwal Gauge over 2-week periods in September 2009, December 2009 and February 2010 prior to the actual blackwater event in 2010. In this report, we present results from three representative flow scenarios; 15 Gigalitres/day (GL/d) in the lower end, 50 GL/d in the medium and finally 120 GL/d at the high end of flows. For modelling work, these flows were picked up based on small, medium and large flow scenario. Calibrated runs were matched to observed data in Barmah Forest. Simulations show that litter accumulation during no flow period leading to mid-2010 is instrumental in reducing DO concentration in the main stem of River Murray. The model was found to be sensitive to upstream DO fluxes suggesting that measured data will improve prediction capabilities. Water temperature and reaeration rates are also essential in driving prediction patterns.

For a DOC leaching experiment, samples were collected from pasture lands around Corowa. Results indicate that the rate constant for DOC leaching from pasture at 20°C is 0.572/day, which is lower than the rate constant for river red gum leaf litters at 0.860/day but higher than native grasses which were found to have a rate constant of 0.380/day. The total bioavailable portion of pasture grass was 1.8% which was much lower than the leaf litter contribution of 30%, but pasture in the study site was found to deliver up to 4,042 tonnes of instantly available carbon during a 1:100-year flood event. This estimate is assumed to be conservative as it did not include the large amounts of carbon that are stored within cowpats, a large carbon pool in most grazed pasture lands.

The effect of the vegetation types on the hypoxic blackwater event of summer 2010/2011 for Barmah forest was tested using the simple Blackwater Risk Assessment Tool (BRAT) model to estimate its effect on DO/DOC dynamics. The effect of pasture as simulated with BRAT for this case shows only a small impact of pasture. However, this is not a main process for the Barmah or Gunbower Forest. Although the BRAT model is a very valuable tool to assess DOC and DO concentrations after flooding on a confined local scale, it cannot describe a more complex river system and its connectivity.

Key messages from the model runs are given in the box below:

Key messages:

- The Blackwater Risk Assessment Tool (BRAT) is a valuable tool to assess DOC and DO concentrations after flooding on a confined local scale but not suitable for a more complex river system and its connectivity.
- The novel blackwater plug-in of eWater Source model allows a regional scale assessment of blackwater events.
- Modelling shows flows between 15,000 and 120,000 ML/d of short duration would have had only low impact on the magnitude of the 2010 blackwater events in the Murray downstream of Barmah-Millewa floodplains.
- Within the Barmah Forest the size of the floods has minimal or no impact and all flows show an increase in the DO compared to the baseline.
- A summer pulse of 2 weeks is not enough to flush out adequate DOC, and the model does not account for leaf litter being washed away.
- Size of the flow pulse is proportional to the DOC response, for example the average DOC during the 2 weeks in December 2009 at 120,000 ML/d flow was 13 mg L^{-1} compared to 11 mg L^{-1} at 50,000 ML/d flow.
- While some DOC is leached out when the flows are diverted to the floodplains, it is not enough to reduce the DOC loads for the actual 2010 event.
- Knowledge on floodplain litter dynamics, inclusion of agricultural/pasture organic matter loads and measured DO data are essential for reliable model outcomes.
- The plug-in needs calibration to specific floodplains reflecting the variability in vegetation/litter accumulation and having good DO/DOC monitoring data.

Project overview

1.1 Rationale

The Murray-Darling Basin Plan (MDBP) sets objectives and targets for ensuring water quality is good enough to protect and restore ecosystems, and should be suitable for domestic use, farming and recreation. Those targets relate to salinity levels, blue-green algae, and dissolved oxygen - which relates to blackwater events, including a target of at least 50% saturation for dissolved oxygen. The MDBA as per the Murray-Darling Basin Agreement is required to monitor and set objectives for water quality, and to examine and take account of the effects that its functions may have on water. In relation to blackwater events, the river operation procedures need to consider the risk of blackwater events, since the timing and release volumes can either have negligible impact or exacerbate the situation.

Water managers such as river operators and environmental water holders have practices in place to have regard to outcomes such as dissolved oxygen when managing water flows and making decisions about using environmental water. These practices can lead to improved water quality in some cases, although options can be quite limited. In addition, there is a wide range of factors outside the Basin Plan causing poor water quality, so it was never envisaged that the Basin Plan would eliminate or control blackwater events.

There was a widespread blackwater event in the southern connected River Murray and its tributaries between Nov 2016 and Jan 2017 extending from Barmah to the Lower Murray in South Australia, affecting NSW, Vic and SA. Low dissolved oxygen water killed a large number of fish, led to disruption for small businesses, and increased cost of water treatment for those relying on River Murray water. To minimise such low dissolved oxygen events in future requires a better understanding of the contributing factors and developing options for managing flows to reduce litter accumulation in floodplains.

The MDBA commissioned CSIRO Land & Water to undertake a study to improve knowledge of floodplain organic matter availability and decomposition rates under flood conditions together with historical data and a scenario modelling tool to develop flow management options to minimize future risks of blackwater events under various flow conditions. The outputs will be specific to local settings, but the tools and processes are generally relevant to the States across wider areas of the Basin.

Importantly, the 2017 Basin Plan Evaluation states that the MDBP is not expected to eliminate hypoxic blackwater events occurring in the system. The Evaluation notes as an interim finding that there have been some large-scale blackwater events over the last five years because of natural flooding, and while Basin governments have acted to mitigate these events, there is still more to learn. Accordingly, the Evaluation recommends that Basin governments and the MDBA should continue to investigate and analyse data on dissolved oxygen levels and the transfer of organic matter into river systems to develop improved management actions which can help mitigate blackwater events. This project directly targets that recommendation.

1.2 Project scope

Blackwater (low dissolved oxygen) in river systems can be a serious threat to aquatic life which is not adapted to low oxygen conditions; in severe cases it can lead to mass fish kills if they have no retreat space with better conditions. In the River Murray, the occurrence of such low oxygen conditions is a natural phenomenon whenever floodplains with a large accumulation of organic material due to non-flood conditions over years are inundated by minor to major floods. In such cases, carbon from organic materials is leached. The dissolved organic carbon is then consumed by microbes, drawing down oxygen levels. These processes are accelerated with increasing water temperature. As the reaeration of the stagnant or only slowly flowing water on the floodplain is hindered, the water turns black (high carbon content). In the worst case, this results in hypoxic conditions (low oxygen), with a blackwater event created which makes its way slowly downstream. While a hypoxic blackwater event has temporary deteriorating effects on fish and other aquatic animals, in the longer term can have a positive impact by supplying fresh carbon and nutrients source for the entire river ecosystem.

As river regulation reduced the small and moderate overbank flows in winter and spring, there is now a higher chance for litter accumulation over a longer period, and when a large flood arrives, it inundates large floodplains and brings a large amount of organic loads with its receding water to River Murray. This, in turn, increases the risk of blackwater events in the river. For river managers, it has been suggested that flow management may be able to reduce the accumulation of litter on the floodplains and reduce the risk of blackwater events.

Given the potential for water management actions to mitigate the severity of blackwater events (albeit sometimes quite constrained), there is a role for functional and reliable models to evaluate options for river operators. Modelling to predict the likelihood of blackwater events has been done in the past, and the main processes leading to hypoxic blackwater events are well known and included in, for example, the blackwater model BRAT. However, applying this localized model to a larger region, embedded in a hydrologic model, requires a broader range of parameters to be defined across a broader geographic area, so that more of the key variables can be included – other vegetation types, different leaching rates, and different temperature dependencies. For example, the mix of vegetation types in different floodplains on different levels makes it necessary to individually parameterise such tools using field and laboratory studies to evaluate the range of the process parameters, e.g., temperature dependence of leaching processes and microbial decomposition, or litter composition (e.g., Red Gum versus Black Box). Together with historical water quality, meteorological and hydrological flow data, hydrodynamic modelling tools can allow for a detailed simulation of the formation of blackwater events depending on litter accumulation in specific flood plains. This can be used to inform river operations to best use environmental water to reduce litter accumulation and thus reduce the risk of blackwater formation.

1.3 Objectives

This project aims to develop recommendations for flow management to reduce the risk of future blackwater events based on historical observations, new field data and scenario modelling. As the variability of contributing factors like vegetation types, flow regimes and climatic conditions are large across the MDB, this project cannot deliver a general account of blackwater events and management options for river operations to reduce risks for the whole River Murray. However, the results exemplified for 2-3 well-known floodplains will inform the build-up of a more general blackwater management tool by (1) providing an overview on the major contributing factors, (2) better process knowledge gained through field experiments, (3) an implementation of a modelling tool for specific floodplains which allows for future upscaling, and (4) providing examples of flow management strategies to minimize the risk of blackwater events, which allows for testing their feasibility on a small scale.

The specific objectives are to:

- Collect available knowledge by performing a desktop study of previous blackwater events and reports
- Conceptualise what are the important drivers of blackwater and associated low dissolved oxygen and how to minimise its risk in future (incl. modelling tools)
- Identify 2-3 hotspots/floodplains along the River Murray and conduct a field study to gather data on litter/organic debris and a laboratory study on kinetics of litter decomposition to close gaps in process knowledge
- Use and adapt modelling tools (source/plug-ins) to develop scenarios of best usage of environmental water for blackwater risk minimisation
- Deliver reports and knowledge products (journal publication) with recommendations for the river operations/environmental water holders to consider smart flow management to minimize future blackwater events.

1.4 Value proposition

A better knowledge of floodplain organic matter availability and decomposition rates under flood conditions together with historical data and a scenario modelling tool allow the generation of flow management options to minimize future risks of blackwater events.

1.5 Project components

The project consists of four parts

1. Review of historical blackwater events in the Basin and expert workshop:
   To understand the dynamics of blackwater, we will analyse historical data and reports on floodplain conditions (e.g., vegetation, litter biomass, climate conditions) and blackwater events along the River Murray. This will inform the parameterization of a blackwater model plug-in as well as validate the outcome of the risk analysis. It will form a basis of better understanding contributing factors of litter accumulation and blackwater generation.

2. Field study:
   The magnitude of blackwater events or the decrease in DO in a river channel depends on the amount of DOC carried in floodwaters leaching from floodplain litter. Depending on the period of non-flood conditions and type of vegetation on different levels in the floodplain, organic material will have different amounts of available carbon. Sample litter on about five different levels (10 replicates) representing different periods of non-flood conditions and vegetation types from one or two key locations. Laboratory studies to determine decomposition rates for these samples allowing for model parameterization depending on (non-flooded) age and vegetation composition thus,

generating new and necessary knowledge of age-dependence of leaching processes.

3. Modelling:
   Based on existing developments of blackwater sub-models (plug-ins) developed for the eWater Source model we will further extend them by including all major drivers and missing dynamics (e.g. temperature dependence) as derived in the desktop study for litter accumulation and leaching under flood conditions. The parameterization can further be generalized using the results of field and lab experiment. The final plug-in will allow for detailed studies of blackwater development (DO and DOC) depending on flow.

4. Scenario analysis:
   To reduce the risk of blackwater events, it is necessary to manage flows in a way to reduce large accumulations of organic matter over large areas in a floodplain. The blackwater plug-in will allow the construction of flow scenarios under which such accumulation and future risk of blackwater could be reduced and thus showing the possible options of flow management with respect to blackwater risk.

1.6 Deliverables

Deliverables as per signed contract between MDBA and CSIRO are as follows:

1. A Progress Report on review of historical events and workshop on blackwater in the MDB
2. Report on field data on litter biomass from floodplains and laboratory analysis of litter leaching rates.
3. A calibrated eWater Source model plug-in for 2-3 floodplains along the River Murray (e.g., Barmah Millewa Forest) using field/laboratory data.
4. Risk analysis of blackwater occurrence under regulated flow conditions based on historical data and scenario modelling.
5. Flow scenario options to minimize litter accumulation in key floodplains.

2 Introduction

Blackwater events, natural phenomena typically in lowland rivers, are caused when plant litters are washed off the floodplains and low-lying agricultural fields into the river and decompose during flooding. These events occur naturally in river systems around the world, especially in lowland rivers with forested floodplains or wetlands (Meyer 1998, King et al., 2012) and play a critical role in mobilizing organic carbon and nutrients from terrestrial environment to the river system, supporting basic functionality of river ecosystems (Robertson et al.,1999). Biswas and Mosley (2019) reported increased flow in the River Murray caused increased colour/dissolved organic carbon (DOC) concentrations due to wash off and breakdown of plant litter during inundation of catchments and floodplains. This DOC under favourable warm conditions promotes the growth of aerobic bacteria, which subsequently consume the dissolved oxygen. When the DOC output is large, aerobic bacteria may consume oxygen faster than it is replenished by diffusion from the atmosphere. In response, the water becomes hypoxic (Whitworth *et al.*, 2012; Whitworth *et al.*, 2014). The likelihood, intensity and duration of the hypoxic blackwater events depend on the temperature, flooding volume and availability of carbon (Howitt et al., 2007, Cook et al., 2015, Baldwin et al., 2015). Direct effects include fish kills, and a disrupted ecosystem is typically impacting juvenile and less mobile species more severely (Whitworth et al., 2012, Small et al., 2014).

Hypoxic blackwater events are exacerbated by anthropogenic factors, such as reduced freshwater flows due to higher demands, more trees and less grassy wetlands, and increased carbon and nutrient loads from agricultural areas. Warmer and drier climates tend to increase the likelihood of an event. Warmer ambient water temperatures result in lower oxygen solubility, increased microbial activity, and drier climates imply less frequent flooding. Long duration between two flooding events allows for greater litter accumulation in the floodplains. A combination of higher organic loading, warmer temperatures, longer retention time and limited freshwater influx often results in severe hypoxic or anoxic blackwater events. Additional factors, such as type and age of leaf litter, also influences the amount of carbon leached to the river (Howitt et al., 2007).

2.1 Blackwater Events in Australia

Historically, there has been an increase in the blackwater events in Australia, primarily driven by changes in the water regime, land use, change in vegetation trends and climatic changes resulting in increasing temperature and reduced precipitation. Figure 1 shows a heatmap of occurrences of fish kills mainly caused by blackwater events in the past century. The data was compiled from various sources, ranging from newspaper articles to government records. Colour is indicative of the severity of events in terms of resulting fish kill, and the timeline spans from 1878 to 2017. It must, however, be noted that the data are reliable and continuous only from 1983 onwards and that there is only high confidence from 1991 onwards for blackwater events. Notable flood years and drought periods are also included. This trend of more frequent and severe blackwater events is expected with climate change and other anthropogenic stressors, such as change in land use, reduced freshwater flows due to higher demands, increased carbon and nutrient loads from agricultural areas. Warmer and drier climates, along with warmer ambient water temperature will increase the likelihood of these events. This trend of increasing blackwater frequency might increase further in future without adaptive management.

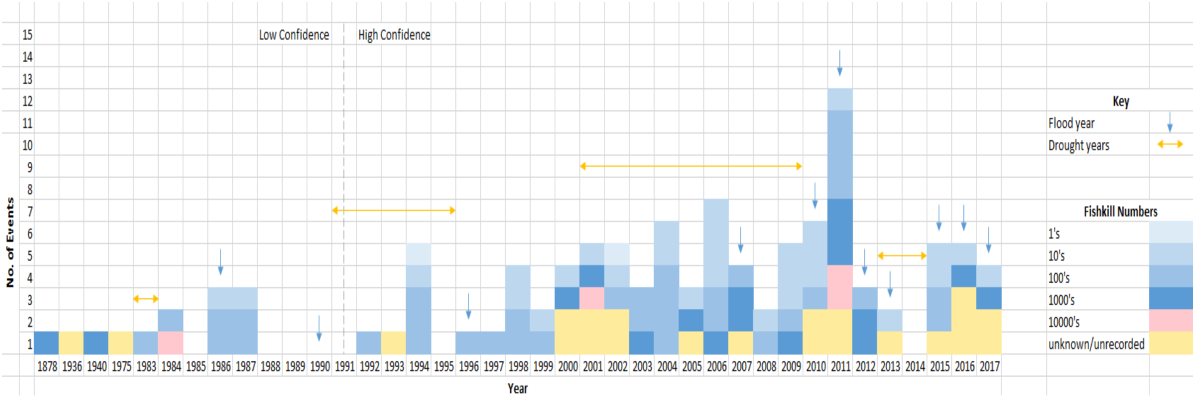

Figure 1. Magnitude of fish kill per year due to blackwater events in Australia since 1978 (Drought years represented by yellow line are years the whole of Australia declared as drought years) (Parascos, 2019)

2.2 Blackwater Events in Murray-Darling Basin

Rivers in the southern MDB are typically well-oxygenated (DO > 6 mg L^{-1}; Tiller and Newall 2010) and carry low to moderate DOC concentrations (<10 mg L^{-1}; Mackay et al., 1988). Large-scale hypoxic blackwater events occurred in the southern MDB as a result of warm-season post-drought flooding affecting hundreds to thousands of kilometres of river channel.

The first major event that occurred in 2010/2011 followed the Millennium Drought. The Murray-Darling Basin had not been flooded in over a decade, and major parts of the Basin displayed symptoms of severe moisture stress (Whitworth et al. 2012, McCarthy et al. 2014, Whitworth et al. 2014). During the drought flows in one section of the basin were less than 25th per cent of flows typically observed in the last two decades.

Record rainfalls towards the end of Millennium Drought that started in spring and continued into the summer resulted in flooding events and mobilising several hundred thousand tonnes of DOC into the waterways triggering blackwater events (Whitworth and Baldwin 2016). The first flush proceeding a period of drought can increase DOC concentrations to over four times the average, with the subsequent floods increasing concentrations to double the average. However, during the 2010/2011 blackwater event, both major flood pulses increased average DOC concentrations to ten times the average (Whitworth et al., 2012). The first of these events recorded was in September 2010, downstream of the Koondrook-Perricoota forest floodplain. By the end of the month 200 km of the Wakool River was affected resulting in widespread fish kills and Murray crayfish (*Euastacus armatus)* were emerging from the waters in an attempt to escape the hypoxic conditions (Whitworth et al. 2012). By late November, hypoxic blackwater had infiltrated most major waterways of southern MDB (Whitworth et al. 2012). The 2010/2011 blackwater event resulted in thousands of fish, and freshwater crustacean kills, and affected 1,800-2,000 km of river within the MDB (Whitworth et al. 2012; McCarthy et al. 2014; Whitworth et al. 2014; Watts et al. 2017). River red gum was a dominant source of DOC in the lowland plains. Long term litter accumulation during the drought period contributed to large organic loads adding to the severity of blackwater events (Whitworth et al. 2012; Whitworth et al. 2014). River water DO concentrations improved to non-lethal levels (>2 mg L^{-1}) by mid to late March 2011 in most waterways, and the event was considered over by the end of April 2011 when DO levels reached 6 mg L^{-1} or more at all monitoring sites (Whitworth et al. 2012).

Recently, a widespread blackwater event occurred between November 2016 and January 2017 extending from Barmah to the lower Murray causing massive fish kills and costing millions of dollars in economic loss, such as increased costs of water treatment and disruption of small businesses that rely directly or indirectly on the river system. Organic matter that had built up in the upper catchment were flushed out after heavy rainfall. A total of 118.5 mm Spring rainfall was 249% above the long-term monthly mean (Taylor et al. 2017). resulting in high DOC loads in the Edward-Wakool system downstream of Barmah-Millewa and Koondrook. The event followed the warmest autumn on record with temperatures 1.86°C higher than historical average. Spring brought record breaking rain across the entire basin, causing massive floods.

3 Key learning from an expert workshop at the beginning of the project

A 2-day workshop on blackwater in the MDB was organised for 30-31 January 2018 to start off this project with the participation of the main experts on the topic.

The topics of this workshop were:

- Representation of historical occurrence and impacts of blackwater in the River Murray region
- Overview of current projects related to blackwater
- Gather relevant processes for hypoxic blackwater events
- Impacts of blackwater events on flora and fauna
- Social and economic impacts
- Mitigation options
- Discuss specific floodplains for model validation
- Discuss specific floodplains for data gathering (vegetation types, litter age).

In the following, a short synopsis on science and policy outcomes of this workshop are given, with main topics underlined.

3.1 Science Synopsis

The main processes responsible for hypoxic blackwater events (leaf litter accumulation, leaching of organic material, decomposition and associated oxygen consumption, and reaeration) are well known and included in the localized blackwater model BRAT (Whitworth and Baldwin, 2016), which simulates dissolved oxygen and dissolved organic carbon depending on a given hydrograph. However, applying this model to a larger region is handicapped with <u>scaling issues in terms of parameterization</u> of processes, and an increase in complexity due to hydrological connectivity. Processes are best known for Red Gum and to some extent for Black Box, the main vegetation types along the river on the floodplains. This comprises litterfall and accumulation and leaching rates at different temperatures (Whitworth et al. 2014). Leaching rates are also available for grass in the BRAT model, however, less is known for other vegetation types, e.g. crop, hay, pasture, which might be dominant factors when return flows come from inundated agricultural lands. Leaching rates are influenced by the litter age, e.g., fresh leaves having a slower leaching rate. Although temperature dependence of leaching rates is known for the major vegetation types, a better knowledge for other vegetation mixes would improve simulation outcomes for a model applied over larger regions.

The risk of blackwater events becoming hypoxic increases with water temperature and thus with floods in late spring and summer due to an increase in leaching rates and microbial activity in warm to hot seasons. <u>Seasonal variability of water temperature as a significant driver</u> of these processes need to be a given input for a blackwater model. This becomes even more important for scenario modelling based on climate forecasts.

A large uncertainty is in the knowledge of sediment oxygen demand, which currently is based on only a few measurements. As this is outside the scope of the current project, the effect of less well-known parameters should be evaluated by sensitivity studies.

Validating a simulation model needs good availability of DO/DOC data. A number of stations have continuous DO loggers installed with additional spot measurements during events. Most of these data are publicly available; others can be accessed from local authorities. The installation of new DO loggers at strategic points could be done with authorities (e.g. WaterNSW)

A large scale blackwater simulation tool depends on the availability of hydrological models for specific floodplains, or the River Murray as a whole. This project will build on the eWater Source model from the MDBA, which is available for the River Murray downstream of Hume Dam. The SA DEWNR has developed a plug-in based on a previous version of BRAT which is now upgraded (Mosley and Rahman 2017) and will be further extended in this project, e.g. more general process parameterizations and inclusion of variable water temperature time series. This model will consistently be applied by both of these projects in the Lower Murray (Pike and Katarapko floodplain) and selected floodplains in Victoria and NSW. Floodplain selection strongly depends on the hydrological models available and their complexity. Thus, less complex floodplains with good data resolution are preferable for model development. Although a large volume of work on blackwater related fieldwork and analysis is done in the Edward-Wakool system, this floodplain was excluded for model development mainly due to its unavailability in the eSource model platform. Discussion focussed on Barmah-Millewa, Gunbower and Koondrook-Perricoota Forests, and Hattah Lakes. Source models exist for all four floodplains, with the Hattah lakes based on a more specific hydrological model describing lake dynamics as well. Gunbower Forest has the simplest structure in terms of hydrological connectivity, and BRAT models were developed for this floodplain. Barmah-Millewa Forest comes with good data availability and well tested hydrological and inundation models.

3.2 Policy Synopsis

This section discusses some key policy implications arising out of the workshop held in Canberra in January 2018. Among several issues, the most important one raised was the need for definition, clarification and use of uniform terminology, for example, a blackwater event is a natural and necessary phenomenon, and typically becomes an issue only when it turns into hypoxic (< 4 mg L^{-1} of dissolved oxygen) for a long period of time. Lack of clarification often leads to “blackwater events” and “hypoxic blackwater events” being used interchangeably, resulting in a negative perception of any blackwater event by the general public.

Even when the event is hypoxic, there is a need to specify the levels of severity based on the extent, duration or dissolved oxygen levels in water. Not every hypoxic blackwater event requires the same degree of intervention. Predetermined sets of management actions according to levels of severity can enable faster responses to the event.

The negative publicity of blackwater events has led to the perception that intervention implies complete treatment or reversal of state from a blackwater event. Even though environmental waters create pockets of refuge and dilution for aquatic life, there is a common perception that there is no impact of the released environmental waters due to the persistence of the blackwater event elsewhere. Better communication is required to reinforce the understanding that blackwater events are necessary in the system, and intervention or management action implies changed frequency or reduction of severity and not elimination of blackwater events. Whitworth et al. (2013) reviewed several strategies for hypoxia mitigation, such as dilution, physical reaeration and diversion of oncoming blackwater from upper catchments. The Goulburn Broken CMA is currently drafting a *hypoxic event management guideline* around preparedness, response and recovery (Hagan, pers. comm.). The workshop discussed the need for an adaptive management process. This system-based approach requires a multi-disciplinary as well as cross-jurisdictional involvement. Setting up a proper feedback loop can not only help mitigate a current event, it will also provide a template for future interventions related to what worked and what did not. The adaptive framework will allow for interventions depending on the levels of events discussed above. These interventions need to be pre-emptive. Therefore, there needs to be a set of triggers rather than established thresholds. Finally, most of the policy bottleneck is around the operational aspect due to constraints such as operational range, liability for exacerbated flooding and threats to security of water supply. There is a need for functional and reliable models to evaluate guidelines and strategies for river operators.

4 Selected Floodplains

For this project we are focussing on floodplains along the mid Murray, Barmah-Millewa Forest, and Gunbower and Koondrook-Perricoota Forests. We did not include the Hattah Lakes in this project as this system includes connected lakes which cannot be handled directly in eWater Source or the blackwater plug-in.

The vegetation at the selected floodplains mainly consist of Red Gum. Additionally, the forest areas are surrounded by extensive pasture and agricultural land (see further below). These agricultural lands would be inundated at relatively high floods and can be an essential source of DOC in other floodplains. The effect of such vegetation types was studied using a specific field sampling for pasture (see below).

4.1.1 Barmah-Millewa Forest

The Barmah-Millewa Forest is Australia's largest river red gum forest, a freshwater floodplain system along the River Murray. River regulation caused considerable reduction in flows in this system. The prolonged Millennium drought resulted in a severe decline in the habitat suitability. Additionally, the long period of low flows led to a large accumulation of leaf litter on the floodplains. In 2012-2013 high flow and then in 2016 a much bigger flow resulted in inundation of large areas of floodplain vegetation triggering blackwater events. The main vegetation types in the Barmah Millewa Forest are presented in Table 1, and an inundation extent is shown in Figure 2.

Table1. Main vegetation in the Barmah Forest

Vegetation Type	Barmah (ha)	Millewa (ha)
Giant rush	531	2,667
Moira grass	850	774
River red gum (flood dependent understorey)	16,617	26,181
River red gum (flood tolerant understorey)	9,711	4,002
River red gum/black box woodland	1,063	2,919
Total	**29,457**	**36,543**

(Source: The Living Murray report)

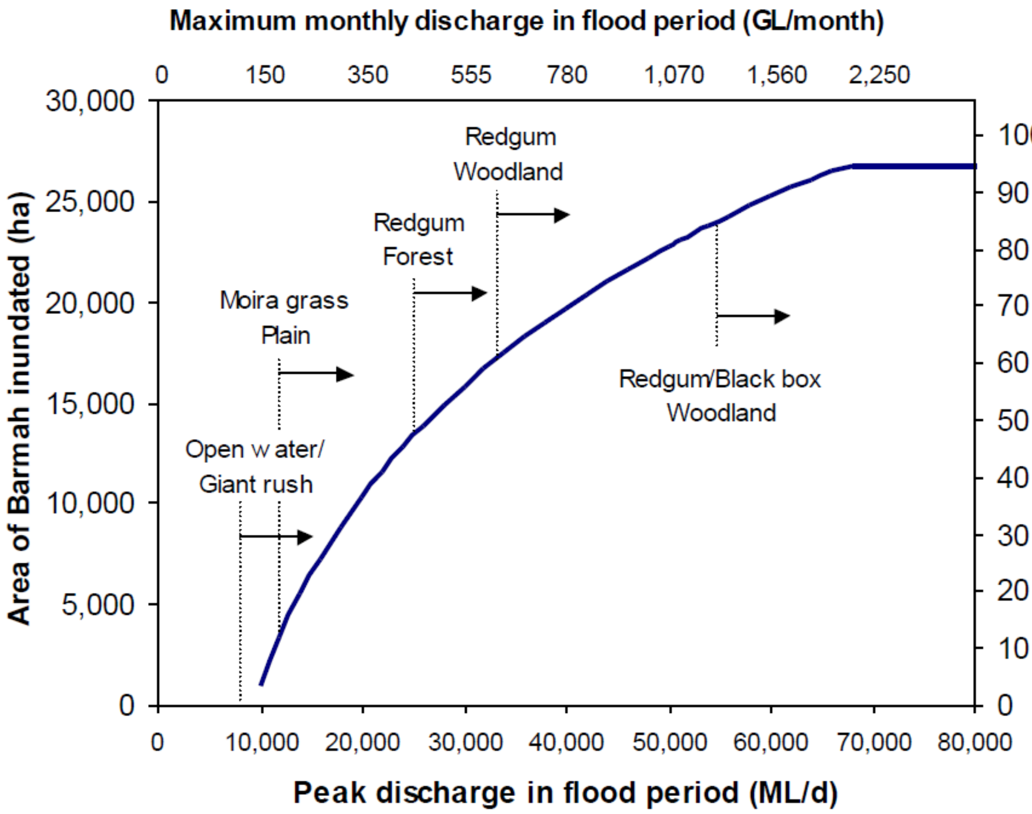

Figure 2. Area of Barmah Forest inundated as a function of River Murray flood peak and at Tocumwal (instantaneous peak discharge, ML/d) and Yarrawonga (monthly total discharge, GL/month) (GBCMA, 2013)

While giant rush and Moira grass are in lower lying (more often flooded) areas, red gum forest will be inundated at higher flood levels.

4.1.2 Gunbower and Koondrook-Perricoota Forest

Located in the Riverina region of New South Wales, downstream of Torrumbarry Weir is a large area of mixed river red gum, black box and grey box communities, with interspersed wetlands in the low-lying areas of the lower forest and along the River Murray. In the north-east, the land surrounding the forest is predominantly flat, with private agricultural lands that supports mainly irrigated and dryland cereal cropping and stock grazing. There is some horticulture, private native forestry and rural residential development.

Gunbower Forest is a part of the Gunbower-Koondrook-Perricoota system with vegetation comprising of red gum, black box and grey box. The health of the forest and the native fauna has been altered by the regulations in the River Murray and Victorian rivers with reduced frequency and duration of flood.

Figure 3 summarizes the vegetation zones in the Gunbower and Koondrook-Perricoota Forest. In terms of blackwater modelling, both sites have similar structures with respect to leaf litter accumulation dominated by red gum.

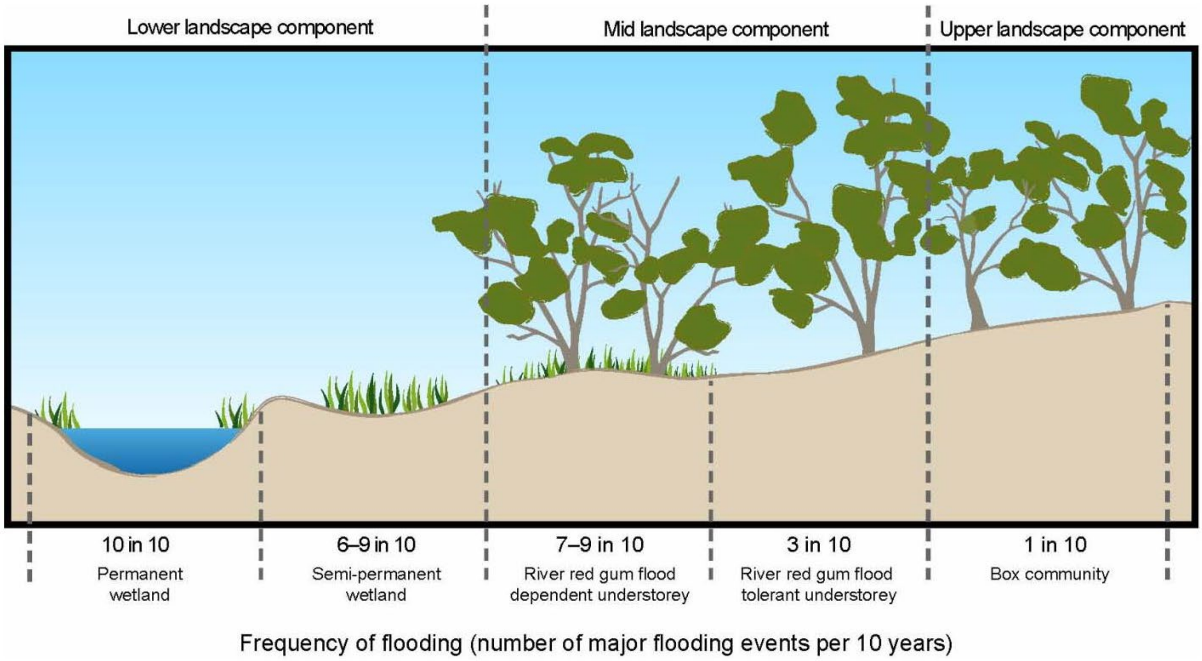

Figure 3. Vegetation associations, geomorphic settings, and flood regime in the Gunbower-Koondrook-Perricoota Forest (MDBA 2012)

5 Blackwater Model and Parameterisation

5.1 Processes and Models

5.1.1 Blackwater Risk Assessment Tool (BRAT)

The BRAT model is a predictive tool which calculates DO and DOC levels during and after flood events, and hence calculates the risk of hypoxic blackwater being generated (Whitworth and Baldwin, 2016). Whitworth and Baldwin (2016) developed the tool by utilising the same concepts and underpinning framework as the previously created Howitt's Blackwater Model (Howitt *et al.* 2005; Howitt *et al.* 2007). The BRAT model improves upon Howitt's design by removing the site-specific restrictions, using refined temperature algorithms for DOC dependence and biotic uptake, more advanced litter load estimation and reaeration rate calculation (Whitworth and Baldwin 2016). While the latest developments in the BRAT models allow for user customisation as hydrographs can be used where available and algorithms are available for modification to adjust the model suitability for different floodplain ecosystems, it is still unable to represent complex hydrology in floodplains and handles only one inflow and outflow in a simple floodplain. BRAT cannot readily simulate multiple floodplain-river interactions along a river reach.

5.1.2 eWater Source for the Mid Murray

The mid-Murray system has been extensively studied, and a number of models exist for this region. The most relevant and up to date model is the eWater Source model developed and maintained by the MDBA. This integrated river system modelling framework links the existing state models. The model is calibrated and validated at a daily time step, and the model functionality accounts for the interstate water sharing arrangements, and individual water sharing plans. The model represents the demands and delivery of water for the environment. The model is configured for a baseline diversion scenario and runs for a period of 114 years.

In this project, we used the MDBA Source model for the relevant sections of the mid-Murray downstream of Tocumwal.

5.1.3 eWater Source Blackwater plug-in

5.1.3.1 Basic description

Mosley and Rahman (2017) developed a dynamic blackwater plug-in with similar concepts to the BRAT model that was integrated into the Source™ Modelling platform (http://ewater.org.au/products/ewater-source/). Source is a hydrological and decision support modelling framework developed by the eWater Cooperative Research Centre which was consequently adopted as the national modelling platform under the National Hydrological Modelling Strategy developed in 2008 by the Council of Australian Governments. Integrating the DO/DOC plug-in with the Source model provides river regulators the opportunity for widespread application. A calibrated and validated hydrological model for the River Murray that captures all the complexities of the system is available at a daily time step, the plug-in was activated for a section of the model covering adequate upstream and downstream segments for the two sites.

The plug-in developed for Source is based on the framework of Howitt et al. (2007) that was incorporated by the MDBA into their BIGMOD hydrological model. A conceptual overview of the blackwater plug-in is shown in Figure 4.

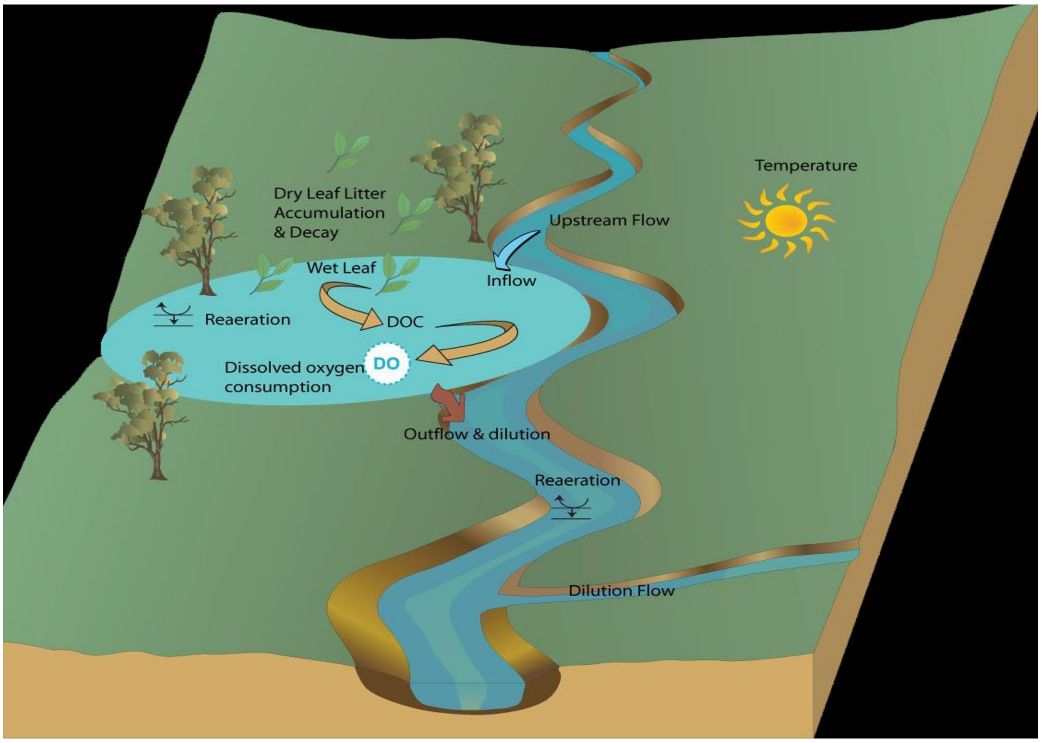

Figure 4. Source model framework overview (Mosley and Rahman 2017)

The hydrology is integrated into the plug-in. This work tests the integration of the plug-in with Source^{TM} (4.6.3 beta version, newer versions might not be backward compatible with the plug-in and eventually need specific handling). The plug-in allows for configuration at links which represent streams and rivers channels and storage nodes that represent wetlands and floodplains. The input points can be configured for inflow-outflow constituent time series, regulated conditions, and routing models. Source currently requires lumped routing to be used with non-conservative constituent models such as the Blackwater model. An individual link model can be divided up into “Divisions”, which can give spatially distributed model outputs (e.g. DO and DOC) down a river channel. The blackwater plug-in was previously tested for the Pike and Katarapko floodplains in South Australia (Mosley and Rahman, 2017). We describe the process below based on Mosley and Rahman (2017) parameter names as used in the eWater Source plug-in. In the plug-in, as the floodwaters enter the floodplain, it comes in contact with litter from the overstorey trees and grass resulting in dissolved organic carbon leaching out. Input of this new organic carbon to the water column leads to an increase in microbial activity leading to an increase in the consumption of dissolved oxygen (Figure 5).

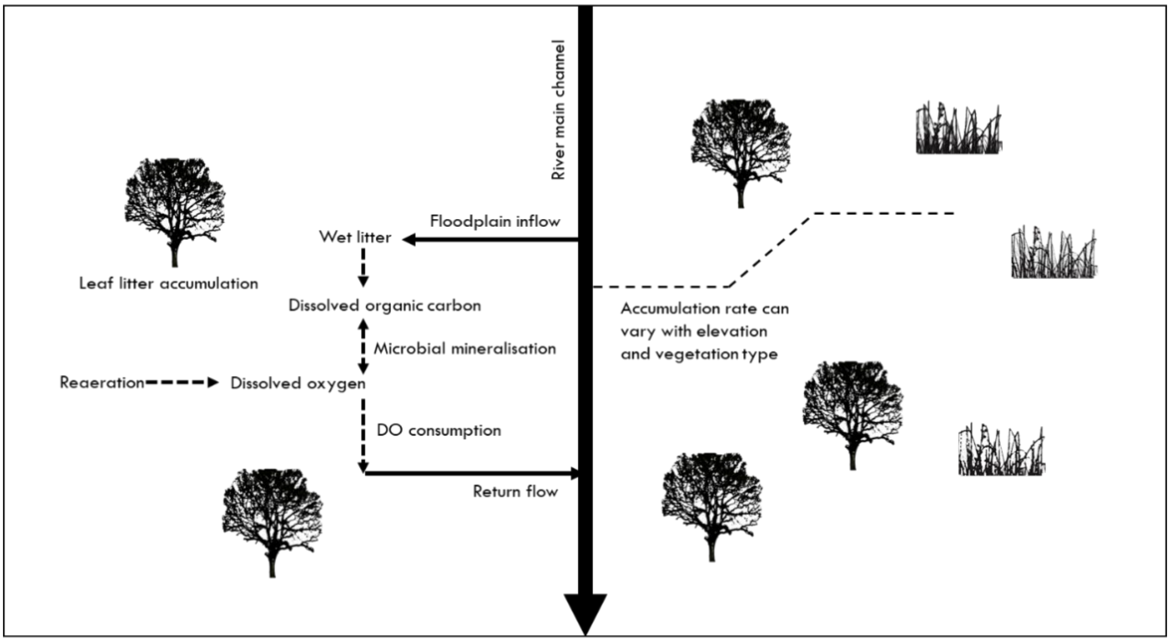

Figure 5. Key processes observed in a floodplain as depicted in the DO/DOC plug-in

As mentioned earlier, the plug-in can be configured on multiple hydrological links representing river reaches as well as storage nodes for lakes, wetlands and floodplains using three available options: nil link instream model, link decay model, and instream DO and DOC model. The first option allows conservative transport of the constituents, the link decay model for first-order decay and instream DO and DOC models which were used in this study for dynamic processing of DO and DOC.

5.1.3.2 Mass Balance Equation in the eWater Source plug-in model

The processing model in the plug-in allows DO and DOC to interact, with DO consumption associated with the breakdown of DOC. A simple total DO mass balance model is applied where change at any given time is driven by the total reaeration and net consumption. Atmospheric aeration and primary production are the primary sources of reaeration while microbial mineralization leading to breakdown of DOC, and sediment oxygen demand (SOD) are the primary causes of net consumption.

Litter loading is defined as either readily degradable or non-readily degradable to account for leaves and grass that can breakdown quicker than woodier material such as barks and twigs (Howitt et al. 2007, Whitworth and Baldwin 2016). The plugin allows for a constant rate for litter accumulation in (kg/ha).

A daily constant rate (kg/ha) is assigned for litter accumulation in the floodplain. This rate can be varied by elevation to represent different accumulation rates according to vegetation types (Figure 6). Any litter accumulation prior to the modelled period is assigned as initial load in the floodplain. Litter loads can vary seasonally and interannually depending on meteorological/climate and soil conditions, however this variability is not yet included in the plug-in. View studies were done in the case studies stating interannual differences statistically insignificant (Baldwin 2018).

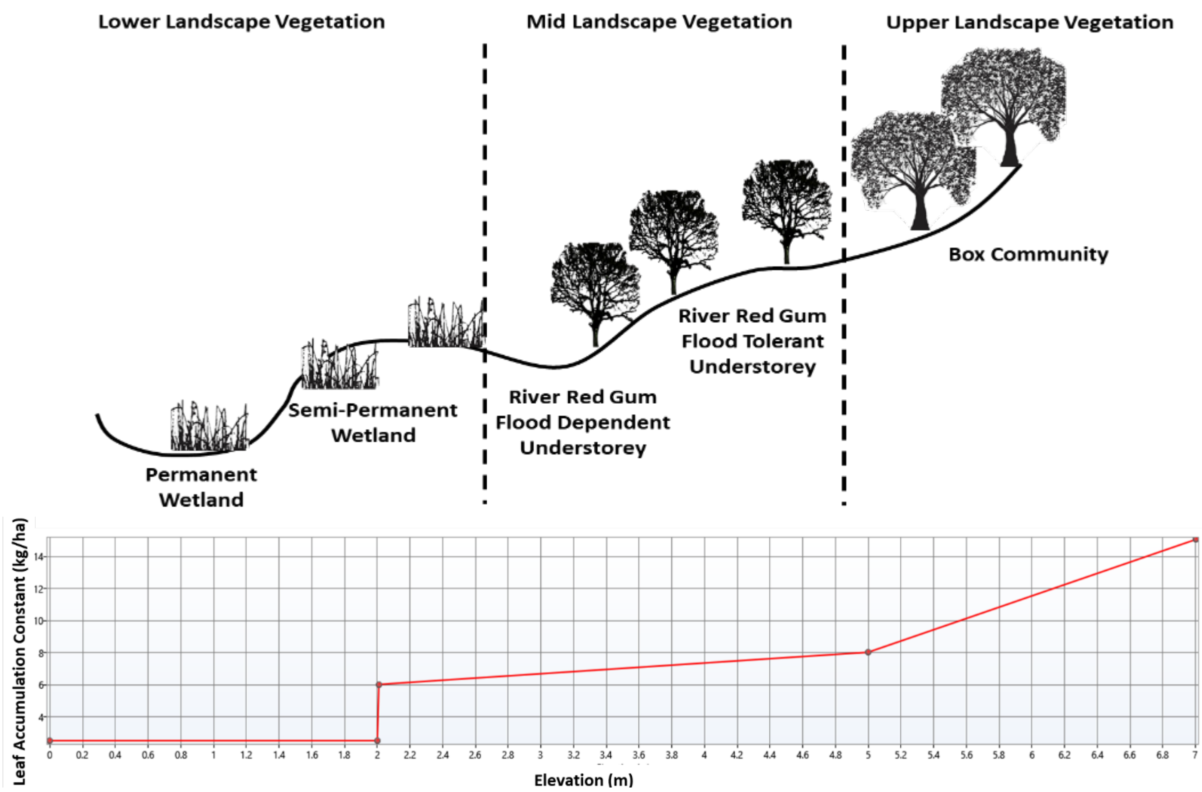

Figure 6. Litter load accumulation varying by elevation to show change in vegetation

It is assumed that only a fraction (0-1) of the accumulated litter is readily degradable by a first-order rate equation. DOC is generated with leaf litter inundation via a first-order rate equation and subsequently consumed by microorganisms in the water. Following Mosley and Rahman (2017) the process dynamics are described below.

The total dissolved oxygen (DO) mass change at each time step in the Blackwater plug-in model is given in the following mass balance equation (1).

$$DO\ mass\ change = (reaeration + primary\ production) - (dissolved\ organic\ carbon\ oxygen\ demand + sediment\ oxygen\ demand) \quad [1]$$

Where reaeration and primary production produce oxygen, the breakdown of Dissolved Organic Carbon (DOC) and Sediment Oxygen Demand (SOD) consume oxygen. A negative mass change is net O_2 consumption, and a positive mass change is net O_2 production. Additional mass import and export equations (via inflows and outflows to the model) are managed via the Source framework.

The initial dry leaf litter load can be established on the floodplain in two operationally defined fractions; “readily degradable” (i.e. leaf or grass litter) and “non-readily degradable” (i.e. bark or twigs). These are represented by the “InitialLeafDryMatterReadilyDegradable” and “InitialLeafDryMatterNonReadilyDegradable” inputs in the model configuration window respectively. This operational definition for dry leaf litter relates to the observations that typically leaves and grass can breakdown quickly whereas bark and twigs (more woody material) break down more slowly.

A rate constant (“LeafAccumulationConstant” parameter, kg ha^{-1} day^{-1}) for litter accumulation on the floodplain is defined in the input parameters. The fraction of the litter accumulation that is readily degradable is defined in the configuration ("LeafA" parameter, between 0 and 1). The fraction of the litter accumulation that is non-readily degradable is then obtained in the model by subtraction (1 – LeafA). The non-readily degradable matter decays at about 10% of the rate of leaf litter. The litter on the floodplain can decay exponentially according to the following first-order rate equations with the rate constants, "LeafK1" and "LeafK2" representing the decay of readily degradable and non-readily degradable litter over time (t) respectively:

$$LeafDryMatterReadilyDegradable_t = LeafDryMatterReadilyDegradable_{t=0} \times e^{-LeafK1 \times t} \quad [2]$$

$$LeafDryMatterNonReadilyDegradable_t = LeafDryMatterNonReadilyDegradable_{t=0} \times e^{-LeafK2 \times t} \quad [3]$$

DOC leaching is dependent on the leaf litter on the floodplain and generated via a first-order decomposition.

$$LeafDOC(mg) = wetleafKg \ \times 1000 \times DOC\_max \ (1 - e^{-DOC_K * \theta * t}) \quad [4]$$

where DOC_max is the maximum amount of DOC that can be leached (mg of C g^{-1} leaf litter) from dry material (DM), t is the time in days, DOC_k is the first-order leaching rate constant (day^{-1}) and θ ϴ ⍰ = 1.05(Temperature – 20 ºC) is the rate adjustment multiplier. The "1000" value converts from mg of C g^{-1} to mg of C kg^{-1}. The default values of DOC_max and DOC_k in the model at 20ºC are those defined by Whitworth and Baldwin (2015), 105 and 0.86, respectively but can be adjusted in the user interface.

DOC consumption is calculated on a daily time step by multiplying the amount of DOC present in the water at the end of the previous day, plus the amount of carbon leached that day, less the amount exported in outflow, by a temperature-dependent decomposition rate constant ("DOC consumption coefficient", Kdoc). The default Kdoc value at 20ºC is 0.03 day^{-1} (i.e. 3% consumed per day) as provided by Whitworth and Baldwin (2016) with the temperature sensitivity of this parameter represented by the linear function:

$$K_{doc,T} = K_{doc,20^0C} \times (-0.2088 + 0.0604T) \quad [5]$$

It is assumed in the model that utilization of dissolved oxygen during consumption of DOC (represented by glucose, $C_6H_{12}O_6$) can be represented by the following equation:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \quad [6]$$

Hence, expressed in mg O_2 consumed per mg C = (6 x 32)/ (6 x 12) = 2.667. In the Blackwater plug-in, the DOC ("leafDOC") released from the leaf litter into the water was multiplied by 2.667 to give mg O_2 consumed (Chapra 1997).

The sediment oxygen demand (SOD) parameter ("soilO2Kg" parameter) is included in the model based on the following equation:

$$SOD = 1e^{-6} \times 148162 \times \left(1 - e^{-0.093 \times 2^{(T-20) \times numberof\ inundation\ days}}\right) \times Area\ inundated \quad [7]$$

Reaeration occurs from the atmosphere in the model based on setting the reaeration rate constant, k_a (day^{-1}). The reaeration (or deaeration) can occur until the saturation dissolved oxygen (O_2) concentration is reached in the water body. The saturation dissolved oxygen concentration can be calculated from water temperature, T (◦C), according to the empirical formula (Howitt et al. 2007)

$$DO_s = 13.41 \times 10^{-0.01905 \times T} \quad [8]$$

Water temperature ("TemperatureEst" parameter) in the model is available in the input GUI as a fixed parameter input or a time series input. If a suitable seasonal time series is not available, temperature can be calculated from the following sine equation:

$$Temperature = A \times \sin(w \times day\ of\ year + \alpha) + C \quad [9]$$

where A is the amplitude (the height of temperature peak above the baseline which is the middle of the sine wave), C is the vertical offset (height of the baseline), ω is the angular frequency, given by ω = 2π//P, P is the period or wavelength (the length of each cycle, 366 days for annual cycle), and α is the phase shift (in radians, the horizontal offset of the sine curve).

For standing waters, the reaeration co-efficient at 20◦C due to wind movement over the water surface can be calculated using the empirical Wanninkhof equation for wind-driven reaeration (Chapra, 1997):

$$k_a = 0.0986 \frac{U_W^{1.64}}{H} \times \theta^{T-20} \quad [10]$$

where U_w is wind speed (m s^{-1}), and H is water depth (m), T is the water temperature (ºC), and θ = 1.024 is an empirical coefficient (Chapra, 1997).

For flowing channels, the reaeration rate constant (ka) used in Eq. 2 can be estimated from the flow velocity, water depth, and temperature according to formulae such as the O'Connor–Dobbins equation (as cited in Chapra 1997):

$$k_a = 3.93 \frac{U^{0.5}}{H^{1.5}} \times \theta^{T-20} \quad [11]$$

where U is the average flow velocity (m s^{-1}); H is the average water depth (m); θ = 1.024 (Chapra 1997); and T is the water temperature (ºC).

Flow over structures (weirs, dams, spillways) can also create reaeration (Butt and Evans, 1983). The reaeration effect of flow over regulatory structures can be modelled using a modified version of the Gameson equation, as cited in Butts and Evans (1983):

$$r = 1 + 0.38abZ(1 - 0.11Z)(1 + 0.046T) \quad [12]$$

where *r* is the ratio of the oxygen deficit (difference from saturation) above and below the structure; *Z* is the distance of fall over the structure (m), and *a* and *b* are empirical coefficients for water quality and structure aeration respectively, as defined by Butts and Evans (1983).

5.1.3.3 Model Boundaries

The eWater Source model and blackwater plug-in are not run over the entire model system but were confined to describe the selected floodplains. Thus, the modelled area is taken from upstream Barmah Forest until downstream Gunbower Forest. In the Barmah Forest system, the upper boundary is set at Gauge 409202 on River Murray at Tocumwal, and the lower boundary is at Gauge 409215 below the Broken Creek confluence. Inflow to the Barmah Forest is set at Barmah Overbank Flow (default link #581) which then flows through the forest via a storage routing (R-19) and a straight through routing (default link #847), the Barmah Lake before flowing back into the main stem of the River Murray (see Figure 7).

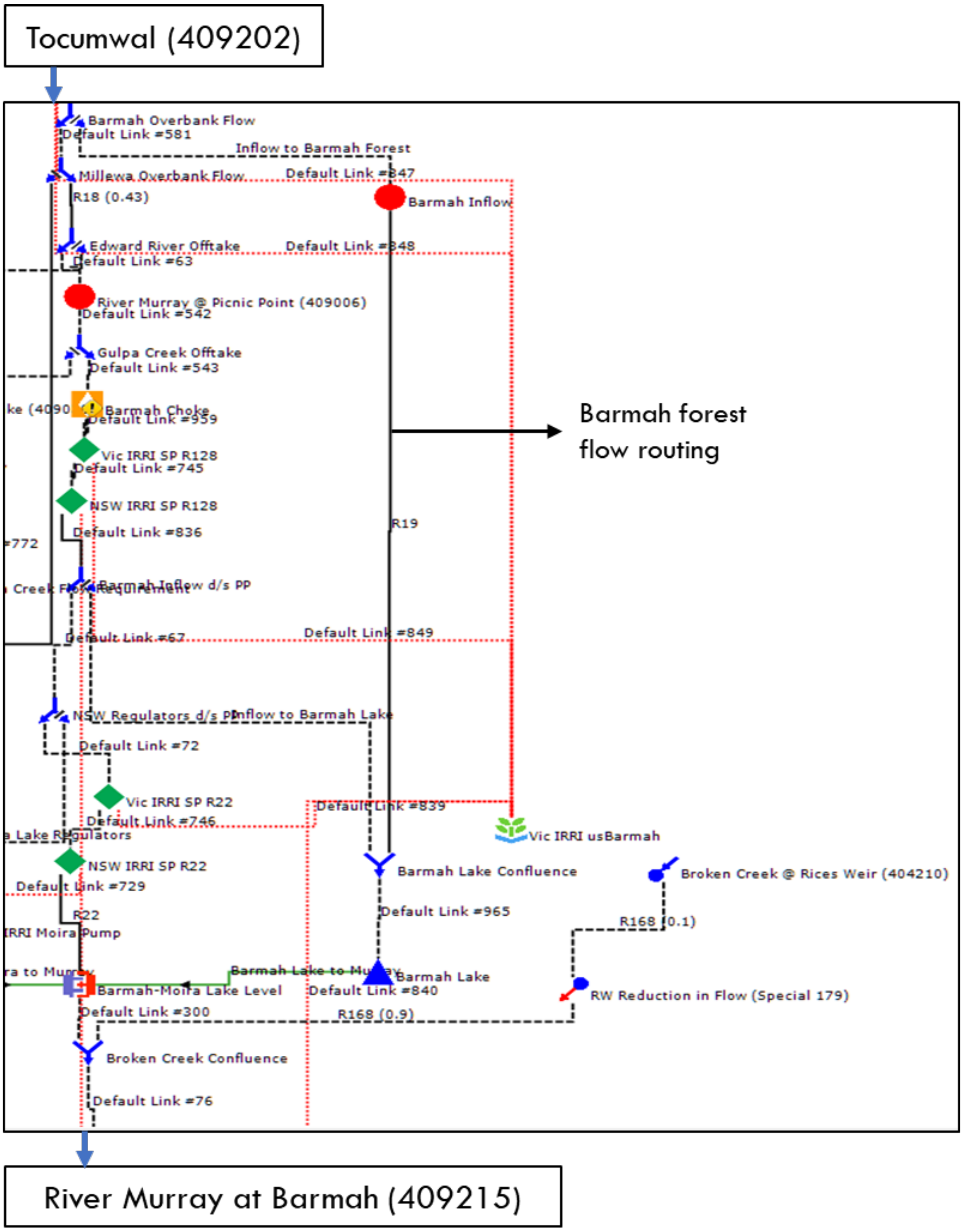

Figure 7. Source set up for Barmah system with upper and lower boundaries

5.1.3.4 eWater Source model and plug-in set-up

A hydrologically calibrated and validated eWater Source model was provided by the MDBA. However, minor changes were implemented for better representation of the DO and DOC processes in the system. For the DO/DOC plug-in, several parameters were configured in the model, including site-specific parameters to rates based on published literature. A simple representation of the modelling process is shown below (Figure 8).

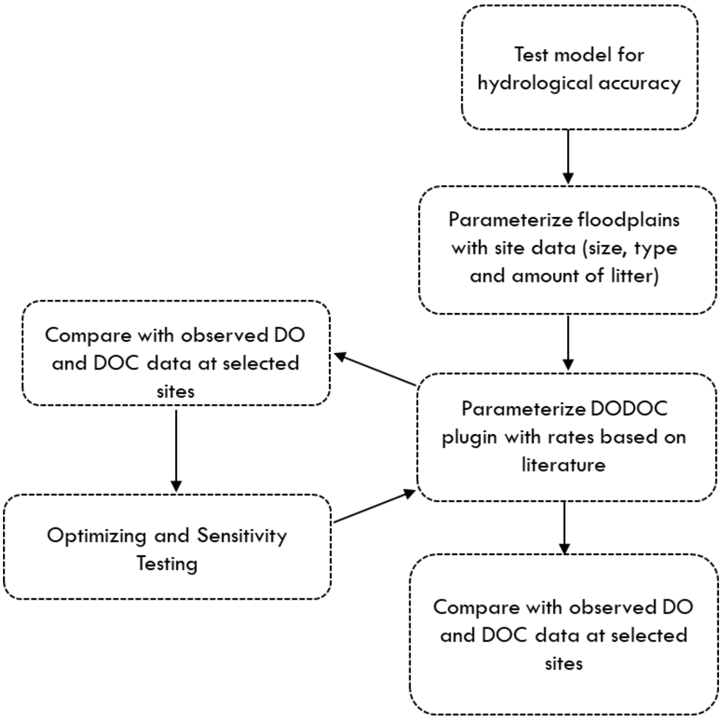

Figure 8. Schematic representation of the modelling workflow

The eWater Source model is driven by given flows (provided by MDBA). A total of 500 km of main Murray channel and two floodplains (28,500 and 28,000 hectares respectively) are modelled in this study (Figure 9). The upper boundary of the model is set to gauged flows at Tocumwal ranging from 1,700 ML/d in 2007 to 92,000 ML/d towards the end of 2010 (Figure 10). This is a variation from the default Source model where the flow resets to observed values at each gauge along the River Murray to facilitate the transport of DO and DOC along the entire reach. Model simulations spanned January 2000 to June 2012. Even with the variation, the hydrological accuracy is maintained through the system (Figure 11). The flows to the two floodplains are splitter controlled, as shown in Figure 12.

Further to this, the blackwater plug-in depends on given measurements of DO and DOC as well as water temperature. Based on literature, the DO concentrations at the prevailing water temperatures are around 6- 10 mg L^{-1} in the system outside of blackwater events. During the 2010-2011 period, DO data was used for model calibration. In addition, water temperature data was downloaded from https://riverdata.mdba.gov.au/.

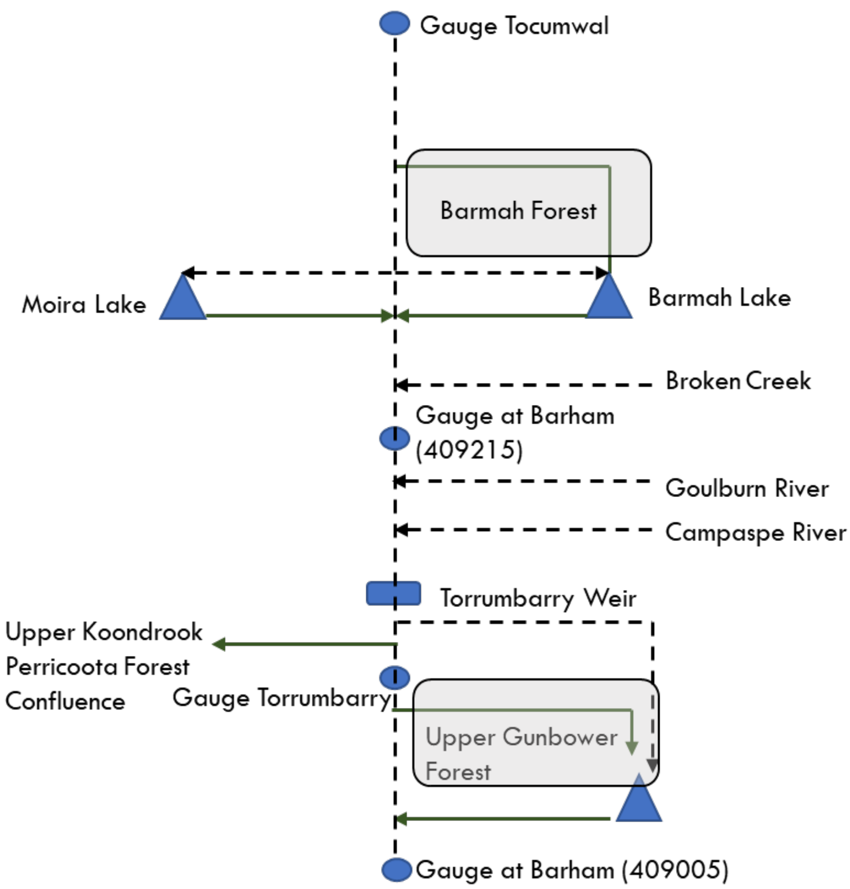

Figure 9. Modelling reach along the main Murray stem and the two floodplains. Barmah Lake (below the Barmah Forest) and Moira Lake play a key role in the DO concentrations along with the Barmah floodplains at downstream locations.

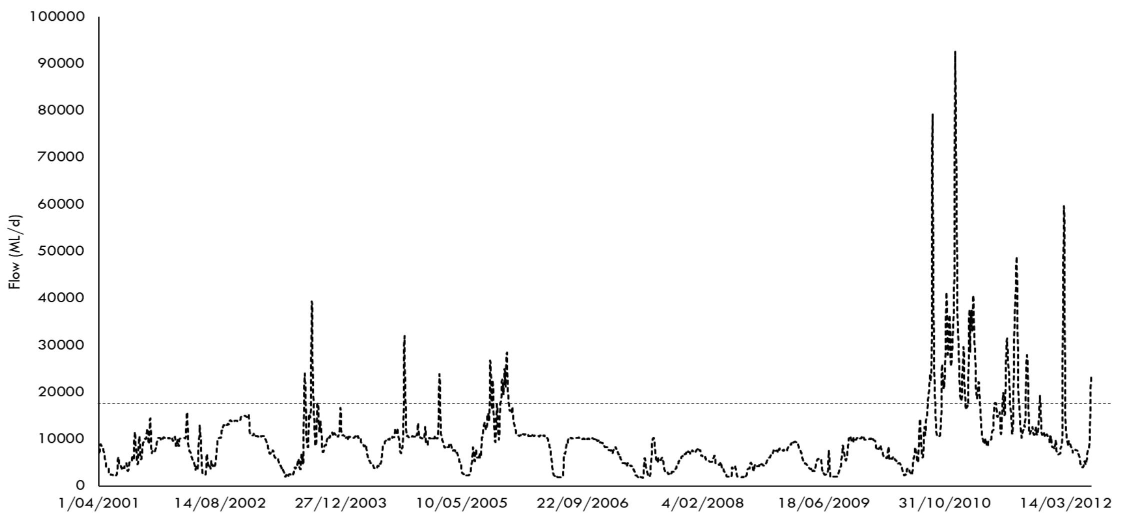

Figure 10. Hydrograph using gauge data at Tocumwal, this is the upstream boundary for the model. The threshold marks where flooding might occur. While minor floods occur between 2003-2005, no peaks are observed between mid-2005 and the large floods of 2010.

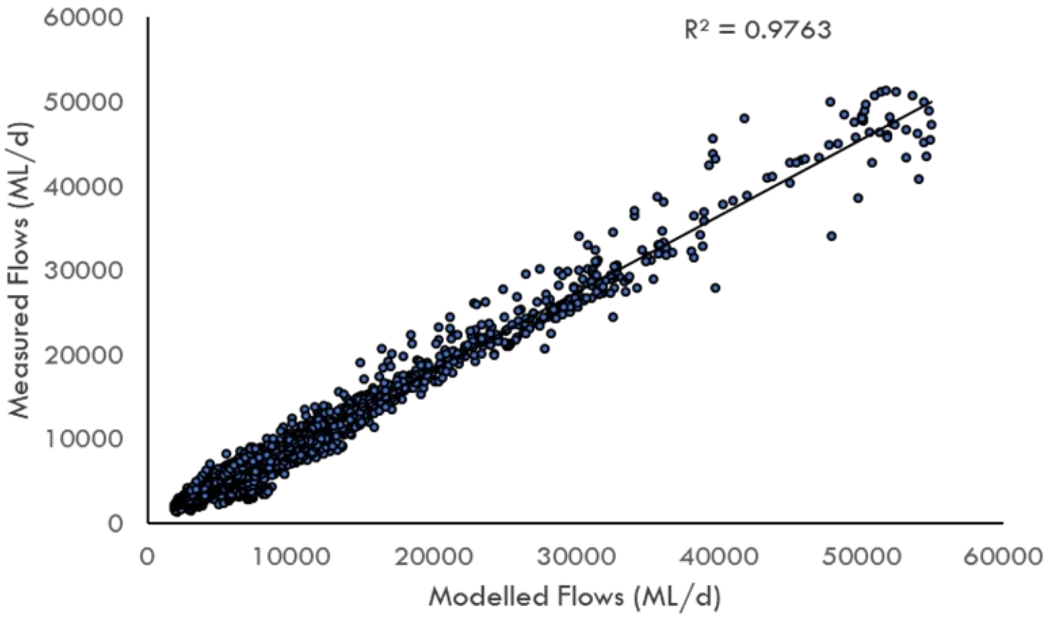

Figure 11. Model fit (observed flows vs. modelled flows) at Torrumbarry

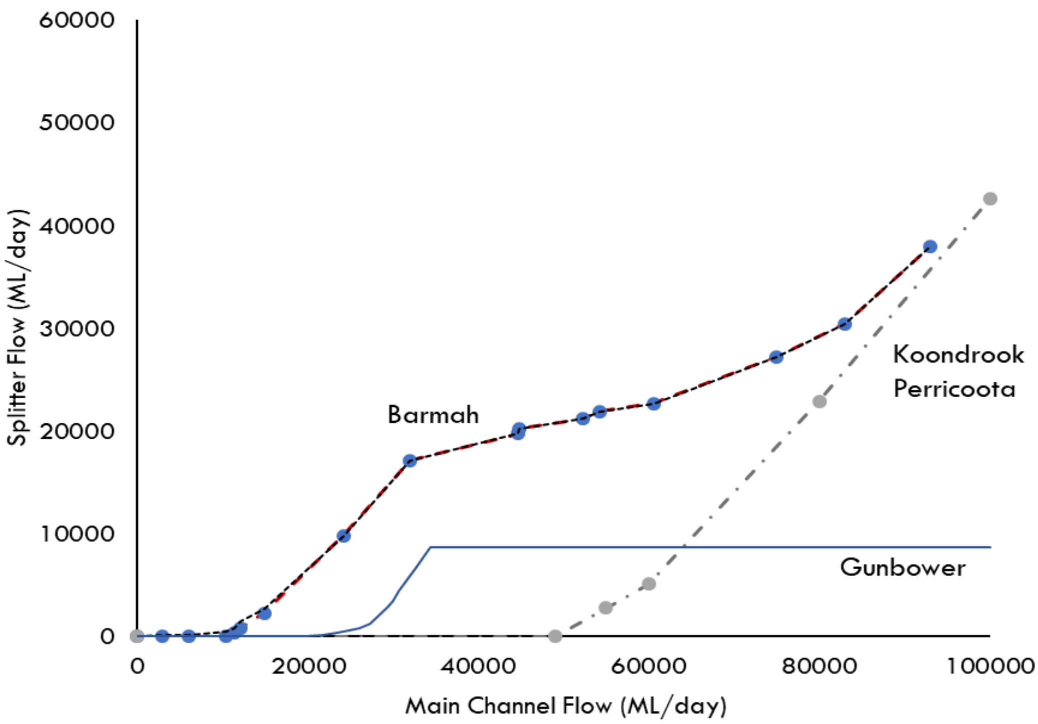

Figure 12. Splitter controlling flows to the Barmah and Gunbower floodplains

5.1.3.5 Blackwater plug-in parameterization

As initial conditions in the floodplain are generally not known (sparse data on DO and DOC), the model system need to include a so-called warm-up period which is later disregarded in the simulation analysis. The initial warm-up model runs were for the period 2004-2006. During the simulation period 2009-2011, there are no flows to the Barmah Forest and lower flows in the main stem of the River Murray. Table 2 shows the selected gauges and links that were activated during the model runs.

Table 2. Model setup around the Barmah Forest Area

Name	Type	Processing Model
River Murray Tocumwal (409202)	Gauge	NA
R-18	Storage routing	Instream DO, DOC
Barmah Inflow	Gauge	NA
R-19	Storage routing	Instream DO, DOC
Picnic point	Gauge	NA
R-22	Storage routing	Instream DO, DOC
Barmah Lake	Storage	Storage DO, DOC
Broken Creek @Rice Weir	Inflow Weir	NA
R-23	Storage routing	Instream DO, DOC
River Murray Barmah (409215)	Gauge	NA

While the gauges and weirs can provide a flux of DO or DOC to the system, the model is set up to run on the storage routing links and storages. At each storage-routing link, the user has the option of setting the height for overbank flow into the surrounding floodplains. The model allows for setting of a discharge to elevation relationship (Figure 13).

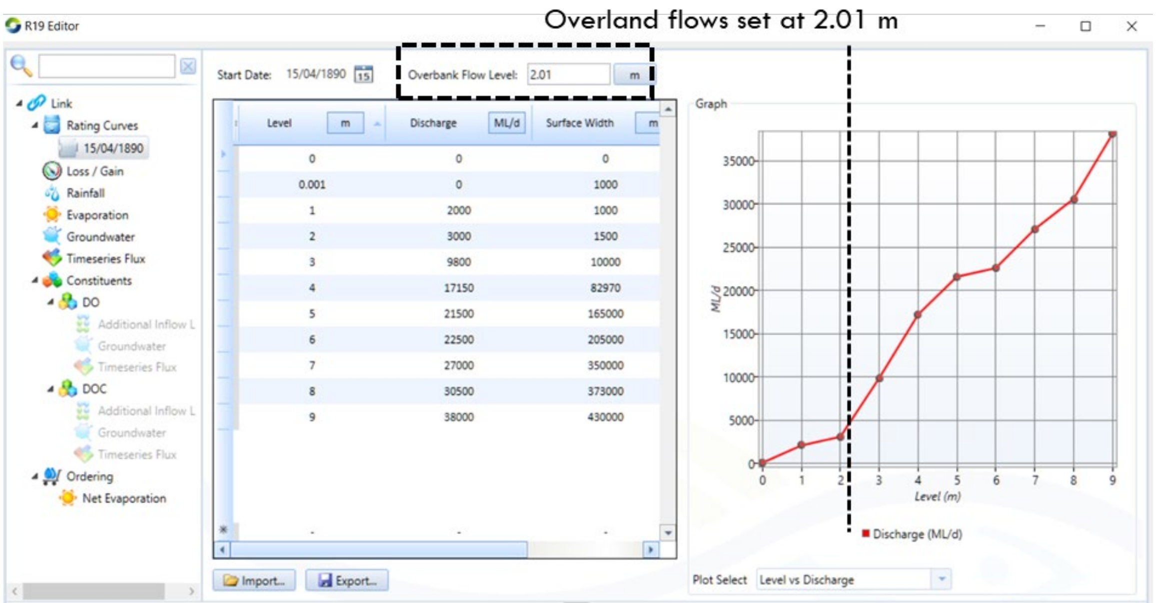

Figure 13. Setting floodplain responses in the adjacent areas

The litter collects in the floodplains when the flows are below the overbank flow threshold, or there is no flow. In the DOC editor (Figure 14), the user has the flexibility to set for decomposition rates based on the type of litter, the fraction of litter that decomposes readily, reaeration rates and provide a water temperature time series.

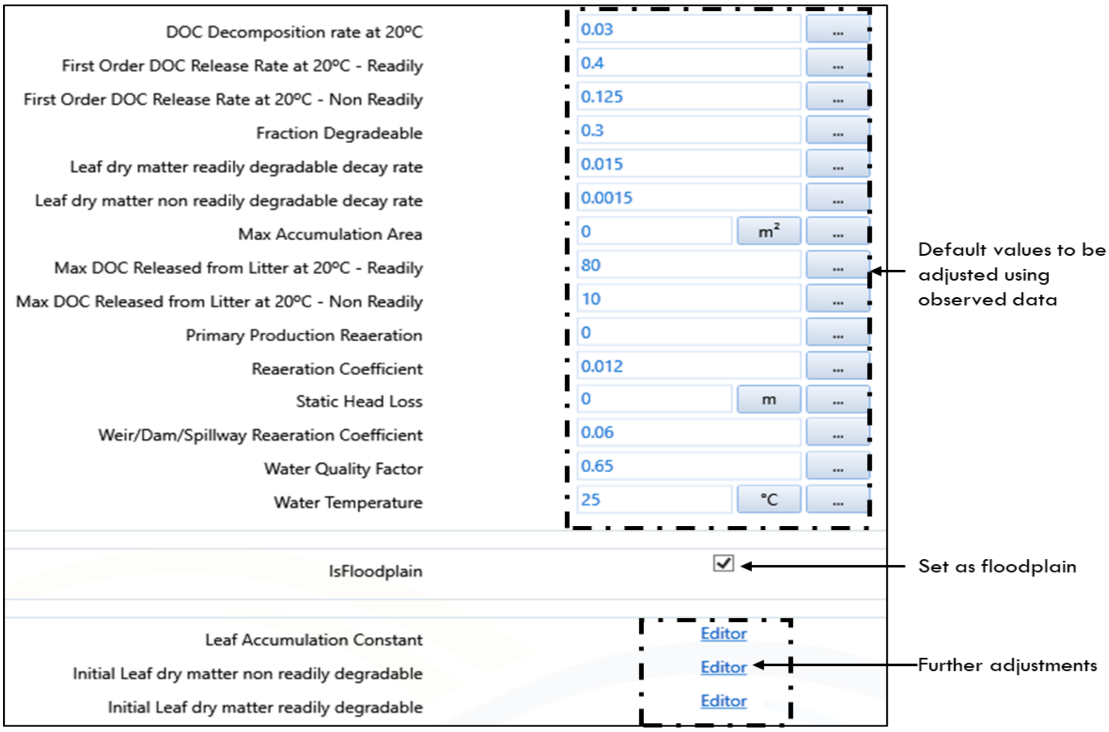

Figure 14. DOC editor for specifications in the floodplain

The user can set different leaf accumulation constants, and kg/ha of initial leaf dry matter that is readily and non-readily degradable at different elevations in the floodplain.

Leaching rates and rates for leaf litter (leaf, bark and twigs) accumulation were taken from the parameterization of the BRAT model. Those rates describe the main vegetation types of the forests, red gum. Additional leaching experiments were done to estimate the effect of pasture cropland (see details in section 6).

6 Field study for leaching rate in BRAT model

Australia's vegetation has undergone vast and abrupt changes since European colonisation, including within the MDB. Much of the basin which was previously dominated by Eucalypts is now mostly grass. Although, it may be expected that if Eucalypt leaf litter (the principal driver of DOC increase and hypoxic blackwater events) was removed then, blackwater event frequency would reduce; in fact, grasslands contribute to sharp and large spikes of DOC into waterways after inundation (Whitworth et al., 2012). The stability of DOC is therefore reduced by these sharp spikes due to grass-related input, rather than the more stable release of DOC from Eucalypts. In combination with localised lowland floodplain Eucalypt forests and other blackwater promoting trends, grasses in the Basin are likely to produce events of similar magnitude to the 2010/2011, and 2016/2017 blackwater events.

Land use pattern (Figure 15) show that outside the forested floodplain cropping and pasture are common types of agricultural activities.

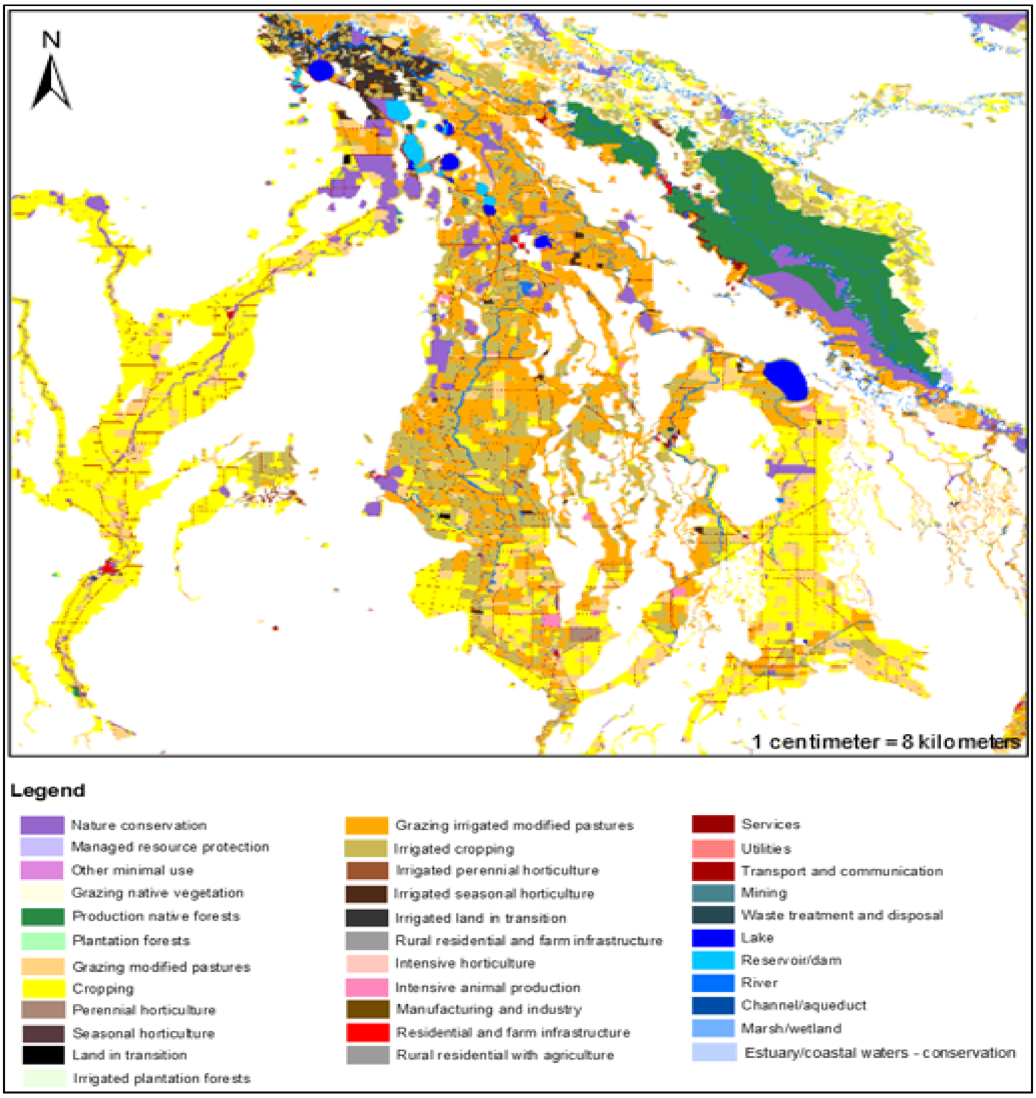

Figure 15. Land-use pattern inundated during a 1/100 year flood near Koondrook-Perricoota Forest (Parascos, 2019)

Leaching rates from vegetation can vary over a large range depending on the vegetation type. Usually we expect floodplains along the River Murray to consist mainly of red gum or black box for which a wealth of data on leaching rates is available. However, less is known what the impact of pasture land and agricultural crop is on blackwater generation. Usually, agricultural crop would have less impact, as it is harvested and thus is not available as a source of DOC on the floodplain. Pasture land, especially adjacent to river reaches, might have a greater influence (Liu et al. 2019). To address this question, a field experiment was run to sample pasture in the area to estimate its potential effect on blackwater.

6.1 Site and sample description.

Private farmland near Corowa (Latitude -36.044730, Longitude 146.359716) was accessed in mid-January 2019 (Figure 16). The field site has an area of approximately 0.078 km^2 (estimated using Google Map's 'distance measure tool') and is situated on the river's floodplain.

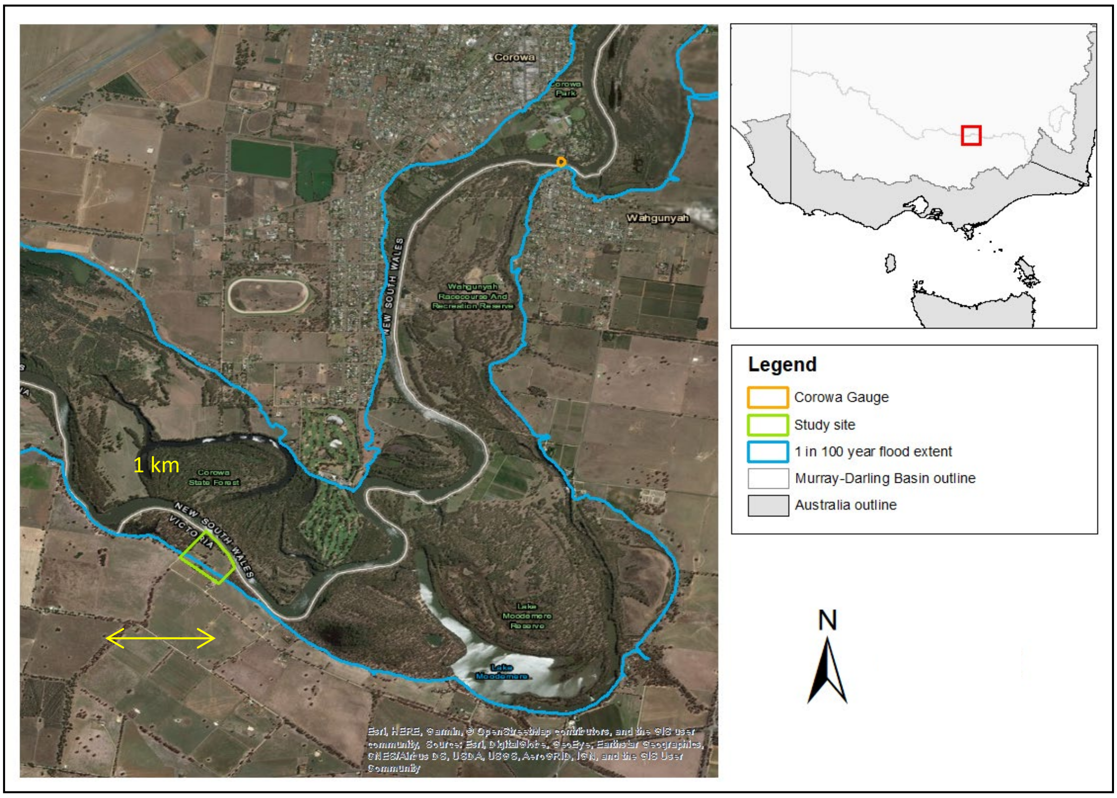

Figure 16. Field and gauge site with 1 in 100-year flood area marked in blue

The site was grazed pasture and represented typical floodplain adjacent to the River Murray and fringed on two sides with red gum forest (Figures 17, 18). The average amount of soil collected from each of the quadrats was 1,616 g (SD = 299 g), with average above-ground plant biomass across all sites being 460 g/m2 (SD = 287 g). Cow pats were clearly a hot spot of organic matter, and when averaged across all samples, they contributed on average 36 g m^{-2} (SD = 11 g). Although this represents approximately one tenth of the amount of above ground plant biomass, it still represents a potentially large amount of organic material and nutrients.

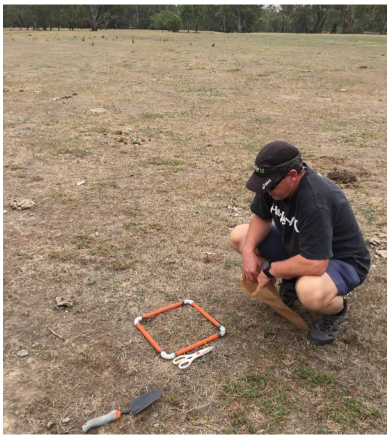

Figure 17. Typical sampling site showing area to be sampled.

Figure 18. Two typical quadrats showing the range of above ground biomass that occurred among the quadrats. The left panel shows vegetation after grazing. The right panel shows a greater level of above ground biomass, including some red gum litter.

Soil moisture was very low across the sites (Table 3) reflecting a combined effect of sampling in summer and the period since last inundation.

Table 3. General soil properties across all the samples.

Parameter	Average (SD)
Soil moisture (%)	3.0 (1.3)
Soil organic matter lost on ignition (%)	14.4 (4.2)
pH	5.5 (0.15)
Conductivity (mS cm^{-1})	0.20 (0.09)
Total Nitrogen (mg kg^{-1})	4170 (1227)
Total Dissolved Nitrogen (mg kg^{-1})	106 (68)
NOx-N (mg kg^{-1})	63 (56)
Total Phosphorus (mg kg^{-1})	672 (162)
Bicarbonate-extracted P (mg kg^{-1})	28 (8)

6.2 Leaching experiments

Ten samples were taken from the single pasture land with variation in distance from tree cover and river to better represent the area (Figure 19). Above ground biomass and soil were augured to determine the DOC contributions from each component of pasture land. Quadrats (30x30 cm) were placed in random locations with the intention to include all area types within the field site (i.e. close to trees, far from trees, close to river border, far from river border). All above-ground biomass within the quadrat was placed in separate paper bags with their locations marked. The top 5 cm of soil within the quadrat was then augured, collected, and refrigerated. Total soil collected per quadrat was measured by weighing each sample, then weighing a few plastic bags (total soil collected was calculated by subtracting the value of the average bag weight from the total mass). The soil was homogenised in the laboratory, and a sub-sample was taken to derive field moisture content (that is, the level of moisture in the soil at the time of sampling) and the total organic content (loss on ignition, see below). The soil was air dried and passed through a mesh sieve. Air dried soil was used for all other soil analyses.

Cowpats were noticed to be an obvious source of above-ground biomass, so samples to account for this were collected. A defined area was created using a 7.5 m length rope pulled from one point in a circle, creating a total area of 176 m^2. All cowpats within this defined area were counted, and an old and fresh sample from each sampling circle was collected.

Soil. While total amount of DOC leached from soil differed amongst each of the samples (Figure 20, providing two examples), the proportion of the DOC that was bioavailable across samples in each of the leaching experiments averaged 0.73 mg L^{-1} (SD = 0.2 mg L^{-1}). This data indicates that a reasonably consistent, and therefore predictable amount of bioavailable DOC would be leached from the pasture soil.

Figure 19. Sample locations at the field site

Above ground biomass. For comparison with soil experiments, vegetation leaching experiments were carried out as two-point incubations, terminated after 16 days. When standardised to a dry above ground measure, the amount of bioavailable DOC in samples ranged from 0.6 to 3.9 mg g^{-1}, with the average (SD) was 1.8 mg g^{-1} (1.0). This translates to a relatively small proportion of DOC for any given amount of vegetation. When scaled on an aerial basis, this represented an average of 634 mg DOC m^{-2}.

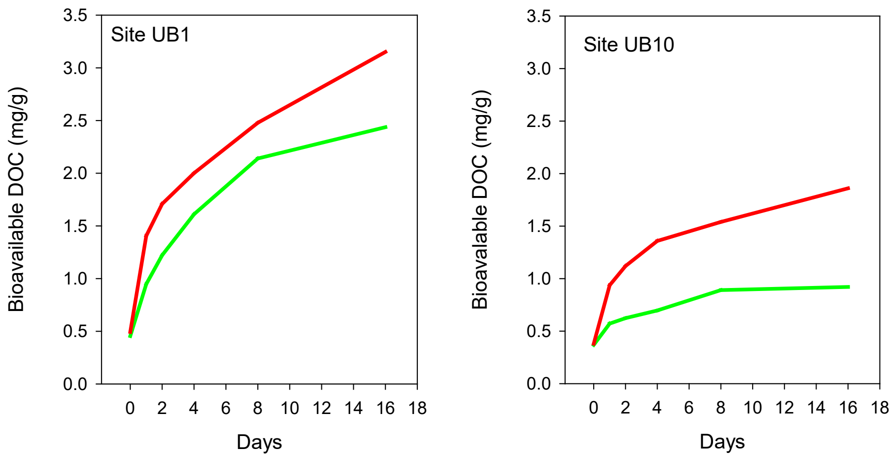

Figure 20. Two examples are shown of the leaching experiments to determine bioavailable DOC released from soil over time. Red lines show DOC leached in presence of a microbial inhibitor and green lines show DOC released with no inhibitor. Bioavailable DOC is calculated as the difference between the two.

Cowpat. Although this work did not initially set out to examine the contribution of cow pats to generating bioavailable DOC, first trials were carried out to develop methods for further use. Overall, it was difficult to establish sufficiently sterile conditions to be certain that true measures of bioavailability could be calculated. In some trials, at least 3.5mg g^{-1} bioavailable DOC was generated, although this is a relatively small value. In further trials, there was no difference in the amount of DOC in the presence and absence of an inhibitor. It is likely that the standard levels of inhibitor were not enough to establish truly abiotic conditions. Further work is required to develop a method that allows estimates of DOC to be made with confidence.

DOC leaching experiments were set up by placing a known mass of 15 g from each soil sample into a Schott bottle with 1,000 mL of water. Each sample was done in duplicate with the second series also containing azide to inhibit microbial activity (Baldwin, 1999; O'Connell et al., 2008). Azide was added as a 2.5 mM, with a final concentration of 162 mg L^{-1}. The azide solution was made by dissolving 2.43 g of sodium azide in 15 mL of water and 1 mL of stick solution to each litre bottle. A T_0 sample was taken 10mins after adding water, with following samples taken at 1, 2, 4, 8 and 16 days. Each water sample was filtered through a 0.45 µm pore-sized membrane filter.

Non-purgeable total organic carbon analysis was used to determine the DOC concentrations of the samples. Samples were filtered through a 0.45 µm pore-sized filter, acidified and total carbon measured using a total carbon analyser (AnalytikJena, Germany).

Cowpat samples were airdried, weighed and homogenised. A series of 1:5 extractions were then carried out with milli-Q water. Nutrients, totals and dissolved totals were then measured and recorded. The DOC of the cowpat samples was determined with the same method as mentioned above.

The amount of DOC released over time for each sample type was normalised for dry mass and fitted to the following equation:

$$DOC = m(1 - e^{-kt})$$

where m is the amount of bioavailable carbon, k is the first-order rate constant, which for example is 0.382 day^{-1} for grasses (Whitworth and Baldwin, 2016) and t is the time since the initial inundation.

To determine the DOC leaching rate of pasture, the average value of bioavailable carbon (Table 4) can be inserted into the above equation. This yields the rate constant for DOC leaching from pasture 0.571 day^{-1}, a value 50% higher than that for grasses.

Table 4. Experimental results from pasture DOC leaching experiments

	Pre-Leaching……………………………			**Post-Leaching……………………………**			**Bioavailable DOC**
Sample ID	Wt Sample (g)	mgC L^{-1}	mg g^{-1} material	Wt Sample (g)	mgC L^{-1}	mg g^{-1} material	mg/material
Pasture 1	15.23	200	13.13	14.93	170	11.39	1.7
Pasture 2	15.29	250	16.35	14.96	220	14.71	1.6
Pasture 3	15.10	230	15.23	15.20	200	13.16	2.1
Pasture 4	15.03	130	8.65	14.92	90	6.03	2.6
Pasture 5	15.11	150	9.93	14.99	130	8.67	1.3
Pasture 6	15.13	150	9.91	14.98	140	9.35	0.6
Pasture 7	15.14	200	13.21	14.98	140	9.35	3.9
Pasture 8	15.18	130	8.56	14.88	140	9.41	-0.8
Pasture 9	14.94	130	8.70	15.13	110	7.27	1.4
Pasture 10	15.11	120	7.94	15.08	110	7.29	0.6

7 Blackwater Modelling Results

7.1 Effect of vegetation type (pastureland) using the BRAT model

The effect of the vegetation types on the hypoxic blackwater event of summer 2010/2011 was tested on the simple BRAT model to estimate its effect on DO/DOC dynamics for the case studies. A comparison of the outputs is shown in Table 5 and Figure 21.

Table 5. Comparison of output summaries

Output summary (at floodplain outfall)		Without pasture	With pasture	
Critical outflow DO concentration (lowest value)	DO_{min} =	0.00	0.00	mg L^{-1}
Duration of hypoxic outflows (DO<2 mg L^{-1})	-	63	63	days
Critical outflow DOC concentration (highest value)	DOC_{max} =	14.1	14.2	mg L^{-1}
Critical downstream DO after mixing	$DO_{ds,min}$ =	4.10	4.10	mg L^{-1}
Duration of hypoxia after mixing	-	0	0	days
Critical downstream DOC after mixing	$DOC_{ds,max}$ =	6.1	6.1	mg L^{-1}
Potential fish biomass production in receiving channels	-	686	682	kg

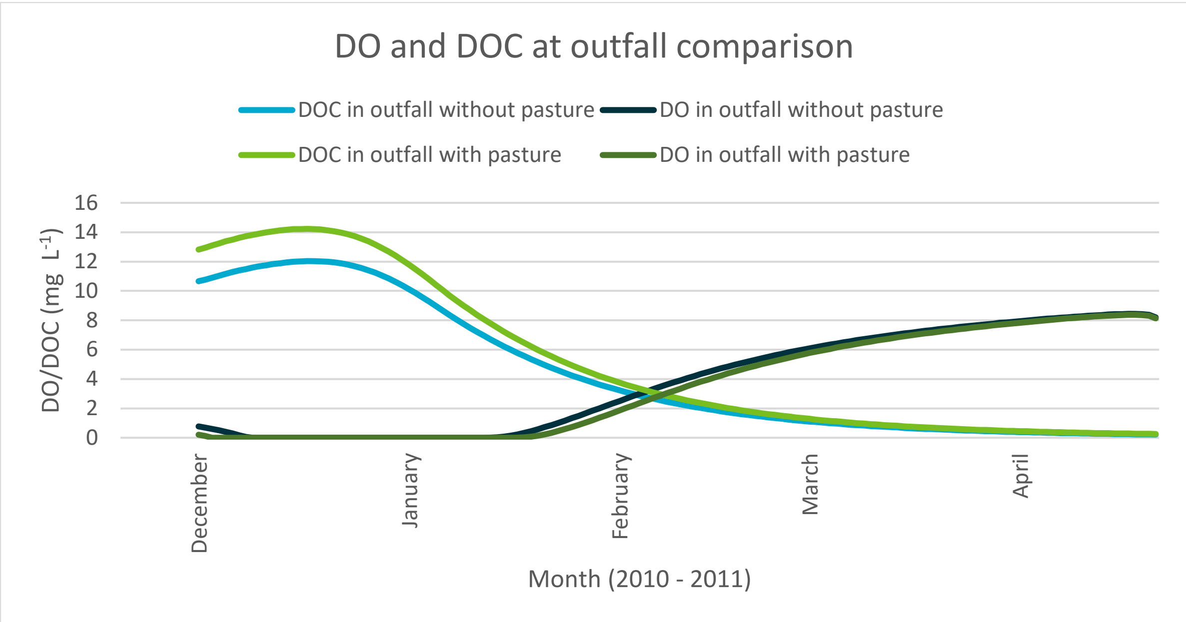

Figure 21. DO and DOC curve comparison

The results in Figure 21 indicate a slight increase in DOC and decrease in DO output when pasture is included alongside native grasses, although these differences are minimal (DOC NSE = 0.935, DO NSE = 0.991). The BRAT model indicates that pasture will increase the maximum DOC leached by

2.2 mg L^{-1} through this value, as well as the differences between the curves, are expected to change with contributions from other pasture cropland above ground biomass sources, such as cowpats.

A comparison of recorded DO levels from the actual event with the modelled outputs is difficult as the raw data recordings from DO loggers from the site during the 2010/2011 summer hypoxic blackwater event are likely no longer in existence nor publicly available (Baldwin 2019, pers. comms). A comparison can only take place when comparing DO spot data from similar locations from other studies (Figure 22). The modelled period in BRAT is from the 20th of November 2010 onwards, so when comparing this data with recorded data from Whitworth *et al.* (2011), at Barbers Creek, directly downstream of Koondrook-Perricoota forest, we can see a similar trend of DO levels approaching 0 mg L^{-1} by December, and then increasing from mid-January onwards.

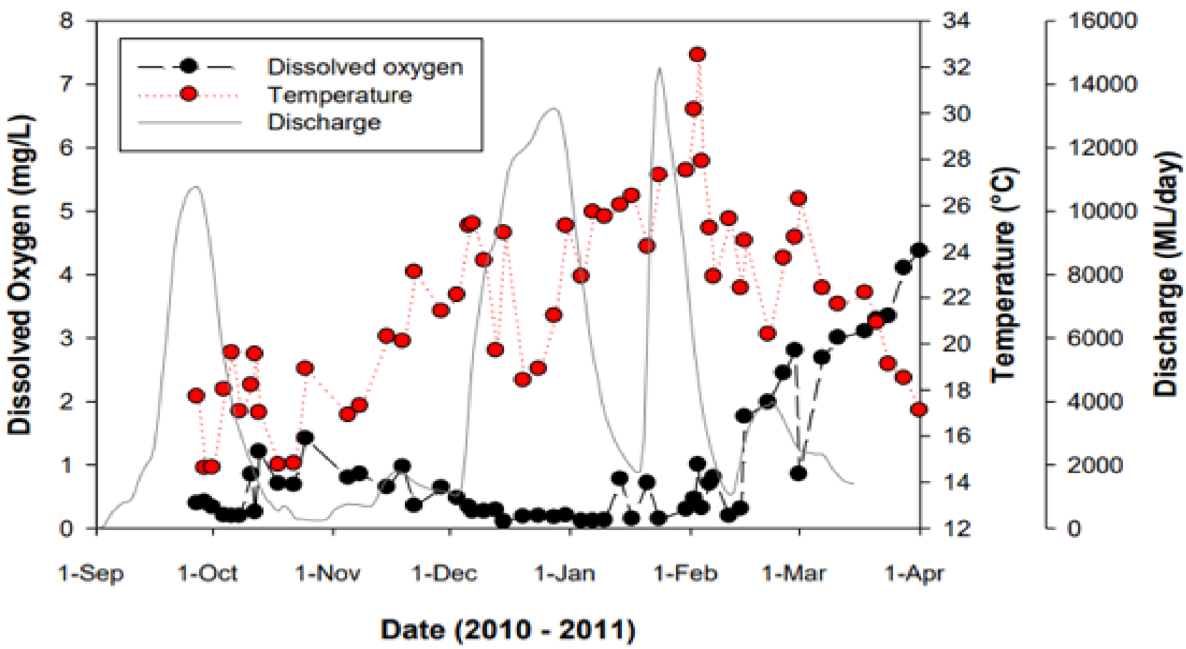

Figure 22. DO spot measurements and temperature at Barbers Creek, Barham-Moulamein Road, immediately downstream of Koondrook-Perricoota Forest during the 2010-2011 floods. Modified from Whitworth et al., 2011.

The effect of pasture as simulated with BRAT for this case shows only a small impact of pasture. Although this is not a main process to take account for in the Barmah or Gunbower Forest, it needs to be taken into account in other studies/floodplains with larger agricultural areas inundated.

7.2 eWater source model plug-in

7.2.1 Model warm-up period

During preliminary warm-up periods, the eWater Source model predicts a good fit between observed and simulated flows at gauge 409215 with R^2 =0.96 (Figure 23).

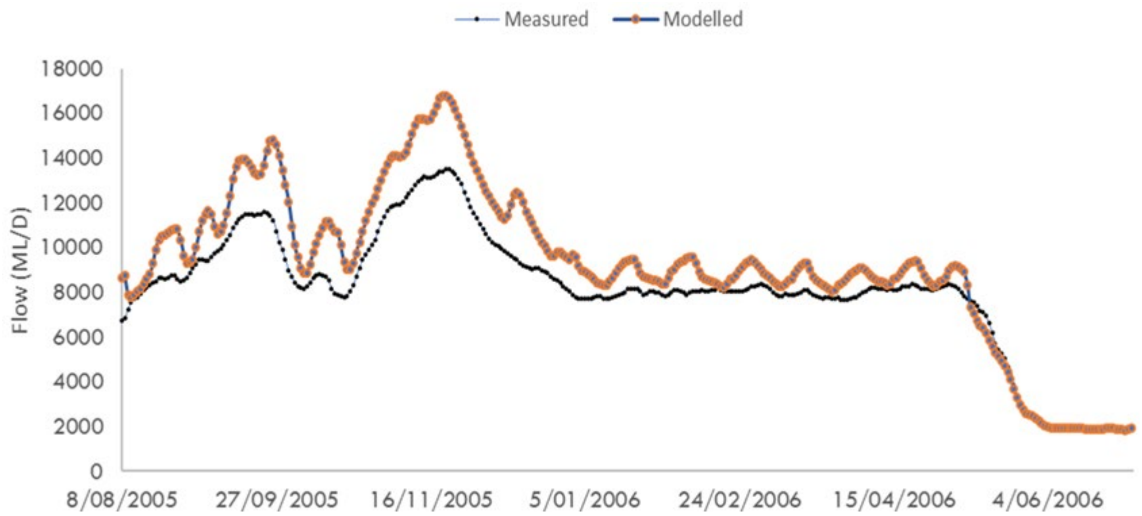

Figure 23. Observed and simulated flows at Gauge 409215 below the Broken Creek confluence

During the same period, the DO and DOC remain within normal range and DO concentrations in the main stem of River Murray responds to increase in DOC loadings (Figure 24). It must be noted that during model set up period, the initial DO concentration at the upper boundary at Tocumwal gauge was set at 10 mg L^{-1}.

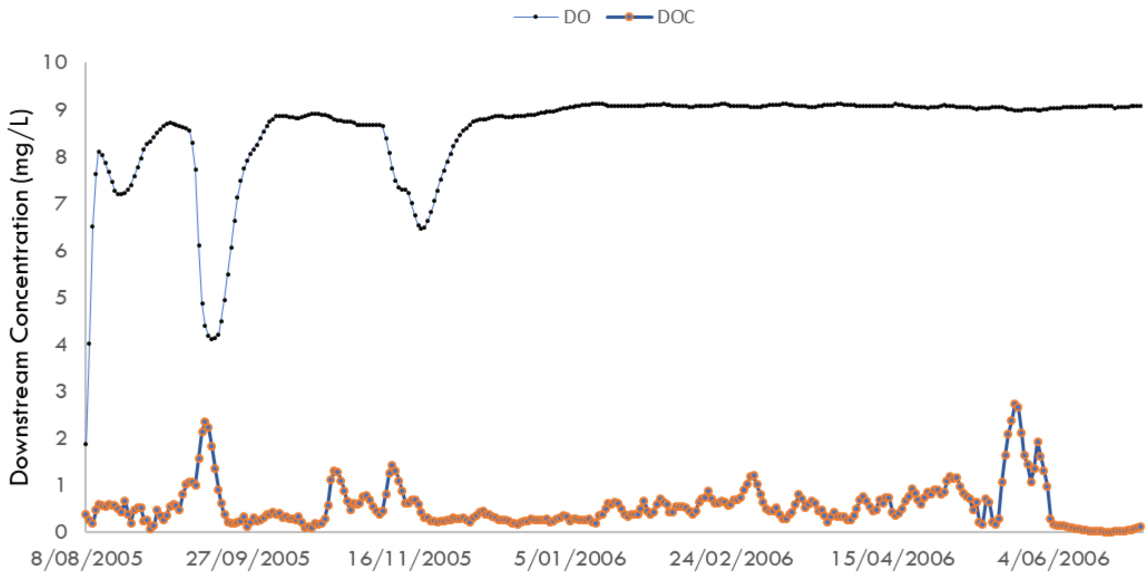

Figure 24. DO and DOC (mg L^{-1}) at Gauge 409215 during the warm-up period

7.2.2 Flow scenarios

Flooding in the Barmah-Millewa Forest occurs when the Murray flows exceed 10,500 ML/d channel capacity upstream of Tocumwal. The 2010/11 flood event in the Barmah-Millewa Forest was a 105 years record flow with flows of more than 100,000 ML/d at approximately ten times the channel capacity through the Forest. The Barmah choke is an important regulator of flows in the River

Murray and flows higher than 8,500 ML/d at the choke results in flooding of Barmah and Millewa Forests.

Flows to the Gunbower are impacted by the regulations at Torrumbarry Weir. The anabranch capacity is around 1,650 ML/d limiting environmental water deliveries. Additional flows of 250 ML/d can be sent through a side channel upping the flows to a total of 1,900 ML/d. Flows to the forest and the wetlands in the Gunbower system is driven by the head difference between the weirs on Gunbower Creek and the receiving channels in the forest. When the flows are in the 30,000 ML/d range, the head difference no longer exists, and hence no flow can be released. Widespread flooding throughout the region during 2010/2011 saw Gunbower Forest receive its first extensive flood event in over 10 years.

To test the hypothesis, that using flow management in years before a flood can reduce the risk of severe blackwater events, we ran pre-wetting scenarios with different flood levels. Furthermore, as temperature can play a major role in decomposition and leaching processes, it is necessary to run test scenarios for different seasons of flood pulses. In this study, twenty pre-wetting flow scenarios were tested with volumes ranging from 10,000 ML/d to 120,000 ML/d over a two-week period in September and December 2009 and in February 2010 (Table 6). Water temperature time series were used from local stations ranging from cold (September) to warm (February) conditions. The scenarios were chosen to simulate a flushing pulse one year before the actual blackwater event 2010/2011 happened.

Table 6. flow scenarios (flows released at Tocumwal Gauge)

Flood Volume (ML/d)	Sep-09	Dec-09	Feb-10
10,000	S1	S8	S15
15,000	S2	S9	S16
25,000	S3	S10	S17
35,000	S4	S11	S18
50,000	S5	S12	S19
80,000	S6	S13	S20
120,000	S7	S14	S21

7.2.3 Baseline Scenario Parameterisation

The baseline scenario was run for a twelve-year period (Jan 2000 – Oct 2012) with observed flows in the system. At the upstream boundary, DO and DOC concentrations were based on observed values under normal conditions at 6 mg L^{-1} (DO) and 10-12 mg L^{-1} (DOC). The total DOC concentration includes 4 mg L^{-1} of labile and 8 mg L^{-1} of recalcitrant carbon to account for other sources of organic carbon in the system (Mosley and Rahman, 2017). Key inputs and ranges to the DO/DOC plug-in are shown in Table 7.

Relevant reaches along the main stem of River Murray and the anabranches supplying flows to Barmah forest and Gunbower forest were set to floodplain, allowing for overbank flows and litter accumulation. Parameters for the DO/DOC plug-in as described in Table 7 (column 2) were used for floodplain calibration. During the calibration process, the performance of the model was tested with different parameter within their range as well as with different litter accumulation rate and initial matter available on the floodplain. River red gum is the primary litter source as the majority vegetation in both Barmah and Gunbower systems. Howitt et al. (2007) reported an accumulation of 1394 kg ha^{-1} and 2096 kg ha^{-1} of leaf litter in previously flooded and unflooded areas during 2005.

During the Millennium drought, the floodplains received no flows except in 2005, when a medium sized event aided by the last release of the Barmah-Millewa Environmental Water Allocation (EWA) flooded approximately 55% of the floodplain. Leaf litter accumulated for at least five years prior to the floods in 2010.

7.2.4 Baseline calibration of the 2010 Blackwater event/Plug-in performance

The pre-wetting scenarios are set at Tocumwal gauge. The flows were changed at the gauge upstream to both sites.

Modelled concentration of DO and DOC along the main stem of River Murray was compared to the observed values at three locations, Picnic Point (above the confluence with Barmah Forest), Torrumbarry gauge (below Barmah Forest and above Gunbower Forest) and finally at Barham gauge located below the confluence with Gunbower Forest.

At Torrumbarry, which has the highest number of observations, the model is able to capture the drop in the DO concentrations in November and December. Observed values of DOC downloaded from (http://data.water.vic.gov.au/) was compared to modelled concentrations at Torrumbarry gauge.

Figure 25a shows the relationship between modelled DO outputs and observed DO at Torrumbarry and Barham in the main Murray channel. Figure 25b shows the DO response in Barmah Forest during the 2010 blackwater event.

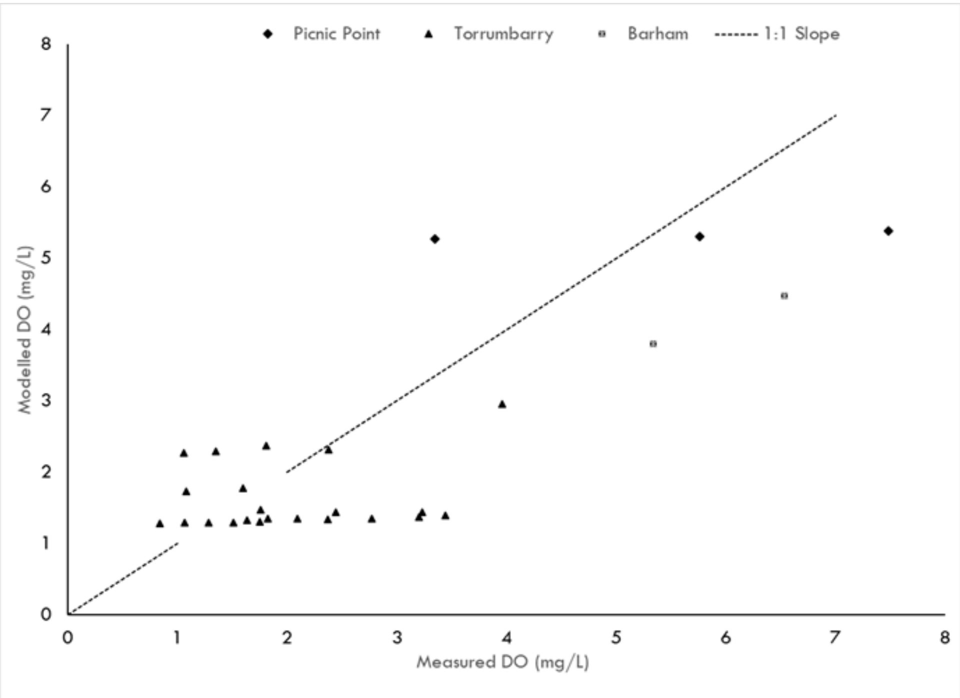

Figure 25a. Modelled DO response to measured DO at Torrumbarry and Barmah in the Murray main channel. Triangles are for the Torrumbarry water quality monitoring site and circles are for Barmah gauge.

Table 7. Parameters to the DO/DOC eWater Source plug-in (adapted from Mosley et al., 2019)

Parameter	Value	Unit	Source/previous published ranges
DOC decomposition rate (20°C)	0.02	day^{-1}	
First order DOC release rate - readily (20°C)	0.125	day^{-1}	0.382 (grass) 0.0864(bark) (Howitt et al., 2007, Whitworth and Baldwin 2012)
First order DOC release rate - non readily (20°C)	0.08	day^{-1}	0.078 (twigs) -0.173 (bark) (Howitt et al., 2007, Whitworth and Baldwin 2012)
Fraction degradable	0.6	unit-less	0.1-0.99 (Howitt et al., 2007)
Leaf dry matter readily degradable decay rate	0.0025	day^{-1}	0.0017-0.03 (Howitt et al., 2007)
Leaf dry matter readily non-degradable decay rate	0.00025		0.00001 - 0.0003 (Howitt et al., 2007)
Max accumulation area	floodplain area	m^2	
Floodplain elevation		m	
Max DOC released from litter-readily (20°C)	80	$mg\text{-}g^{-1}$	45-125 (Howitt et al., 2007, Whitworth and Baldwin 2016)
Max DOC released from litter-non readily (20°C)	10	$mg\text{-}g^{-1}$	10 (Whitworth and Baldwin 2016)
Primary production reaeration	0	day^{-1}	Recommended that this parameter is left as zero on the basis that oxygen supply from photosynthesis is usually balanced on a daily basis by night-time respiration (Whitworth and Baldwin, 2016)
Reaeration coefficient	0.0012	day^{-1}	Variable dependent on the type of system
Weir/spillway reaeration	0.6	unit-less	0.05-1.05 depending on the type of structure
Water quality factor	0.65	unit-less	0.65-0.8 (Whitworth et al 2013)
Water temperature	observed	°C	Variable
Leaf accumulation constant	10	$Kg\ ha^{-1}\ day^{-1}$	0.6-9 (Whitworth and Baldwin 2016)
Initial leaf dry matter readily degradable	1,000	$Kg\ ha^{-1}$	Variable dependent on vegetation community

Initial leaf dry matter non-readily degradable	1,000	Kg ha^{-1}	Variable dependent on vegetation community

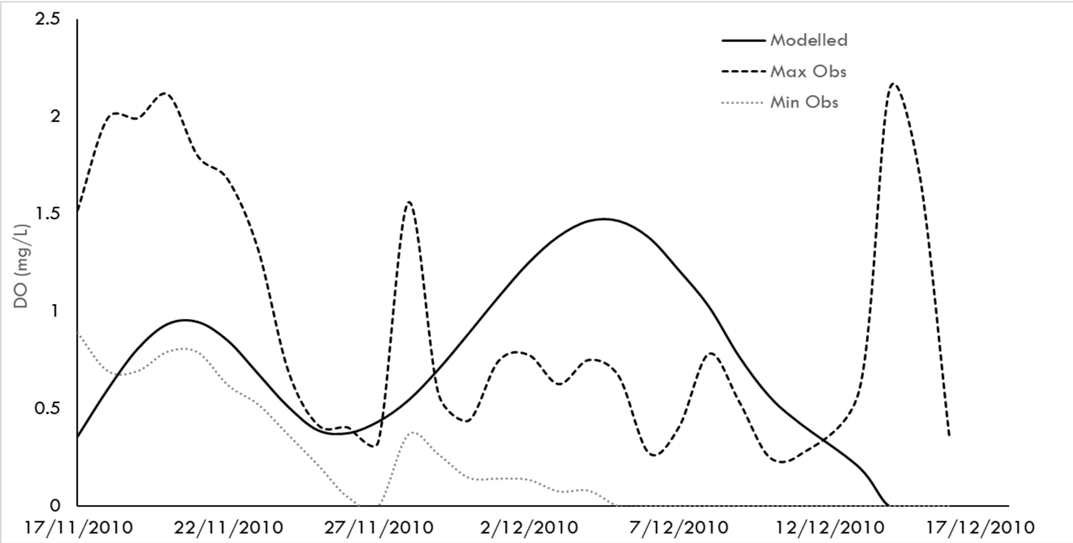

Figure 25b. Modelled DO response to observed DO in Barmah Forest (maximum and minimum observations on a given day)

The combination of recalcitrant DOC and labile DOC generated by the plug-in is in the median range of the observed values, but unable to generate the peaks (Figure 26). In this case, the poor fit is due to lack of site-specific measured DOC data. Model output is as good as the quality of input data; hence, frequent targeted measurement of DOC data is needed to improve model calibration.

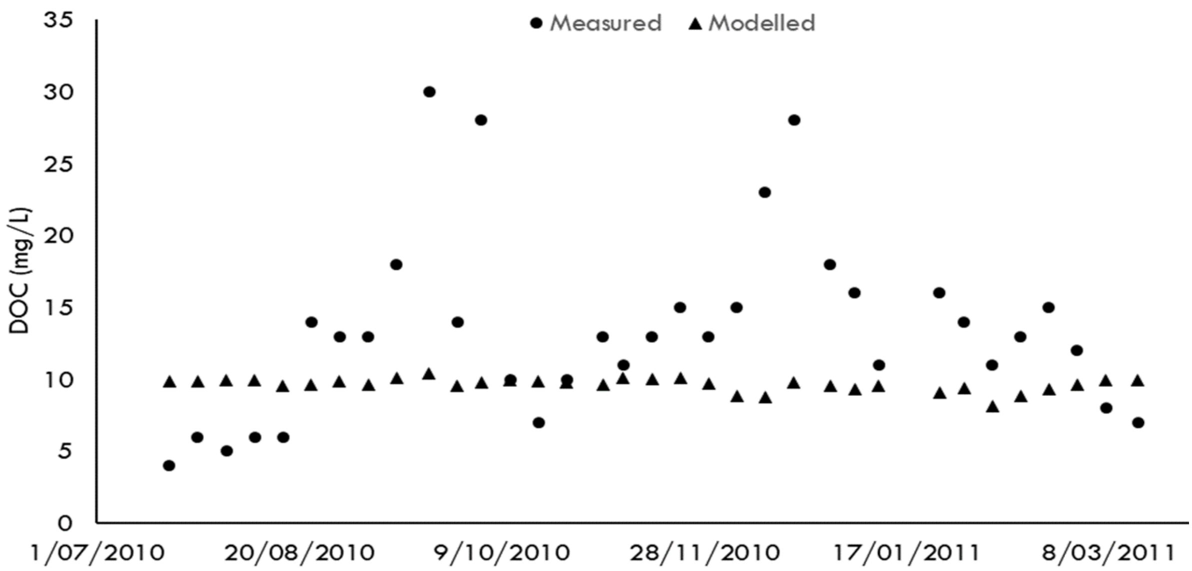

Figure 26. Measured DOC (mg L^{-1}) compared to modelled DOC (mg L^{-1}) at Torrumbarry Gauge

7.2.5 Sensitivity analysis

Plug-in sensitivity was tested by changing the parameters in the storage routing reach through the Barmah Forest (Table 8). The local sensitivity of these parameters was tested for predicting the DO and DOC concentrations in the Barmah Forest.

Table 8. Range of parameters for local sensitivity test

		Modified	
	Baseline	Run 1	Run 2
DOC decomposition rate	0.02	0.002	0.2
First order DOC release rates (readily)	0.125	0.0125	1.25
First order DOC release rates (non-readily)	0.08	0.008	0.8
Fraction degradable	0.6	0.06	
Leaf dry matter readily decay rate	0.003	0.025	0.25
Leaf dry matter non-readily decay rate	0.00025	0.0025	0.025
Max DOC released from litter readily	80	45	125
Reaeration coefficient	0.001	0.012	0.12
Weir/spillway reaeration	0.6	0.06	1
Water quality factor	0.65	0.1	0.8

7.2.6 Hydrological impacts of the flow scenarios

A total of 21 flow scenarios (Section 7.2.2) were tested in this study, with pre-wetting flows released at Tocumwal Gauge over 2-week periods in September 2009, December 2009 and February 2010 (14 months, 12 months, and 9 months) prior to the actual blackwater event in 2010 (Figure 27). Flows in Barmah Forest peak 2 days after releases at Tocumwal gauge, and is approximately 20% of the Tocumwal flows during the 120,000 ML/d releases, 35% during the 50,000 ML/d release and 18% during the 15,000 ML/d releases. Table 9 shows per cent flows in the Barmah Forest and downstream at Barmah and Torrumbarry gauges. The following are key observations:

- In normal condition about 20% of the flows from Tocumwal is diverted towards Barmah Forest
- There is a decrease in the flows at Barmah Gauge mostly from other diversions, such as flows to Millewa Forest.
- Flow increases at Torrumbarry due to inflow of other tributaries

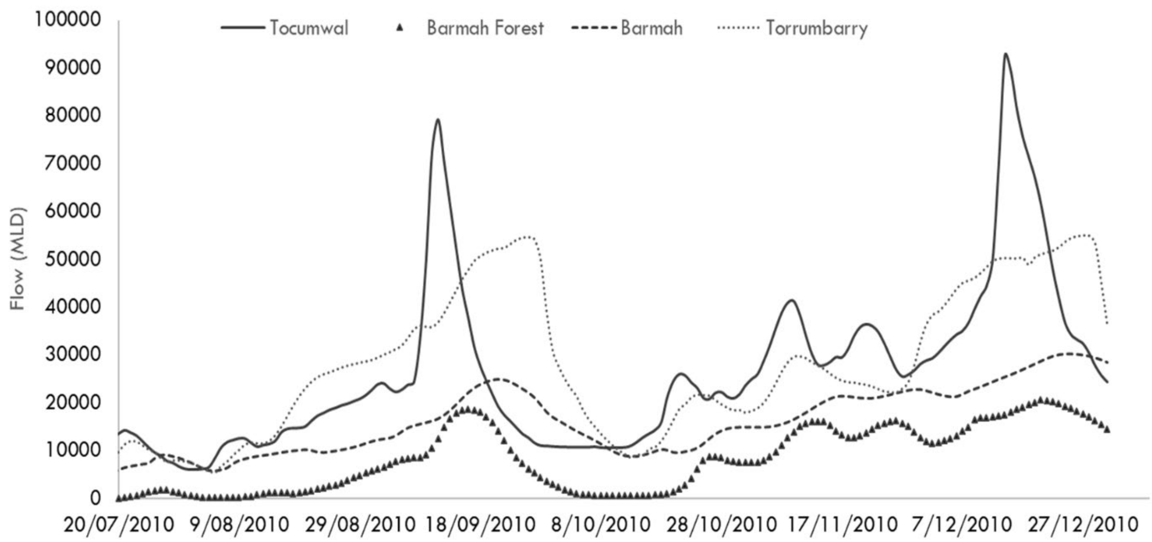

Figure 27. Hydrograph of the main reach of the Murray and Barmah Forest during the 2010 floods

Table 9. Range of flows diverted to Barmah Forest and along the main stem of the River Murray

Flows	Barmah Forest	Barmah Gauge	Torrumbarry Gauge
GL/L		Destination of Flow (%)	
2010 flood	20		
15,000	18		
50,000	35	47	47
120,000	20	20	20

7.2.7 Impacts on Dissolved Oxygen and DOC

A short DO response is observed during the release of the flows in the Barmah Forest, though the impact is nominal for the actual 2010 blackwater event. Below we compare the DO response upstream of Barmah Forest out flow point at Picnic Point gauge, in the reach through the Barmah Forest and then just below at Barmah Gauge for one flow scenario, 120,000 ML/d released for the first two weeks of December. This particular scenario was selected because the temperature is in the range where strong leaching of DOC is expected (Figure 28). As there is no flow in the Barmah Forest prior to the flow pulse, the modelled DO concentration shows as 0, and a spike is observed immediately as water flows into the floodplain. The DO levels remain in the range of 6 mg L^{-1} at Picnic Point upstream of Barmah Forest (Figure 29), however at the Barmah Gauge downstream of the forest, the DO concentration responds to the flow of water into the Barmah Forest albeit with a delay of 2 weeks required for the DOC to leach in the floodplain and reach the main channel. Similarly, downstream in the Gunbower Forest and Torrumbarry Gauge (Figure 30), the DO response is controlled by the volume of water transferred, with a spike as water flows through Gunbower and a dip at Torrumbarry as the plug of DOC laden water flows downstream. The DO concentrations at Torrumbarry mostly show trends similar to the upstream gauge at Barmah, though the values are slightly lower than that observed upstream. This is a result of the DOC coming from Goulburn and Campaspe rivers. High DO in the Gunbower is a result of the Source model setup and requires measured data for better calibration.

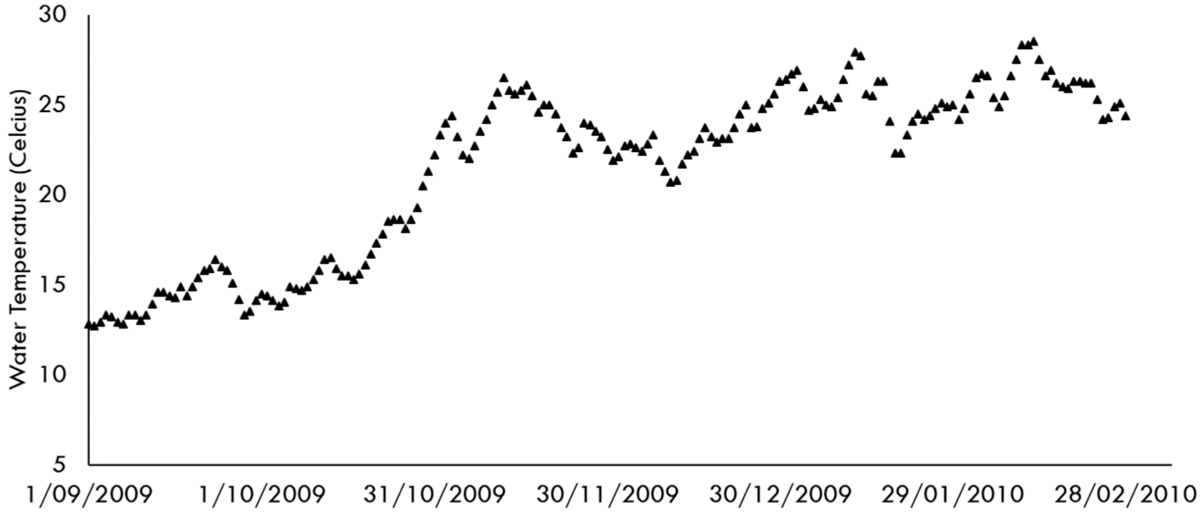

Figure 28. Observed water temperature at Tocumwal Gauge used in the model

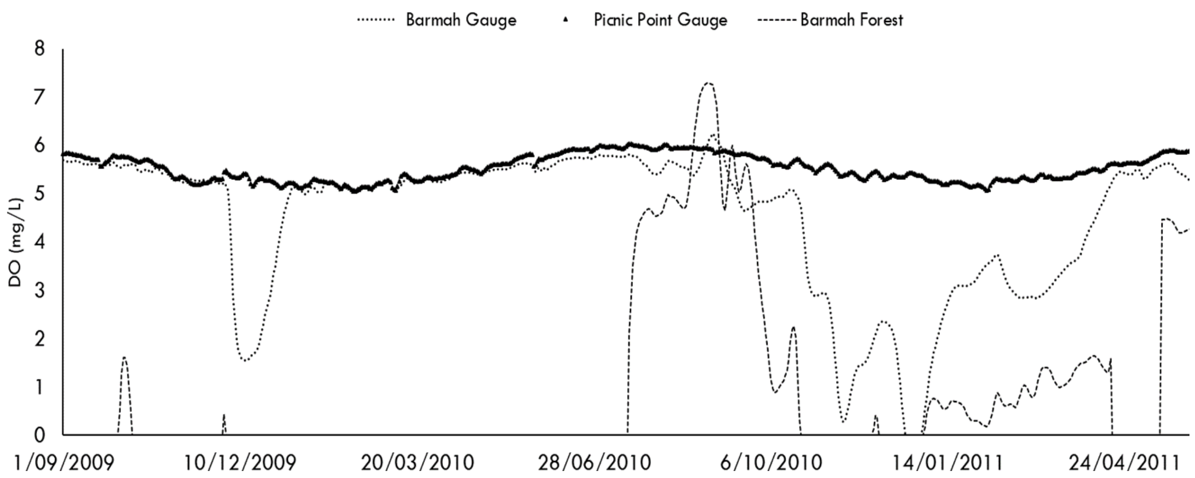

Figure 29. Dissolved Oxygen response in 2010 to pre-wetting flows of 120,000 ML/d (1-15th December 2009) at upstream (Picnic Point), downstream (Barmah Gauge) and in Barmah Forest

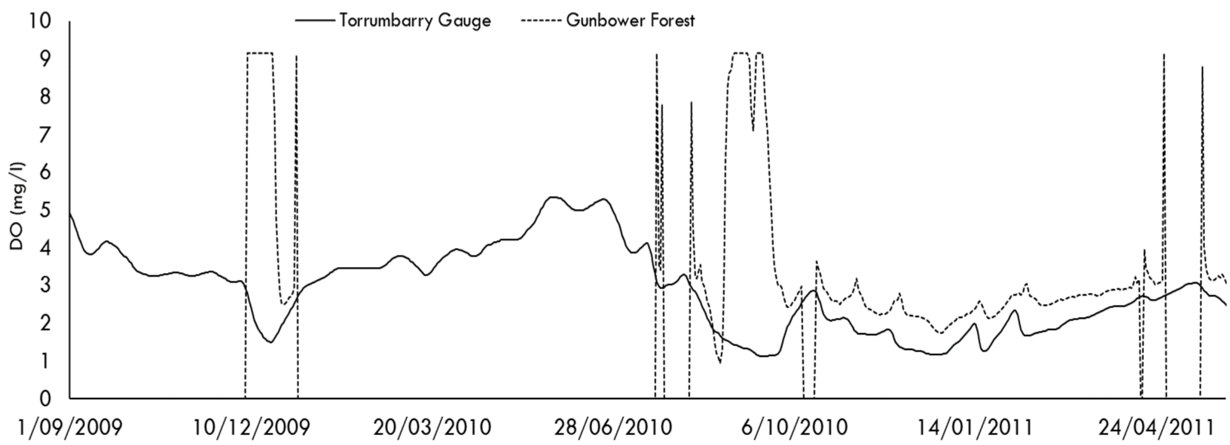

Figure 30. Dissolved Oxygen response to flows of 120,000 ML/d (1-15th December 2009) at Torrumbarry Gauge and Gunbower Forest

The impact of different flow pulse volumes and timing were compared to the baseline. First, the impact of timing is shown for the 120,000 ML/d flows on the DO concentrations in the Barmah Forest and downstream at Barmah Gauge for the 2010 blackwater event. As seen in Figure 31 and Figure 32, that flushing in the hotter months reduces the severity at the start of the event, but the effect dissipates as the blackwater event is prolonged through the months. It is interesting to note that flushing in September leads to a drop in the DO concentrations in the Barmah Forest. At Barmah gauge on the main stem, flushing in December leads to a short-term increase in the DO concentration followed by a sharp drop. Flushing in February leads to an overall increase in the DO that is sustained through the life of the blackwater event. Flood sizing is important for mitigating impacts in the main reach, for example, flows of 50,000 ML/d and 120,000 ML/d in February doubles the DO concentrations compared to the 15,000 ML/d pulse which tracks the baseline response (Figure 33a,b). However, in the Barmah Forest, the size of the floods has minimal or no impact and all flows show an increase in the DO compared to the baseline.

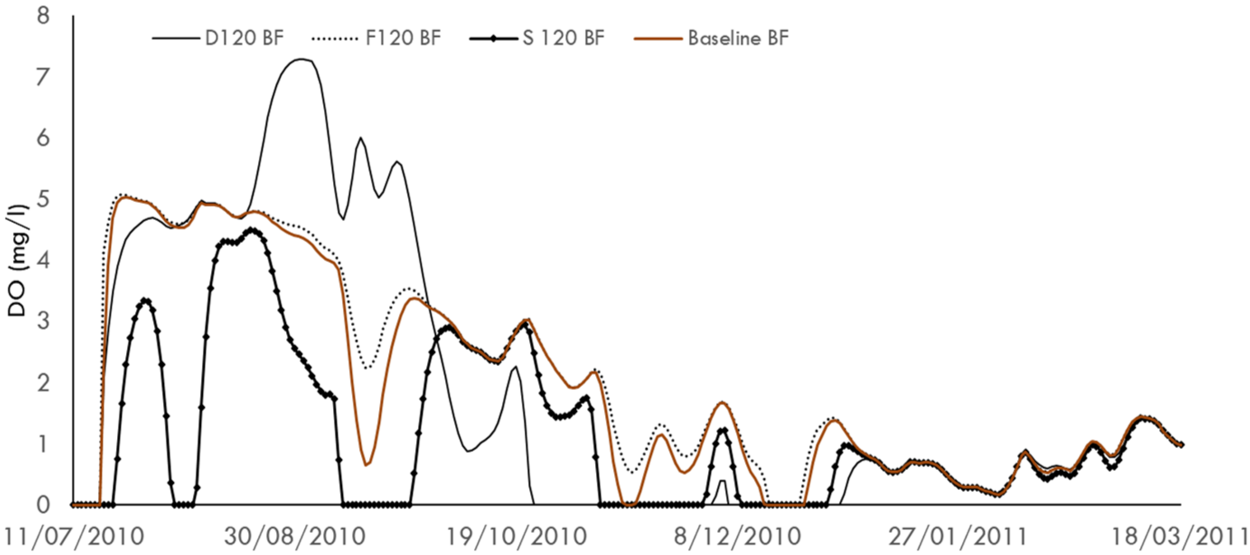

Figure 31. Temporal variation of DO in Barmah Forest (BF) in response to flow pulse (120,000 ML/d). S 120, D 120 and F 120 denotes flows in September and December 2009 and February 2010 respectively.

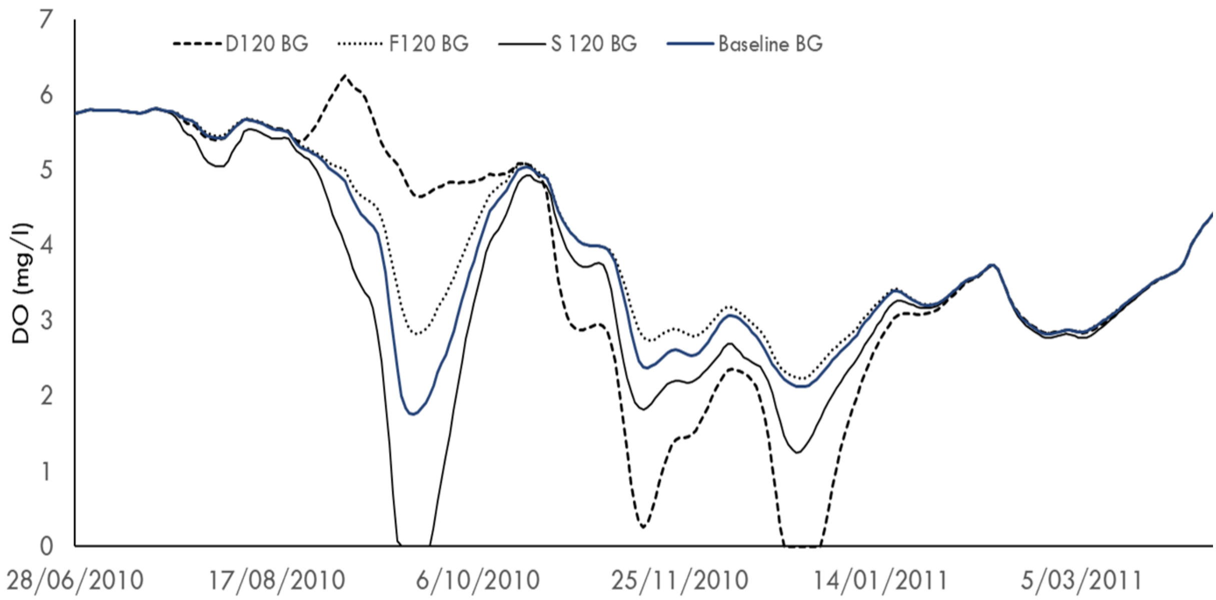

Figure 32. Temporal variation of DO in Barmah Forest in response to flow pulse (120,000 ML/d). S 120, D 120 and F 120 denotes flows in September and December 2009 and February 2010 respectively. Modelled values are shown at Barmah Gauge (BG).

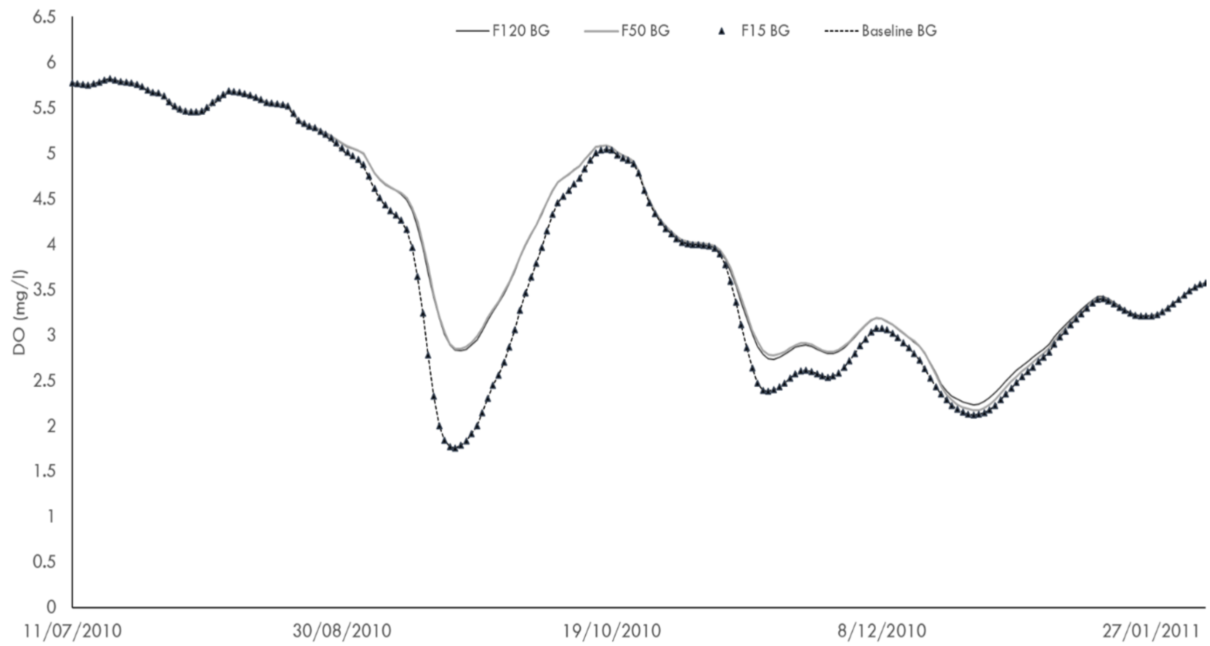

Figure 33a. Dissolved Oxygen response to flow pulses in February, F120 = 120,000 ML/d, F50 = 50,000 ML/D and F15 = 15,000 ML/D). Modelled values are shown at Barmah Gauge (BG).

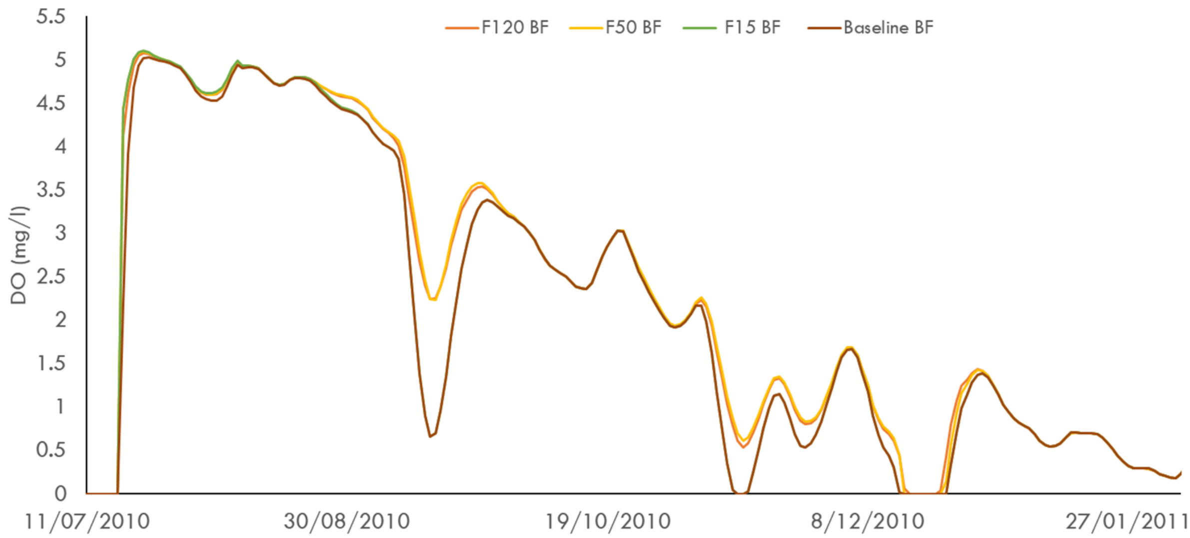

Figure 33b. Dissolved Oxygen response to flow pulses in February, F120 = 120,000 ML/d, F50 = 50,000 ML/d and F15 = 15,000 ML/d). Modelled values are shown at Barmah Forest (BF).

While some DOC is leached out when the flows are diverted to the floodplains, it is not sufficient to reduce the DOC availability for the actual 2010 event. To better understand the DOC response, measured DOC data are required from the main channel as well as the two floodplains through the calibration period. However, it is evident that the size of the flow pulse is proportional to the DOC response during the flow event, for example, the average DOC during the 2 week 120,000 ML/d flows in December is 13 mg L^{-1} whereas during the 50,000 ML/d flow it is approximately 11 mg L^{-1} (Figure 34).

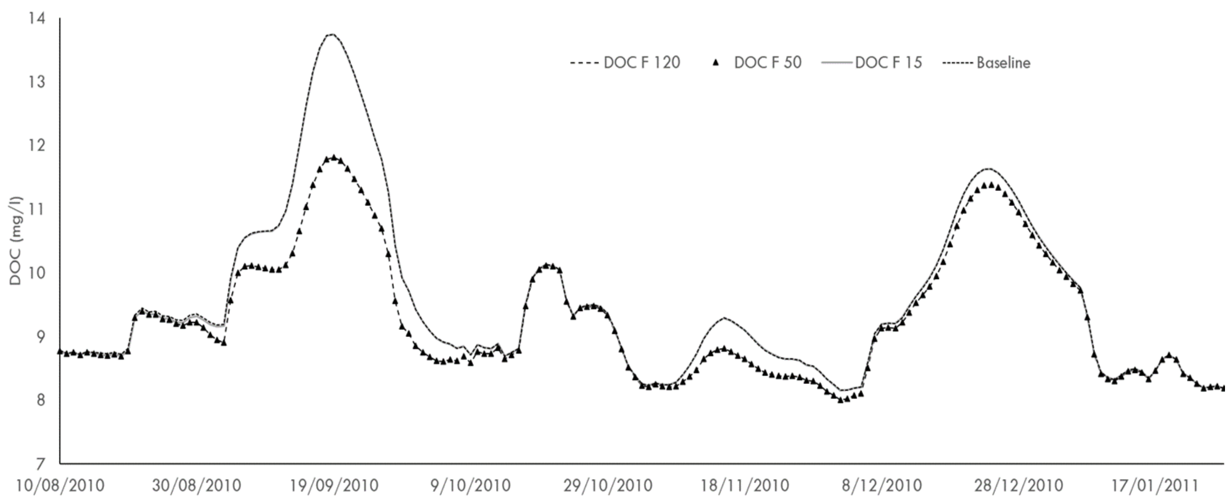

Figure 34. DOC concentrations at Barmah Gauge

7.2.8 Model limitations and knowledge gaps

The plug-in model simulates DO and DOC outcomes on connected floodplains resulting from flooding (natural or due to environmental watering) compared to site-specific BRAT model.

While the plug-in model is suitable for complex floodplains, its use is limited by the underlying hydrological model, which in this instance is not set-up to capture a complex floodplain such as the Barmah Forest. The model was calibrated and validated with limited observed DO and DOC data, which is a major handicap in the current set up. Further limitations in simulation outcomes are due to the coarse description of floodplains with only a few main routings across a larger, complex connected floodplain. Usually watering is regulated at different locations in a connected system, allowing for flows to be distributed (unless there is a big flood). This would change the DOC production and distribution significantly if implemented in the underlying hydrologic model (eWater Source).

The main process of the DO/DOC dynamics in the plug-in is leaching of DOC from inundated organic material. Currently only a single litter type is specified in the plug-in. This is sufficient in cases were the main vegetation type is relevant for an inundated floodplain. The litter accumulation varies by elevation but not seasonal, and also not able to account for different sources of litter. We have shown that other vegetation types such as pasture or agricultural crop are usually inundated at higher flood levels and can contribute a significant amount of carbon loads. Furthermore, depending on litter types and age of litter, leaching needs to be parameterized adequately, which in turn needs further lab analysis (Liu et al., 2019). More measured data may improve the model performance.

Plug-in or BRAT models do not account for the process of flushing out and redistribution of leaf litter during larger flood events. The impact of sediment oxygen demand on the overall DO dynamics is included as a process term; however, very limited knowledge is available for proper parameterization. The latter is usually not a central part in the floodplain dynamics but can become a vital factor in river channels and weir pools.

Calibration and validation of the models need to be based on an extended monitoring program. The more data available (DO, DOC, litter accumulation), the better the calibration and thus minimizing uncertainties in simulation results. Current limited data availability will ultimately limit the predictive power of the plug-in model. Any mitigation flow management action would require assessing the band of possible outcomes of environmental watering on DO/DOC given uncertainty in parameters, data and drivers (flow, temperature).

Therefore, there is a need for further refinements in process dynamics and description, better calibration/validation and uncertainty analysis, including more complex storage routing in larger floodplain.

Finally, the use of the plug-in is not yet “user friendly” and needs expert knowledge to set up, parameterize and run.

8 Summary

The Basin Plan sets objectives and targets for ensuring water quality is good enough to protect and restore ecosystems, and should be suitable for domestic use, farming and recreation. Those targets relate to salinity levels, blue-green algae, and dissolved oxygen - which relates to blackwater events, including a target of at least 50% saturation for dissolved oxygen.

As river regulation has reduced the frequency of small to moderate overbank flows in winter and spring, there is now a higher chance for litter accumulation over a longer period, and when a large flood arrives, it inundates large floodplains and brings huge organic loads with its receding water to the River Murray. This, in turn, increases the risk of blackwater events in the river. For river managers, it is necessary to develop options of flow management to reduce the accumulation of litter on the floodplains and reduce the risk of blackwater events.

There was a widespread blackwater event in the southern connected River Murray and its tributaries between November 2016 and January 2017 extending from Barmah to the Lower Murray in South Australia, affecting NSW, Vic and SA. Low dissolved oxygen water killed many fish, led to disruption for small businesses, and increased cost of water treatment for those relying on River Murray water. To reduce such low dissolved oxygen events in future requires a better understanding of the contributing factors and developing options for managing flows to reduce litter accumulation in floodplains.

This report describes a comprehensive overview of literature and data and highlights the processes that contribute to hypoxic blackwater events in the River Murray system. It discusses the consequences of inundation and carbon leaching from pasture lands. Addition of agricultural residues is likely to improve the functionality of the new blackwater plug-in eWater Source modelling platform. The model used in this study tests the sensitivity of DO responses to changing temperature and upstream DO fluxes.

For DOC leaching study from pasture indicates that the rate constant at 20ºC is 0.572/day, which is lower than the rate constant for river red gum leaf litters (0.860/day) but higher than native grasses (0.380/day). The total bioavailable portion of pasture grass was 1.8% which was much lower than the leaf litter contribution of 30%. Pasture in this study was found to deliver nearly 4,042 tonnes of instantly available carbon for a 1:100-year flood event. This estimate did not include the large amounts of carbon that are stored within cowpats, a big carbon pool in most grazed pasture lands.

Field study has shown that care must be taken to include all possible DOC sources, e.g. pasture, or even agricultural crop. It depends largely on the general land-use within a floodplain. The selected case studies on pasture carbon loads indicates limited effect on blackwater generation, as the pasture area inundated is small compared to vast red gum forest in the study area. Other areas, e.g. Lachlan, or Edward-Wakool might experience a higher dependence on such non-forest sources of DOC.

The effect of the vegetation types on the hypoxic blackwater event of summer 2010/2011 for Barmah Forest was tested using the simple Blackwater Risk assessment Tool (BRAT) model to estimate its effect on DO/DOC dynamics. The effect of pasture as simulated with BRAT for this case shows only small impact of pasture. However, this is not a main process for the Barmah or Gunbower Forest.

Although the BRAT model is a very valuable tool to assess DOC and DO concentrations after flooding on a confined local scale, it cannot describe a more complex river system and its connectivity. The novel blackwater plug-in of eWater Source allows a regional scale assessment of blackwater events.

In this study, a total of 21 pre-wetting flow scenarios were tested using the blackwater plug-in model, with flows released at Tocumwal Gauge over 2-week periods in September 2009, December 2009 and February 2010 (14 months, 12 months, and 9 months) prior to the actual blackwater event in 2010. The impact of different pre-wetting flow pulse volumes and timing were compared to the baseline. Three major flow ranges, 15,000, 50,000 and 120,000 ML/d were assumed as small, medium, and large pre-wetting flows as reported. For the 120,000 ML/d flow, flushing in the hotter months reduced the severity at the start of the event, but the effect dissipated as the blackwater event is prolonged through the months. However, flushing in September led to a drop in the DO concentrations in the Barmah Forest. Flushing in February leads to an overall increase in the DO that is sustained through the life of the blackwater event. Flood sizing were found to be important for mitigating impacts in the Murray main channel, for example, flows of 50,000 ML/d and 120,000 ML/d in February doubles the DO concentrations compared to the 15,000 ML/d pulse which tracks the baseline response. However, within the Barmah Forest, the size of the floods has minimal or no impact and all flows show an increase in the DO compared to the baseline.

Dynamic modelling of blackwater events require better data for set up and calibration in the main reach as well as the floodplains. As observed in the simulation outputs, while Barmah Forest responses were captured well, the model with the same input parameters as Barmah Forest fails to show blackwater response in the Gunbower Forest.

Water temperatures impact DOC leaching, with lowest impact in September when water temperature varies between 12.6-14.6^{o}C and highest in February when water temperature varies between 24.9-28.5^{o}C. Therefore, the timing of a flow release is key, with December and February releases having a greater impact on DO in the main reach. The effect of flows in the Barmah Forest reach was limited, this in part can be attributed to a short flushing period, as two weeks is not enough to leach out adequate DOC given that the actual leaves are not washed away. The lack of litter dynamics in the model is one of the shortcomings; the eWater Source model lacks the capacity to mimic leaf flushing away in bigger floods.

While some DOC is leached out when the flows are diverted to the floodplains, it is not enough to reduce the DOC availability for the actual 2010 event. However, it is evident that the size of the flow pulse is proportional to the DOC response during the flow event, for example, the average DOC during the 2 week 120,000 ML/d flows in December is 13 mg L^{-1} whereas at the 50,000 ML/d flow it is approximately 11 mg L^{-1}.

While the plug-in is easily manageable for a simple floodplain, it is more difficult to capture a complex set-up as the Barmah Forest, which has several connected wetlands and is heavily managed. The litter accumulation varies by elevation but not seasonal, and there is currently no ability to account for different sources of litter. The model needs improvement in terms of hydrodynamic processes in such more complex settings.

The current blackwater plug-in already includes the capability to read measured time series of water temperature and can handle oxygenation of water across weir structures. This allows a broader applicability to diverse floodplains within the MDB.

Although the current blackwater plug-in for eWater Source has been used successfully in different environments to run several flow scenarios, there is a need to advance this type of simulation tool to make it MDB wide operational too. These developments are:

(i) plug-in centred process enhancements (e.g., inclusion of different vegetation and litter types, litter age, litter flushing, decomposition processes, etc.),
(ii) additions to the eWater Source model node structure in larger floodplains for a more detailed description what areas are inundated, and
(iii) continuous in-stream and floodplain water quality monitoring and tighter coupling with remote sensing (satellite and drone) monitoring.

9 Recommendations

To have high confidence in the model simulation for developing flow management options for mitigating future high risk blackwater events in the Murray system we recommend the following:

1. The MDBA establish a continuous measurement regime for DO concentrations and if possible, DOC in strategic locations prone for blackwater events with reference to upstream and downstream of major floodplains which historically produce high loads of DOC.
2. The MDBA establish a better link with State agencies for DO and DOC monitoring in the floodplains of interest to better calibrate the blackwater model simulation.
3. The MDBA to investigate a larger set of scenarios to better understand the varying influences of timing, duration, distribution, and sequencing of inundation especially under future climate change conditions.
4. Explore novel technologies (satellite, earth observation) to see real-time blackwater generation and movement from space.
5. To achieve better simulation capability of scenarios, the following parameters must be included in the modelling exercise:
    a. Vegetation types based on land-use maps without tedious, manual setting of parameter per Source node,
    b. A mixture of different vegetation types for a specific area within a floodplain,
    c. A comprehensive record of litter accumulation and leaching rates of different vegetation types mapped for specific flood prone areas.

10 References

Baldwin, D.S. (2018). Litter Loads and hypoxia in Barmah-Millewa Forest: June 2018. A report prepared for the Goulburn Broken Catchment Management Authority, Shepparton, Victoria. 7 pp.

Baldwin, D.S. (1999). Dissolved organic matter and phosphorus leached from fresh and 'terrestrially' aged river red gum leaves: implications for assessing river-floodplain interactions, Freshwater Biology, 41(4): 675–685. Available at: 10.1046/j.1365-2427.1999.00404.x

Baldwin, D.S., Paul, W.L., Wilson, J.S., Pitman, T., Rees, G.N., & Klein, A.R. (2015). Changes in soil carbon in response to flooding of the floodplain of a semi-arid lowland river. Freshwater Science, 34(2), 431-439.

Biswas, T.K. and Mosley, L.M. (2019) From Mountain Ranges to Sweeping Plains, in Droughts and Flooding Rains; River Murray Water Quality over the Last Four Decades, Water Resources Management, 33(3), 1087-1101.

Butts, T.A., Evans, R.L. (1983) Small stream channel dam aeration characteristics. Journal of Environmental Engineering 109(3), 555–573.

Chapra, S.C. (1997) Surface water-quality modelling. McGraw-Hill.

Cook, R. A., Gawne, B., Petrie, R., Baldwin, D. S., Rees, G. N., Nielsen, D. L., & Ning, N. S. (2015). River metabolism and carbon dynamics in response to flooding in a lowland river. Marine and Freshwater Research, 66(10), 919-927.

GBCMA (2013). Barmah Forest Seasonal Watering Proposal 2013-2014. pp 75. Goulburn Broken Catchment Management Authority (GBCMA), Shepparton, Victoria 3632, Australia.

Howitt, J.A., Baldwin, D.S., Rees, G.N., & Williams, J.L. (2007). Modelling blackwater: predicting water quality during flooding of lowland river forests. Ecological Modelling, 203(3-4), 229-242.

Howitt, J., Baldwin, D.S., Rees, G.N. (2005): BLACKWATER MODEL – A revised computer model to predict dissolved oxygen and dissolved carbon downstream of Barmah-Millewa Forest following a flood (Report prepared for the Barmah-Millewa Forest Forum).

King, A.J., Tonkin, Z., Lieshcke, J. (2012): Short-term effects of a prolonged blackwater event on aquatic fauna in the River Murray, Australia. Considerations for future events. In Mar. Freshwater Res. 63 (7), p. 576. DOI: 10.1071/MF11275.

Liu X, Watts R.J., Howitt J.A., McCasker, N: (2019) Carbon and nutrient release from experimental inundation of agricultural and forested floodplain soil and vegetation: influence of floodplain land use on the development of hypoxic blackwater during floods. *Marine and Freshwater Research* **71**, 213-228.

MacKay, N., Hillman, T., Rolls, J. (1988) Water quality of the River Murray: review of monitoring 1978 to 1986. Murray–Darling Basin Commission, Canberra ACT 2601.

McCarthy, B., Zukowski, S., Whiterod, N., Vilizzi, L., Beesley, L., King, A. (2014): Hypoxic blackwater event severely impacts Murray crayfish (Euastacus armatus) populations in the River Murray, Australia. In Austral Ecology 39 (5), pp. 491–500. DOI: 10.1111/aec.12109.

MDBA (2012). Assessment of environmental water requirements for the proposed Basin Plan: Gunbower-Koondrook-Perricoota Forest. Pub No.22/12. pp 28. Murray-Darling Basin Authority (MDBA), Canberra, ACT 2601.

Meyer, J.L., Wallace, J.B., & Eggert, S.L. (1998). Leaf litter as a source of dissolved organic carbon in streams. Ecosystems, 1(3), 240-249.

Mosley L.M. and Rahman J. (2017). Development and testing of a blackwater plugin model for the Source Modelling Framework. The University of Adelaide and Flow Matters Pty Ltd. Report to the Department for Environment, Water and Natural Resources (South Australia). June 2017.

O'Connell, M., Baldwin, D. S., Robertson, A. I., Rees, G. (2000): Release and bioavailability of dissolved organic matter from floodplain litter. Influence of origin and oxygen levels. In Freshwater Biol 45 (3), pp. 333–342.

Parascos, J. (2019). Incorporating agricultural analysis into hypoxic blackwater modelling to improve forecasting of future events. pp 64. Honours Thesis, Fenner School of Environment and Society, Australian National University, Canberra ACT 2601.

Robertson, A. I., Bunn, S. E., Boon, P. I., & Walker, K. F. (1999). Sources, sinks and transformations of organic carbon in Australian floodplain rivers. Marine and Freshwater Research, 50(8), 813-829.

Small, K., Kopf, R.K., Watts, R.J., & Howitt, J. (2014). Hypoxia, blackwater and fish kills: experimental lethal oxygen thresholds in juvenile predatory lowland river fishes. PloS one, 9(4), e94524.

Taylor, H., Campbell, B., McRae, D., Ferla, L., Hart, T., Owens, H., Lenon, E., Mullin, E., Johnson, H., Webber, K., Lowe, A., Pinner, L., Noakes, M., Commens, S., Baldwin, D., Ellis, I., Dyer, F., Biswas, T., Lenehan, J., Packard, P. and Davies, S. (2017). Blackwater Review: Environmental water used to moderate low dissolved oxygen levels in the southern Murray-Darling Basin during 2016/17. Commonwealth Environmental Water Office, pp.9-104.

Tiller, D., Newall, P. (2010) Water quality summaries and proposed water quality targets for the protection of aquatic ecosystems for the Murray–Darling Basin. Karoo Consulting.

Watts, R., Kopf, R., McCasker, N., Howitt, J., Conallin, J., Wooden, I. and Baumgartner, L. (2017). Adaptive Management of Environmental Flows: Using Irrigation Infrastructure to Deliver Environmental Benefits During a Large Hypoxic Blackwater Event in the Southern Murray–Darling Basin, Australia. Environmental Management, 61(3), pp.469-480.

Whitworth, K.L., Baldwin, D.S. (2016): Improving our capacity to manage hypoxic blackwater events in lowland rivers. The Blackwater Risk Assessment Tool. In Ecological Modelling 320, pp. 292–298. DOI: 10.1016/j.ecolmodel.2015.10.001.

Whitworth, K.L., Baldwin, D.S., Kerr, J.L. (2014): The effect of temperature on leaching and subsequent decomposition of dissolved carbon from inundated floodplain litter. Implications for the generation of hypoxic blackwater in lowland floodplain rivers. In Chemistry and Ecology 30 (6), pp. 491–500.

Whitworth, K.L., Kerr, J.L., Mosley, L.M., Conallin, J., Hardwick, L., Baldwin, D.S. (2013): Options for managing hypoxic blackwater in river systems: case studies and framework. In Environ Manage 52 (4), pp. 837–850.

Whitworth, K.L., Baldwin, D.S., & Kerr, J.L. (2012). Drought, floods and water quality: drivers of a severe hypoxic blackwater event in a major river system (the southern Murray–Darling Basin, Australia). Journal of Hydrology, 450, 190-198.

Whitworth, K.L., Williams, J., Lugg, A., Baldwin, D.S. (2011): A prolonged and extensive hypoxic blackwater event in the southern Murray-Darling Basin. Final Report prepared for the Murray-Darling Basin Authority (MDFRC Publication 30/2011).

Appendix 1: CSIRO BW Workshop participants 30/31 January 2018

Klaus Joehnk	CSIRO
Ashmita Sengupta	CSIRO
Tapas Biswas	MDBA
Alistair Korn	MDBA
Matt Coleman	MDBA
Matt O'Brien	MDBA
Jacqui Russell	MDBA
Damian Green	MDBA
Sarah Commens	MDBA
Meg Edmonds	MDBA
Brian Lawrence	Consultant, InfoRail
Luke Mosley	Univ Adelaide
Gavin Rees	CSIRO/MDFRC
Judy Hagan	DELWP Victoria
Joanna Lockwood	DELWP Victoria
Matt Gibbs	SA DEW
Gerhard Schultz	WaterNSW
Julia Howitt	CSU
Todd Wallace	Univ Adelaide
Richard Greene	ANU
Jimmy Parascos	CSIRO/ANU

CONTACT US

t 1300 363 400

+61 3 9545 2176

e csiroenquiries@csiro.au

w www.csiro.au

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FOR FURTHER INFORMATION

Klaus Joehnk

CSIRO Land and Water

Black Mountain Campus, Canberra ACT 2601

t +61 2 6246 5636

e Klaus.Joehnk@csiro.au