LA TROBE UNIVERSITY

CENTRE FOR FRESHWATER ECOSYSTEMS (CFE)
School of Life Sciences

ALLOCHTHONOUS CARBON LOADS AND MODELLED DISSOLVED ORGANIC CARBON CONCENTRATIONS AT LINDSAY ISLAND, MULCRA ISLAND AND HATTAH LAKES FLOODPLAINS DURING ENVIRONMENTAL WATERING

A report prepared for the Mallee Catchment Management Authority

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Traditional Owner acknowledgement

The Centre for Freshwater Ecosystems, Albury–Wodonga is located on the land of the Latje Latje and Wiradjuri peoples. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future.

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Executive Summary

This project aims to determine the potential risks of low dissolved oxygen concentrations occurring during controlled environmental watering events on the Lindsay and Mulcra Islands, and Hattah Lakes floodplains. Field estimates of floodplain organic matter litter loads (leaves, bark etc.) and laboratory experiments were carried out to determine quantities of dissolved organic carbon (DOC) available on the floodplains, the rates of DOC production from litter materials, and the associated rates of dissolved oxygen (DO) drawdown. These metrics were coupled with a hydrodynamic model to quantify DOC concentration and DO draw-down dynamics for simulated environmental watering events and scenarios.

Litter and soil cores were collected from 4 vegetation communities, Red gum (RG), Black box (BB), Lignum (LG) and Other (OT) within each floodplain. Litter was subsequently fractionated into leaves, bark, sticks, plants, scats and 'other' (which included all material not assigned to any one of the other categories) and weighed to determine mass (and percentages) of each fraction and overall total litter loads. Dissolved organic carbon (DOC) leaching experiments were conducted to determine the potential amount of DOC produced from each material and leach rate constants. Oxygen drawdown experiments were also conducted on individual litter fractions. Litter loads varied between floodplains and vegetation types, with Hattah containing the highest litter loads. Rate constants for DOC production from litter ranged between 0.63 d^{-1} (Scats) and 1.04 d^{-1} (Plants). Maximum DOC values were attained in less than 5 days and ranged between 10 mg-C/g material (Sticks) and 48 mg-C/Lg material (Leaves). Oxygen consumption rates varied across litter fractions and ranged from 0.06 mg O_2/g sample/hr (LG-Bark) to 0.42 mg O_2/g sample/hr (OT-Other). DOC decomposition rates were also calculated to allow for direct comparison to rates used in the Blackwater Risk Assessment Tool (BRAT). These rate constants ranged from 0.01 d^{-1} (LG-Leaves) and 0.12 d^{-1} (BB-Bark, Ot-Sticks, RG-Sticks). For all litter fractions except LG-Leaves, LG-Plants, and OT-Plants the DOC decomposition rates exceeded the 0.03 d^{-1} value in the BRAT model.

For the Lindsay and Mulcra Island floodplains, a coupled hydrodynamic water quality model was built using the MIKE ECO Lab Template built on a MIKE21 MODEL to estimate potential DOC and DO concentrations. The model encompassed both floodplains, and thus treated Lindsay and Mulcra Islands as a single floodplain complex. While the hydrodynamic model was initially parameterised using values from BRAT, this model takes into account floodplain hydrodynamics, variability in water residence times as well as variability in litter loads across the floodplain. The approach therefore allows for more realistic scenario testing as well as the introduction of chemical models that more accurately describe DOC generation and DO draw-down. Due to the lack of a hydrodynamic model for Hattah Lakes, a water quality model was not developed for this site and will need to be developed as a (future) separate study.

The coupled hydrodynamic-water quality model developed here was used to simulate 6 scenarios for the Lindsay and Mulcra Islands floodplain complex (referred to as Lindsay-Mulcra in the model simulations) to assess the sensitivity of the results to different sets of DOC and oxygen drawdown parameter values, flow conditions and simulation periods. Localised hypoxic areas were predicted to form for even a one-week flow pulse and increased in extent with longer flow pulses and during recessional flows. Lake Wallawalla in particular was shown to be susceptible to the formation of hypoxic blackwater. DOC decomposition rate constants determined in this study were higher than that in the BRAT and the inclusion of these higher rates within the model led to increased hypoxia within the susceptible regions. The presence of the regulator on the Mulcra floodplain caused a significant backwater effect, leading to greater local inundation extent and increased water residency time on the floodplain. This led to predicted increases in DOC concentrations and reductions in DO concentrations in the vicinity of the regulator. These results highlight the risks from operation of floodplain infrastructure to increase inundation heights, and it would be advisable to undertake additional scenario analyses once the model has been validated.

The spatially and temporally explicit model predictions for Lindsay-Mulcra require field validation. Locations such as Lake Wallawalla and the Mulcra regulator would be of particular interest in terms of monitoring DO in future inundation events. Data collected at these sites could be used to calibrate the model and guide possible improvements as well as giving confidence in the model for assessing risks to a broader range of inundation scenarios. The model could also be used to assess the possible effect of different environmental conditions, including temperature effects and variation in litter loads arising from different sequencing of watering events over multiple years

Background & Context

'Blackwater' events are flows of highly coloured tannin stained hypoxic water following floodplain inundation. Blackwater events are driven by high concentrations of dissolved organic carbon (DOC) leached from floodplain litter and soils during flood events. Under warm conditions, this DOC can be rapidly consumed by microbial organisms (bacteria and fungi), depleting dissolved oxygen in the water column and leading to hypoxia. Decomposition of organic matter transported into rivers during flooding events is a natural process. However, flow regulation in the River Murray has greatly reduced the frequency of flood events that might otherwise episodically remove floodplain organic matter. Increased intervals between flood events leads to larger floodplain litter loads, which consequently results in greater leaching of DOC following flooding. In turn, this fuels much higher rates of microbial respiration, which increases the likelihood of oxygen removal by microbial respiration, exceeding rates of oxygen production by photosynthesis or re-aeration from the atmosphere. Hypoxic conditions, if they develop, represent a major risk of mortality to aquatic fauna such as fish and Murray crayfish.

A critical yet unanswered question for floodplain managers is how best to manage the risks associated with hypoxic blackwater events. Hypoxia during managed events can in part be influenced by controlling the timing of flooding (e.g. to avoid warm weather conditions) and avoiding ponding of water for excessive periods of time. For example, flow regulators often re-aerate and re-oxygenate throughflow, but may increase the residence time of relatively small volumes of water on the floodplain upstream. In these areas, higher DOC concentrations may develop than during natural connection events. Effective, targeted application of management strategies thus requires identification of high-risk areas. In particular, knowledge of litter loads, and the differences in DOC production and oxygen consumption between different litter types, are important pieces of information in assessing those risks.

Initial investigations into litter loads and DOC leaching behaviour of litter fractions on the Lindsay and Mulcra Island floodplains concluded that: i) variability in the leaching rates of different litter fractions required refined estimates for accurate modelling, ii) contributions of soil carbon to DOC leaching needed quantification, iii) differences in dissolved oxygen drawdown from different litter fractions represented an important unknown, and iv) mapping of DOC consumption and oxygen drawdown incorporating different vegetation types, litter loads, and hydrological modelling would be advantageous (Silvester et al. 2019). This project therefore aims to fill these knowledge gaps, with the overall purpose of developing and validating an operational modelling tool for quantitative blackwater risk assessment.

Project objectives

The primary objective of this project was to quantify potential risks of hypoxia at Lindsay and Mulcra Islands, and Hattah Lakes floodplains, by developing a coupled hydrodynamic-water quality model. The model was parameterized using field estimates of organic matter litter loads, and laboratory estimates of the rate and quantity of DOC leached from different types of litter materials (e.g. leaves vs bark) for different overstory vegetation types (e.g. Red gum vs Black box). This approach allows DOC production and DO draw-down predictions to be developed for a range of operational scenarios that are sensitive to local variations in litter loads and litter types. In particular, this information can be used to estimate the potential risks of hypoxic blackwater events during managed flooding of these floodplains.

Methodology

This project consisted of 2 stages and the following components:

Part One:

1. Mapping the intersection of water extent during managed inundation with dominant floodplain vegetation types
2. Field collection of litter from four vegetation types (Red gum, Black box, Lignum, Other) at Hattah, Lindsay and Mulcra floodplains
3. Fractioning and weighing of litter material (leaves, bark, sticks, scats, plants and other)
4. Leaching experiments on litter fractions and analysis of leached dissolved organic carbon (DOC)
5. Experiments to quantify oxygen drawdown rates for individual litter fractions
6. Rate parameter fitting for litter material DOC leaching and oxygen drawdown rates
7. Calculation of maximum carbon loads from each floodplain

Part Two:

8. Development of a hydrodynamic model to simulate water movement and residency time across the floodplain based on specific hydrologic scenarios (in this case a pre-existing MIKE21 model was used for Lindsay and Mulcra Islands floodplain complex)
9. Development of a water quality model to quantify DOC and oxygen concentrations based on hydrodynamics and floodplain litter loads.
10. Evaluation of alternative floodplain inundation scenarios

Each of these components are described in further detail below.

Part One: Litter Loads, DOC Leaching and Oxygen Drawdown

FIELD LITTER AND SOIL COLLECTION

The field component consisted of a stratified sampling design that focused on three floodplains, Lindsay Island, Mulcra Island and Hattah Lakes, three dominant overstory vegetation types (Red gum (RG), Black box (BB) & Lignum (LG)) along with a fourth category "other (OT)" for any vegetation community that didn't fall into the first three categories. Vegetation types were delineated based on the mapped distribution of Victorian Ecological Vegetation Communities (EVCs), which were aggregated into 4 classes based on the dominant overstorey vegetation type. Each floodplain was further subdivided into areas likely to receive environmental water (as per provided maps). Areal extents of each vegetation type in watered areas of floodplains are shown in Appendix Table 1.

Litter survey locations were selected using spatially balanced survey design based on the Generalised Random Tessellation Stratified (GRTS) sampling algorithm (Stevens Jr and Olsen 2004). Sites were restricted to areas of the floodplain within 400m of the nearest track to ensure reasonable access. This was done by applying a 400m buffer zone around access tracks prior to applying the GRTS algorithm in R (R Core Team 2018). Locations of sampling sites are shown in Figures 1, 2 and 3. At each of 20 sites identified using the GRTS method outlined above, three fixed area quadrats (1 m^2 quadrat) were randomly distributed within the associated vegetation community type within an approximately 20 m radius of the point. This resulted in a total of 60 litter samples for each vegetation community type at each floodplain location being collected (Lindsay Island, Mulcra Island, and Hattah Lakes; Figure 1 to Figure 3 respectively). Within each quadrat all of the litter and dead organic material, including leaf and twig fall, understorey vegetation and animal scats were collected down to the soil horizon. This material was then removed and bagged for subsequent laboratory processing. Soil cores were also collected from 12 sites from each floodplain (three from each vegetation type) to determine amount of dissolved organic carbon leached from soil.

DETERMINATION OF LITTER LOADS

Litter material from a random subset of quadrats (n = 7 from Lindsay and Mulra Islands and n = 10 from Hattah; see Appendix Table 2 for further details) was fractionated into the following litter materials: bark, leaves, sticks, scats, plants and other (any material that didn't fit into the other 5 categories). The fractions were then oven dried at 60 °C for at least 12 hours (but no more than 24 hours) to determine dry-weight of each fraction (g/m^2). Sub-samples from these separated litter materials were then used in the leaching experiments described below. The remainder of the floodplain quadrats were not sorted into fractions, but instead were directly oven dried to give a total dry weight of litter per quadrat (g/m^2).

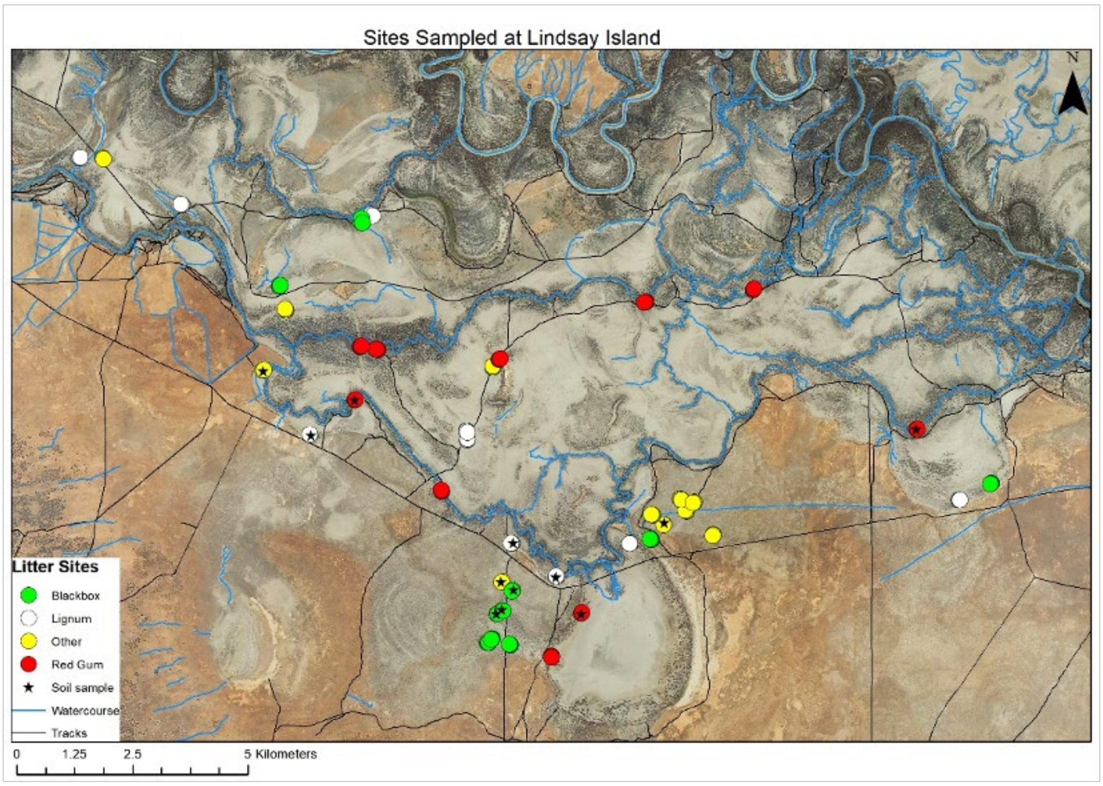


Figure 1. Lindsay Island floodplain sampling sites. Circles indicate sites sampled for litter, colours indicate vegetation communities (red = red gum, green = black box, white = lignum, yellow = other), black stars indicate soil samples collected.

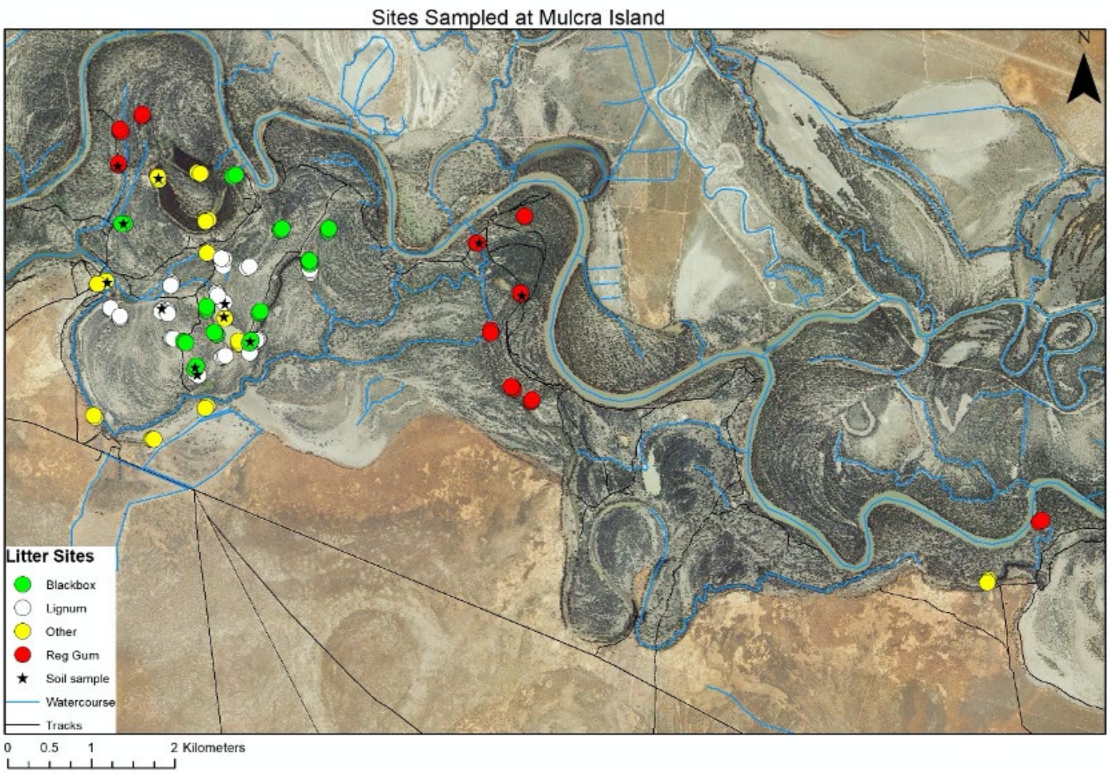


Figure 2. Mulcra Island floodplain sampling sites. Circles indicate sites sampled for litter, colours indicate vegetation communities (red = red gum, green = black box, white = lignum, yellow = other), black stars indicate soil samples collected.

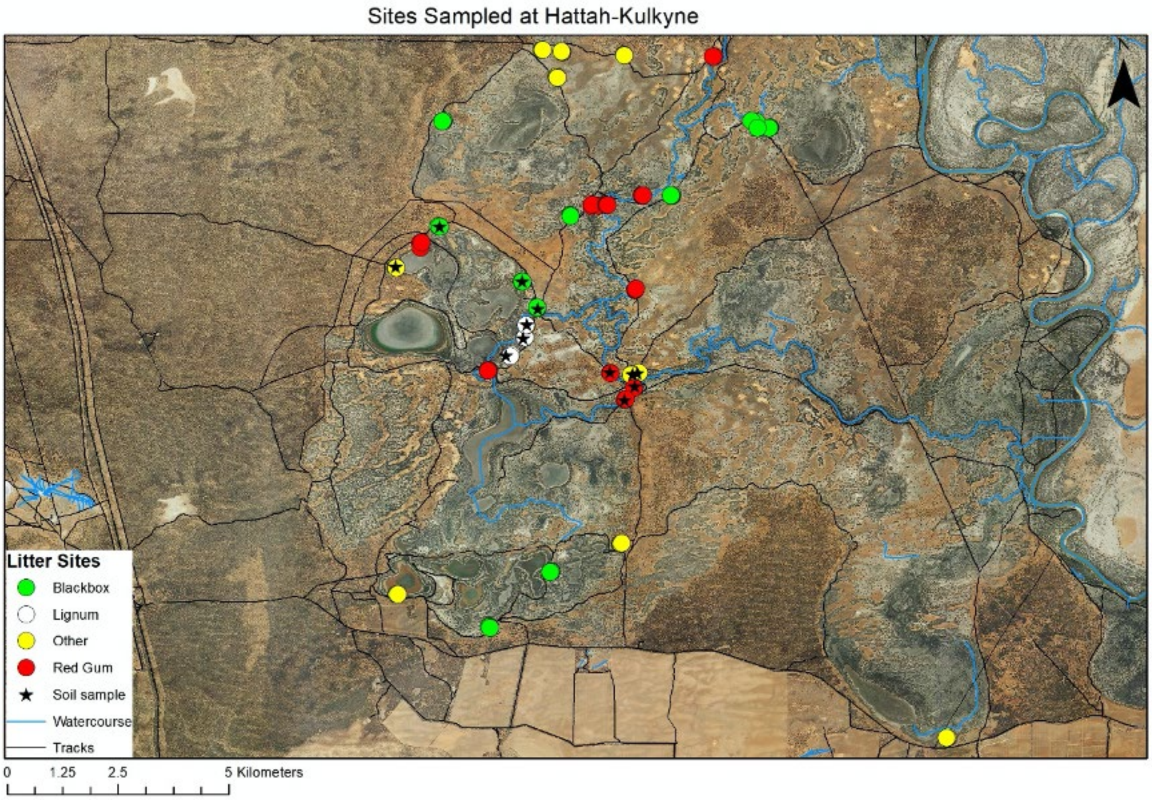


Figure 3. Hattah Lakes floodplain sampling sites. Circles indicate sites sampled for litter, colours indicate vegetation communities (red = red gum, green = black box, white = lignum, yellow = other), black stars indicate soil samples collected.

LEACHING EXPERIMENTS

Leaching experiments were conducted on each litter material type (leaves, sticks, bark, plant, other) and soils from each vegetation type (RG, BB, LG and OT) where sufficient material was available. Leaching experiments were conducted in the dark in a controlled climate room at 25°C, following the method developed by O'Connell et al. (2000) and used previously by Silvester et al. (2019). A known mass of each litter material (see Appendix Table 3 for details), was weighed and placed in a 1 L Schott bottle with 1 L of Murray River Water (starting DOC concentration: 1.3 ± 0.2 mg/L), and with the addition of a microbial inhibitor (2.5 mM sodium azide). Litter material suspensions were mixed daily for the first 4 days and thereafter prior to sampling only. DOC samples were collected by first mixing the leach mixture, removal of 40 mL solution and filtration through 0.45 µm cellulose-acetate filter membranes. Samples were collected at 1, 2, 4-5, 8, and 15 days and analysed using a total organic carbon (TOC) analyser as non-purgeable organic carbon (NPOC). DOC concentrations were then converted into milligrams of DOC leached per gram of litter material (mg-C/g-substrate).

LITTER MATERIAL LEACHING AND CALCULATION OF COMBINED LITTER LEACH RATES

DOC concentrations obtained from leaching experiments were modelled according to a first-order rate process, with fitted parameters: k (first order rate constant; d^{-1}) and maximum leachable carbon (DOC_{inf}; mg-C/g-substrate). These individual litter material parameters were then used to calculate combined litter leaching curves using the mean fractional litter composition in each vegetation type and each floodplain. Data analysis was carried out using the open-source software R (R Core Team 2018). DOC leaching data fitting was achieved using the nls package (Baty et al., 2015) and error propagation using the propagate package. All figures were generated using ggplot 2 (Wickham 2016).

OXYGEN DRAWDOWN EXPERIMENTS

Oxygen drawdown experiments were conducted on each litter material type (leaves, sticks, bark, plant, other) from each vegetation type (RG, BB, LG and OT) where sufficient material was available. Leaching experiments were conducted in the dark in a controlled climate room at 25°C over 24 hours, following the method developed by O'Connell et al. (2000). Ten grams of each litter material type (see Appendix Table 3 for details), was weighed and placed in a 1 L Schott bottle with 1 L of Murray River Water (starting DOC concentration: 1.3 ± 0.2 mg/L). Oxygen concentrations (mg/L and % saturation) were measured every hour for the first 6-7 hours and then again at approximately 24 hours. The natural log of the oxygen concentrations (DO mg/L) and oxygen consumption rates were then calculated. DOC was also measured in each bottle at the end of the experiment and used to calculate DOC consumption rates.

Part Two: Model Development

Modelling Approach

The water quality modelling approach was initially based on an existing 2D MIKE FLOOD hydrodynamic model developed in 2019 for Lindsay and Mulcra Floodplains with the addition of a 1D water quality module. However, problems arose as a result of the difference in computational technology between the 2D hydrodynamic model, which uses GPU technology, and the water quality module which runs using CPU processing power. This mix of technologies ultimately proved incompatible despite efforts to work with the software developers to find a solution. This problem remains unresolved but is being discussed with DHI Group the developers for the MIKE software product.

The solution to this problem was to update both models to a full 2D simulation, but of reduced spatial complexity so as to decrease computational complexity and associated model run times (Further details can be found in Appendix 2 sections 1-9). While a number of elements have been simplified, structures such as Locks on the Murray River, weirs at offtakes, and dike lines representing linear topographical features have been maintained in the 2D models (see Appendix 2 section 5). A regulated scenario in the Mulcra model was also set-up to analyse the impact of watering scenarios on DO levels on the floodplain. In order to reproduce the opening and closing of the gate on the lower Potterwalkagee Creek regulator, a dike line with a crest level that varies in time was used.

A template (The MIKE ECO Lab template “MalleeBW”) for use within the water quality module was developed following the schematization of the processes in the Blackwater Risk Assessment Tool (BRAT) developed by La Trobe University (Whitworth and Baldwin, 2016) and described in Appendix 2. Table 1 presents the values used in our modelling approaches: Set 1 consists of the original BRAT model, Set 2 includes the updated values for DOC leaching rates derived by La Trobe University as part of this project, Set 3 includes the updated DOC leaching rates as well as a upper limit DOC decomposition rate derived during part one of this project.

In total, six scenarios were run (Table 2; Appendix 2 Section 8). As part of the sensitivity testing, we compared three leaching rate parameter sets (Scenarios 1-3) under the conditions of a 4 week flow pulse. Scenario 1 used rate constants from the BRAT model, Scenario 2 used revised rate constants for DOC leaching, and Scenario 3 used revised rate constants for DOC leaching and an additional revised rate constant for DOC decomposition. Scenarios 2, 4 and 5 contrasted the effects of different flow pulses (Figure 4; but using similar biogeochemical process rates), and Scenarios 2 and 6 contrasted different operation of a floodplain regulator (again using similar biogeochemical process rates). Results are summarized below and further details are provided in Appendix 2 and in Morales and Barriere (2020).

As outlined earlier, the final modelling solution was applied only to the Lindsay-Mulcra Island floodplain complex, and was not feasible for Hattah Lakes. Development of a model for Hattah Lakes will require further work in the future.

Table 1: Parameters used within the MalleeBW MIKE ECO LAB Template. Set 1 (BRAT model) and Set 2 and 3 (derived as part of this study)

Parameter	Description	Set 1	Set 2	Set 3
ka20	Rate constant for re-aeration at 20 C (per day)	0.08		
kd20	Rate constant for DOC decomposition at 20 C (per day)	0.03		0.06
ksod20	Rate constant for soil oxygen demand at 20 C (per day)	0.093		
kll20	Rate constant for DOC leaching from leaves at 20 C (per day)	0.86	0.77	0.77
klt20	Rate constant for DOC leaching from twigs at 20 C (per day)	0.078	0.65	0.65
klb20	Rate constant for DOC leaching from bark at 20 C (per day)	0.173	0.75	0.75
klg20	Rate constant for DOC leaching from grass at 20 C (per day)	0.38	1.00	1.00
mll20	Maximum DOC leached from leaves at 20 C (mg/g)	80	48.16	48.16
mlt20	Maximum DOC leached from twigs at 20 C (mg/g)	10	10.27	10.27
mlb20	Maximum DOC leached from bark at 20 C (mg/g)	10	11.76	11.76
mlg20	Maximum DOC leached from grass at 20 C (mg/g)	45	39.56	39.56
msod	Maximum soil oxygen demand (mg/m2/day)	14.816		
lfl	Litterfall rate leaf (g/m2/day) • Summer • Autumn • Winter • Spring	 0.90 0.20 0.06 0.40		
lfb	Litterfall rate bark (g/m2/day) • Summer • Autumn • Winter • Spring	 0.45 0.10 0.02 0.02		
lft	Litterfall rate twigs (g/m2/day) • Summer • Autumn • Winter • Spring	 0.20 0.15 0.04 0.18		

Table 2: Scenarios used for water quality simulations

Scenario	Spatial extent	Flow condition	Simulation period	Parameter set
1	Lindsay-Mulcra	Pulse 1	5 weeks	Set 1
2	Lindsay-Mulcra	Pulse 1	5 weeks	Set 2
3	Lindsay-Mulcra	Pulse 1	5 weeks	Set 3
4	Lindsay-Mulcra	Pulse 2	6 weeks	Set 2
5	Lindsay-Mulcra	Pulse 4	8 weeks	Set 2
6	Mulcra	Pulse 1 and regulator scenario A and B	5 weeks	Set 2

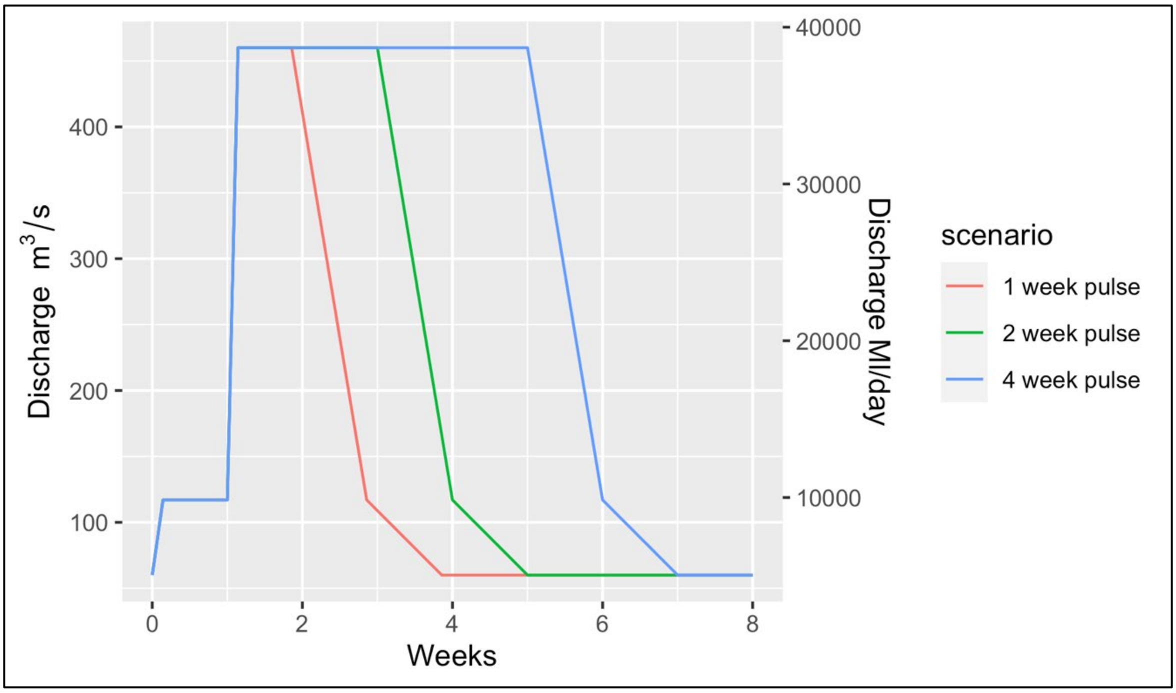


Figure 4. Inflow hydrographs for the modelled scenarios. These flows are for the Murray river at RV60510 upstream of the Potterwalkagee Creek offtake. Coordinates: (544550,6219571) to (544550, 6219769). Additional details are shown in Table 2.

RESULTS

Part One: Litter Loads, DOC Leaching and Oxygen Drawdown

LITTER LOADS

Litter loads varied across the floodplains and vegetation communities (Figure 5 and Appendix Table 4). RG communities contained more litter than the other three vegetation types on all three floodplains (Figure 5 and Appendix Table 4). In general the Hattah Lakes Floodplain contained higher litter loads for the RG, BB and OT vegetation communities than the other floodplains, with on average 2007 g/m^2 of litter present within the RG community; 871 g/m^2 present within the BB community; 396 g/m^2 within the LG community and 472 g/m^2 within the OT community (Figure 5). Lindsay and Mulcra Islands on the other hand contained on average 1360 g/m^2 and 1184 g/m^2 respectively, of litter present within the RG community; 467 g/m^2 and 681 g/m^2 respectively, present within the BB community; 309 g/m^2 and 478 g/m^2 within the LG community and 200 g/m^2 and 174 g/m^2 within the OT community (Figure 5).

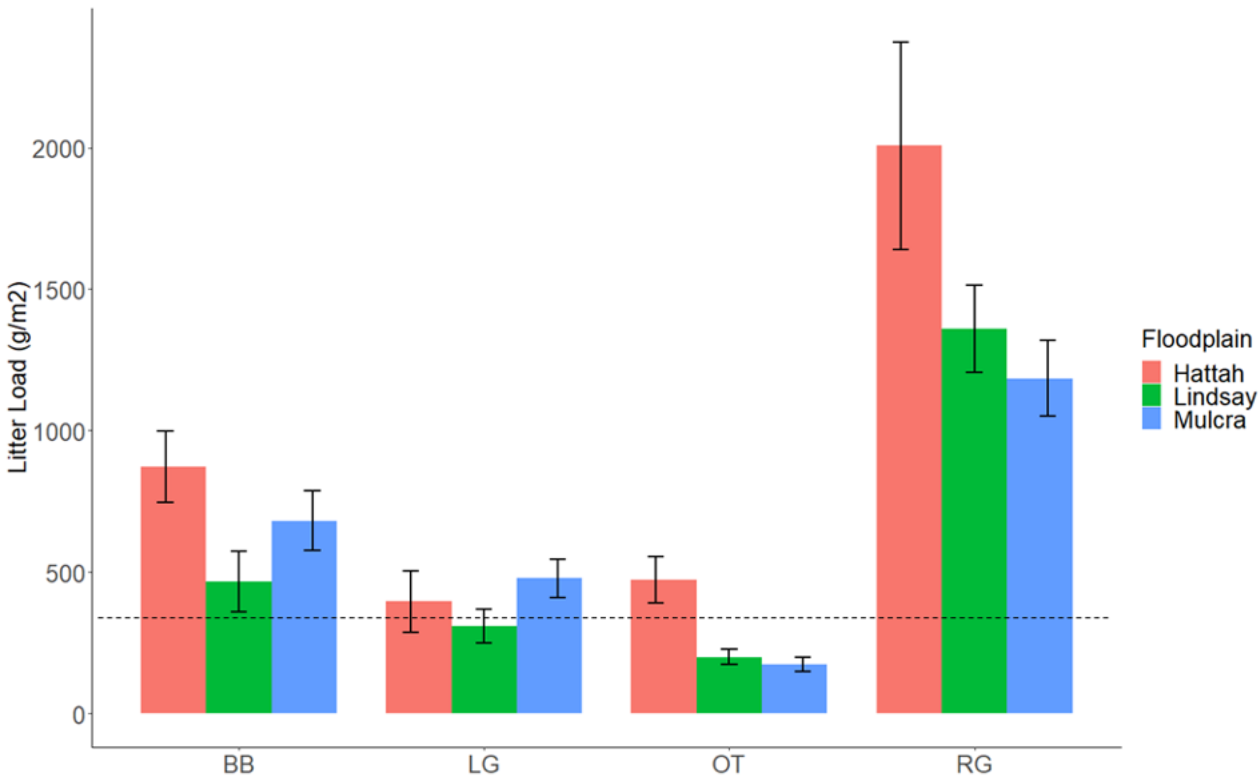


Figure 5. Mean Litter loads (± SE) for each plant community within the Lindsay, Mulcra and Hattah floodplains. Dotted line indicates the 'Oxygen threshold' which refers to a critical litter load value above which oxygen drawdown might be expected (from: Hladyz et al., 2011). See Discussion for details. RG = Red gum, BB = Black box, LG = Lignum and OT = Other

FRACTIONATION OF LITTER MATERIALS

Litter was separated into six main fractions: leaves, bark, sticks, plants, scats and other (typically fruits and unidentified woody debris). Sticks tended to dominate the RG, BB and LG litter loads making up approximately 40% or more of the litter on all three floodplains, whereas the dominant fraction within the OT vegetation community was floodplain specific, with ‘other’ dominant at Hattah Lakes, plants at Lindsay Island and sticks at Mulcra Island (Figure 6). The field-survey and laboratory results for plants, which included grass and other small herbs, were used as a source of the ‘grass’ model parameters when parameterising the water quality model. The litter load for each litter component and vegetation type was combined with the EVC vegetation layer to develop a spatial map of the load of each litter material type across the floodplain for input to the water quality model (Figure 7).

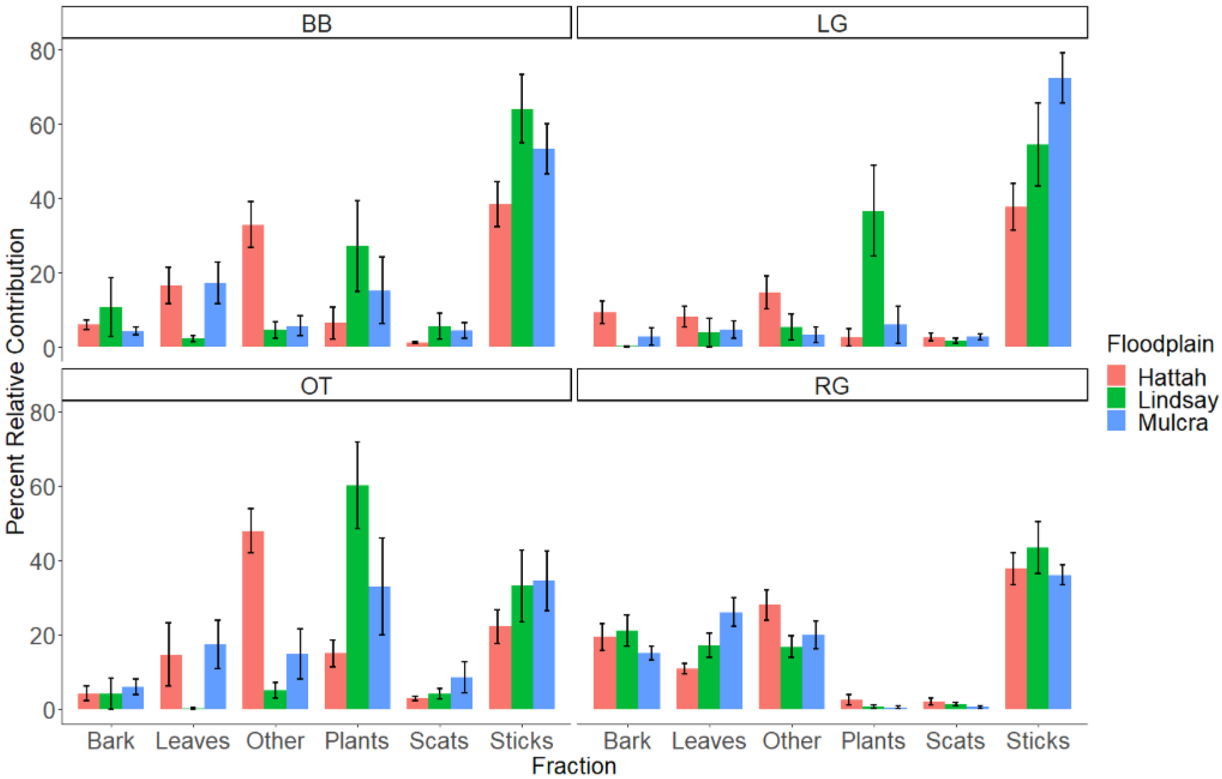


Figure 6. Percent relative contribution of each litter material fraction (± SE) from each vegetation type and each floodplain. RG = Red gum, BB = Black box, LG = Lignum and OT = Others

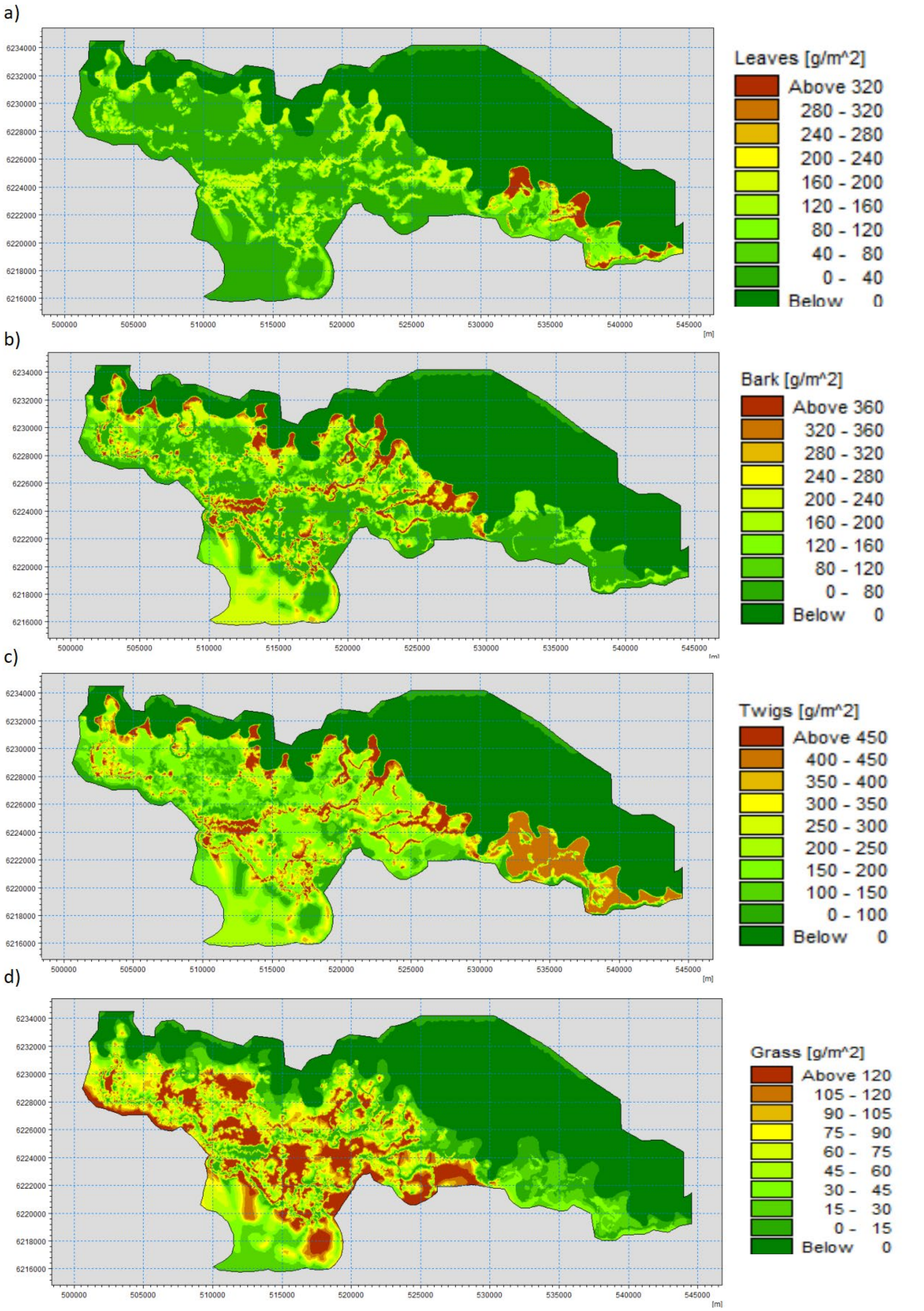


Figure 7. Litter loads (g/m^2) of a) leaves; b) bark; c) sticks and d) plants (grasses) within the Lindsay-Mulcra floodplain. Floodplains in the right bank of the Murray River (i.e. NSW) were not part of this study.

LEACHING OF LITTER MATERIALS

All DOC leaching curves for litter materials were well described by a first order process (i.e. the leaching rate was proportional to the amount of DOC in the sample), except for soils, due to the small amount of DOC leached from this fraction (average 0.2 mg-C/g soil) (Figure 8). Leaching rate constants varied between floodplains and litter fractions, with rates ranging from 0.31 d^{-1} (BB-Bark: Lindsay/Mulcra) and 1.34 d^{-1} (RG- Bark: Lindsay/Mulcra) (Appendix Table 5 and 6; Appendix Figures 1 and 2). Accordingly, in all litter types and across all vegetation types for all floodplains, maximum DOC values were attained in less than 5 days. RG-leaves leached the highest amount of DOC with a maximum of 54 ± 6 mg-C/g-substrate (Lindsay/Mulcra) and 45 ± 5 mg-C/g-substrate (Hattah), respectively (Appendix Table 5 and 6; Appendix Figures 1 and 2).

DOC leaching rates for each fraction, across all vegetation types, were used to calculate average litter fraction leaching rates (Figure 8). Rate constants and maximum DOC leached and their associated confidence limits are provided in Table 3. The amount of DOC leached from each litter type varied greatly and followed the general order: leaves > plants > other > bark > scats > sticks > soil (Figure 8).

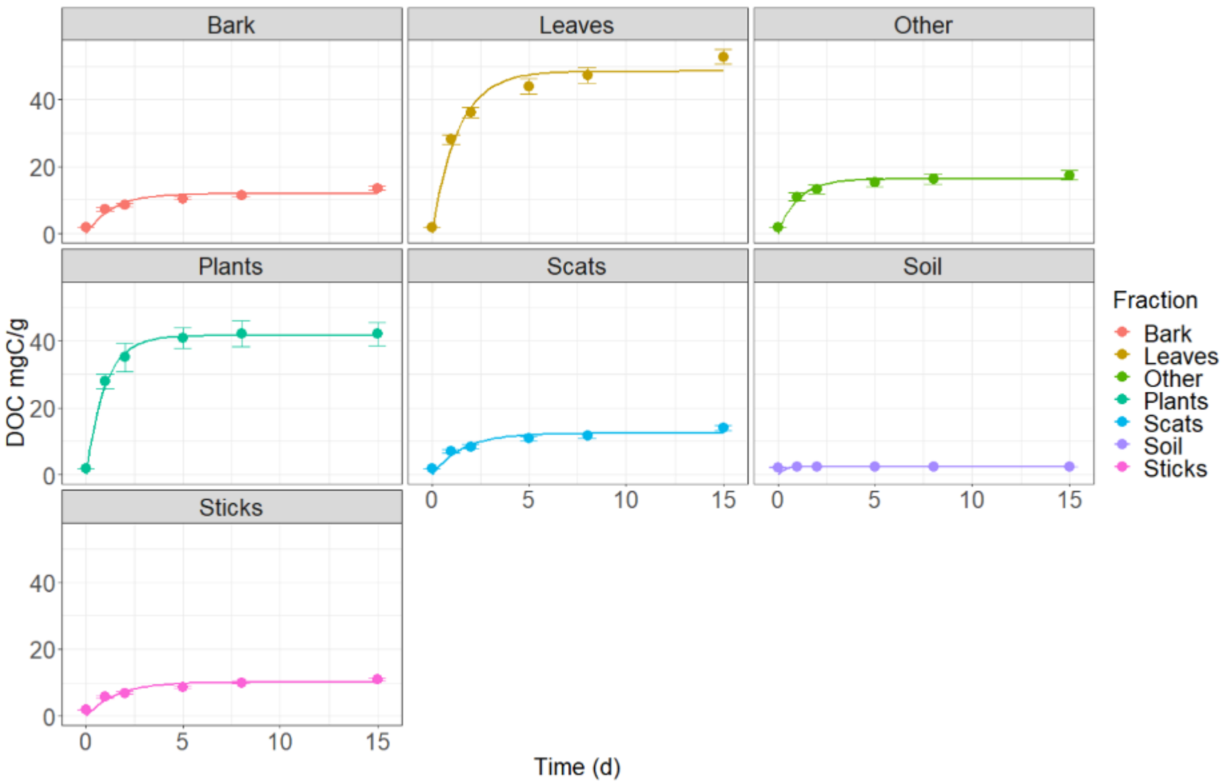


Figure 8. DOC leaching behaviour for six litter materials (leaves, bark, sticks, plants (grasses), scats and other) averaged across all vegetation types. Experimental data from all three floodplains and all vegetation communities have been combined and modelled according to a first-order process (solid line ± SE).

Table 3: Rate Constants (k) and maximum leachable carbon (DOC_{inf}; mg-C/g-substrate) for each litter fraction.

FRACTION	FIRST-ORDER PARAMETER	Estimate	Lower CI	Upper CI
Bark	DOC_{inf} (mgC/g)	11.88	11.22	12.58
	k (d^{-1})	0.75	0.59	0.97
Leaves	DOC_{inf} (mgC/g)	48.49	46.15	50.91
	k (d^{-1})	0.76	0.62	0.93
Other	DOC_{inf} (mgC/g)	16.25	14.87	17.68
	k (d^{-1})	0.98	0.67	1.56
Plants	DOC_{inf} (mgC/g)	41.63	38.04	45.34
	k (d^{-1})	1.04	0.71	1.67
Scats	DOC_{inf} (mgC/g)	12.42	11.51	13.41
	k (d^{-1})	0.63	0.46	0.87
Sticks	DOC_{inf} (mgC/g)	10.09	9.56	10.64
	k (d^{-1})	0.66	0.53	0.83
Soil	DOC_{inf} (mgC/g)	2.37	2.22	2.53
	k (d^{-1})	3.34	-0.74	7.42

DISSOLVED OXYGEN DRAWDOWN AND DOC DECOMPOSITION RATES

Dissolved oxygen was shown to decrease to less than 1 mg/L (from 10.2 mg/L starting conditions) over 24 hours for all litter fractions at the solid-liquid ratios used in these experiments. Oxygen consumption rates varied across litter fractions and ranged from 0.06 mg O_2/g sample/hr (LG-Bark) to 0.42 mg O_2/g sample/hr (OT-Other) (Appendix Table 7 and Appendix Figure 3). Across the litter materials, leaves (RG and BB) and 'other' (BB and OT) depleted oxygen more quickly than all other litter fractions levels (rate constants (k): RG-leaves = 0.38; BB-leaves = 0.3; OT-Other = 0.42; OT-Other = 0.33).

DOC decomposition rate constants were also calculated to allow for direct comparison to rates used in the BRAT model (parameter K_d; Figure 9 and Table 4). Rate constants calculated in this way ranged from 0.01 (LG-Leaves) and 0.12 (BB-Bark, Ot-Sticks, RG-Sticks), with an average value of 0.06 d^{-1}. The rate constant for all fractions except LG-leaves, LG-Plants, and OT-Plants exceeded the 0.03 d^{-1} rate constant within the BRAT model (Whitworth and Baldwin, 2016).

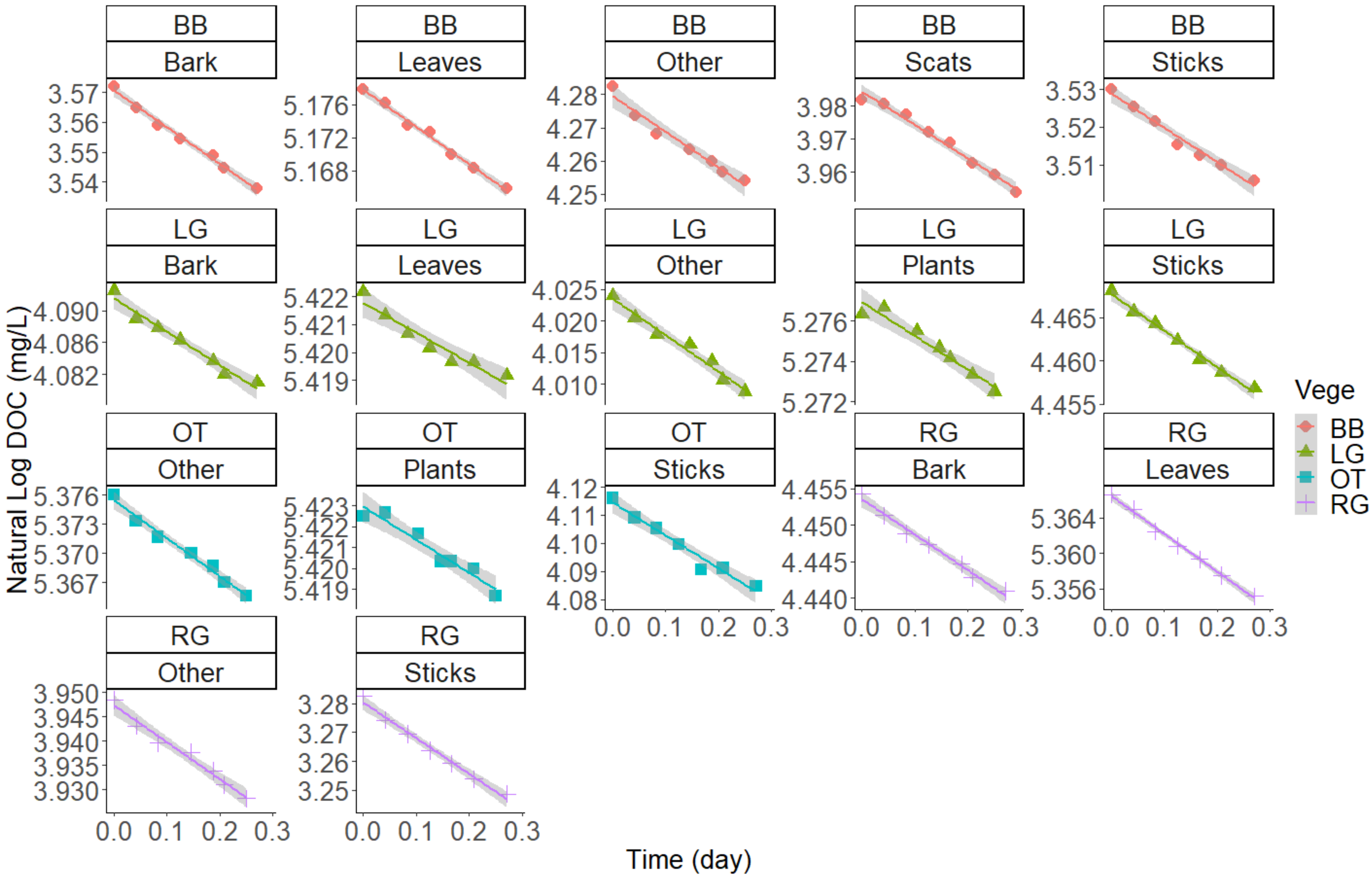


Figure 9. Dissolved organic carbon decomposition rates for each litter fraction within each vegetation community.

Table 4: Rate constants (k) for DOC decomposition for each litter fraction. RG = Red gum, BB = Black box, LG = Lignum and OT = Other

Fraction	Vege Community	Rate constant DOC decomposition (day)	Lower CI	Upper CI
Bark	BB	0.12	0.11	0.14
	LG	0.04	0.03	0.05
	RG	0.05	0.04	0.06
Leaves	BB	0.04	0.04	0.05
	LG	0.01	0.08	0.01
	RG	0.04	0.04	0.05
Other	BB	0.11	0.08	0.13
	LG	0.06	0.05	0.07
	OT	0.04	0.03	0.04
	RG	0.08	0.06	0.09
Plants	LG	0.02	0.01	0.02
	OT	0.02	0.01	0.02
Scats	BB	0.10	0.09	0.11
Sticks	BB	0.09	0.08	0.11
	LG	0.04	0.04	0.05
	OT	0.12	0.09	0.14
	RG	0.12	0.11	0.14

Part Two: Model Development

COMPARISON BETWEEN PARAMETER SETS

Initial sensitivity testing revealed some differences in predicted DOC and DO concentrations on the floodplain when comparing the original BRAT model leaching rates with those derived in the experiments done as part of this study. However, such differences tended to be localized and the overall trends were similar for all three parameter sets. The concentrations of DOC at 1 and 4 weeks under each parameter set were not markedly different, but were obviously higher in some areas (Figure 10 and Figure 11). Differences in DO concentrations were minor after 1 week (Figure 12) and more noticeable after 4 weeks (Figure 13) due to prolonged DOC decomposition and DO depletion. Notable localized hypoxic zones occurred in less connected habitats such as Lake Wallawalla (Figure 13 and Figure 14), where hypoxic conditions arose by week 4 In contrast, anabranches and areas connected to the Murray River benefited from incoming DO-rich water from the river, and hence still maintained high DO levels (Figure 13).

Given the similarity in outputs between the three parameter sets, Set 2 which utilises updated rates of

DOC leaching was chosen to conduct future scenarios. Parameter Set 3 was not used due to limited validation of the DOC decomposition rates. Further work is required to validate which of these 3 parameter sets is most reliable in matching observed oxygen concentrations over time.

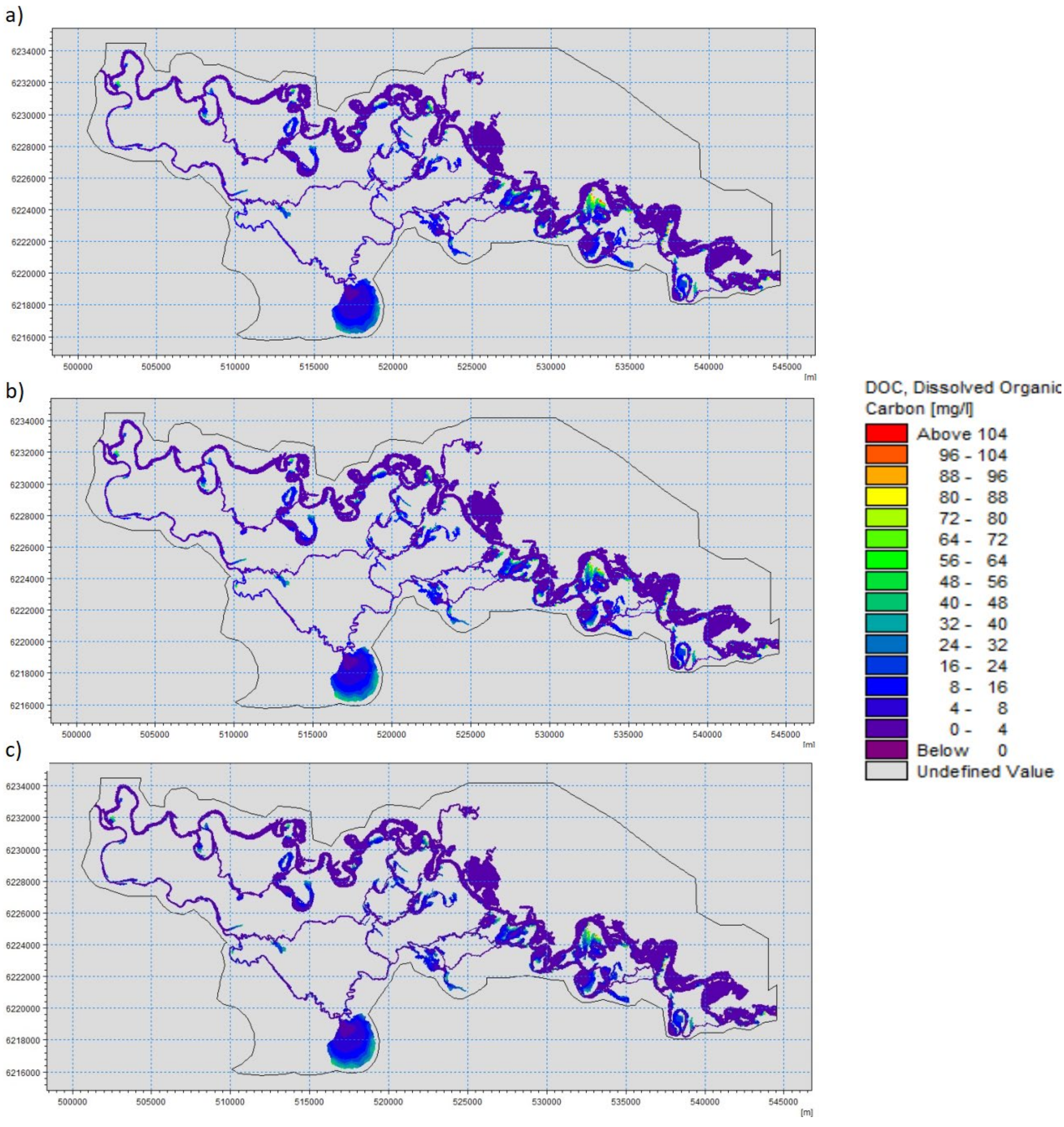


Figure 10. Dissolved organic carbon concentrations (mg/L) in the Lindsay and Mulcra floodplains after 1-week flow pulse; a) using BRAT model constants (Set 1), b) revised leaching rate constants (Set 2), and c) revised leaching rate and DOC decomposition rate (Set 3).[1]

[1] **Note that 'Below 0' values in the legend of this and other plots are not physically meaningful and where such values occur they should be interpreted as 0 mg/l.**

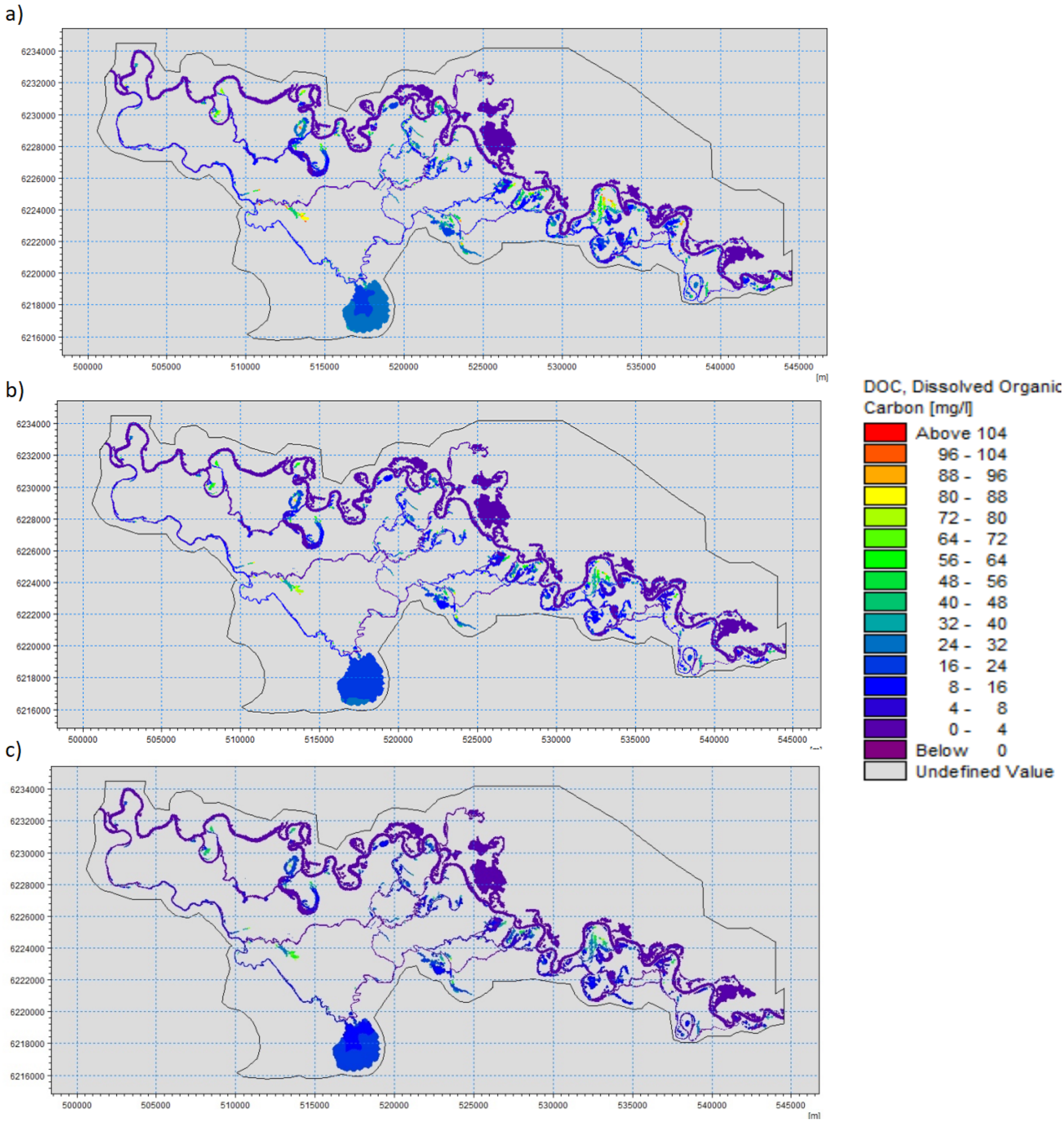


Figure 11. Dissolved organic carbon concentrations (mg/L) in the Lindsay and Mulcra floodplains after 4-week flow pulse; a) using BRAT model constants (Set 1), b) revised leaching rate constants (Set 2), and c) revised leaching rate and DOC decomposition rate (Set 3).

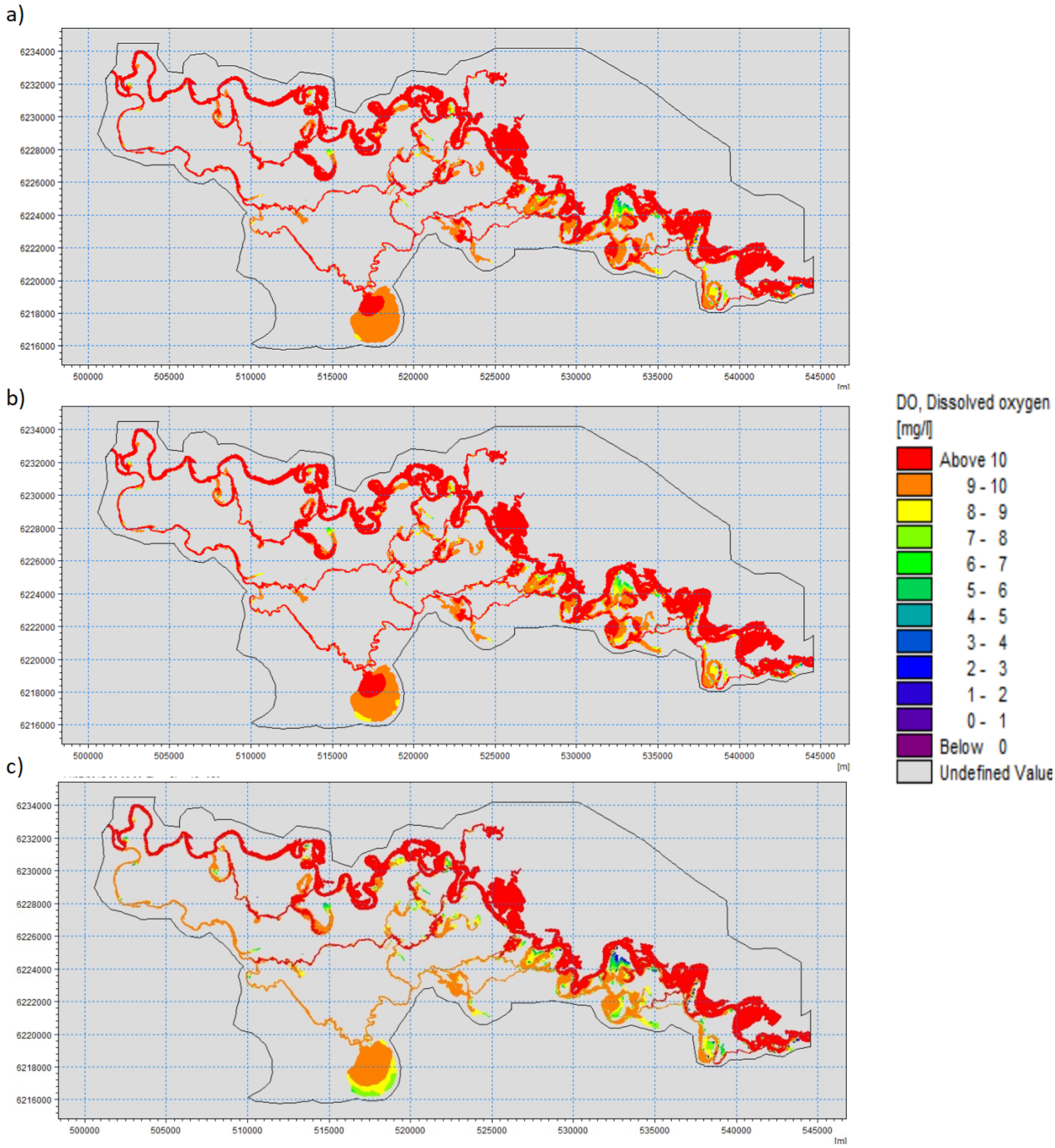


Figure 12. Dissolved oxygen concentrations (mg/L) in the Lindsay and Mulcra floodplains after 1-week flow pulse; a) using BRAT model constants (Set 1), b) revised leaching rate constants (Set 2), and c) revised leaching rate and DOC decomposition rate (Set 3).

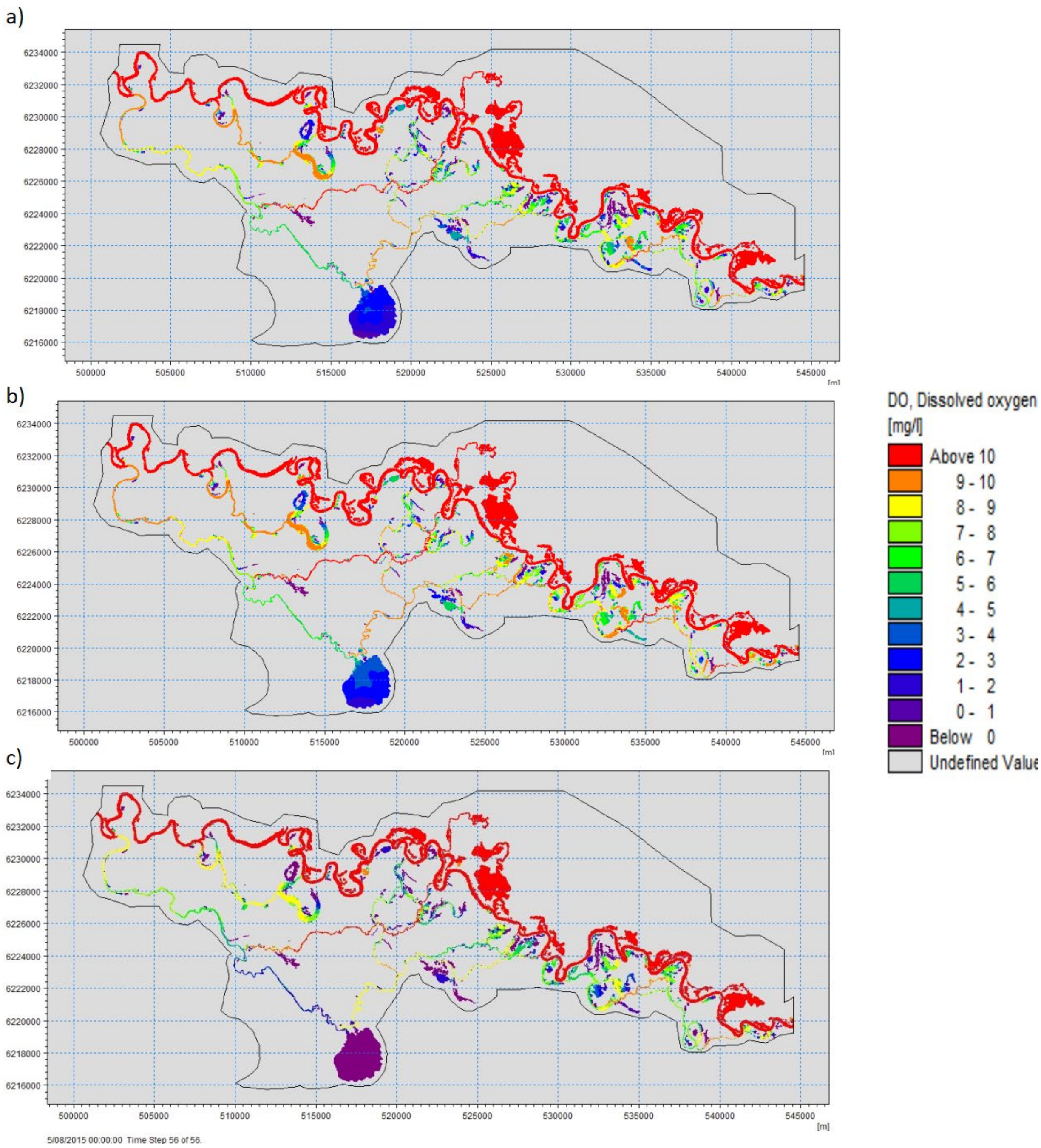
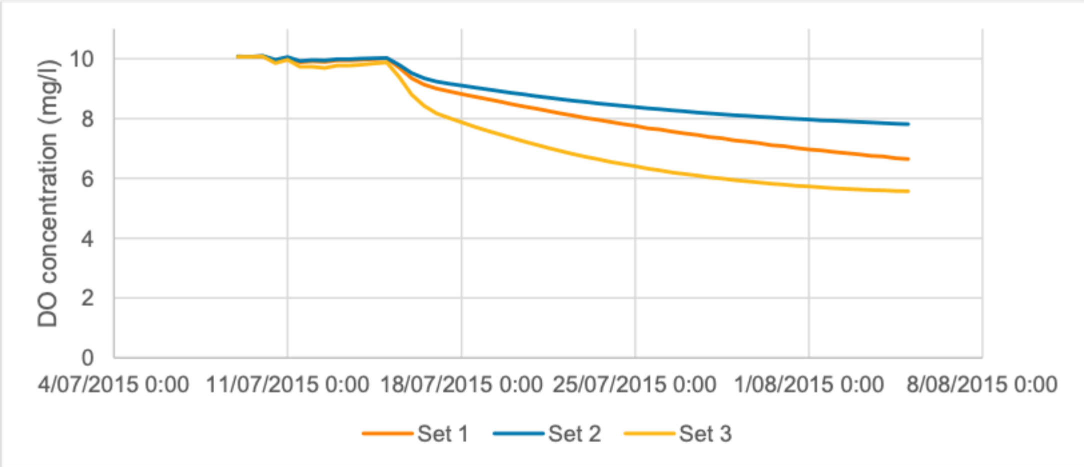
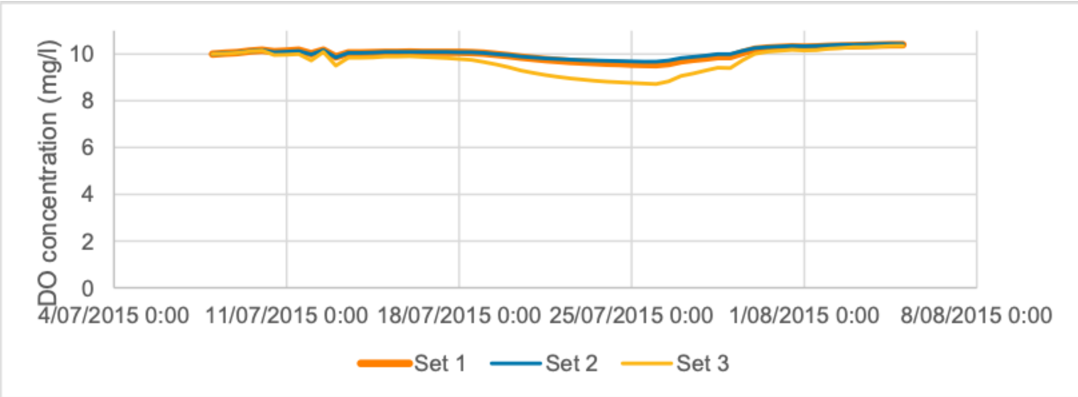


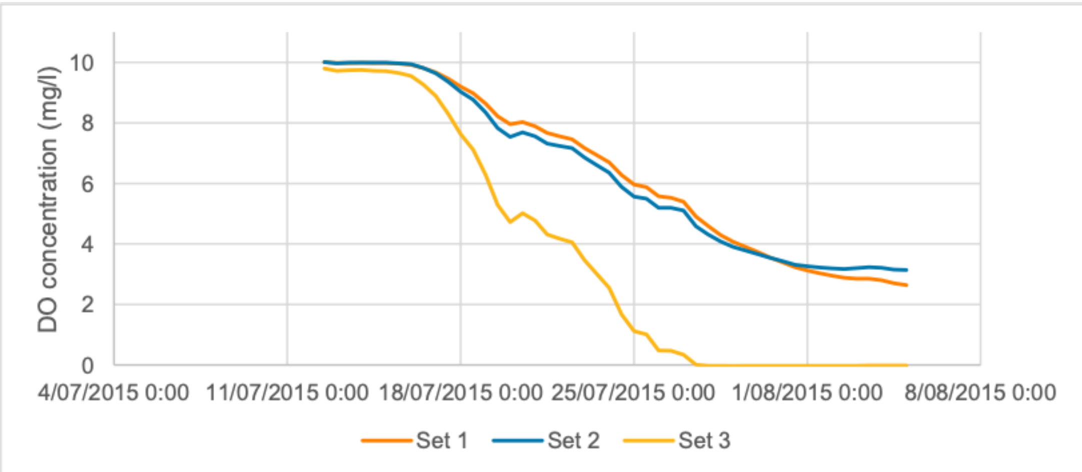
Figure 13. Dissolved oxygen concentrations (mg/L) in the Lindsay and Mulcra floodplains after 4-week flow pulse; a) using BRAT model constants (Set 1), b) revised leaching rate constants (Set 2), and c) revised leaching rate and DOC decomposition rate (Set 3). Note: 'Below 0' corresponds to where the oxygen demand associated with DOC decomposition exceeds re-supply rates.



a. Mulcra upstream of confluence with Murray River.



b. Lindsay river just upstream of confluence with the Murray River.



c. Lake Wallawalla

Figure 14. Time series of oxygen concentration at three sites of interest; a) Mulcra, upstream of confluence with the Murray River, b) Lindsay, upstream of the confluence with the Murray River, and c) Lake Wallawalla, which showed some of the lowest DO values.

DIFFERENT FLOW CONDITIONS

Scenarios 2, 4 and 5 were used to assess the effects of flow pulse duration on oxygen dynamics (see Figure 4 for flow pulse characteristics). At the end of each flow pulse (i.e., at 1-week, 2-weeks, and 4-weeks respectively), oxygen concentrations were high across most of the floodplain due to the sustained inflow of oxygen rich water from the river (Figure 15). Nonetheless, in areas with limited mixing of flows, the longer flow pulse allowed hypoxic conditions to arise in some locations such as the southern perimeter of Lake Wallawalla. A comparison of the different duration flow pulses allowing for a one week (Figure 16) and three week (Figure 17) recession period after the flow pulse has ended shows the role of hydrodynamics in driving spatial variability in oxygen concentrations, with much more variable concentration profiles in some areas, such as Lake Wallawalla, where the additional volumes of water associated with the longer flow pulse help to maintain higher oxygen concentrations in well mixed areas, while at the same time leading to lower oxygen concentrations in poorly mixed areas where the longer flow pulse would have contributed additional leached material by pushing higher onto the floodplain.

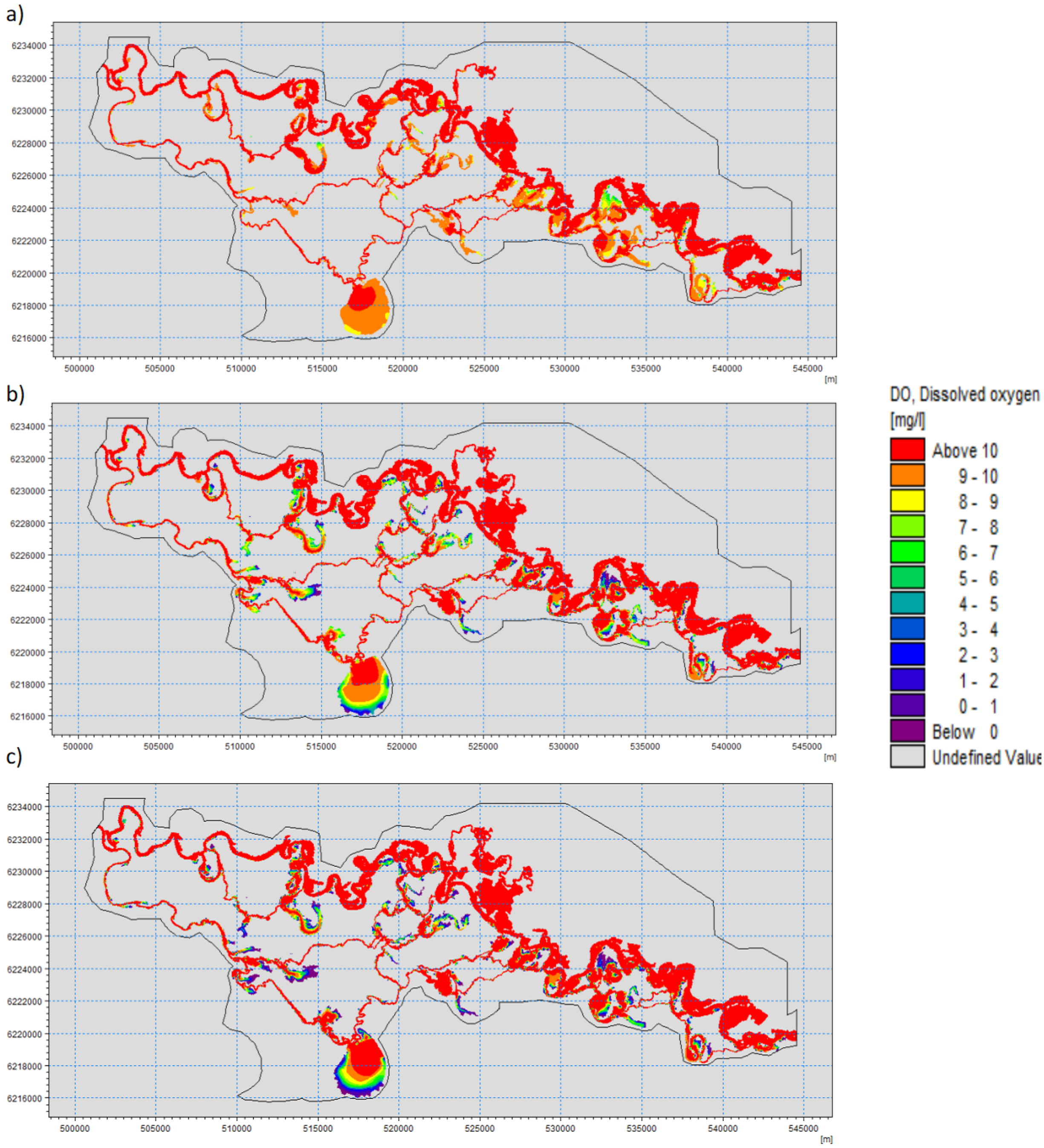


Figure 15. Simulated dissolved oxygen concentrations (mg/L) in the Lindsay and Mulcra floodplains after flow pulses of different lengths; a) 1 week pulse b) 2 week pulse and c) 4 week pulse.

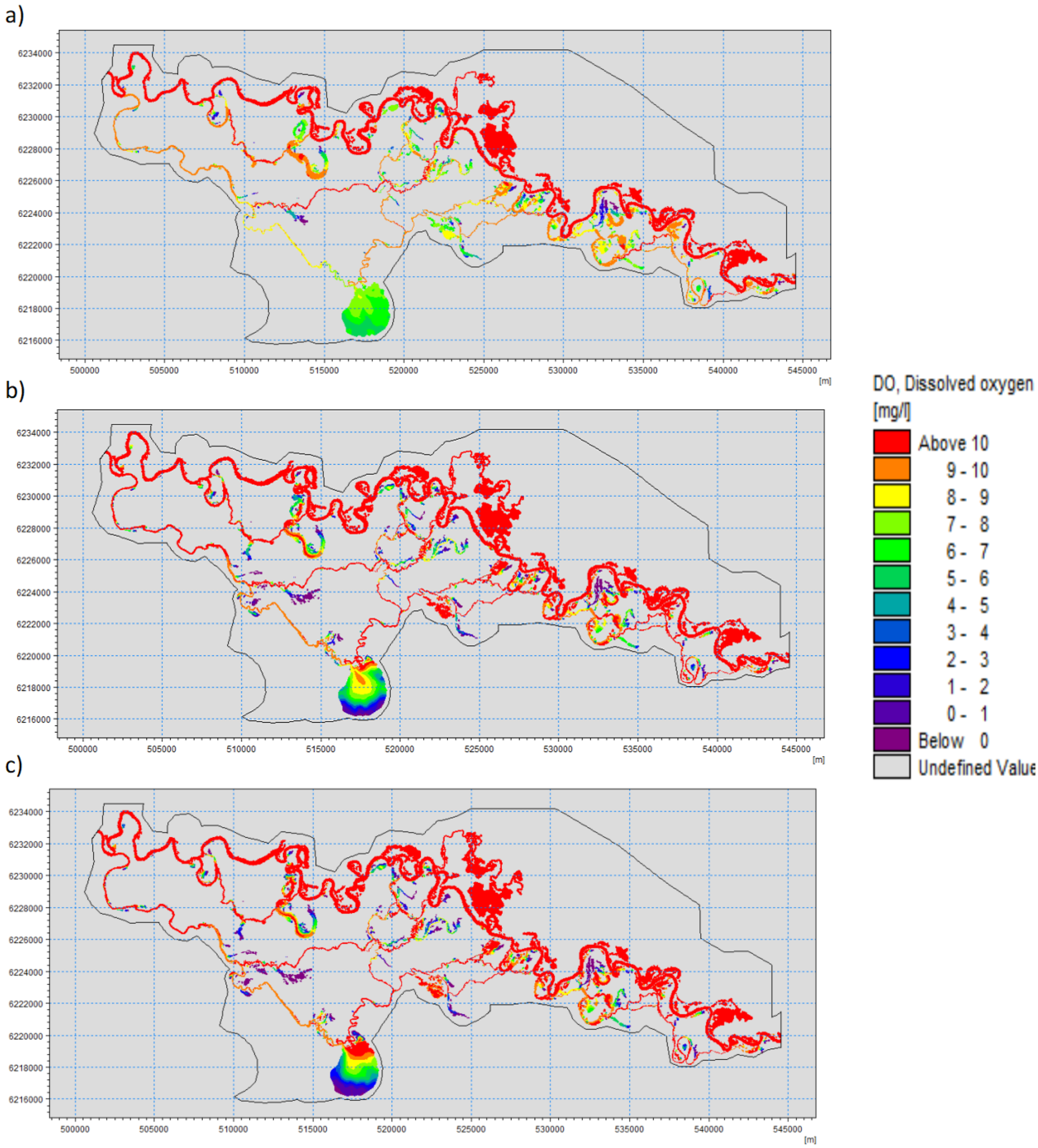


Figure 16. Simulated Dissolved oxygen concentrations (mg/L) in the Lindsay and Mulcra floodplains after flow pulses of different lengths and 1 week recession flows; a) 1 week pulse b) 2 week pulse and c) 4 week pulse.

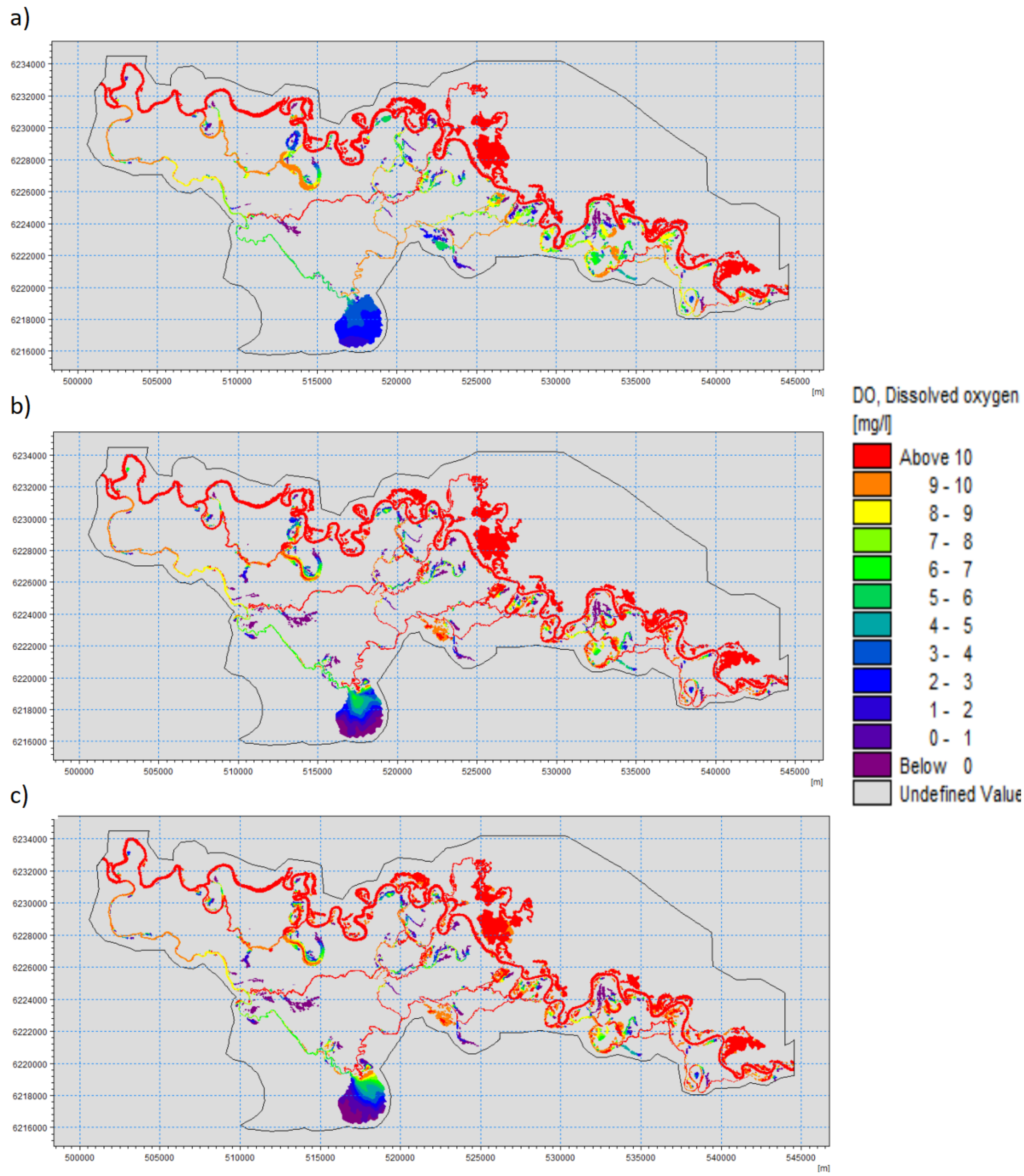


Figure 17. Simulated Dissolved oxygen concentrations (mg/L) in the Lindsay and Mulcra floodplains after flow pulses of different lengths and 3 weeks recession flows; a) 1 week pulse b) 2 week pulse and c) 4 week pulse

EFFECT OF FLOW REGULATOR IN MULCRA

Scenario 6 was used to assess the effect of the flow regulator at the exit of Mulcra on DO concentrations (by contrasting with Scenario 2). Two closing settings were simulated; a) starting with the regulator open, then closing it 1-week after (once the flow recession starts) and opening it again two weeks after, b) Starting with the regulator closed and opening it three weeks after, and c) no regulator in place (i.e. Scenario 2).

The structure created a significant backwater effect extending several kilometres along the tributaries. In setting B, all the water entering the floodplain is retained, which causes a larger inundation area, and all the DOC produced in the floodplain is retained, which causes higher DOC (Figure 18), more DO depletion and lower DO concentrations in shallow areas (Figure 19). It would be possible to change the settings of the structure to explore different management strategies. Some hypoxic zones were still shown to develop in presence and absence of the regulator in areas with higher DOC concentrations (Figure 15).

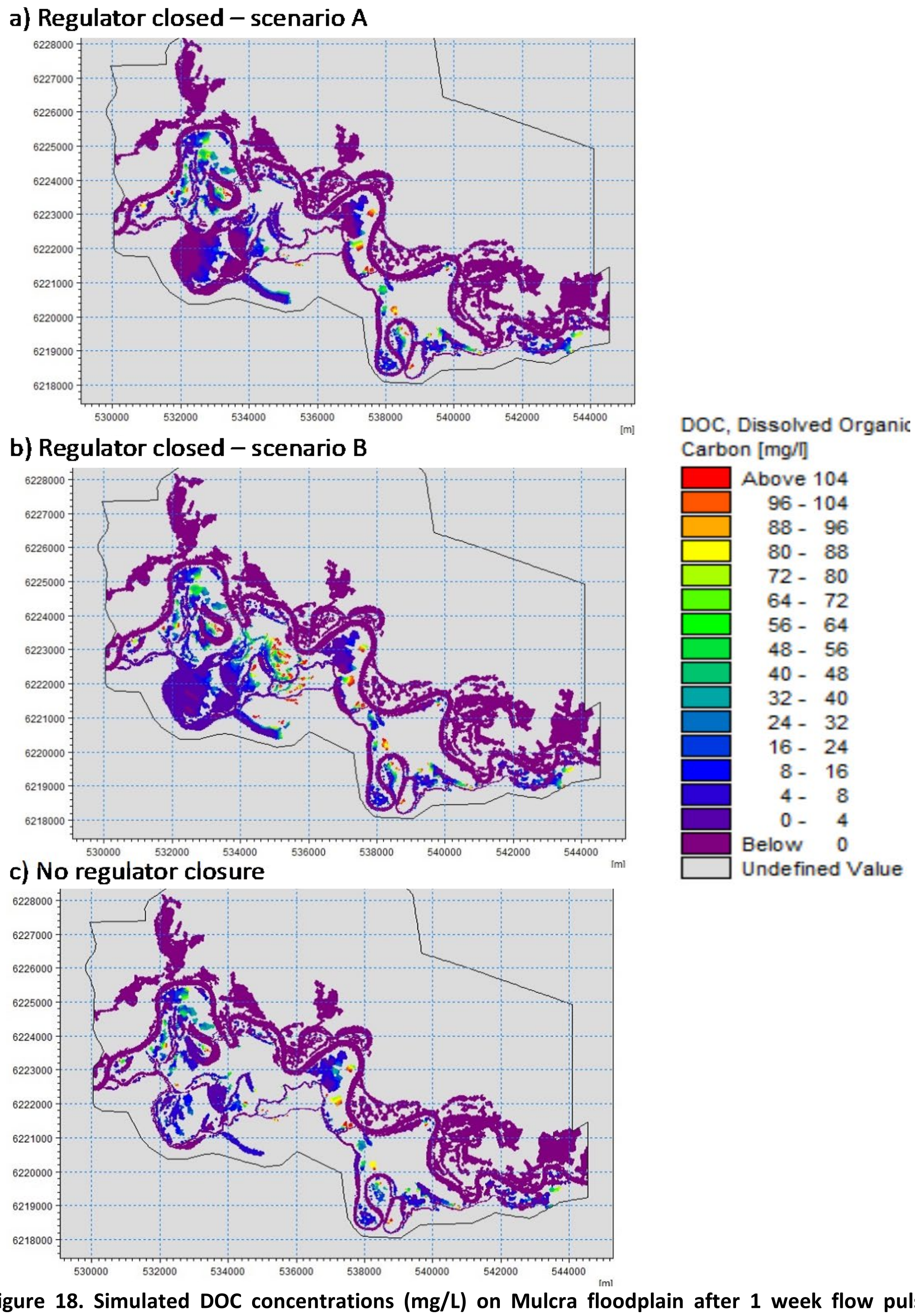


Figure 18. Simulated DOC concentrations (mg/L) on Mulcra floodplain after 1 week flow pulse + 2 weeks recessional flows; a) Starting with the regulator open, then closing it 1-week after (once the flow recession starts) and opening it again two weeks after; b) Starting with the regulator closed and opening it three weeks after, and c) no regulator in place.

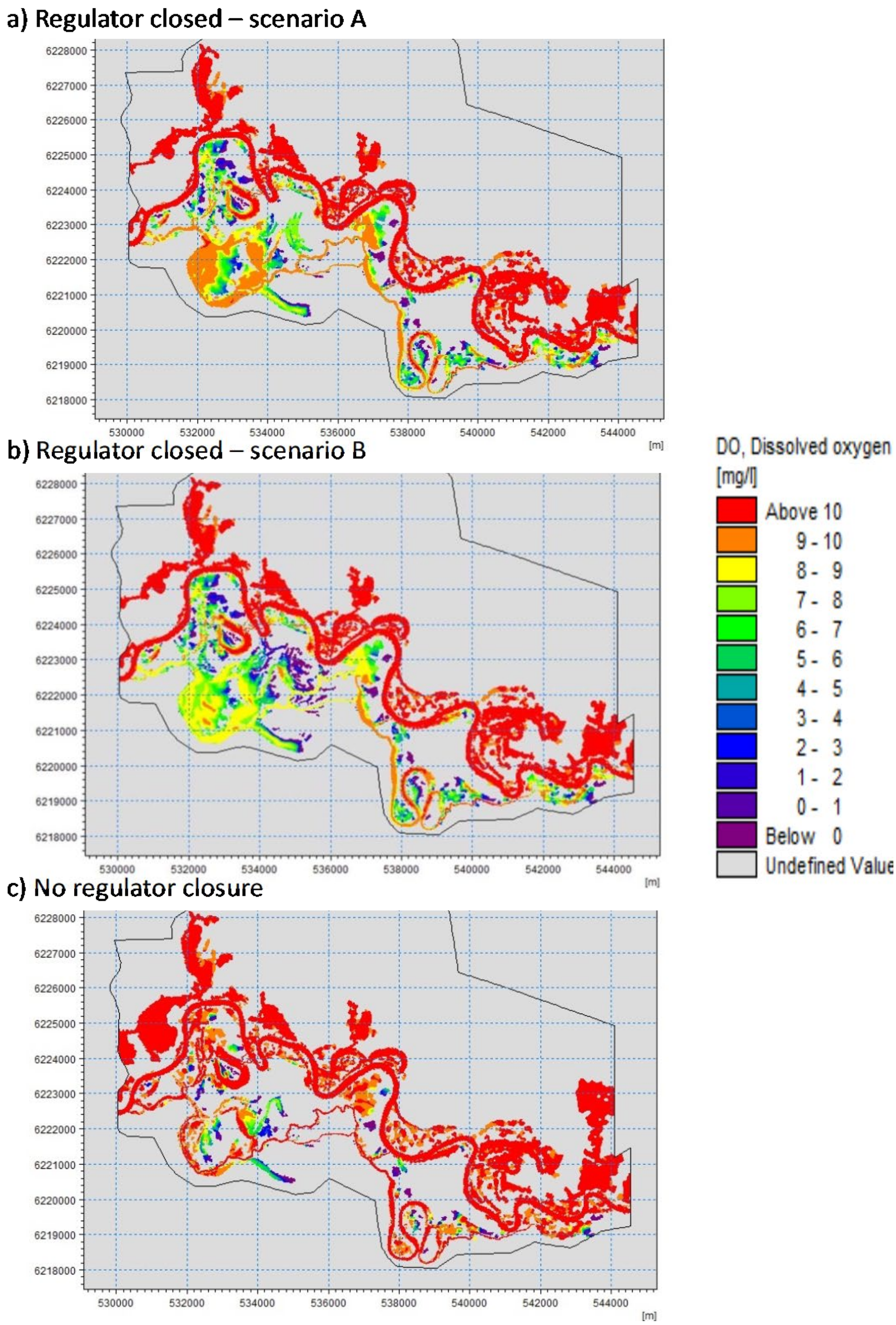


Figure 19. Simulated DOC concentrations (mg/L) on Mulcra floodplain after 1 week flow pulse +2 weeks recessional flows; a) Starting with the regulator open, then closing it 1-week after (once the flow recession starts) and opening it again two weeks after; b) Starting with the regulator closed and opening it three weeks after, and c) no regulator in place.

DISCUSSION

LITTER LOADS, LITTER COMPOSITION AND DOC LEACHING

Litter loads differed between floodplains with higher litter loads on the Hattah floodplain compared to Lindsay and Mulcra. Litter loads also differed between vegetation types, decreasing in the order: RG > BB > LG > OT. The composition of the litter varied between vegetation types, with sticks generally the dominant fraction. This supports results found previously for Lindsay and Mulcra floodplains (Silvester et al. 2019). Hattah, Lindsay and Mulcra litter loads were consistent with that reported previously for floodplain forests of the Murray River which range from 400 – 6100 g/m^2 (Glazebrook and Robertson 1999; Brooks et al. 2007; Hladyz et al. 2011). The distribution of litter materials within the RG community is also very similar to that reported elsewhere, with a dominance of sticks (Baldwin et al. 2013; Whitworth and Baldwin 2016) and lesser amount of leaves (Glazebrook and Robertson 1999; Hladyz, 2011). Hladyz et al. (2011) reported a threshold litter loading of 370 g/m^2 in 20 cm of overlying water resulted in 'zero' dissolved oxygen after 2 days contact. This litter loading was exceeded in all vegetation types on the Hattah floodplain, within RG, BB and LG on the Mulcra flood plain and RG and BB within the Lindsay floodplain (Figure 5).

For all litter fractions studied as part of this project all DOC leaching was near complete after 5 days. As previously shown in Silvester et al. (2019), leaching behaviour (both rate and maximum DOC) was similar between litter materials of the same types, i.e. sticks were similar regardless of the vegetation type, etc. The amount of DOC leached over the 15 day period decreased in the order: leaves > plants > other > barks > sticks > soils and is consistent with that reported by O'Connell et al. (2000) for RG litter materials. While there are few studies that have investigated DOC leaching from bark, sticks and other debris, leaching from leaves (particularly RG) has received more attention. Reported rate parameters for RG leaves by Whitworth et al., 2014 ($k = 0.5\ d^{-1}$ and $DOC_{inf} = 80 – 100$) and O'Connell et al. 2000 ($k = 0.26 – 2.16\ d^{-1}$ and $DOC_{inf} = 45 – 80$) are very similar to that found in this study (Hattah: $k = 0.78\ d^{-1}$ and $DOC_{inf} = 44.5$ mg-C/g; Lindsay and Mulcra: $k = 0.68\ d^{-1}$ and $DOC_{inf} = 53.9$ mg-C/g; combined leaves: $k = 0.76$ and $DOC_{inf} = 48.5$ mg-C/g). Similarly, DOC_{inf} values for sticks and bark found here are very similar to that reported by O'Connell et al. (2000) for RG litter, in range 5 – 20 mg-C/g. The soil collected from all three floodplains was also shown to leach less DOC than litter, with less than 1 mg-C/g soil leached over the 15 day leaching experiment.

OXYGEN DRAWDOWN AND DOC DECOMPOSITION EXPERIMENTS

The interest in estimating carbon loads in floodplains is largely driven by concerns about oxygen drawdown and related effects on aquatic biota; DOC is a potential microbial energy source and utilisation of this carbon through aerobic pathways leads to depletion of oxygen from the water column (Whitworth et al., 2012). However, the bio-availability of DOC leached from different litter materials likely presents quite different risks to dissolved oxygen levels, i.e. bioavailability of DOC from highly lignified sticks or bark is expected to be lower than DOC from leaves or plants; leaves for example can contain high amounts of leachable bioavailable carbon and nitrogen (O'Connell et al., 2000: Harris et al., 2016).

In this study, the addition of 10 g of material from all litter fractions in 1L of river water resulted in complete depletion of oxygen levels over a 24 hour period. RG and BB leaves as well as BB and OT 'other' material depleted oxygen levels (rate constants (k): RG-leaves = 0.38 d^{-1}; BB-leaves = 0.3 d^{-1}; OT-Other = 0.42 d^{-1}; OT-Other = 0.33 d^{-1}) more quickly than other litter fractions. Given that all litter fractions at a solid-liquid ratio of 10g litter per litre depleted oxygen concentrations within 24 hours, reducing bulk litter loads rather than specific fractions may be an appropriate strategy for risk management. However, care must be taken when considering the results of the oxygen drawdown experiments as the solid-liquid ratio may be substantially lower under field conditions.

DOC decomposition rates determined as part of this study were shown to vary with litter fractions and were also generally higher (average K_d of 0.06) than what is currently used within the BRAT model (K_d = 0.03 Whitworth and Baldwin, 2016). Given this difference future models of DO draw-down should consider using K_d values more appropriate to the dominant litter type.

DEVELOPMENT OF AN APPROPRIATE HYDRODYNAMIC WATER QUALITY MODEL

At the start of the project, it was thought that it would be possible to use the existing MIKE FLOOD models for the study area. Nevertheless, two major problems were encountered:

- First, the MIKE ECO Lab module would run without a problem for the 1D part in MIKE HYDRO and the 2D part in MIKE21 separately, but it kept crashing after a few timesteps when they were linked in MIKE FLOOD. We contacted the developer of the software (DHI) and they investigated the problem, but after several weeks they had not been able to propose a solution. In the meantime, WaterTech created a new version of the model migrating most elements to MIKE21 and keeping only the hydraulic structures in MIKE HYDRO. Still the coupling through MIKE FLOOD created problems for the water quality computation. Finally, a fully MIKE21 model was developed and used for the simulations presented in this report.
- Second, the computational time for the water quality module was extremely long. In one of the most powerful computers at the WaterTech Melbourne office, a 1-week simulation for the Lindsay-Mulcra domain at a steady flow of 117 m3/s, required almost 6 days of computation. The reason for this was a combination of the resolution of the mesh for the 2D part and the solution scheme for the MIKE ECO Lab module (as explained below). After various adjustments, the original mesh

(700,877 elements) was simplified to a coarser mesh (282,699 elements), keeping the essential elements of the system to achieve realistic results with the hydrodynamic and water quality models. This reduced the computational time from 6 to 2.1 days. After migrating the model fully to MIKE21, the computational time was reduced to about 0.5 days.

The solution scheme in MIKE ECO Lab is fully explicit, i.e. conditionally stable. To avoid instabilities, the model automatically reduces the simulation time step, in some cases to fractions of a second. The stability criteria used (the Courant number) is directly proportional to flow celerity, thus, the time step is further reduced for higher flow velocities. In our case, this created difficulties due to high velocities across the hydraulic structures and when increasing the flow rate from 117 m^3/s to 460 m^3/s.

Long computational times have been one of the limiting factors in the project. They have significantly hindered the progress of the model testing and precluded the running of long-term simulations. Even though it is known that large flood events in the study area usually last several months, it was not possible to simulate such long periods due to the computational time required. Therefore, we focused on the first weeks of inundation, when the leaching and decomposition of the accumulated vegetation litter would cause a sharp decline in dissolved oxygen.

Simulations of 1- to 4-weeks were used for testing and initially proposed for the sensitivity analysis (Appendix C) to observe the propagation of the flow pulse through the floodplains and the short-term dynamics of litter leaching. Nevertheless, as we progressed with the simulations, it became apparent that longer simulations were needed to assess the extent of oxygen depletion in the floodplains. As computational times were reduced with the MIKE21 model, flow Pulse 2 and Pulse 4 were added. In addition, it was possible to conduct the sensitivity analysis for the whole domain and not only for Mulcra. The hydrodynamics of the system was sped up with the use of the synthetic flow pulse, however, the water quality processes governing the dissolved oxygen concentrations could not be equally accelerated. Longer simulation times would be required to give a more realistic representation of the system dynamics.

Due to the considerable time taken to develop the MIKE21 model for Lindsay and Mulcra floodplains even though they already had hydrodynamic models developed, it was not possible to develop a model for the Hattah Floodplain as part of this project. Accordingly, the results discussed below relate specifically to the Lindsay and Mulcra floodplains.

MODELLED DISSOLVED ORGANIC CARBON AND DISSOLVED OXYGEN CONCENTRATIONS IN REGARD TO MODEL PARAMETERS AND FLOW CONDITIONS

This project utilized three sets of parameters: set 1 consisted of parameters within the BRAT model, set 2 consisted of updated parameters for DOC leaching developed during part one of this study and set 3 consisted of updated parameters for DOC leaching developed plus an updated DOC decomposition rate developed during part one of this study. Overall simulated DOC and DO concentrations were similar between the first two models. Set 1 tended to predict slightly higher concentrations of DOC and thus lower DO concentrations on the floodplains and this was most visible within Lake Wallawalla. After a one week flow pulse DOC concentrations were generally below 30 mg-C/L., except within Mulcra in areas with high abundance of leaves where DOC concentrations in some spots exceeded 100 mg/L. This is not surprising given leaves leached the highest amount of DOC during part one of this study and their role in development of blackwater is widely known (Hladyz et al. 2011, Kerr et al. 2013). DO concentrations were generally above 5 mg/L during this one week flow pulse. After an additional 3 weeks of recessional flows DOC concentrations within most floodplains increased slightly to approximately 40 mg-C/L, with a small number of pockets containing DOC concentrations of 80 mg-C/L or above. Pockets of hypoxia developed in certain regions of the floodplains especially within Lake Wallawalla. This highlights the potential of Lake Wallawalla to develop hypoxic blackwater. Given the similarity between the two models, parameter set 2 developed as part of this study was used for future simulations.

Modelled simulations of different flow pulses (1, 2 and 4 week pulses) and associated recessional flows (0, 1 and 3 weeks) highlighted the impact of length of flood pulse and recessional flows on development of hypoxic conditions. Extending the time of flow pulses increased the areas affected by hypoxia (Kerr et al. 2013). Increasing the length of recessional flow also exacerbates the hypoxic conditions. The susceptibility of Lake Wallawalla to hypoxia was highlighted during these scenarios, which is a concern given its eutrophic status (Lind & Wills 2018). The presence of a regulator on Mulcra caused a significant backwater effect, leading to more areas becoming flooded and increased depth in some regions leading to lower DOC and high DO, however small pockets of hypoxia still developed in areas with low water depth and higher DOC concentrations. A downstream re-aeration effect of regulators has previously been reported however was not explored in this instance (Whitworth et al. 2013).

The effect a change in DOC decomposition rates might have on modelled DO concentrations was explored via use of parameter set 3, by the addition of an increased DOC decomposition rate (K_d = 0.06 d^{-1}) to parameter set 2 and compared with outputs from all three models (parameter sets 1-3). The increased DOC decomposition rate after a one week flow pulse and three weeks recessional flows lead to the development of more hypoxic zones of lower DO concentrations than what was modelled for parameter sets 1 and 2. The higher k_d value (0.06 d^{-1}) used in parameter set 3 is the average rate constant developed during part one of this project and suggests that the K_d value within the BRAT model (0.03 d^{-1}) may be underestimating the rate of DOC decomposition which may occur on the floodplains and thus the amount of potential DO depletion. Therefore, it is important that future models using rate constants developed for specific litter fractions if available be considered for use over the constant within the BRAT model.

RECOMMENDATIONS AND FUTURE WORK

This project has shown that litter loads within all three floodplains within the RG and BB vegetation communities exceed the critical litter load threshold above which oxygen drawdown is likely to occur (Hladyz et al. 2011). Lignum communities within Hattah and Mulcra floodplains also exceeded this threshold, along with the "other" vegetation community within the Hattah floodplain. We recommend reducing and maintaining where possible litter loads on all three floodplains in areas likely to be inundated, to below the 370g/m^2 critical litter load threshold.

Modelling also highlighted that several regions within the Lindsay and Mulcra floodplains are highly susceptible to the potential development of hypoxic blackwater under various flow scenarios. One main area of concern is Lake Wallawalla. Oxygen concentrations in and around Lake Wallawalla were also predicted to change in response to flow pulse length. For example, under the 1-week pulse scenario, DO concentrations for the lake were predicted to drop to 2-4 mg/l, however with a 4-week flow pulse the southern shoreline was predicted to become hypoxic (<2 mg /l), but with higher oxygen concentrations occurring along the northern shoreline. This spatial variability may be important in providing local oxygen refuges for aquatic biota. To validate and test these predictions, dissolved oxygen sensors should be installed within at-risk areas to accurately monitor DO concentrations. Intervention plans for at risk areas such as Lake Wallawalla that allow for rapid response to combat formation of hypoxic blackwater should also be developed.

The time and funding restraints of this project did not allow for the development of a model for Hattah floodplain. However, it is clear that this floodplain is likely to be most at risk of developing hypoxic conditions due to the high litter loads found within all four vegetation communities sampled as part of this project. Therefore, developing such a model should be considered a high priority for future work.

We also recommend the following be conducted in the future to validate the Lindsay-Mulcra model and increase confidence in modelled outputs.

1. Historical event(s) with existing records of flow and dissolved oxygen concentrations along the main channels and across the floodplains should be analysed to assess the accuracy of the model. This would allow us to validate the model by simulating the real dynamics of the system and the coupling of the hydrodynamic and water quality processes at the correct time and space scales.
2. The current simulation results can be used to identify areas in the floodplains with higher risk of hypoxia. These would be locations of interest for monitoring DO during future inundation events. The current simulation also identifies areas with lower risk of hypoxia, which may be used as reference measurement sites. Data collected at these sites could be used to benchmark the model and guide possible improvements.
3. Regarding the water quality processes simulated, it would be advisable to compare the approach used for the sediment oxygen demand in the BRAT model to other methods to assess which one would be more appropriate for the blackwater risk analysis. Some alternatives are offered within MIKE ECO Lab that would be easy to implement. It is also possible to code new equations and the future comparison studies should also include comparison with the oxygen drawdown rates calculated as part of this project for the different litter fractions. Litterfall rates for the floodplains should also be calculated for summer, autumn, winter and spring within the floodplains and added to the model.
4. As it was shown with the model for the flow regulator in Mulcra, it is possible to create subdomains and extract boundary conditions for those subdomains from the complete Lindsay-Mulcra model. This can be used to make a more refined analysis at specific areas of interest.

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Appendix Part One

Appendix Table 1: Area of each vegetation community within the watered extent of each floodplain

	FLOODPLAIN		
	Lindsay (km^2)	Mulcra (km^2)	Hattah (km^2)
Red gum (RG)	8.6	0.93	35.00
Black box (BB)	16.3	1.87	14.85
Lignum (LG)	13.5	2.00	0.21
Other (OT)	10.9	1.96	15.39

Appendix Table 2: Number of quadrats fractionated into litter material fractions

	FLOODPLAIN		
	Lindsay	Mulcra	Hattah
Red gum (RG)	7 replicates*	7 replicates*	10 replicates
Black box (BB)	7 replicates*	7 replicates*	10 replicates
Lignum (LG)	7 replicates*	7 replicates*	10 replicates
Other (OT)	7 replicates*	7 replicates*	10 replicates

*This is combined with 3 replicates already fractioned in 2019 for these floodplains (Silvester et al. 2019) to bring up to 10 replicates.

Appendix Table 3: Approximate weights of each fraction used in the Leaching experiments

FRACTION TREATMENT	WEIGHT (g)
Leaves	10
Bark	20
Sticks	50
Plants	10
Other	10
Scats	10
Soils	Core (5cm diameter by 5cm high)
Control	Murray River water

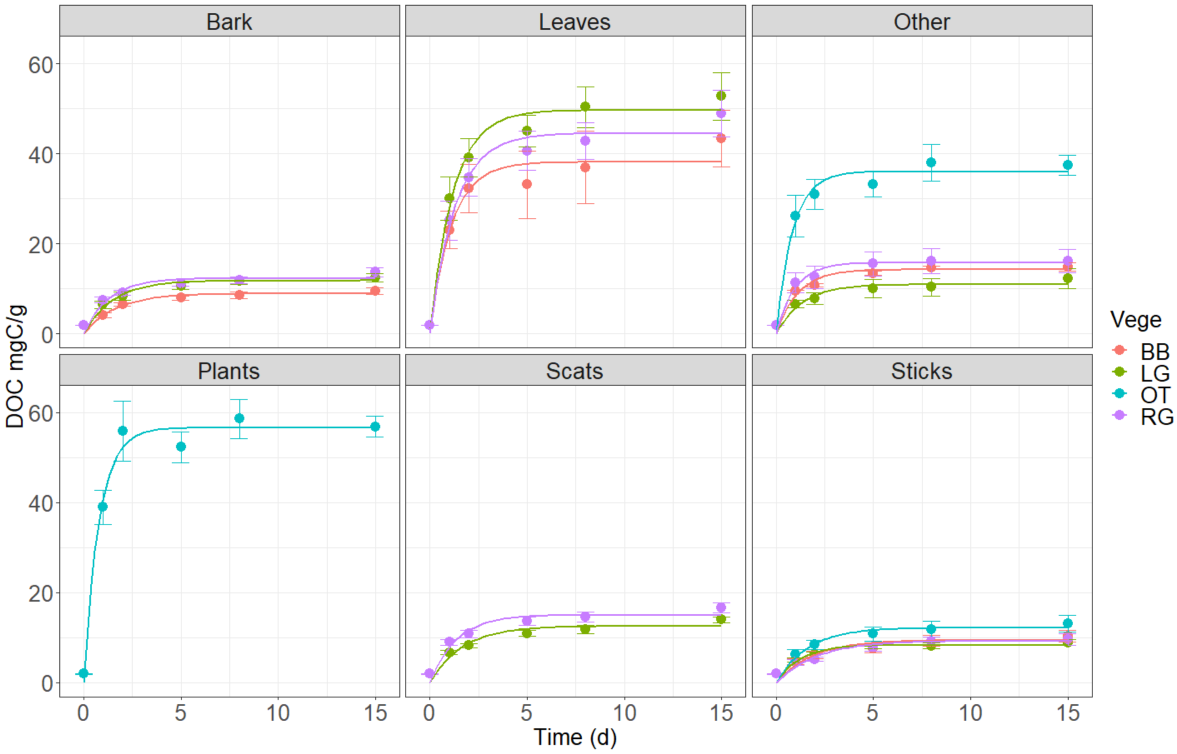
Appendix Table 4: Mean Litter loads (g/m^2 ± SE) from each vegetation type across the three floodplains

VEGETATION COMMUNITY	FLOODPLAIN	MEAN LITTER LOAD (g/m^2)
Black Box (BB)	Hattah	871 ± 126
	Lindsay	467 ± 107
	Mulcra	681 ± 105
Lignum (LG)	Hattah	396 ± 109
	Lindsay	309 ± 60
	Mulcra	478 ± 68
Other (OT)	Hattah	472 ± 81
	Lindsay	200 ± 26
	Mulcra	174 ± 24
Red Gum (RG)	Hattah	2007 ± 368
	Lindsay	1360 ± 154
	Mulcra	1184 ± 134

Appendix Table 5: Rate Constants (k) and maximum leachable carbon (DOC_{inf}; mg-C/g-substrate) for each litter type present in Hattah Floodplain. RG = Red gum, BB = Black box, LG = Lignum and OT = Others

VEGETATION COMMUNITY	FRACTION	FIRST-ORDER PARAMETER	Estimate	Lower CI	Upper CI
BB	Bark	DOC_{inf} (mgC/g)	8.92	8.08	9.84
		k	0.61	0.42	0.90
	Leaves	DOC_{inf} (mgC/g)	38.12	31.44	45.68
		k (d^{-1})	0.91	0.41	2.92
	Other	DOC_{inf} (mgC/g)	14.25	13.47	15.05
		k (d^{-1})	0.91	0.71	1.19
	Sticks	DOC_{inf} (mgC/g)	9.47	8.10	11.20
		k (d^{-1})	0.54	0.29	1.02
LG	Bark	DOC_{inf} (mgC/g)	11.80	10.71	12.97
		k (d^{-1})	0.68	0.46	1.01
	Leaves	DOC_{inf} (mgC/g)	49.63	44.71	54.85
		k (d^{-1})	0.84	0.55	1.37
	Other	DOC_{inf} (mgC/g)	10.94	8.97	13.26
		k (d^{-1})	0.75	0.34	2.14
	Scats	DOC_{inf} (mgC/g)	12.57	11.49	13.76
		k (d^{-1})	0.60	0.42	0.87
	Sticks	DOC_{inf} (mgC/g)	8.39	7.64	9.17
		k (d^{-1})	0.82	0.56	1.25
OT	Other	DOC_{inf} (mgC/g)	36.03	32.41	39.81
		k (d^{-1})	1.18	0.74	2.35

	Plants	DOC$_{inf}$ (mgC/g)	56.61	52.2 6	61.09
		k (d^{-1})	1.28	0.90	2.02
	Sticks	DOC$_{inf}$ (mgC/g)	12.21	10.4 3	14.29
		k (d^{-1})	0.62	0.34	1.21
RG	Bark	DOC$_{inf}$ (mgC/g)	12.31	11.3 0	13.38
		k (d^{-1})	0.79	0.55	1.16
	Leaves	DOC$_{inf}$ (mgC/g)	44.53	39.6 3	49.83
		k (d^{-1})	0.78	0.49	1.31
	Other	DOC$_{inf}$ (mgC/g)	15.78	13.1 2	18.64
		k (d^{-1})	1.06	0.51	*NA*
	Scats	DOC$_{inf}$ (mgC/g)	15.06	13.8 1	16.40
		k (d^{-1})	0.74	0.52	1.09
	Sticks	DOC$_{inf}$ (mgC/g)	9.30	8.06	10.77
		k (d^{-1})	0.48	0.29	0.83

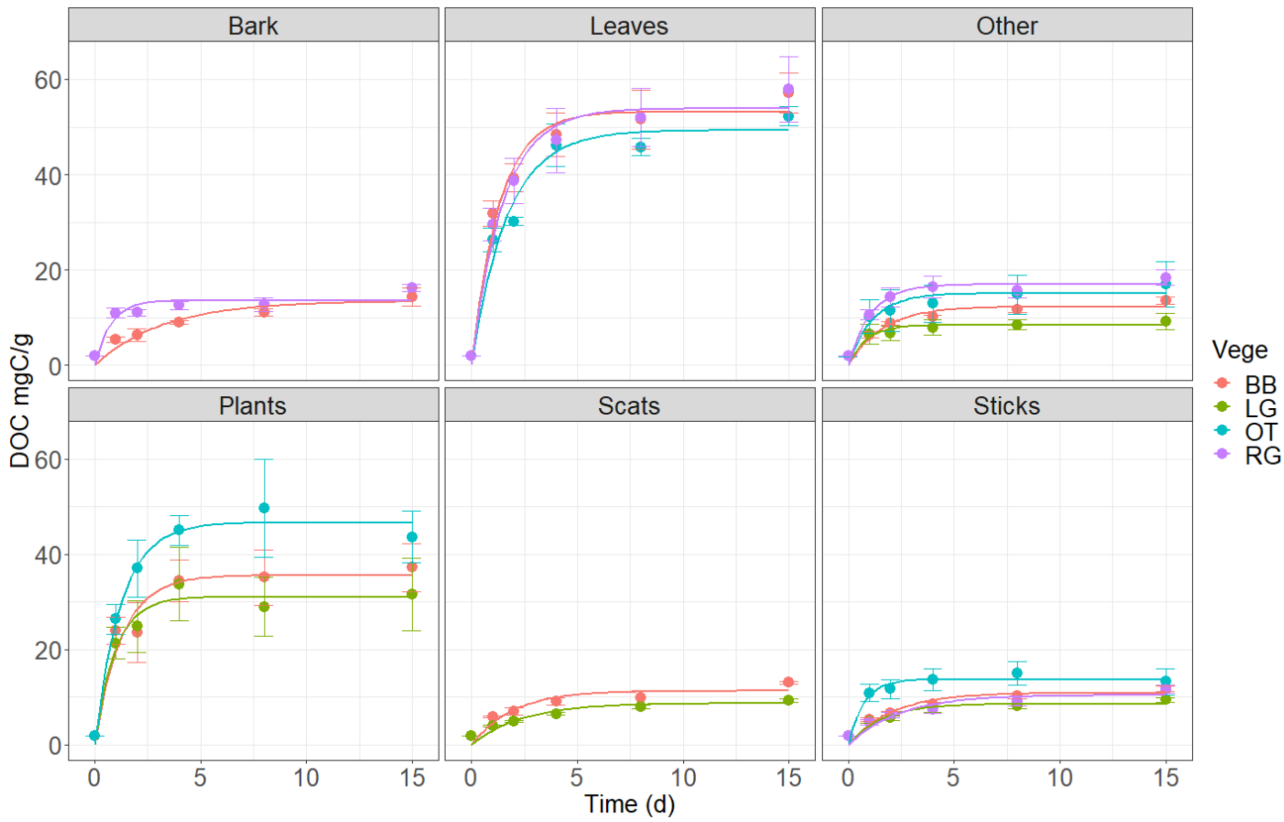


Appendix Figure 1: DOC leaching behaviour for six litter materials (leaves, bark, sticks, plants, scats and other) for the four (4) vegetation types (Red Gum (RG), Black Box (BB), Lignum (LG), Other (OT)) for litter collected from Hattah floodplain. Experimental data have been modelled according to a first-order process (solid line ± SE). Missing leaching plots correspond to vegetation types where the litter material was either absent or present in insufficient replicates.

Appendix Table 6: Rate Constants (k) and maximum leachable carbon (DOC_{inf}; mg-C/g-substrate) for each litter fraction present in Lindsay/Mulcra Floodplain. RG = Red gum, BB = Black box, LG = Lignum and OT = Others

VEGETATION COMMUNITY	FRACTION	FIRST-ORDER PARAMETER	Estimate	Lower CI	Upper CI
BB	Bark	DOC_{inf} (mgC/g)	13.43	11.31	15.55
		k	0.31	0.17	0.45
	Leaves	DOC_{inf} (mgC/g)	53.21	48.20	58.21
		k (d^{-1})	0.77	0.49	1.05
	Other	DOC_{inf} (mgC/g)	12.30	11.33	13.27
		k (d^{-1})	0.62	0.45	0.79
	Plants	DOC_{inf} (mgC/g)	35.59	29.82	41.36
		k (d^{-1})	0.81	0.29	1.32
	Scats	DOC_{inf} (mgC/g)	11.34	9.70	12.98
		k (d^{-1})	0.52	0.27	0.78
	Sticks	DOC_{inf} (mgC/g)	10.92	10.06	11.79
		k (d^{-1})	0.49	0.36	0.62
LG	Other	DOC_{inf} (mgC/g)	8.42	6.70	10.15
		k (d^{-1})	1.19	0.00	2.38
	Plants	DOC_{inf} (mgC/g)	31.09	24.48	37.70
		k (d^{-1})	1.05	0.04	2.06
	Scats	DOC_{inf} (mgC/g)	8.73	7.65	9.81
		k (d^{-1})	0.43	0.26	0.59
	Sticks	DOC_{inf} (mgC/g)	8.62	7.85	9.39
		k (d^{-1})	0.62	0.43	0.82

OT	Leaves	DOC_{inf} (mgC/g)	49.31	45.66	52.96
		k (d^{-1})	0.60	0.44	0.75
	Other	DOC_{inf} (mgC/g)	15.06	10.59	19.53
		k (d^{-1})	0.89	-0.20	1.98
	Sticks	DOC_{inf} (mgC/g)	13.78	11.45	16.11
		k (d^{-1})	1.38	0.12	2.64
	Plants	DOC_{inf} (mgC/g)	46.69	39.92	53.46
		k (d^{-1})	0.82	0.35	1.29
RG	Bark	DOC_{inf} (mgC/g)	13.59	12.39	14.78
		k (d^{-1})	1.34	0.72	1.96
	Leaves	DOC_{inf} (mgC/g)	53.87	47.05	60.69
		k (d^{-1})	0.68	0.36	0.99
	Other	DOC_{inf} (mgC/g)	16.96	15.02	18.90
		k (d^{-1})	0.95	0.49	1.41
	Sticks	DOC_{inf} (mgC/g)	10.45	9.25	11.66
		k (d^{-1})	0.42	0.27	0.57

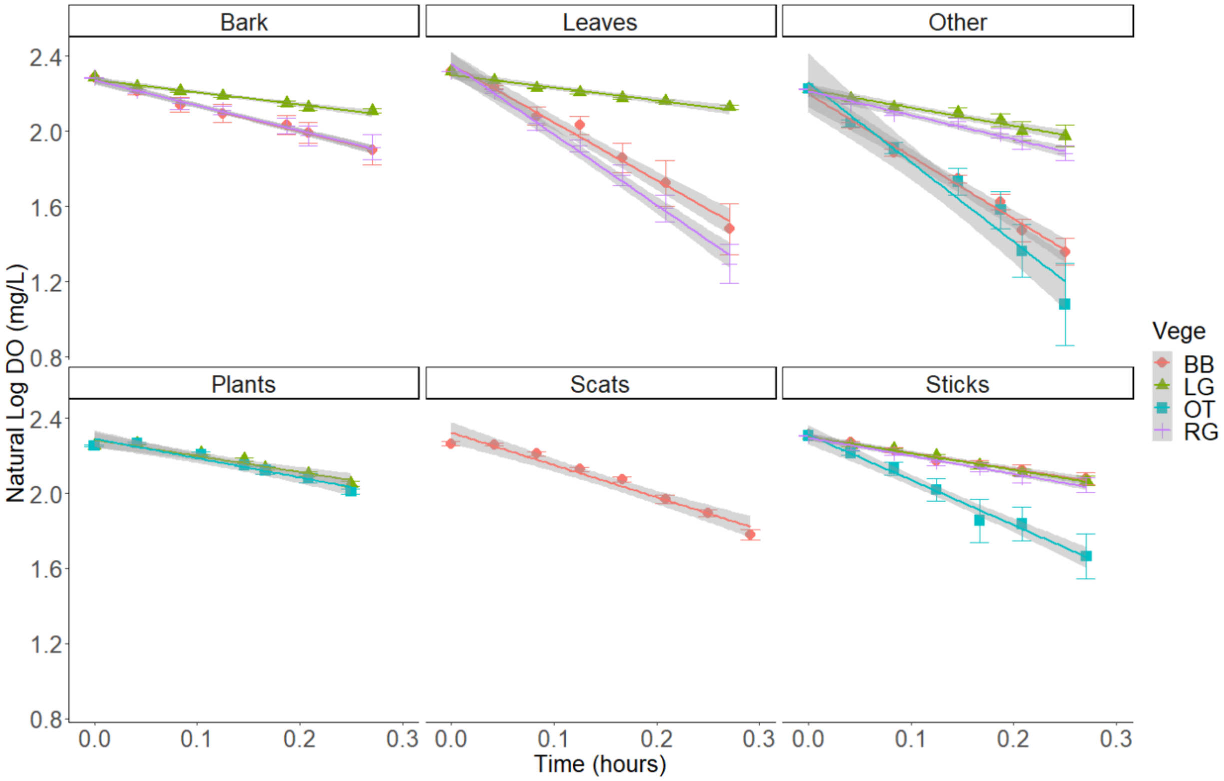


Appendix Figure 2: DOC leaching behaviour for six litter materials (leaves, bark, sticks, plants, scats and other) for the four (4) vegetation types (Red Gum (RG), Black Box (BB), Lignum (LG), Other (OT)). Experimental data have been modelled according to a first-order process (solid line ± SE). Missing leaching plots correspond to vegetation types where the litter material was either absent or present in insufficient replicates.

Appendix Table 7: Dissolved oxygen consumption rate constants (k) for each litter fraction per g material. RG = Red gum, BB = Black box, LG = Lignum and OT = Others

Fraction	Vege Community	Rate constant DO consumption (mg O_2/g sample/d)	Lower CI	Upper CI
Bark	BB	0.13	0.10	0.17
	LG	0.06	0.06	0.07
	RG	0.13	0.11	0.17
Leaves	BB	0.30	0.24	0.37
	LG	0.07	0.06	0.08
	RG	0.38	0.33	0.42
Other	BB	0.33	0.30	0.37
	LG	0.10	0.07	0.13
	OT	0.42	0.33	0.52
	RG	0.13	0.11	0.15
Plants	LG	0.09	0.08	0.10
	OT	0.10	0.09	0.12
Scats	BB	0.17	0.16	0.19
Sticks	BB	0.09	0.07	0.10

	LG	0.09	0.08	0.10
	OT	0.24	0.18	0.30
	RG	0.10	0.08	0.12



Appendix Figure 3: Dissolved oxygen concentrations over time in different litter fractions. Dissolved oxygen consumption rates were calculated using linear regressions and are provided in Appendix Table 7.

Appendix Part Two

SECTION 1: MODELLING APPROACH

In 2019, during the Lindsay and Mulcra Islands model conversion project, the hydrodynamic models for the two sites were successfully converted to the latest software version of MIKE FLOOD and the 2D domains were developed under flexible mesh technology. Furthermore, the simulations were run using GPU technology for faster run-times.

Blackwater modelling requires the use of water quality modules in addition to the existing HD (hydrodynamic) module used for the calibrated floodplain models. The water quality modules (WQ) are not compatible with GPU calculations and therefore run with CPU. This means that while the HD component can be calculated rather fast, with 3-month scenarios running in 1 to 3 days (indicative duration, run time depends on type and number of GPU cards used for the calculations), the WQ component will take much longer.

Additionally, during the project the tests undertaken brought to light problems with the software in relation to the linking of the 1D (waterways) and 2D (floodplain) components of the model. These issues can only be resolved by the software developers and the timeframe require for that does not match the project timeline.

For these reasons and in order to develop a practical tool for blackwater modelling, it was decided to reduce the complexity of the models as much as possible and update the Lindsay and Mulcra Island models to full 2D setups. Hence, in the revised model setups all elements in the floodplain (waterways and hydraulic structures) have been represented in the 2D component and all 1D elements and 1D/2D links have been removed.

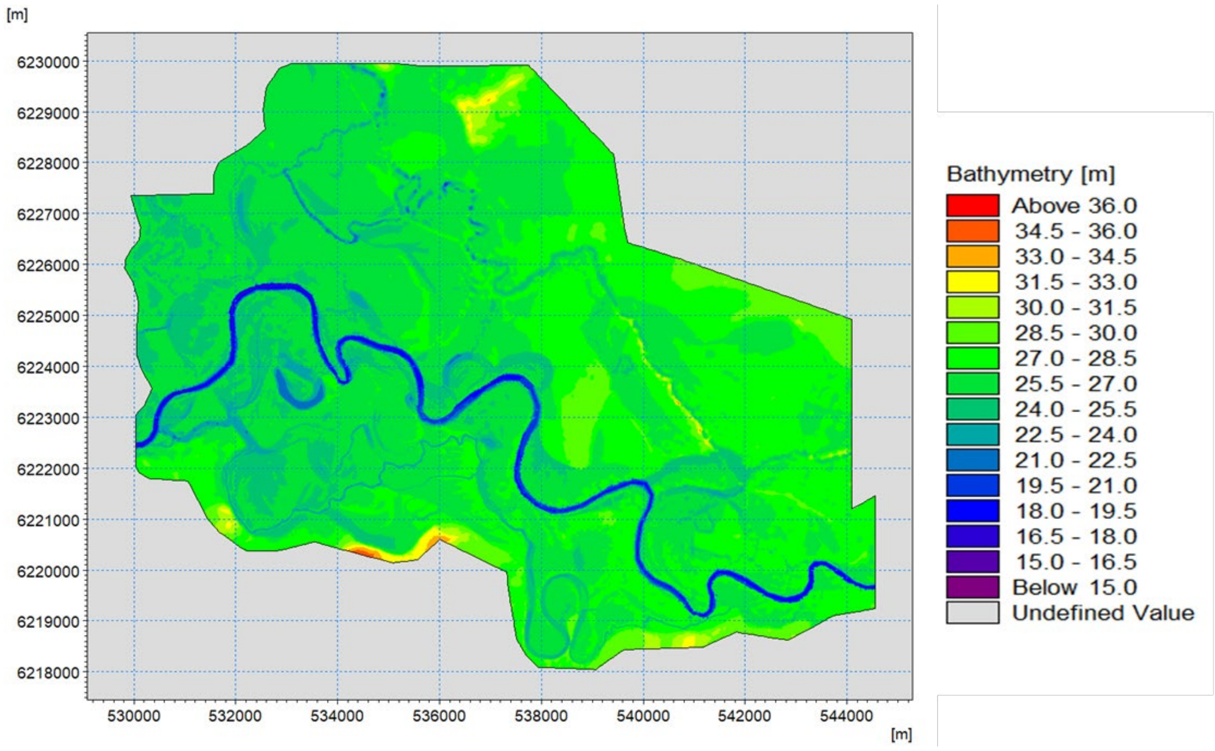
As indicated by CMA Mallee on 28th February 2020, the models have been developed considering only the current infrastructure. They do not include the proposed SDL structures that were included to assess environmental watering events in 2019.

SECTION 2: MESH DEVELOPMENT

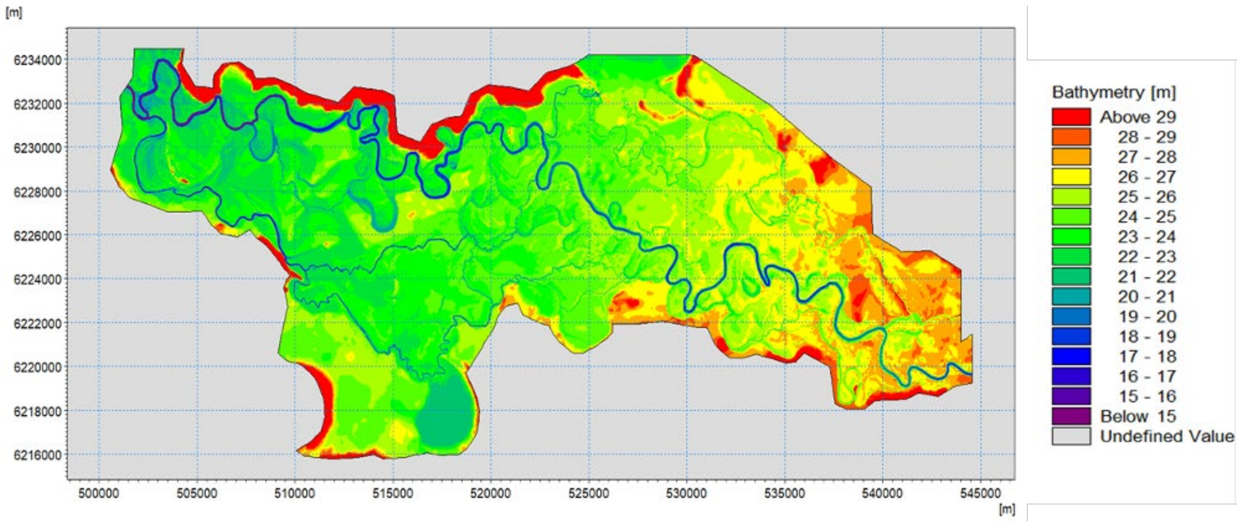
The MIKE mesh generator software was used to develop the structure of the meshes. Starting with the model domains developed previously, all the hydraulic and topographical features were maintained, and the resolution simply reduced for more efficient modelling. As mentioned above, the Murray River and waterways within the floodplains have been converted from a 1D representation to _a 2D representation. Where these areas (in between channel banks) were previously excluded from the flexible mesh domain, they have been included with a high enough resolution to appropriately represent the conveyance of the channels.

Appendix Figure 4 and Appendix Figure 5 below, present the revised flexible mesh for the Lindsay-Mulcra and Mulcra domains. The mesh for each model, which forms the basis of the topographic representation, has been constructed in a way such that there is higher resolution in frequently inundated areas within the floodplains to better represent the floodway connectivity

The bathymetry for the Murray River and other waterways was extracted from the available cross sections. The cross sections were used to create DEMs within the channel banks that were in turn used for the interpolation of elevation data on the flexible mesh. The bathymetry superseded the LiDAR data along the channels for a better representation of channel capacity throughout the floodplain.



Appendix Figure 4: Flexible mesh used in the modelling approach for the Mulcra approach



Appendix Figure 5: Flexible mesh used in the modelling approach for the Lindsay-Mulcra approach

SECTION 3: MODEL BOUNDARIES

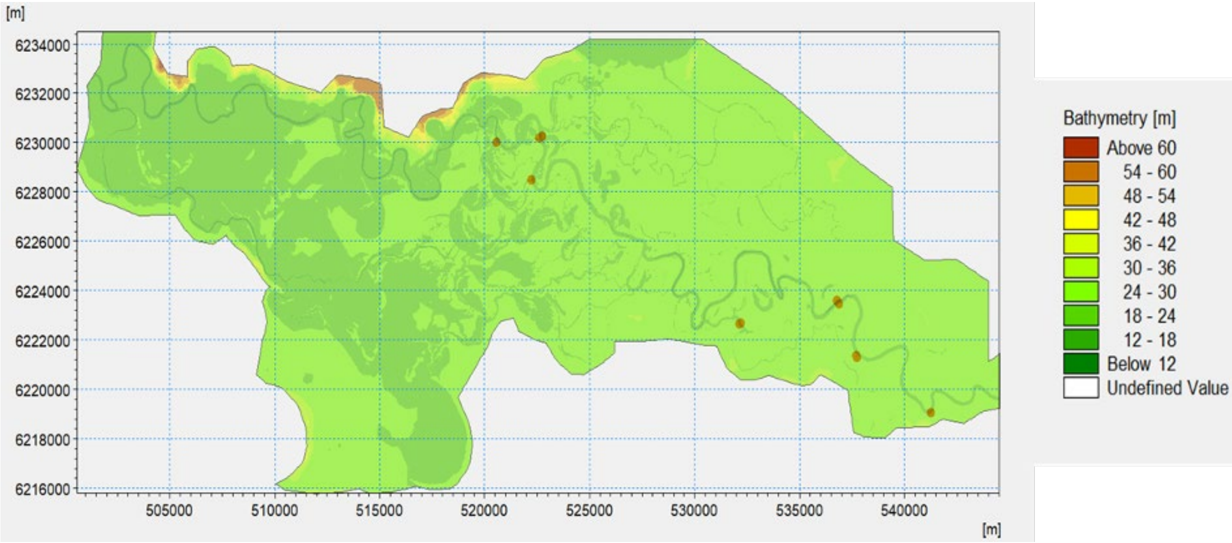
The inflow to the Lindsay-Mulcra and Mulcra models is located on the Murray River upstream of the Potterwalkagee Creek offtake. The downstream boundary of the Lindsay-Mulcra model is located on the Murray River downstream of the confluence with the Lindsay River. The boundary is a free outflow to allow water to leave the model boundary. In the Mulcra model, the downstream boundary is a water level timeseries extracted from the Lindsay model, located on the Murray River downstream of the confluence with the Potterwalkagee Creek. Additional outflow boundaries (QH relations) were added on the northern part of the floodplain in order to allow flows to leave the model area to the northern floodplain.

SECTION 4: ROUGHNESS

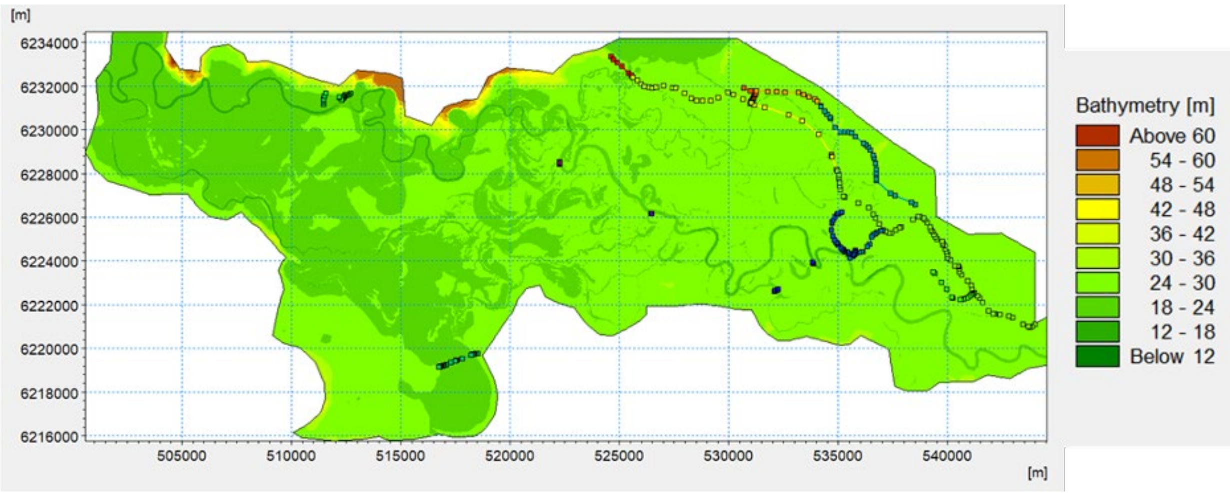
A constant roughness value was applied to the model domains. The roughness coefficient applied to the calibrated models developed in 2019 was retained, with a manning's value of n=0.04

SECTION 5: HYDRAULIC STRUCTURES

While a number of elements have been simplified, structures such as Locks on the Murray River, weirs at offtakes and dike lines representing linear topographical features have been maintained in the 2D models. Locks 8 and 7 on the Murray River are represented via weir structures in the 2D model, hence with a fixed crest level set to 20 and 18 mAHD respectively. Certain structures at offtakes have represented via a combination of dike lines and weir structures. Namely the regulator on the lower Potterwalkagee Creek and the regulator on Mullaroo Creek. The locations of structures in the Lindsay and Mulcra model domains are presented in Appendix Figures 6 and 7. A regulated scenario in the Mulcra model has been set-up to analyse the impact of watering scenarios on DO levels in the floodplain. In order to reproduce the opening and closing of the gate on the lower Potterwalkagee Creek regulator, a dike line with a crest level that varies in time was used.



Appendix Figure 6: Location of weirs in the models (structures in the Mulcra are the same as those in the Lindsay model



Appendix Figure 7: Location of dike lines in the Lindsay model (structures in the Mulcra are the same as those in the Lindsay model

SECTION 6: WATER QUALITY MODULE

The MIKE ECO Lab template “MalleeBW” has been developed following the schematization of the processes in the Blackwater Risk Assessment Tool (BRAT) developed by La Trobe University (Whitworth and Baldwin, 2016). The template includes the following “substances of interest”, state variables:

- DO – Dissolved Oxygen (mg/l)
- DOC – Dissolved Organic Carbon (mg/l)
- LL - Leachable Leaves (g/m2)

- LB - Leachable Barks (g/m2)
- LT - Leachable Twigs (g/m2)
- LG - Leachable Grass (g/m2)

The water quality module uses this template to simulate the state variables, and their interdependencies, through a set of coupled ordinary differential equations indicating the rate of change of the state variables due to the different processes.

This application differs from the existing BRAT spreadsheet model in the following:

- The process rates at timestep t are computed as a function of the values of the state variables at timestep t-1 only (fully explicit scheme).
- The calculation is made at the cell level (2D model) instead of the domain level. Cells have fixed areas, what changes is their water depth.
- The hydrodynamic transport process is simulated using the results of the MIKE21 model.
- Vegetation litter loads are given as input data. There are not options for calculation in the template.

The values of the model parameters are defined by the user. Table 1 presents the values in the original BRAT model (Set 1) and the updated values for some of the parameters derived by La Trobe University in the field and laboratory tests conducted in 2020 as part of this project (Set 2).

The template was originally developed considering four vegetation litter compartments: leaves, barks, twigs and grass. It is possible to add, rename or delete compartments, as necessary. It is also possible to use some of the built-in functions in MIKE ECO Lab for some of the processes (e.g. sediment oxygen demand). When modifying the template, attention must be given to the parameters and processes added, modified or deleted, as well as the interdependencies between state variables.

SECTION 7: VEGETATION LITTER LOADS

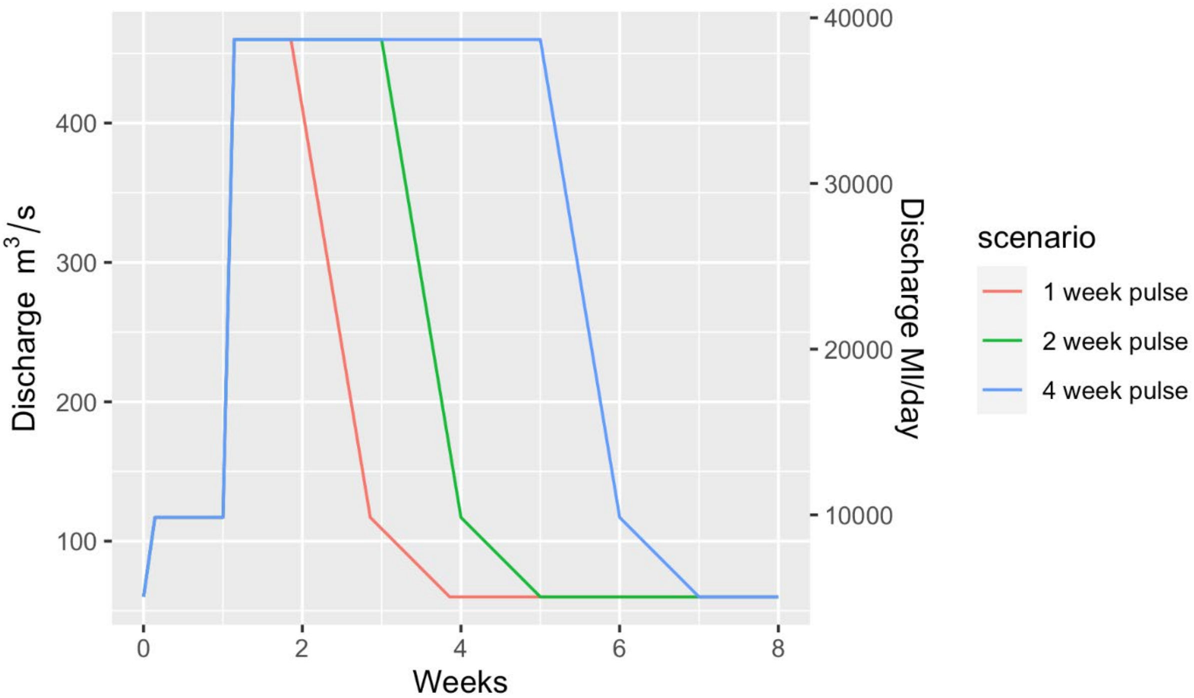
The spatial distribution of the four vegetation types considered in the model was provided by La Trobe University and is shown in Figure 6. The values were interpolated to match the mesh of the hydrodynamic model (Appendix Figures 4 and 5). Given that the floodplains in the right margin of the Murray River are not part of this study, the litter loads in that section were not considered.

SECTION 8: SCENARIO ANALYSIS

The six scenarios described in Table 2 were simulated to assess the sensitivity of the modelling results to the following parameters:

- Flow conditions:

  This parameter was regulated through the boundary inflow at Murray River RV60510. Events producing significant flooding in Lindsay and Mulcra were required. According to the records, this magnitude of events last for several months, which would require extremely long times to simulate; thus, it was not possible to use them for the sensitivity analysis. A synthetic hydrograph was used instead (Appendix Figure 8). It starts with a steady flow of 117 m3/s (10,108.8 ML/day) to bring the system to bank full conditions, then a rapid flow increase to 460 m3/s (39,744 ML/day) for a given duration, followed by a slow recession curve back to 117 m3/s and finally to 60 m3/s where it remains. Simulations were conducted for 1-, 2- and 4-weeks duration of this flow pulse.



Appendix Figure 8: Inflow hydrographs at Murray River RV60510 used for the simulations.

The possible effect of a flow regulator at the exit of the Mulcra floodplain was also analysed. The 1-week flow pulse event was used to simulate two different settings:

A. Regulator open at the start of the event, closed on 14/05/19 (as flow recession starts) and opened again two weeks after on 29/07/15.

B. Regulator closed at the start of the event and opened on 29/07/15.

- Simulation period:

  The length of the simulation was determined by the corresponding flow pulse. It varies between 5 and 8 weeks. Longer simulations were not possible due to time constraints.

- Parameter sets:

  The sensitivity of the modelling results to vegetation leaching rates was assessed by running simulations with the values from the BRAT model (Set 1) and the values derived by La Trobe University in 2020 (Set 2). The latter were used for the rest of the simulations.

SECTION 9: SIMULATION CONDITIONS

All simulations were conducted using the same initial conditions:

- For the hydrodynamic model, water surface elevation = 20 m and flow velocities =0 m/s.
- For the water quality model, dissolved oxygen concentration DO=10 mg/l (saturation value), dissolved organic carbon DOC=0 mg/l, and Leachable Leaves, Barks, Twigs and Grass according to the spatial distributions presented in Figures 2.5 to 2.8.

The boundary conditions were defined as follows:

- For the hydrodynamic model, the upstream boundary condition was the inflow at Murray River RV60510 according to the scenario (Table 2.2) and corresponding hydrograph (Figure 2.9). The downstream boundary condition for the Lindsay-Mulcra domain was set to free outflow. The downstream boundary condition for the Mulcra domain was the water level on the Murray River downstream of the confluence with the Potterwalkagee Creek extracted from the Lindsay-Mulcra simulation for the same flow conditions.
- For the water quality simulations, the upstream and downstream boundaries were set to DO=10 mg/l and DOC=0 mg/l.

The hydrodynamic simulations started on 01/07/2015 with a steady state period of 1-week to allow the appropriate local flow conditions to develop. This was followed by the corresponding flow pulse and recession period for each scenario. The water quality simulations started on 08/07/2015, at the start of the floodplain inundation, as lasted until the end of the recession period.

Test were conducted running the two modules simultaneously and separately (first the hydrodynamic model, then the water quality module. For the full MIKE21 model, the decoupled option required lower computational time, so it was adopted for the simulations of the sensitivity analysis. This also allowed to "save" time in the simulation of scenarios 1 and 2, that have the same flow conditions, but different water quality parameter sets.

The computation time step used for the hydrodynamic simulations was 4 s. This is also the maximum time step for the water quality simulation; however, the model automatically reduces this value when needed to avoid instabilities. The output time step was set to 12 h.