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Constraining organic matter composition and dynamics as a dominant driver of hypoxic blackwater risk during river Murray floodplain inundation

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Abstract

The ecology of floodplain ecosystems evolved according to the historical frequency and extent of inundation. In many dryland rivers, inundation frequency has reduced due to regulation, competition for water resources and climate change. In some rivers infrastructure has been constructed to enable temporary rises in water level and more frequent floodplain inundation, delivering environmental water to ecosystems that are dependent on surface water. During such events, the release of dissolved organic carbon (DOC) from inundated plant material may result in depletion of dissolved oxygen (DO). If the rate of DO depletion exceeds re-aeration, hypoxic conditions can occur. Models have been developed to represent these processes, however, there is a wide range of chemical and biological interactions, and hence model parameters, involved. The aim of this research was: (1) identify the dominant parameters through sensitivity analysis, (2) design and implement a field monitoring program to quantify the inherent variability in those parameters, and (3) translate that input variability into the modelled DO, ultimately to support risk management decisions when planning delivery of environmental water. The results indicated that the mass of organic matter on a floodplain had the greatest impact on the modelled DO concentrations. Based on the field monitoring results, the steady state load of organic matter, that is, when the accumulation and decay rates are equal, was estimated, and vegetation mapping used to apply the field monitoring results across the floodplain for a 206 km reach of river of the River Murray, Australia. The model results from multiple, cumulative, operations identified one particular high-risk operational site. The results are useful to prioritize monitoring effort to focus on the most sensitive model parameters and indicate that the likelihood of hypoxic conditions can be reduced through slower rates of inundation and timing events to coincide with periods with lower water temperature. The methodology developed can be transferred to other sites where hypoxic conditions are a potential outcome associated with delivery of environmental water.

KEYWORDS
dissolved organic carbon, dissolved oxygen, floodplain inundation, hypoxia, modelling, Murray-Darling basin, river management, River Murray

1 | INTRODUCTION

The frequency and extent of floodplain inundation has specific ecological significance in river systems and is a major factor in shaping and sustaining ecosystems (Leigh et al., 2010). In many dryland rivers, inundation frequency has reduced due to regulation and competition for water resources (Mac Nally et al., 2011; Tooth, 2018), and inundation frequency and duration is expected to continue to decline with climate change (Sandi et al., 2020). One example is the southern Murray-Darling Basin (MDB), Australia, where widespread die-off and decline in floodplain tree condition (Baker et al., 2000; Walker, 2006; Walker & Thoms, 1993) have been attributed to changes in hydrological processes driven by river regulation and diversion for consumptive water use.

In the Murray-Darling river system, as well as others worldwide, there has been increasing focus on using large constructed infrastructure and delivery of environmental water to restore some components of the natural flooding regime (e.g., Wallace & Furst, 2016). This typically involves the use of large, constructed infrastructure on floodplain creeks that can be partially closed to temporarily increase water levels independent from river discharge, and hence restore some components of the natural flooding regime.

During periods of elevated water level, due to high flows and/or infrastructure operation, the inundation of soils and accumulated plant and other organic material in the riparian zone and on the floodplain results in the mobilization of water-soluble dissolved organic carbon (DOC). The episodic return flows from these floodplain inundation events, and associated high loads of readily degradable DOC, are recognized as potentially one of the most important sources of carbon in lowland rivers (Findlay & Sinsabaugh, 1999; Hadwen et al., 2010; Robertson et al., 1999). However, our understanding of the relative role of these terrestrially derived inputs relative to instream (autochthonous) sources of DOC is complicated by the inherent variability within and between rivers; and the construction and operation of storages and weirs that generate barriers to longitudinal transport of resources (Ward & Stanford, 1983).

Whilst the episodic inputs of DOC from the floodplain may temporally increase in-stream metabolism (i.e., productivity), and support trophic cascades (Arthington et al., 2003; Ballinger & Lake, 2006; King et al., 2010), the microbial degradation (heterotrophic metabolism) of this DOC consumes dissolved oxygen (DO). When pelagic and sediment oxygen demanding processes exceed oxygen re-supply via re-aeration, photosynthesis, or supply of oxygen rich water from inflows, DO concentrations are depleted, and hypoxic (<2 mg L^{-1}) and/or anoxic (~ 0 mg L^{-1}) conditions become established. Hypoxia can trigger sub-lethal and lethal impacts to fish and other aquatic biota, and negatively affect other water quality parameters (Davidson et al., 1998; Roman et al., 1993; Sabo et al., 1999). Even short periods of exposure to hypoxia can impact on the survival and condition of aquatic biota. Blackwater events can be described as conditions where the concentration of DOC in surface water is sufficient to discolour the water such that is resembles dark tea. Such events may, or may not, be associated with hypoxic conditions.

Currently, application of the existing modelling tools to realistic floodplain inundation applications is difficult. Analytical approaches are available to model the instream biochemical oxygen demand-DO dynamics (Li et al., 2013). However, approaches to simulate the generation of additional oxygen demanding material from floodplain vegetation are less advanced. The Blackwater Risk Assessment Tool (BRAT, Whitworth & Baldwin, 2016) represents the litter accumulation and decay processes and includes contemporary information on litter dynamics specific to the River Murray, Australia. A limitation of that tool is that it is difficult to apply to situations that involve (i) water continuously flowing through the inundation zone, (ii) complex hydrological interactions between floodplains and rivers, and (iii) multiple sites.

A recent development included the BRAT litter dynamics as a constituent model coupled to a hydrological model, the DODOC model for eWater Source (Mosley et al., 2021). This inclusion of the DO and DOC model in the Source hydrological model allows litter accumulation over longer periods, different scales of regulator operations at a floodplain site, as well as cumulative impacts along the river, to be assessed. The DODOC model was developed to enable complex hydrological situations to be represented, however the model has 19 parameter values that must be specified for each model node, which can be difficult to specify for the general user and generate results that managers have sufficient confidence in to inform operational decisions.

This work has been undertaken to help inform the application of blackwater risk assessment tools, focused on the DODOC Model, but also relevant for the BRAT model, through (i) sensitivity analysis to identify the dominant parameters for a managed floodplain inundation application (ii) a monitoring program to collect site-specific information to inform sensitive model parameter values, and (iii) application of monitoring data in the DODOC model to quantify input parameter uncertainty on the risk of generating hypoxic or anoxic conditions.

2 | METHODS

2.1 | Study location

The study was conducted in the Lower River Murray, South Australia, within a reach of the river in which stabilization of water levels via a series of 11 low-level (c. 3 m head) weirs has produced a shift from highly variable riverine conditions to conditions representative of a string of lakes and disconnected natural relationships between discharge, depth and velocity (Bice et al., 2017; Kilsby & Walker, 2012; Walker, 2006). The model boundaries represent 206 km of river from the Victoria - South Australian border to Lock and Weir Number 3 (henceforth referred to as 'Lock 3'). This section of river includes a number of operational structures including Locks 3, 4, 5 and 6, as well as environmental regulators on the Chowilla, Katarapko, and Pike anabranches that can be used to manipulate water levels and deliver environmental water to sections of the respective floodplains (Figure 1).

Field monitoring was undertaken at the Chowilla-Calperum floodplain complex (adjacent Lock 6) and the Eckerts-Katarapko Floodplain complex (adjacent Lock 4) (Figure 1). The Chowilla floodplain (17 700 ha) is managed as an Icon Site under the Murray-Darling Basin Authority's (MDBA) The Living Murray Program and as a game reserve by the South Australian Government Department for Environment and Water. The Calperum Floodplain (12 130 ha) is managed by the Australian Landscape Trust. Both floodplain areas form part of the 30 600 ha Riverland Ramsar Site (DEH 2010). Katarapko floodplain is located on 38 km of waterways along the Katarapko/Eckert Creeks anabranch system and the floodplain covers 9000 ha. Katarapko floodplain is part of the South Australia Riverland Floodplains Integrated Infrastructure Program to improve the environmental health and resilience of wetlands and floodplains in the region.

The two dominant floodplain eucalypt tree species in the lower Murray River; river red gum (*Eucalyptus camaldulensis Dehnh.*) and black box (*E. largiflorens F.Muell*) generate a large standing biomass of litter material (e.g., leaves, bark, twigs), that represents a large source of allochthonous organic matter to floodplains and wetlands (Francis & Sheldon, 2002; Glazebrook & Robertson, 1999). The inundation of woodland and/or forested areas on floodplains results in the rapid release (within hours) of dissolved organic compounds from plant material (leaf, bark, twig, understory vegetation) (Baldwin, 1999; O'Connell et al., 2000), and soils (Banach et al., 2009; Kobayashi et al., 2008; Scholz et al., 2002; Wilson et al., 2011). The amount of carbon leached into the water column during any given inundation (an unregulated flood or a managed inundation) will depend on a number of factors including; (i) the type of leaf litter/vegetation inundated (ii) the age of the leaf litter, (iii) the amount of litter that has

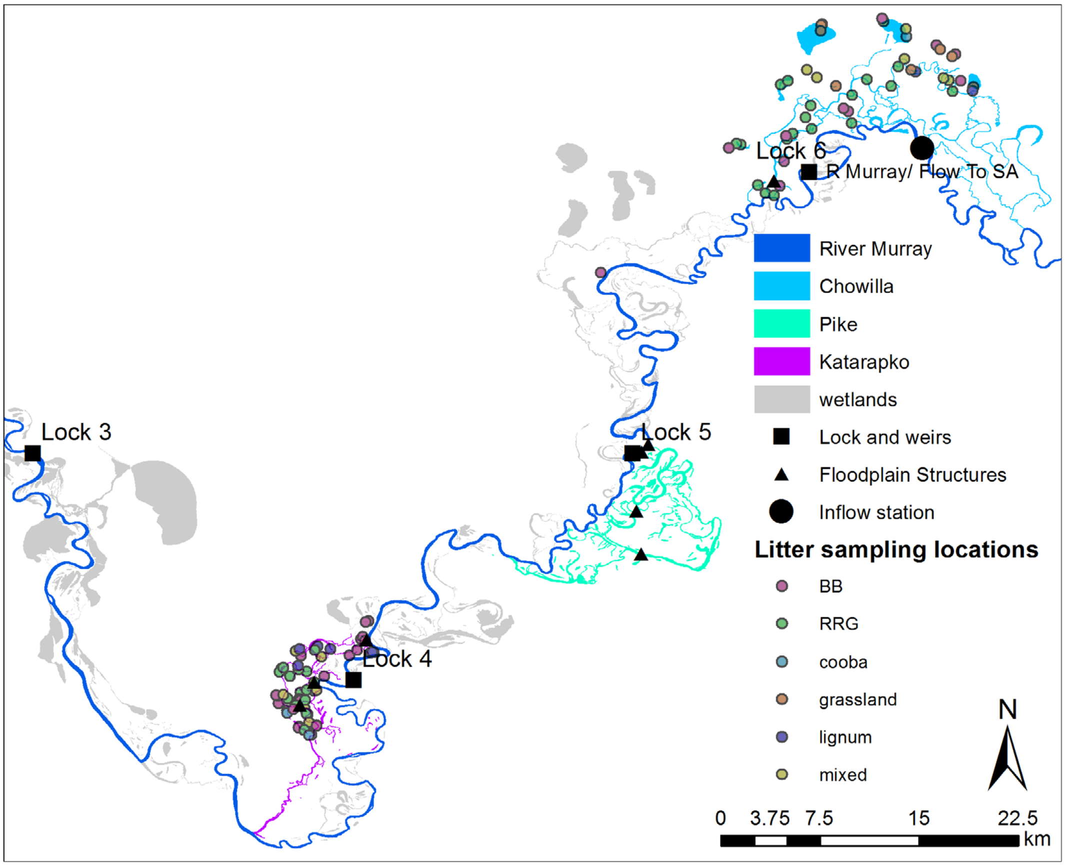

FIGURE 1 Map of the study location, including the three anabranches with infrastructure that can be used to create inundation events (Chowilla, pike and Katarapko, with triangles for infrastrucutre locations), the main river Murray (blue), and other permanent wetlands in region (grey). Coloured circles indicate the plant litter sampling locations for different vegetation types

TABLE 1 Bounds of uniform distributions used to testing sensitivity of DODOC parameters

Parameter	Min.	Max.	Basis for range
DOC Decomposition rate (d^{-1})	0.02	0.3	0.03 d^{-1} (Whitworth et al., 2012; Whitworth et al., 2014) 0.3 d^{-1} for red gum leaves (Wallace et al., 2008)
DOC Release Rate – readily degradable (d^{-1})	0.5	0.99	0.86 d^{-1} for leaves (Howitt et al., 2007)
DOC Release Rate – non-readily degradable (d^{-1})	0.05	0.3	0.078 d^{-1} for twigs (O'Connell et al., 2000) 0.173 d^{-1} for bark (Howitt et al., 2007)
Maximum DOC Release rate – readily degradable (mg g^{-1})	45	125	River red gum leaf litter: 70–100 mg g^{-1} (Whitworth et al., 2014) 45–125 mg g^{-1} (Whitworth & Baldwin, 2016)
Maximum DOC Release rate – non-readily degradable (mg g^{-1})	4.5	12.5	10 mg g^{-1} for twigs and bark (Howitt et al., 2007; Whitworth & Baldwin, 2016)
Reaeration rate (d^{-1})	0.01	0.08	Empirical equations based on water depth and wind speed or water velocity (Chapra, 1997)
Water temperature (°C)	10	25	Temperature data from the study region
Initial load of readily degradable plant litter (g m^{-2})	0	1000	Based on field monitoring in the present study (see below)
Initial load of non-readily degradable organic matter (g m^{-2})	0	3000	Based on field monitoring in the present study (see below)

Note: Values for rates are at 20°C where appropriate.

accumulated, and (iv) whether or not the litter has been flooded before (O'Connell et al., 2000).

2.2 | DODOC model sensitivity analysis

The model used was the DODOC model calibrated to historical DO and DOC data by Mosley et al. (2021), based on a an eWater Source (Welsh et al., 2013) hydrological model developed previously (Department for Environment and Water, 2020). The hydrological model is a node-link routing model that accounts for travel time, losses, and diversions along the river, and includes nodes to represent operational structures and their influence on storage, surface area, and discharge rates. eWater Source uses a particle tracking method to transport constituents along the system, and allows for conservative and simple (e.g., first order decay) water quality models. eWater Source has a 'plugin' model functionality, which allows model extensions to be developed and used with the core software. Mosley et al. (2021) developed the DODOC model to model DO and DOC constituents, including organic litter build up and degradation at each model node and link, DOC leached from this litter when inundated, DO consumption arising from microbial decomposition of the DOC, and reaeration processes.

A Sobol' sensitivity analysis (Sobol', 2001) using the method of Touati (2016) has been undertaken to determine which factors are most influential on the outputs from the DODOC model. The Sensitivity package v 1.16.1 in R 3.5.0 was used. The Sobol' sensitivity analysis method uses a decomposition of variance approach, similar to the Analysis of Variance (ANOVA), to estimate the influence of each input variables, or groups of variables, on the model output (Sobol', 2001).

A uniform distribution was used for each of the DODOC model parameters, with the minimum and maximum values for each parameter shown in Table 1. 2000 samples from the uniform distribution were used for the sensitivity analysis. For the sensitivity analysis, the initial load of organic matter was used as the input, with the accumulation of organic matter over time not explicitly modelled, as the litter accumulation is dependent on the inundation regime experienced. This means that the initial litter loads for the readily and non-readily degradable material used are representative of a combination of model parameters that are used to dynamically model the litter loads: (i) initial litter load, (ii) accumulation rate, (iii) fraction of the accumulated litter that is readily degradable, and (iv) the decay rate of dry matter (Mosley et al., 2021). The accumulation and decay rates were set to zero for the sensitivity analysis, given their influence is captured through the two initial litter loads (readily and non-readily degradable material) on the floodplain at the start of the inundation event (see Mosley et al., 2021). The three parameters associated with reaeration over structures or from primary productivity have not been included, and site-specific parameters for the maximum accumulation area and floodplain elevation are known for a given location. Therefore, of the original 19 parameters required by the DODOC model, nine have been considered in this sensitivity analysis (Table 1).

The modelling scenario considered was an operation of the Pike floodplain regulator, with water levels raised from normal operating conditions (14.55 m Australian Height Datum, AHD) to the maximum operating height of the structures (16.4 m AHD). The model predicts that this scenario inundates an additional 1690 ha of floodplain above that which is inundated under normal operating conditions, and was selected as a scenario within which existing conceptual understanding predicted that DO concentrations below saturation are likely to be created. The model configuration was to use the Pike floodplain regulator (and ancillary structures) to raise water level from 14.55 to 16.40 m AHD at a rate of rise of 0.05 m d^{-1}, and hold that water level for 40 days, before returning to the normal operating water level at the same rate of water level change. The sensitivity of the average DO downstream of the regulator to the parameter values of the DODOC model was then evaluated.

2.3 | Field monitoring

Given the factors outlined above that could influence the amount of DOC leached, the field monitoring focused on two methods (i) the use of litter fall traps to assess the rate of leaf litter accumulation, and (ii) field surveys of standing load of natural organic matter (NOM).

2.3.1 | Litter fall rates for river red gum and black box

Estimates of litter fall rates were made by deploying leaf litter traps within woodland habitats that were not inundated for the duration of the experiment. The traps were steel mesh boxes (560 × 450 mm 0.25 m^2) with an open top, that were lined with hessian to retain organic material, but allow free draining of rainfall (Figure 2). A wooden ramp was installed in each trap to provide an exit for any biota that entered the trap. Traps were deployed at 20 sites across Chowilla ($n = 16$) and Calperum ($n = 4$) floodplains, comprised of 10 black box and 10 river red gum sites. At each site, a single trap was deployed under each of three trees, with each trap placed within the drip zone (under the branching structure) of the respective tree. All selected sites were on existing transects where data on tree crown condition (extent and density) is routinely collected using the standardized "The Living Murray" method (Souter et al., 2010). Traps were installed in November 2017 and emptied on 4 occasions: March 2018 (125 days), July 2018 (113 days), August 2018 (51 days) November 2018 (63 days). The period between sampling traps was shortened as weathering processes degraded the hessian (data from some traps for some sampling periods needed to be discarded as the hessian broke down between sampling trips).

Pairing the traps with trees with known crown condition offered a mechanism to assess if there is a relationship between crown condition and litter fall rate. Tree condition was assessed using the method detailed by Wallace et al. (2020) in which field scores for crown extent and density are multiplied together to provide a modified Tree Condition Index (mTCI) score from 0 to 1.

For sampling trips 1 and 2, bulk litter fall was measured in the field by transferring the contents of the trap to a 5 L PPE container and weighing it on site to the nearest gram. For trips 3 and 4, the collected material was transported to the laboratory, air-dried at 20–22 °C, and weighed in four fractions (i) leaves that were essentially intact, (ii) bark, (iii) twigs (≤2 cm in diameter) and (iv) coarse particulate organic matter (CPOM). CPOM included small material (passing through a 1 cm sieve) such as reproductive structures (fruits and buds), leaf fragments and bark fragments. This approach ensures the categories utilized are consistent with regionally relevant contemporary studies on blackwater (e.g., Hladyz et al., 2011) where branch/twig material greater than 2 cm in diameter was discarded. In all cases, litter fall was recorded as grams per m^2 per day.

2.3.2 | Standing load of organic material

The standing load of natural organic matter (NOM) loading was assessed at 111 sites distributed across Calperum ($n = 3$ sites, 30 July 2018), Chowilla ($n = 48$ sites, 31 July–1 August 2018) and Katarapko ($n = 60$ sites, 13–16 August 2018) (Figure 1). The meso-habitats sampled included temporary and permanent creeks, temporary wetlands, and shedding floodplain, with samples collected from black box woodland (248 samples), cooba woodland (40 samples), river red gum woodland (311 samples), mixed tree species woodland (119 samples), grassland (88 samples) and lignum shrubland (72 samples).

At each site, eight replicate samples were collected (total n recorded $= 879$) via an adaptation of the method previously utilized at Chowilla Floodplain (Brookes et al., 2007; Hackbusch, 2011; Wallace, 2008; Wallace et al., 2015; Wallace & Lenon, 2010) and Pike Floodplain (Wallace, 2009). At each site, sampling locations were pseudo-randomly selected on site via a "blind-throw" in which a marker was thrown backwards over the shoulder. Samples were collected from the location at which the marker landed. The position of each subsequent sample was selected in this manner from the location of the preceding sample. At each location, a 12 L bucket was inverted over the marker, organic material outside the bucket was cleared away, and the bucket re-inverted. From within the area that had been covered by the inverted bucket (0.0573 m^2), all recognizable organic material from trees (leaf litter, twigs and bark), understory vegetation and animal scats (i.e., the organic surface layer) down to the A horizon (surface soil) was collected. Samples were transported to the laboratory, air-dried, and weighed in six fractions (leaves, bark,

FIGURE 2 Litter trap used to estimate litter fall rates. The traps were steel mesh boxes (560 × 450 mm = 0.25 m^2) with an open top, that were lined with hessian to retain organic material

twigs, CPOM, scat and understory vegetation). Standing load is reported as grams per m^2.

2.4 | DODOC model uncertainty analysis

The results from the field monitoring were used to inform random variables for the DODOC model. This allows the variability in the monitoring data to propagate through the model and quantify the uncertainty in the modelled DO due to the inherent variability in loads of organic matter on the floodplains of the study location.

2.4.1 | Fraction of readily degradable organic matter

The litter trap data was used to determine the fraction of all organic matter that is readily degradable (labile), which will release DOC at relatively fast rate. The litter trap data was selected as this data may be more representative of the litter available across the floodplain compared to the standing load data, which may be redistributed across the floodplain over time due to wind (for example) and hence not sampled in the standing load data. The readily degradable component of the litter has been assumed to be the leaf fraction of the samples, as twigs, bark and CPOM are expected to release DOC at a slower rate compared to leaves (Whitworth & Baldwin, 2016). A Box-Cox distribution was fit to the proportion of the organic matter that was leaves, irrespective of the vegetation type.

2.4.2 | Decay rate of dry litter

The DODOC model assumes an exponential decay in the mass of dry litter on the floodplain, and this can be a different rate for the readily and non-readily degradable components. To determine the decay rate of readily degradable material, the accumulation rates and standing loads of leaves were compared to determine how much of the litter that fell could be expected to have decayed. To overcome issues of variability between different sampling locations and redistribution and removal through mechanisms other than decay, all sampling data has been pooled to calculate an indicative decay rate. For each day, the litter will change by:

$$L_{d+1} = L_d e^{-k} + A \tag{1}$$

where a proportion of the litter on the floodplain, L_d (g m^{-2}), on day d will decay by rate, k (d^{-1}), and there will be some accumulation of new litter, A (g m^{-2} d^{-1}).

The sampling sites were all inundated during a high flow event in 2016. As would be expected, the standing load data indicated that not all of the organic matter was completely removed during this event, as the total standing loads measured in July–August 2018 greatly exceed that which would otherwise be expected based on the accumulation rates from the litter fall trap rates, multiplied by the number of days between the inundation event and the time of sampling (i.e., g m^{-2} d^{-1} × n days).

However, the more readily degradable material, which is the smaller and lighter component of the organic matter, and breaks down quicker, is more likely to have been reset during the inundation event. In the absence of any post flood monitoring to confirm, the methodology has assumed that the readily available material (i.e., leaves only) was reset to zero mass on the floodplain by the 2016 flood event, but some, unknown, mass of non-readily available material (e.g., twigs and sticks) did remain on the floodplain. Based on the standing loads of readily degradable material for river red gum and black box, fall rate of readily degradable material for river red gum and black box, and accumulation over 584 days between the last inundation event and the time of sampling, a decay rate for readily degradable material was estimated. For non-readily degradable organic matter, a decay rate an order of magnitude slower has been assumed (based on Whitworth & Baldwin, 2016).

2.4.3 | Standing load of organic matter

The standing load of plant litter on a floodplain is a balance between accumulation rates from litter fall, decay rates, and fraction and breakdown of readily degradable material during inundation events. These processes are dynamically represented in the DODOC model to determine the standing litter load on a floodplain over time, after setting an initial standing litter load at time zero. Hence, it is particularly important to understand and constrain these parameters, particularly for longer term simulations.

To determine the steady state standing litter load for all vegetation types across the floodplain, first the sampled standing load of readily degradable material was converted to an accumulation rate using the decay rate for the number of days of accumulation since the 2016 inundation event, and the fraction of material that was readily degradable. Then the accumulation rate was used to determine a steady-state litter load for both readily and non-readily degradable fractions, effectively extending the litter load sampled at a point in time, to the maximum steady-state load, when decay and accumulation rates are equal (based on Equation 1). Box-Cox distributions were fit to the readily degradable standing load samples for each vegetation classification. The derived accumulation rates were compared to the fall rates determined from the leaf litter traps for redgum and blackbox to validate the approach.

The DODOC model can be configured with different initial standing loads for the readily and non-readily degradable components at different floodplain elevations to represent the changes in vegetation increasing distances from the river. The SA Vegetation layer (available from https://data.environment.sa.gov.au/NatureMaps) was used to aggregate the standing loads for a given vegetation type to represent the vegetation types across the floodplain for different elevation bands. The SA Vegetation layer was simplified into five categories for this purpose: black box woodland, lignum shrubland, mixed woodland, river red gum woodland and shrublands.

2.4.4 | Model approach

An event-based analysis was used to undertake the uncertainty analysis, where the litter load at the start of the simulation was determined using the steady-state litter load approach outlined above. The readily and non-readily degradable litter loads at different elevation bands were determined using the derived Box-Cox distributions. The 500 separate simulations were undertaken based on samples drawn from these distributions.

Deterministic values were used for all other model parameters, based on the field monitoring (for the litter decay rates), monthly patterns of recorded data (for water temperature, as well as net evaporation) or values previously used at the same site (Mosley et al., 2021).

The larger reach from the Victoria-South Australia border to Lock 3 (Figure 1) has been used for the uncertainty analysis The model run is for a six-month period from 1 July to 31 December, which represents the typical late winter to early summer period when infrastructure operations are undertaken for environmental benefits. Three scenarios have been considered, with:

1. No operations: The inflow at the SA border (R Murray/Flow to SA on Figure 1) was based on an operational hydrograph, representing relatively low in channel flows, but with sufficient volume to operate infrastructure. The discharge varied each month reaching a maximum of 14 000 ML d^{-1} in November (for context, the long-term average daily flow is 18 000 ML/d.
2. Site operations: Multiple operations across the lower River Murray, at Chowilla, Pike and Katarapko floodplains with associated weir pool raisings at Locks 6, 5 and 4. These operations were based on operation plans and increase the water surface area from 7925 Ha in Scenario 1 (no operations) to 12 135 Ha in Scenario 2 (53% increase). A small additional volume of water was added to the inflow for this scenario on top of that used for Scenario 1, to account for filling and losses from the operations, assumed to be additional environmental water delivered to support the infrastructure operation.
3. A high flow event: Inflows were adopted based on observed flows during 1978, exceeding 40 000 ML/d for 96 days and peaking to 60 000 ML d^{-1} at the SA border, creating some overbank inundation and increasing the surface area to 21 940 Ha (177% increase).

3 | RESULTS

3.1 | DODOC model sensitivity analysis

The Sobol' sensitivity indices suggest that the load of readily degradable material on the floodplain had by far the largest influence on the modelled DO (Figure 3). There is a clear negative correlation between the load of readily degradable material and the average DO simulated (Figure 4). Reaeration rate and then water temperature had the next biggest impact on the modelled DO, similar to the non-readily degradable litter load. This provides useful information to guide risk management when planning operations and provides justification for the collection of data on standing load of organic matter on the floodplain during the environmental water planning process.

3.2 | Litter fall rates for river red gum and black box

A primary driver of the amount of standing litter load on these three floodplains is the fall of leaves, bark and twigs from trees and other plants. The data for litter fall rates (Figure 5) indicates that the mean rate of litter fall was higher for river red gums (1.91 g $m^{-2}d^{-1}$) than black box (0.44 g $m^{-2}d^{-1}$) for the summer period (Nov 17 – Mar 18), but the rates are similar between the two species, and significantly smaller for the for the remainder of the year. The data for litter fall rate over the November 2017 to November 2018 period (Figure 6) did not have a strong relationship between tree crown condition and litter fall rates for either river red gum or black box, indicating there was limited value in using available tree condition data to explain variability in litter fall rates.

When considering the full distribution of all samples for both vegetation types, the accumulation rate of leaves was similar, with a median value of a fraction of 0.3 of the total litter load (Figure 7). For the uncertainty analysis a Box-Cox distribution was fit to the combined readily degradable proportion data ("all data" in Figure 7), and Kolmogorov–Smirnov test indicates there is no evidence to reject the hypothesis that the samples were generated from the same distribution.

3.3 | Standing load of organic material

The highly skewed nature of the standing load data is evident from Figure 8, given the higher mean (dashed line) than median (solid line). The highest loads were recorded at Katarapko in both the river red gum (2.81 kg m^{-2}) and black box samples (1.9 kg m^{-2}).

To simplify presentation, the data on percentage of total standing load of organic material in each of the six fractions (leaf litter, bark, twig, CPOM, scat, and understory vegetation) is pooled for each meso-habitat (e.g., black box, red gum, cooba) (Figure 9). The data indicates some differences in the proportion of total organic material comprised of different fractions across different meso-habitats. Mean values for leaf litter were 12% of total standing load of organic matter in both the river red gum and black box woodlands and were highest in the river cooba (*Acacia stenophylla*) woodlands (19%). As would be expected, understory vegetation (68%) dominated the grassland sites, with a large proportion of the balance comprised of scat (15%). Scat represented a higher proportion of the organic matter in the grassland, compared to the other meso-habitats. CPOM represented approximately half (45 to 54%) of the organic matter in the woody vegetation meso-habitats, but only 8% in the grassland meso-habitats. In the river red gum meso-habitats, bark (10%) represented more than twice that observed in all other meso-habitats.

3.4 | Decay rate of readily degradable leaf litter

Decay (i.e., via microbial degradation) of standing loads of litter can occur in between inundation events. An assessment of the efficacy of the 2016 high-flow event on removing all of the standing load of organic material (resetting the standing load to zero) was undertaken. Between the 2016 high flow and the sampling reported here, there was approximately 584 days for matter to accumulate. Considering the measured median litter fall rate values of 1 and 0.4 g m^{-2} d^{-1} for river red gum and black box, this results in median values of 584 g m^{-2} and 234 g m^{-2} of standing load, before any decay of this material over time. These values are substantially below the median of the standing loads sampled (Figure 8) of 1517 g m^{-2} and 1070 g m^{-2} for river red gum at Chowilla and Katarapko floodplains, respectively, and 1221 g m^{-2} and 945 g m^{-2} for black box at Chowilla and Katarapko floodplains, respectively. Hence, there must have been residual standing stock of plant litter material remaining on the floodplains after the 2016 event.

Using only the readily degradable standing loads (i.e., leaves) for river red gum and black box, fall rate of readily degradable material for river red gum and black box, and accumulation over 584 days between the last inundation event and the time of sampling, a decay rate of $K_{\text{readily}} = 6\text{e-}4\ d^{-1}$ has been estimated using Equation 1. For non-readily degradable organic matter, a decay rate an order of magnitude slower has been assumed (based on Whitworth and Baldwin (2016)), $K_{\text{non-readily}} = 6\text{e-}5\ d^{-1}$, and in line with the range of $K_{\text{non-readily}} = 1\text{e-}5\ d^{-1}$ in winter to $K_{\text{non-readily}} = 3\text{e-}4\ d^{-1}$ reported by (Howitt et al., 2007).

3.5 | Validation of derived litter accumulation rates

The derived litter fall rates has been compared to the fall rates determined from the leaf litter traps, and it can be seen that similar distributions have been generated for the river red gum and black box vegetation types (Figure 10), with the skewness in the data captured by the Box-Cox distributions. This approach has enabled fall rates to be estimated for other vegetation types where litter fall rates were not collected, based on the standing load data.

3.6 | DODOC model uncertainty analysis

The modelled DO concentrations were at saturation for the majority of the time at most locations, even when considering the variability in litter loads (seen as the shaded areas between the 95% intervals for each scenario) along the river from Lock 6 to Lock 3, including the three anabranch systems of Chowilla, Pike and Katarapko (Figure 11). The 'stepped' nature of the results is a product of the monthly average water temperature used, whereby, as the temperature increases each month, the concentration of DO at 100% saturation decreases. The influence of the operations storing, and then releasing, water later in the period, or differences in flow, and hence travel time, produce the differences in the timing of the change in saturated DO along the river.

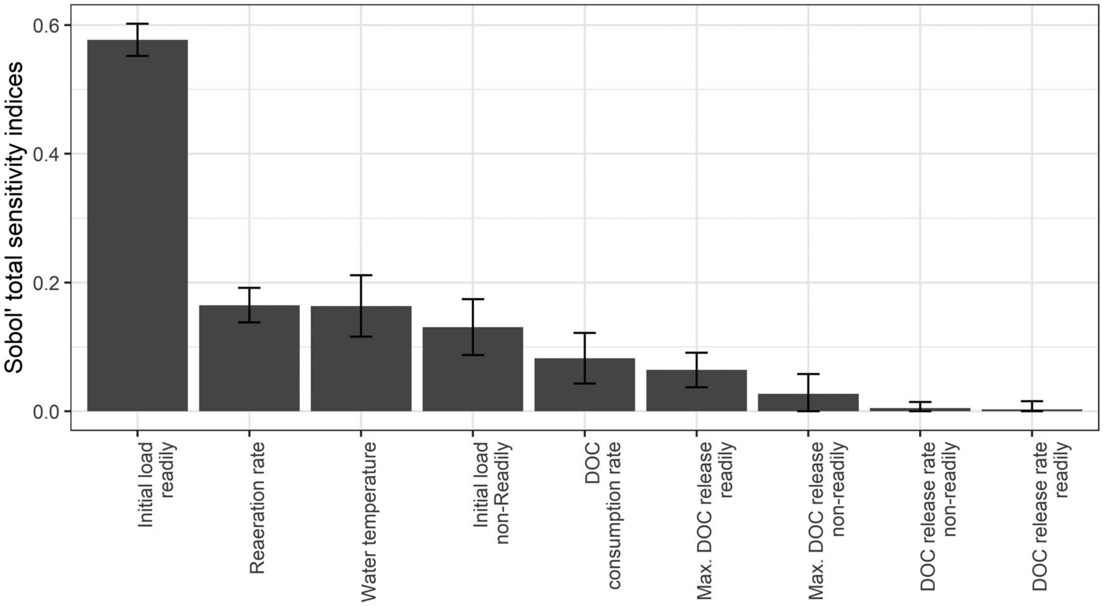

FIGURE 3 Sobol' total sensitivity indices representing the sensitivity of average DO over a model simulation to each DODOC model parameter considered

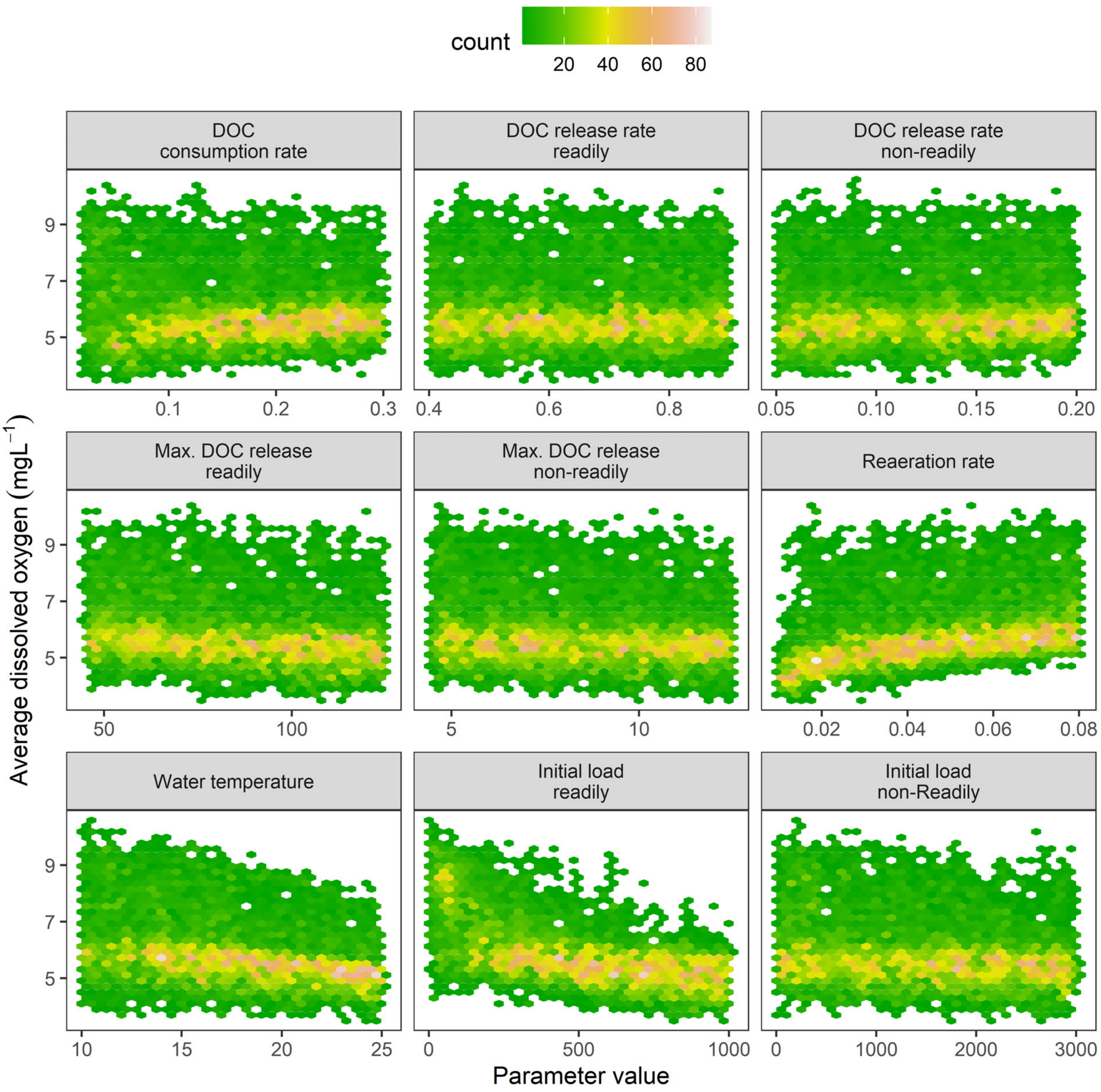

FIGURE 4 Scatter plot results of the sensitivity analysis for each DODOC model parameter on average DO concentration modelled. All simulations are shown on all panels, as such the variability for a given parameter value in a panel is due to the changes in the values for other parameters

The Lock 6 results provide an indication of the inflow concentration at saturation, with no reductions in DO due to DOC consumption. Chowilla Creek bypasses Lock 6, where for the 'site operations' scenario Lock 6 is used to direct more flow out of the main River Murray channel upstream of Lock 6 into Chowilla Creek, and there is a small reduction in DO in November when water levels recede from the highest levels created using the Chowilla regulator, compared to the no operations scenario.

The next site downstream, at Pike floodplain, has the least dilution capacity of the floodplains considered. With relatively low inflows compared to the volume retained behind the structures used to increase water levels, the depletion of DO due to the consumption of the DOC released during inundation of the floodplain can be seen for the 'site operations' scenario. The median DO concentration shows a relatively small decline, with DO approximately 1 mg L^{-1} less than the no operations scenario in August. However, the model result produced by the highest organic litter loads (i.e., the bottom line in the 95% band), has a much larger impact on DO from this operation, with values approaching 4 mg L^{-1} (Figure 11). This is a product of the highly skewed nature of the leaf litter accumulation rates (Figure 10) and loads (Figure 8).

The lower DO concentration water from the Pike floodplain returns to the main River Murray, before this mix of source waters contribute to the Katarapko floodplain. The results indicate that the River Murray provides sufficient dilution of the Pike floodplain water, with the River Murray discharge 20–30 times greater than that leaving the Pike floodplain. Hence, the low DO concentrations seen at the upstream Pike floodplain do not have a large influence on operations at Katarapko floodplain. Finally, at Lock 3 downstream, the total cumulative effect of all upstream operations is represented, and again, the model predicts only small impacts on the DO concentrations from the site operations scenario compared to the no operations scenario.

4 | DISCUSSION

Model sensitivity analysis indicated that the load of readily degradable organic material on the floodplain had by far the largest influence on the modelled DO outcomes. The results provide guidance on where investment in future sampling is likely to be most informative, with the representation of the readily degradable litter load by far the most influential parameter in the model. This parameter can be surveyed relatively simply to provide data for the model, compared to some of the less sensitive parameters that require experiments to determine local values (e.g., DOC leaching rates).

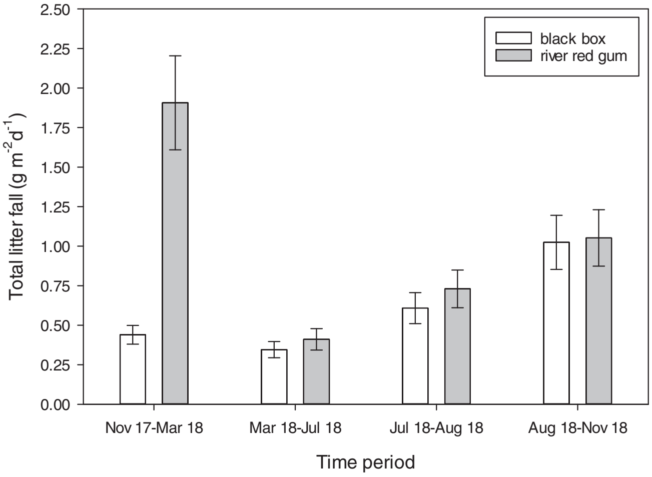

FIGURE 5 Litter fall rates (g $m^{-2}d^{-1}$) (type 1 traps) for each of the survey periods between November 2017 and November 2018. Symbols show mean; bars are ±1 standard error

Reaeration rates and water temperature were the next most influential parameter for the resulting modelled DO concentrations based on the operational scenario used for testing. Increases in water temperature increase rates for leaching and consumption of DOC, hence water temperature is expected to be an important factor when modelling DO concentrations. The saturated concentration for DO also reduces with higher water temperatures, hence the difference between the saturation level and critical ecological thresholds is reduced in warmer water. Timing operations earlier in the season to coincide with colder water temperatures can be a strategy to reduce risk of hypoxic conditions (as previously identified by Mosley et al., 2021). The model indicates similar sensitivity between temperature and reaeration rate, which can determine how far as DO deficit will propagate downstream, depending on the balance with consumption. There are well established equations to estimate reaeration rates (Chapra, 1997), however estimating representative values for the input parameters (e.g., water depth, velocity or wind speed) can be difficult as these factors vary widely in space and time, and can have material influence on reaeration rates. It can also be difficult to calibrate a reaeration rate in the case where DO concentrations are at saturation most of the time, as there is no information available on this process. One mechanism to increase reaeration is in the design of structures to increase fall height and/or mixing with the atmosphere, and the DODOC model can represent this process (see Mosley et al., 2021). The use of overshot structures provides more capacity for reaeration than undershot structures. However, increasing fall height requires either (i) increasing water level on the upstream side of the structure, which inundates a larger area and introduces more organic load, or (ii) decreasing the water level on the downstream side of the structure, which typically requires less discharge, and reduces dilution capacity.

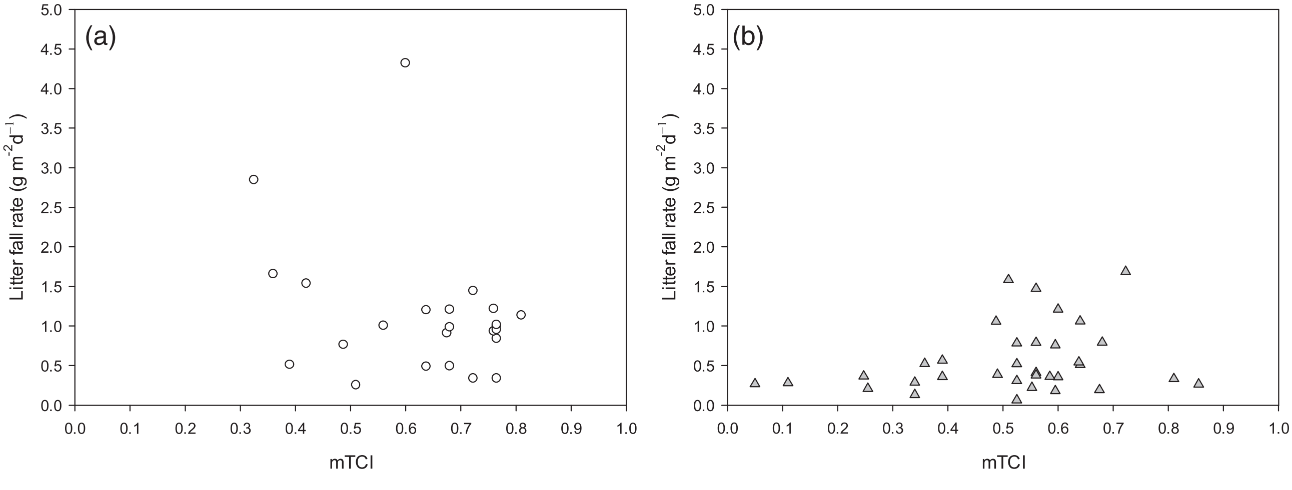

FIGURE 6 Relationship between litter fall rate (g m^{-2} d^{-1}) November 2017–November 2018 and tree crown condition (mTCI) [a] = red gum, [B] = black box

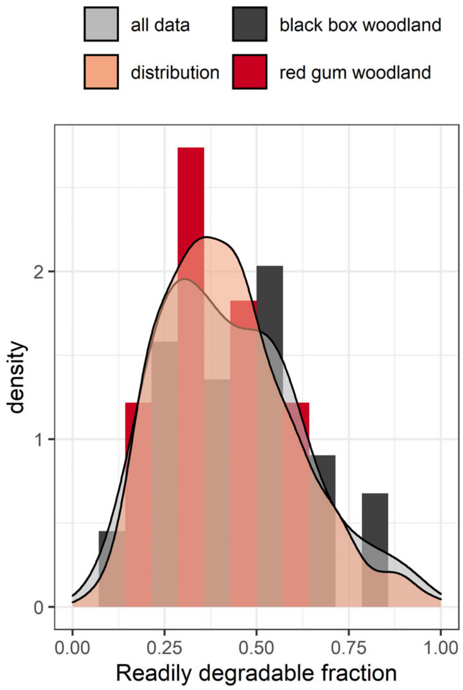

FIGURE 7 Distribution of the fraction of organic matter that is readily degradable (leaves), for the sampled data for black box (black) and red gum (red), empirical distribution representing the combined red gum and black box data (grey) and box-cox distribution fit to the combined data (light red)

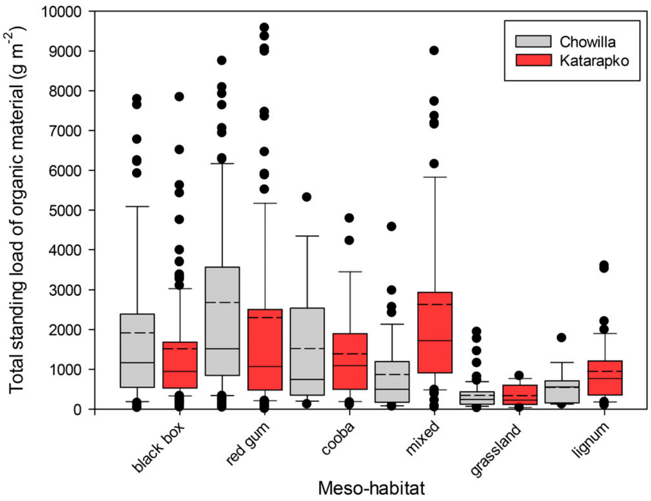

FIGURE 8 Total standing load of organic material (g m^{-2}) in each of the six meso-habitats sampled. Boxes enclose the 25%–75%, whiskers enclose the 10%–90%, outliers are identified by closed circles; dashed line within box plots depicts mean and solid line the median. Outliers with very high loading (>10 000 g m^{-2}) are not shown in this plot but are included in the mean, median and percentiles shown

The values for standing load of organic material recorded here (Figure 8) for Chowilla and Katarapko floodplains on the River Murray are substantially higher than those recorded by Hladyz et al. (2011) of 798 ± 265 g m^{-2} in the Edwards-Wakool river system (New South Wales). However, they are of the same magnitude as results from previous assessments at Chowilla Floodplain by Brookes et al., (2007) and Wallace et al., (2015). Wallace et al., (2015) recorded mean total standing loads of 2090 g m^{-2} for river red gum, and 670 g m^{-2} for grassland areas. As per previous assessments, loads are typically highest in river red gum woodland areas along the permanent creek lines. The data collected from Katarapko in this study is the first assessment of standing load at that floodplain and expands the spatial resolution of data from Chowilla to enable site-specific assessments of potential organic loads during managed inundations. Not surprisingly, the abundance of scats was higher in grassland area than woodland areas, and this is considered likely to reflect the abundance and palatability of vegetation in the contrasting meso-habitat types to native grazing animals such as Red kangaroo's (*Macropus rufus*), Western Grey kangaroo's (*Macropus fuliginosus*) and feral herbivores such as goats (*Capra hircus*) and rabbits (*Oryctolagus cuniculus*).

The data indicate that the mean percentage of material that was leaves in the litter fall rate traps was 47%–56% for black box, and 32%–39% for river red gum. These values are higher than (i) the 21%–29% reported by Briggs and Maher. (1983) for river red gums in the Lachlan River catchment, and (ii) substantially higher than the mean value of 12% leaf litter we recorded in the standing load samples for both river red gum and black box meso-habitats. Those values are similar to the 10% recorded by Hladyz et al. (2011) for river red gum woodlands in the Edwards-Wakool river system. The differences between the mean values for percentage of leaf litter in the litter fall traps and the standing load samples may be explained by the leaf litter being able to be more easily dispersed away from its source by wind or water flow. Hence, an estimate of fraction of leaf litter based on standing load samples measured in wooded areas may substantially under-represent the actual load that is distributed across the floodplain. Whilst field data was not collected to validate this hypothesis, field observations provide a strong indication that ground structural complexity (ground surface topography and the presence/absence of understory vegetation and woody debris) has a substantial influence on the retention of organic debris (leaf litter, bark) within any given area. Hence, while the leaf litter may not be on the floodplain where it first fell (i.e., under a tree), it could still be expected to be on the floodplain, and release DOC when inundated. Future floodplain organic material monitoring program designs should consider this.

Based on the median rate of 1 g m^{-2} d^{-1} calculated from this study, an annual accumulation rate of 365 g m^{-2} year^{-1} could be expected. This is similar to the rates recorded by Briggs and Maher (1983) of 369–580 g m^{-2} year^{-1} in the Lachlan River catchment (New South Wales). Whilst these annual average rates are useful for modelling, it is important to recognize that peak litterfall occurs in summer (Figure 5, also Hladyz et al., 2011; Pressland, 1982), and may be an order of magnitude higher than the annual average. For example, Hladyz et al. (2011) recorded peak rates of 11.8 g m^{-2} d^{-1}, and calculated that 1 month of peak litter fall is sufficient to cause a hypoxic blackwater event in shallow water courses. The combination of elevated load, higher litterfall rates and higher water temperatures

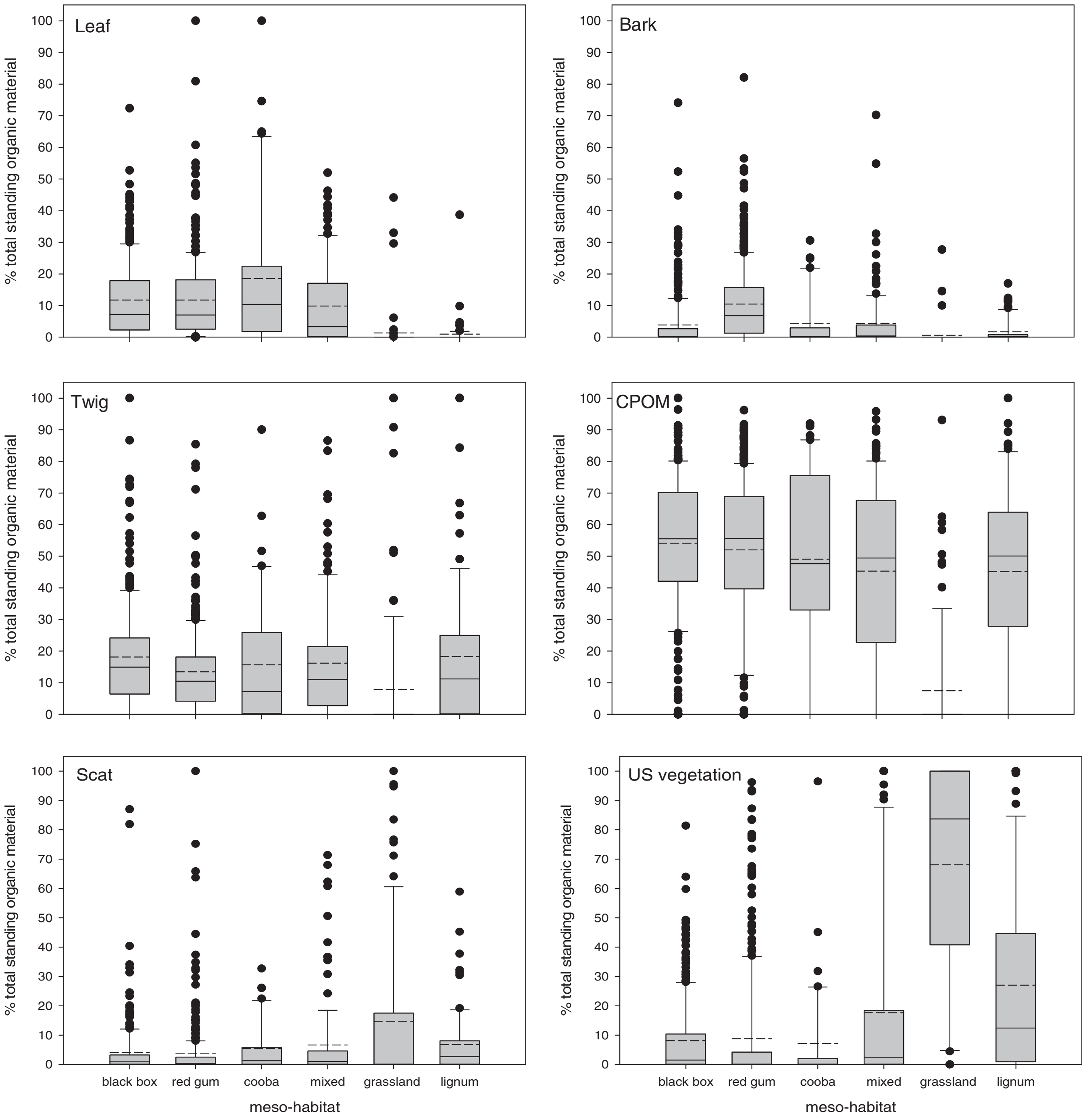

FIGURE 9 Percentage of total standing load of organic material in each of the six fractions (leaf litter, bark, twig, CPOM, scat, and understory vegetation) in each of the six meso-habitats sampled. Boxes enclose the 25%–75%, whiskers enclose the 10%–90%, outliers are identified by closed circles; dashed line within box plots depicts mean and solid line the median

may be expected to increase the likelihood of raid depletion of DO. Therefore, managed inundations that occur in summer should be regarded to have a higher risk of onset of hypoxia.

Currently the DODOC model does not have the capability to represent a seasonal pattern in litter accumulation rates. Ultimately, a representation of the organic matter on the floodplain at the time of inundation is the objective of the litter dynamics modelling, and it is assumed that adopting constant rates of accumulation and decay over the year can provide model outputs that allow managers to consider the benefits/consequences of altering the timing of delivery of environmental water. Other potential improvements to the DODOC model could include the ability to represent the release and consumption rates of a wider range of fractions within the total DOC pool.

The scenarios presented considered a single watering event. The model calibration undertaken by Mosley et al. (2021) involved a longer simulation that included multiple natural inundation events, hence the

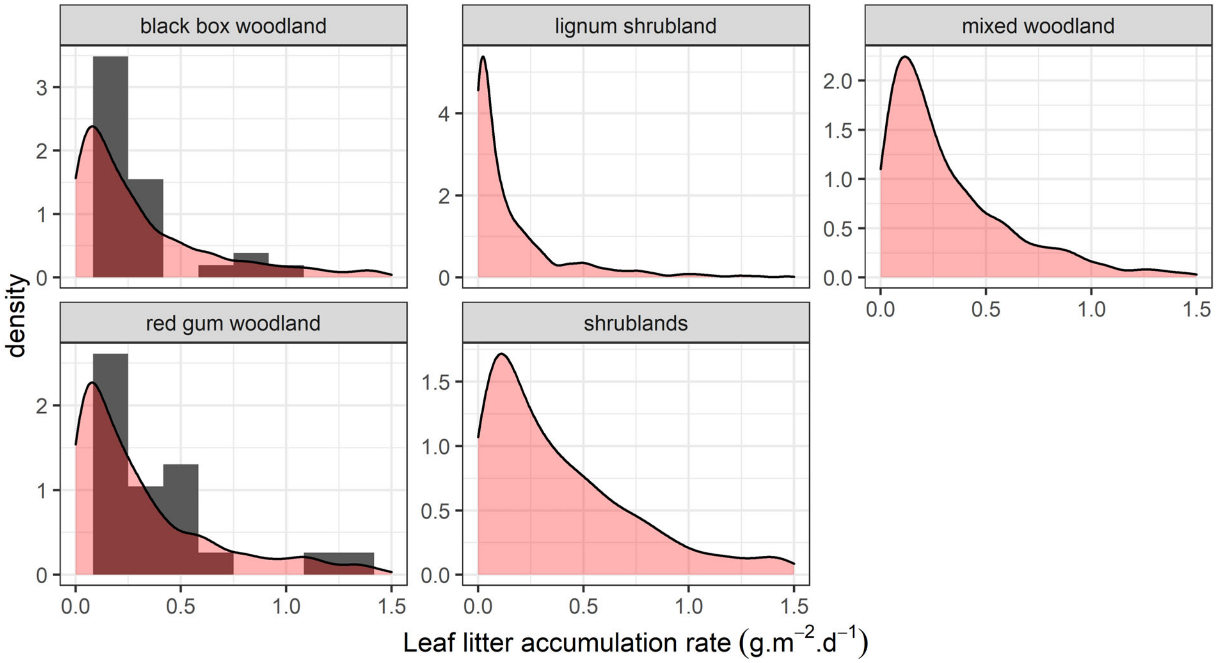

FIGURE 10 Generated distributions for leaf accumulation rates (red area), compared to variability in litter fall rate data for red gum and black box sites (grey histogram). Litter fall rate data was collected for red gum and black box vegetation only

model is capable of assessing the consequences of repeated inundations, where the organic matter could potentially be leached faster than accumulated. It is considered that modelling a continuous litter accumulation rate over extended periods (e.g., >5 years) would provide unrealistic loads as weathering and microbial breakdown would preclude this. Whitworth et al. (2013) cap the amount of litter accumulated at 4 years post-flooding, but those authors note that this timeline could be increased/decreased if site-specific rates on accumulation and breakdown are available. The tool could be used to assess if shortening inter-flood durations facilitates maintaining higher DO concentrations and mitigates the risk of onset of hypoxic conditions for any given inundation, either managed or unregulated.

Other parameters had more limited influence on the modelled DO outcomes. The sensitivity analysis results found the maximum DOC release rate, as mg of carbon per g of litter, had a greater influence on simulated DO than the release rate of DOC, d^{-1}. In this work, supported by previous studies, DOC release rate has been assumed to be an order of magnitude lower for the non-readily degradable material than the readily degradable material. Therefore, although the field data indicates the standing load of non-readily degradable material can be 2–3 times higher than the readily degradable material, non-readily degradable material has a much smaller influence on the amount of DOC leached, and hence simulated DO response, than the readily degradable material. Consequently, the load of readily degradable material should be the focus of model application studies.

The results of a risk assessment undertaken using this modelling approach can be used to either (i) identify the need for further data collection to improve model predictions, or (ii) alter the timing, rate of change in water level or extent of inundation of a planned managed inundation. For example, the river-floodplain model results suggest there is a low probability of DO concentrations reaching 4 mg L^{-1} occurring at the Pike floodplain for the site operations scenarios. This is likely to be a product of the leaf litter loads utilized in the model scenario. That data was collected at Chowilla-Calperum and Katarapko. If site-specific knowledge suggests that standing loads at Pike are lower (or higher) than these values, a rapid field assessment could be undertaken to determine site-specific values for standing loads. If this site-specific assessment is not possible, or such data shows that the loads are representative, then the model can be used to refine the planned operation to achieve a lower likelihood of triggering the onset of hypoxic conditions. In this case, reducing the rate of rise of the regulator (m d^{-1}), and the total area of floodplain inundated (hence the amount to DOC released) each day, would be expected to further reduce the likelihood of establishing low DO concentrations (Mosley et al., 2021).

It should be noted that the modelling results are to some extent specific to the floodplains considered. The values used to sample parameter values from for the sensitivity analysis are based on both local monitoring as well as literature values and expected to be representative of the systems modelled (Table 1). However, the sensitivity analysis results are, to some degree a product of the data range. The hydrology of a site, and any operational scenarios, will also influence the specific results. Dilution rate (the proportion of the stored volume within the managed inundation zone that can be replaced with inflowing (low DOC/high DO) water in a given period and the rate of inundation of new organic matter (e.g., rate of change in inundation extent, which is controlled primarily by rate of rise of water level) are key parameters. Irrespective of these site-specific factors, this work

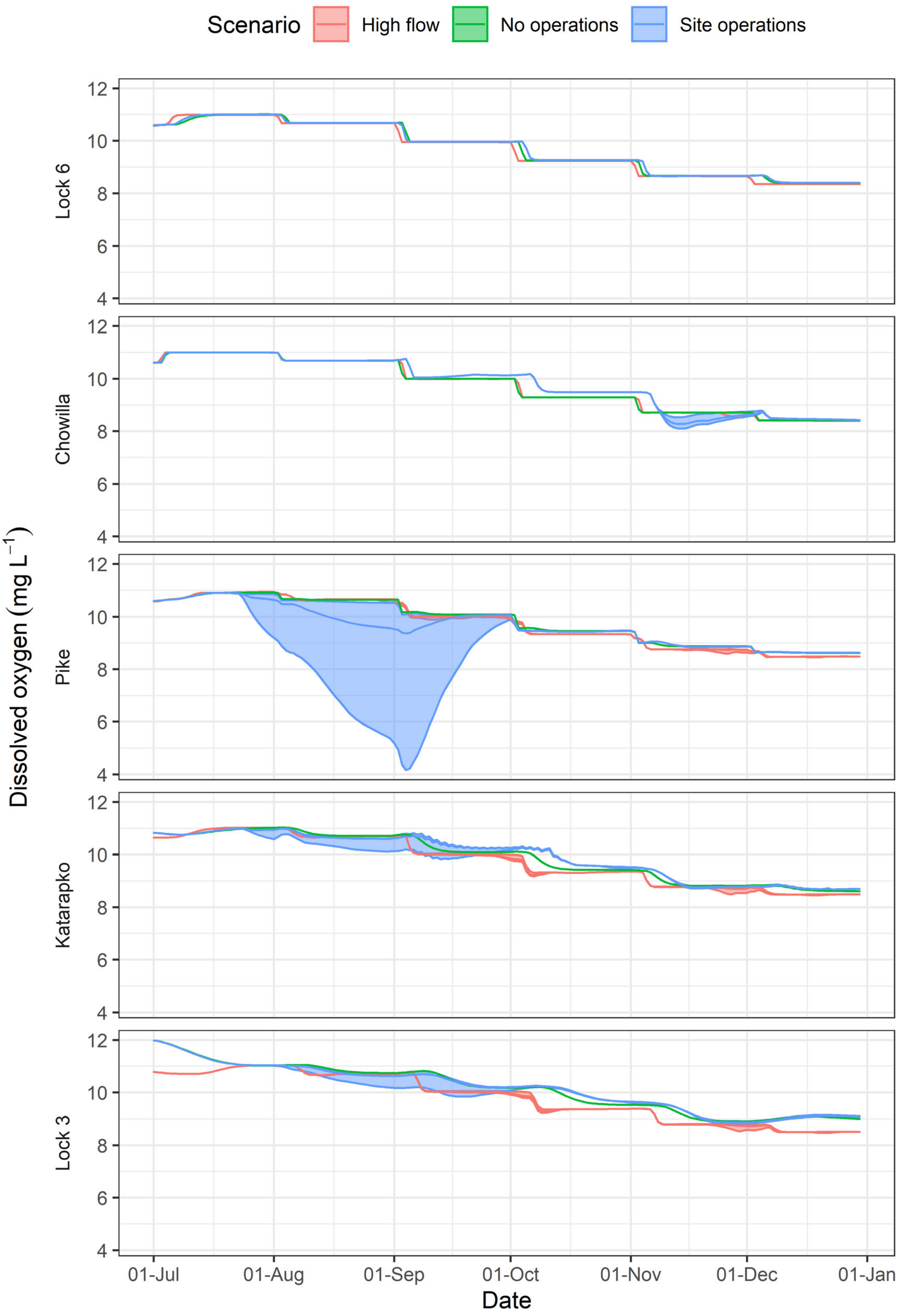

FIGURE 11 Modelled DO concentrations for the three scenarios considered, with the reporting location for the locks and anabranches presented in Figure 1 (most southern floodplain structure triangle for each anabranch). The 95% range based on the variability in organic matter loads is shown as the shaded area, with the median result shown as the line within the 95% range. The 'stepped' nature of the results is a product of the monthly average water temperature used with the highest concentration representing the DO at 100% saturation for that temperature

has outlined an approach that can be used to inform risk assessments for a range of potential operational scenarios with either (i) local field data that can be easily and quickly collected, or (ii) provide indicative results for systems that may be expected to have similar standing loads of material where local data is not available.

5 | CONCLUSIONS

The use of environmental water provisions in conjunction with purpose built infrastructure (environmental regulators) is fast becoming a "go-to" tool to achieve some ecological objectives in rivers where a return to more natural hydrological conditions is not currently achievable. This can provide some benefits to floodplain vegetation, biota and biogeochemical processes that are dependent on the intermittent presence of surface water (i.e., inundation events). However, this intervention tool does not provide all of the ecological outcomes associated with an unregulated flood and increasing the stored volume for a given discharge can increase the risk of negative water quality impacts, most notably low DO and potentially hypoxic events.

This research has identified the parameters in a DO-DOC model that have the largest influence on the DO simulation to assist practitioners to focus monitoring and calibration efforts when applying this model. The load of organic material that is readily degradable was found to have by far the largest influence on predicted DO concentrations followed by the reaeration rate to replenish any consumed DO, and water temperature, which influences rates of DOC release, consumption and DO saturation. DOC release rates were the least sensitive parameters.

Field monitoring approaches to determine the rates at which organic matter accumulates on the floodplain during dry (non-inundated) phases, what proportion of that material is readily degradable, and how the organic matter decays over time, were designed and undertaken, with the results used to parameterise a DO-DOC model. By representing the variability in the monitoring results, the model can now be used to assess the likelihood that planned operations will lead to undesirable hypoxic conditions, and to modify potential operations to reduce the likelihood of low DO events if it is considered necessary.

Floodplain regulators, such as those considered in the modelling undertaken in this study, are relatively new management levers. Consequently, there is limited historical experience to support decisions on how to undertake operations under different hydrological and seasonal conditions. The predictive modelling outlined in this work provides managers with a valuable tool to confidently plan undertake, or modify, managed inundations that have a high likelihood of achieving positive outcomes with low risk of negative processes dominating outcomes.

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DATA AVAILABILITY STATEMENT

The code and model used to produce the results presented in this manuscript are available from https://github.com/matt-s-gibbs/DODOC_SA_Calib and https://github.com/matt-s-gibbs/OrganicMatterDynamics.

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