

# Options for Managing Hypoxic Blackwater in River Systems: Case Studies and Framework

Kerry L. Whitworth · Janice L. Kerr ·  
Luke M. Mosley · John Conallin · Lorraine Hardwick ·  
Darren S. Baldwin

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**Abstract** Hypoxic blackwater events occur when large amounts of organic material are leached into a water body (e.g., during floodplain inundation) and rapid metabolism of this carbon depletes oxygen from the water column, often with catastrophic effects on the aquatic environment. River regulation may have increased the frequency and severity of hypoxic blackwater events in lowland river systems, necessitating management intervention to mitigate the impacts of these events on aquatic biota. We examine the effectiveness of a range of mitigation interventions that have been used during large-scale hypoxic blackwater

events in the Murray–Darling Basin, Australia and that may be applicable in other environments at risk from hypoxic blackwater. Strategies for hypoxia mitigation include: delivery of dilution flows; enhancement of physical re-aeration rates by increasing surface turbulence; and diversion of blackwater into shallow off-channel storages. We show that the impact of dilution water delivery is determined by relative volumes and water quality and can be predicted using simple models. At the dilution water inflow point, localized oxygenated plumes may also act as refuges. Physical re-aeration strategies generally result in only a small increase in dissolved oxygen but may be beneficial for local refuge protection. Dilution and natural re-aeration processes in large, shallow lake systems can be sufficient to compensate for hypoxic inflows and water processed in off-channel lakes may be able to be returned to the river channel as dilution flows. We provide a set of predictive models (as electronic supplementary material) for estimation of the re-aeration potential of intervention activities and a framework to guide the adaptive management of future hypoxic blackwater events.

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K. L. Whitworth · J. L. Kerr · D. S. Baldwin (✉)  
The Murray–Darling Freshwater Research Centre,  
PO Box 991, Wodonga, VIC 3689, Australia  
e-mail: darren.baldwin@csiro.au

K. L. Whitworth · J. L. Kerr  
La Trobe University, PO Box 821, Wodonga,  
VIC 3689, Australia

L. M. Mosley  
Environment Protection Authority South Australia,  
GPO Box 2607, Adelaide, SA 5001, Australia

J. Conallin  
Murray Catchment Management Authority, 315 Victoria St.,  
Deniliquin, NSW 2710, Australia

L. Hardwick  
NSW Office of Water, PO Box 10, Wagga Wagga,  
NSW 2650, Australia

D. S. Baldwin  
CSIRO Land and Water, PO Box 991, Wodonga,  
VIC 3689, Australia

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Basin

## Introduction

Dark-colored water with a low dissolved oxygen (DO) concentration (“hypoxic blackwater”) develops when high concentrations of dissolved organic carbon (DOC) are leached into a water body, and metabolism of this carbon consumes DO from the water column more rapidly than re-aeration can occur (Koetsier and others 1997; O’Connell

and others 2000; Valett and others 2005; Howitt and others 2007; Hladyz and others 2011). Hypoxic blackwater events can have catastrophic effects on the aquatic environment (Whitworth and others 2012; King and others 2012). DO concentrations below  $4 \text{ mg L}^{-1}$  are generally considered to impose stress on fish and DO below  $2 \text{ mg L}^{-1}$  is lethal to many aquatic organisms, although these thresholds vary considerably with species and size class (Gehrke 1988; McNeil and Closs 2007). Low DO can also lead to an increase in solubilized metals, which may degrade aquatic habitats and drinking water quality (NHMRC and NRMCC 2011).

Hypoxic blackwater events typically occur in low-gradient river systems with forested floodplains or extensive wetlands, such as the Paraguay River, Brazil (Hamilton and others 1997); the Atchafalaya River, Louisiana, USA (Fontenot and others 2001); and rivers of the Murray–Darling Basin, Australia (McKinnon and Shepherd 1995; Baldwin and others 2001; Howitt and others 2007; Hladyz and others 2011; Whitworth and others 2012). Although hypoxic blackwater events can occur naturally, human influence on river-floodplain environments may have increased their severity and frequency. For example, river regulation and water extraction have dramatically altered the frequency, timing, magnitude, and duration of floodplain inundation events in many lowland river systems (Poff and others 1997; Buijse and others 2002; Thoms 2003). Many of these changes, particularly reduced flood frequency and magnitude, allow increased floodplain organic matter accumulation and less frequent but more concentrated delivery of organic matter to the aquatic environment (Robertson and others 1999). Climate change is also predicted to reduce runoff and increase the variability in global water resources, including the Murray–Darling Basin (Suppiah and others 2007; Chiew and others 2008), which may also increase the prevalence of blackwater events. Where human influence has increased the frequency or severity of hypoxic blackwater events, or where biota are already under pressure from other human activities, management interventions to mitigate the impact of hypoxic events on aquatic biota are warranted.

Although considerable literature exists regarding the biogeochemical factors leading to hypoxic blackwater development (e.g., Howitt and others 2007; Hladyz and others 2011; Whitworth and others 2012), there is a paucity of documented instances of successful management of hypoxic blackwater to minimize harm to the aquatic environment (Kerr and others 2013). In this paper we present and evaluate case studies of a range of re-oxygenation strategies that were implemented by water management agencies during two recent large-scale hypoxic blackwater events in the southern Murray–Darling Basin (MDB), Australia (Whitworth and others 2012; Whitworth

and Baldwin 2012). This evaluation provides a basis for adaptive management and future research of hypoxic blackwater in lowland river systems.

## Methods

### Study Area Overview

The MDB is Australia's largest river basin, with a total catchment area of  $1,061,469 \text{ km}^2$  (see Fig. S1, Online Resource 1). The catchment is characterized by low rainfall and runoff and susceptibility to drought (Murphy and Timbal 2008). The three major river systems in the basin are the Darling (2,740 km), Murray (2,530 km), and Murrumbidgee (1,690 km). The natural flow regime has been highly altered by river regulation and extraction of water for agriculture (Kingsford 2000).

Rivers in the southern MDB are typically well-oxygenated ( $\text{DO} > 6 \text{ mg L}^{-1}$ ; Tiller and Newall 2010) and carry low to moderate DOC concentrations ( $< 10 \text{ mg L}^{-1}$ ; Mackay and others 1988). Large-scale hypoxic blackwater events occurred in the southern MDB as a result of warm-season post-drought flooding between September 2010 and April 2011 and again between March and May 2012, affecting hundreds to thousands of kilometers of river channel. The spatial and temporal trends in water quality and key drivers of hypoxic blackwater generation during these events are discussed in detail in Whitworth and others (2012) and Whitworth and Baldwin (2012).

### Site Descriptions

#### *Edward–Wakool River System*

The Edward–Wakool River system diverges from the Murray River at the downstream end of a large river red gum (*Eucalyptus camaldulensis* Dehnh.) forested floodplain (Barmah–Millewa Forest) (see Fig. S2, Online Resource 1). Drainage of hypoxic blackwater from this floodplain caused hypoxia in the upper Edward–Wakool River system during summer 2010–2011 (Whitworth and others 2012). Upstream of the floodplain, water is diverted from the Murray River into the Mulwala Canal for irrigation purposes. Water in this canal remained well-oxygenated and low in DOC ( $< 10 \text{ mg L}^{-1}$ ) during the 2010–2011 hypoxic blackwater event.

#### *Murrumbidgee River*

The lower Murrumbidgee River passes through an extensive river red gum forested floodplain (the “Lowbidgee” floodplain) before meeting the Murray River (see Fig. S3,

Online Resource 1). Flooding in the Murrumbidgee River system during spring and summer 2010–2011 resulted in a brief period of hypoxia at sites upstream of the Lowbidgee floodplain and in severe and persistent hypoxia in the river channel downstream of this floodplain (Whitworth and others 2012). Severe hypoxia was also recorded in the lower Murrumbidgee River in during summer and autumn 2012 (Whitworth and Baldwin 2012).

#### *Swan Hill Marina*

An off-channel marina (area  $\sim 5000 \text{ m}^2$ ) is located at the township of Swan Hill on the middle reach of the Murray River (35.338°S, 143.563°E), where hypoxia was recorded between December 2010 and March 2011 (Whitworth and others 2012). Accumulations of distressed fish (numbering into the thousands; predominantly Murray cod, *Maccullochella peelii peelii* Mitchell) were observed in this marina during February 2011.

#### *Frenchmans Creek and Lake Victoria*

Frenchmans Creek diverges from the Murray River and flows into Lake Victoria (see Fig. S5, Online Resource 1), a shallow freshwater storage (capacity 677 GL; area approximately  $120 \text{ km}^2$ ; average depth at full supply level 5.6 m). Regulators (sluice gates) allow control of the flow from the Murray into Frenchmans Creek and from there into Lake Victoria. Outflows from Lake Victoria may be returned to the Murray via an outlet regulator on the Rufus River. Wind speed at the lake averages  $10 \text{ km h}^{-1}$  during summer (Australian Government Bureau of Meteorology 2011). Lake Victoria received prolonged inflows of hypoxic blackwater during 2010–2011.

#### *The Lower Lakes*

Before terminating in the southern ocean, the Murray River enters two large “Lower Lakes,” Lakes Alexandrina and Albert (see Fig. S6, Online Resource 1). The lakes have a total capacity of 2,015 GL (Murray–Darling Basin Authority 2011) and at normal pool level have a mean depth of 2.4 m (Lake Alexandrina) and 1.5 m (Lake Albert), respectively (Mosley and others 2012). Average wind speed at the lakes is  $21.7 \text{ km h}^{-1}$  (Australian Government Bureau of Meteorology 2011). The Lower Lakes are generally well-oxygenated and at times become supersaturated with oxygen. The lakes received hypoxic inflows from the Murray River from December 2010 until March 2011.

## Intervention Descriptions

### *Dilution Flows*

During the 2010–2011 and 2012 hypoxic blackwater events dilution flows for the mitigation of hypoxia occurred: at channel junctions, where well-oxygenated water (i.e., containing sufficient oxygen to support biota) was added to hypoxic channels (Wakool River 2010–2011 and Murrumbidgee River 2012); and when discharge from an upstream regulatory structure was increased to add to flow in a hypoxic river reach (Murrumbidgee River 2010–2011).

### *Dilution at Channel Junctions*

An irrigation escape was used to deliver dilution flows from the Mulwala canal to the hypoxic Wakool River during the 2010–2011 event. DO was monitored regularly in the escape water and in the Wakool at sites 10 river km upstream and 2.5 river km downstream of the escape. On a single occasion in mid-February 2011, DO was also measured in the Wakool immediately ( $\sim 100 \text{ m}$ ) upstream and downstream of the escape.

During the 2012 event, the Murray River provided oxygenated dilution water at the Murrumbidgee River confluence. DO, water temperature, and DOC were monitored regularly in the Murrumbidgee upstream of the confluence and in the Murray 300 m upstream and 5 and 110 river km downstream of the confluence. Additionally, a survey was undertaken on 8 May 2012 to examine mixing patterns at the confluence. A boat was used to traverse six transects in: the Murray  $\sim 500 \text{ m}$  upstream of the confluence; the Murrumbidgee  $\sim 750 \text{ m}$  upstream of the confluence; and the Murray 170 m and 0.5, 1.0, and 5.0 km downstream of the confluence. At approximately six points along each transect, DO was measured at 0.2, 1, 2, 3, 4, and 5 m depths. DO isopleths were then calculated using the contour function in Sigmaplot v 11.0.

### *Dilution by Increasing Flow in a Hypoxic Reach*

To alleviate severe hypoxia in the lower Murrumbidgee River during summer 2010–2011, releases (including environmental water allocations) from upstream regulatory structures (Maude and Redbank Weirs) were managed to maintain high discharge in the main river channel, slowing the in-channel flow recession and providing additional dilution to the hypoxic floodplain return water (Maguire 2011). DO was monitored at Maude and Redbank Weirs and near Balranald (downstream of the floodplain).

### Physical Re-aeration

Mechanical re-aeration during the 2010–2011 hypoxic blackwater event was performed using paddle wheel aerators and pumps and by manipulating flow over regulatory structures.

**Mechanical Aeration Using Paddle Wheels** The paddle wheels (3 m diameter; 1.2 m floats; 22 rpm) of a paddle boat moored in the Swan Hill marina were operated during daylight hours for ~2 weeks in order to create an oxygenated fish refuge by providing physical re-aeration to the water (see Fig. S4, Online Resource 1). Small aquaculture paddle wheel aerators were also used on occasion to contribute to re-aeration. DO concentrations were monitored regularly in the main Murray River channel at Swan Hill during this period. Several sites within and outside the marina were also monitored for DO on a single occasion (3 February 2011) during the period of paddle wheel operation. Observations of fish behavior within the marina were recorded by the marina operator.

**Mechanical Aeration Using Pumps** The Yallakool regulator diverts water from the Edward River into Yallakool Creek (see Fig. S2, Online Resource 1). Coincident with the 2010–2011 hypoxic blackwater event, a block-bank was installed upstream of the regulator to facilitate upgrade works. This terminated flow downstream of the regulator and reduced the creek to a series of pools. To protect native fish in downstream refuge holes, a pump was used to divert water around the block-bank, providing a flow of approximately  $0.1 \text{ m}^3 \text{ s}^{-1}$  to Yallakool Creek. The pump discharge was located above the creek water level. DO was monitored regularly at the Edward River off-take, in the Yallakool Creek upstream of the block-bank, at the pump discharge point, and in a refuge hole a further 90 m downstream.

**Use of Regulatory Structures for Aeration** During the 2010–2011 hypoxic blackwater event, the Frenchmans Creek inlet regulator was adjusted such that blackwater entering the creek fell a distance of approximately 3 m over the regulatory structure, in an attempt to increase DO in the water entering Lake Victoria. DO, temperature, and DOC were monitored in the Murray River near the off-take and DO was monitored at regular intervals along Frenchmans Creek between January and March 2011.

### Re-aeration and Dilution in Large Lakes

During the 2010–2011 hypoxic blackwater event, hypoxic blackwater from the Murray River entered large, shallow lake systems at Lake Victoria and the Lower Lakes, where

both dilution and physical re-aeration processes occurred. In both systems, DO was monitored in the inflow water and at several locations across the lakes. For Lake Victoria, DO was also monitored in the outflow water.

### Sampling and Analysis

River discharge data were obtained from fixed gauging stations maintained by state and federal water management agencies. DO and DOC were monitored during each intervention activity by water management agencies (with community assistance in some instances) and/or research organisations (see Acknowledgements). DO data were obtained from a combination of data loggers (10–30 min logging interval) and hand-held probes (sampling performed at 12 noon  $\pm$  5 h). DOC samples were collected, stored, and analyzed using standard methods (APHA 2005). All data are from surface measurements (<1 m deep) and where more than one value was obtained from a site on a single day, averages are used.

## Results

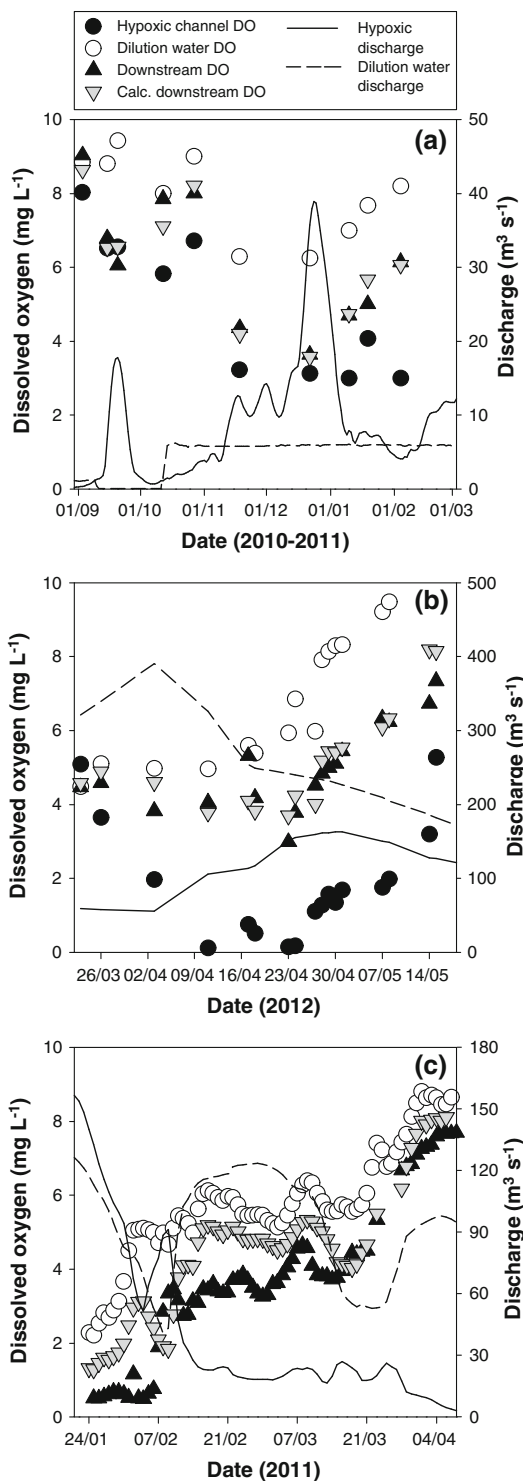
### Use of Dilution Flows for Hypoxic Blackwater Management

#### Dilution at Channel Junctions

**Immediate Dilution Effect** Our case studies of dilution interventions from both the Wakool and Murrumbidgee Rivers show that delivery of dilution water at channel junctions had an immediate beneficial impact on downstream water quality (Fig. 1a, b), generally resulting in a downstream DO of  $>4 \text{ mg L}^{-1}$ —above the general threshold for fish stress (Gehrke 1988). The average increase in DO between upstream and downstream of the escape on the Wakool River during the hypoxic period (November 2010–February 2011) was  $1.5 \text{ mg L}^{-1}$  ( $n = 5$ ; range  $0.5\text{--}3.1 \text{ mg L}^{-1}$ ). The average increase in DO between the Murrumbidgee River and the Murray River downstream of the junction during the hypoxic period (April–May 2012) was  $3.4 \text{ mg L}^{-1}$  ( $n = 16$ ; range  $1.7\text{--}4.6 \text{ mg L}^{-1}$ ). Based on relative flows and DO concentrations on all sampling occasions downstream DO was close (generally within  $1 \text{ mg L}^{-1}$ ; see Fig. 1a, b) to that expected upon simple mixing of the two water bodies:

$$\text{DO}_{\text{ds}} = \frac{(F_{\text{bw}} \times \text{DO}_{\text{bw}}) + (F_{\text{dil}} \times \text{DO}_{\text{dil}})}{F_{\text{bw}} + F_{\text{dil}}} \quad (1)$$

where:  $\text{DO}_{\text{ds}}$  is the downstream concentration of DO ( $\text{mg L}^{-1}$ );  $\text{DO}_{\text{bw}}$  is the DO in the blackwater plume ( $\text{mg L}^{-1}$ );  $\text{DO}_{\text{dil}}$  is the DO concentration in the dilution



◀ **Fig. 1** Effect of dilution water inflows on downstream dissolved oxygen during hypoxic blackwater events in **a** the Wakool and **b**, **c** the Murrumbidgee River systems. A calculated downstream DO based on simple mixing of the two flows (Eq. 1) is also shown. Part **a** and **b** show dilution at channel junctions. Part **c** shows dilution by increasing flow in a hypoxic reach with: calculated floodplain return (“hypoxic”) and river (“dilution water”) discharge components at Balranald and measured DO at Redbank Weir (“dilution water DO”; offset 3 days to account for travel time) and Balranald (“downstream DO”)

*Downstream Persistence of Dilution Effect*

Although DO immediately downstream of a confluence can be predicted using a simple mixing model, the persistence of any DO increase is dependent on the rate of decomposition of organic matter in the water column after dilution compared to re-aeration processes. Blackwater flows typically contain high concentrations of reactive carbon and, even after dilution, decomposition of this carbon may consume oxygen at a faster rate than it can be replenished, rendering any benefits of dilution short-lived.

The impact of the balance between oxygen consumption and re-aeration processes on downstream DO can be modeled using a rearrangement of the classic Streeter-Phelps equation for oxygen dynamics following a point source input of oxygen demand (Streeter and Phelps 1925):

$$DO_{ds,t} = DO_s - \left[ (DO_s - DO_{ds,0})e^{-k_a t} + \frac{k_d L_0}{k_a - k_d} (e^{-k_d t} - e^{-k_a t}) \right] \tag{2}$$

where  $DO_{ds,t}$  is the downstream DO  $t$  days after mixing,  $t$  is the time since mixing (days);  $DO_s$  is the saturation oxygen concentration ( $mg\ L^{-1}$ );  $DO_{ds,0}$  is the downstream DO immediately after mixing,  $L_0$  is the oxygen demand immediately after mixing ( $mg\ L^{-1}$ ;  $L = 2.664 \times [DOC]$  if all DOC is aerobically respired);  $k_a$  is the re-aeration rate constant ( $day^{-1}$ ); and  $k_d$  is the oxygen consumption rate constant ( $day^{-1}$ ). If the average flow velocity ( $U$ ,  $m\ s^{-1}$ ) is known, distance downstream ( $x$ ,  $m$ ) can be substituted for  $t$  ( $t = x/(86400U)$ ).

In lowland river systems the saturation oxygen concentration ( $DO_s$ ) is primarily dependent on water temperature and can be calculated using the empirical formulae such as (Cox 2003):

$$DO_s = 14.652 - 0.41022T + 0.00799T^2 - 7.7774 \times 10^{-5}T^3 \tag{3}$$

where  $T$  is the water temperature ( $^{\circ}C$ ). At higher altitudes or salinities, Eq. 3 can be modified to incorporate the effect of atmospheric pressure or salinity on saturation oxygen

water ( $mg\ L^{-1}$ );  $F_{bw}$  is the discharge (flow rate) the blackwater plume ( $m^3\ s^{-1}$ ); and  $F_{dil}$  is the flow rate in the dilution flow ( $m^3\ s^{-1}$ ). This equation can also be used for prediction of other conservative parameters (e.g., DOC) after mixing.



**Table 1** Comparison between the predicted (based on Eqs. 1 and 2) and measured persistence of dilution effect 110 river km downstream of dilution water inflow point at the Murrumbidgee and Murray River confluence

Date	Model inputs								Model output	Actual
	$F_{bw}$ ( $m^3 s^{-1}$ )	$DO_{bw}$ ( $mg L^{-1}$ )	$DOC_{bw}$ ( $mg L^{-1}$ )	$T_{bw}$ ( $^{\circ}C$ )	$F_{dil}$ ( $m^3 s^{-1}$ )	$DO_{dil}$ ( $mg L^{-1}$ )	$DOC_{dil}$ ( $mg L^{-1}$ )	$T_{dil}$ ( $^{\circ}C$ )	$DO_{ds}$ ( $x = 110$ km) ( $mg L^{-1}$ )	$DO_{ds}$ ( $x = 110$ km) ( $mg L^{-1}$ )
27/04/2012	160	1.1	22.5	19.0	235	6.0	12.8	19.0	4.6	4.6
1/05/2012	163	1.7	19.7	17.0	226	8.3	9.2	17.0	6.0	5.7
8/05/2012	149	2.0	10.6	15.5	205	9.5	6.0	15.5	7.0	6.6
15/05/2012	127	5.3	15.0	14.5	182	10.1	5.3	14.5	8.0	7.6
30/05/2012	98	7.5	7.7	13.0	134	10.2	4.9	13.0	8.9	9.1

concentration (APHA 2005); modifications which were not necessary in the current studies.

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

$$k_a = 3.93 \frac{U^{0.5}}{H^{1.5}} \times \theta^{(T-20)} \quad (4)$$

where  $U$  is the average flow velocity ( $m s^{-1}$ );  $H$  is the average water depth (m);  $\theta \approx 1.024$  (Chapra 1997); and  $T$  is the water temperature ( $^{\circ}C$ ).

During blackwater events, the oxygen consumption rate constant will depend primarily on DOC reactivity. For the Murray River system, where most of the DOC is derived from the leaf litter of the river red gum, *E. camaldulensis*, an oxygen consumption rate constant of  $k_d = -0.03 \text{ day}^{-1}$  at approximately  $20 \text{ }^{\circ}C$  has been derived from field and laboratory experiments (Whitworth and others 2012; Whitworth unpublished).

This simple model of downstream oxygen dynamics assumes that background primary production and community respiration are balanced (Oliver and Merrick 2006) and not modified by blackwater inputs. It is also assumed that DOC in the dilution water is of the same reactivity as DOC in the blackwater and that temperature and channel profile are constant downstream of the mixing point. We provide an electronic version of this model in Online Resource 2.

This model was applied to monitoring data from the Murrumbidgee confluence during the 2012 blackwater event, assuming an average water depth and channel width downstream of the confluence of 5 and 120 m, respectively. Modeled DO 110 river km ( $\sim 2$  days water travel time) downstream of the confluence proved to be very close to the measured values (Table 1). Although additional data from other river systems experiencing hypoxic blackwater events is required to fully verify the model, it serves as a useful management tool for estimation of the expected downstream persistence of dilution interventions for the mitigation of blackwater-associated hypoxia.

### Dilution Inflows as Refuge Plumes

Measurement of DO immediately ( $\sim 100$  m) upstream and downstream of the irrigation escape inflow point on the Wakool River on a single occasion in February 2011 revealed a greater DO increase than would be expected upon simple mixing of the two flows (escape DO =  $8.2 \text{ mg L}^{-1}$ , discharge =  $5.8 \text{ m}^3 \text{ s}^{-1}$ ; upstream DO =  $3.0 \text{ mg L}^{-1}$ , discharge =  $4.2 \text{ m}^3 \text{ s}^{-1}$ ; predicted downstream DO =  $6.0 \text{ mg L}^{-1}$ ; measured downstream DO =  $7.0 \text{ mg L}^{-1}$ ). This suggests a delay in mixing between the hypoxic and oxygenated waters. At this time, fish were observed to be congregating in the plume of oxygenated water.

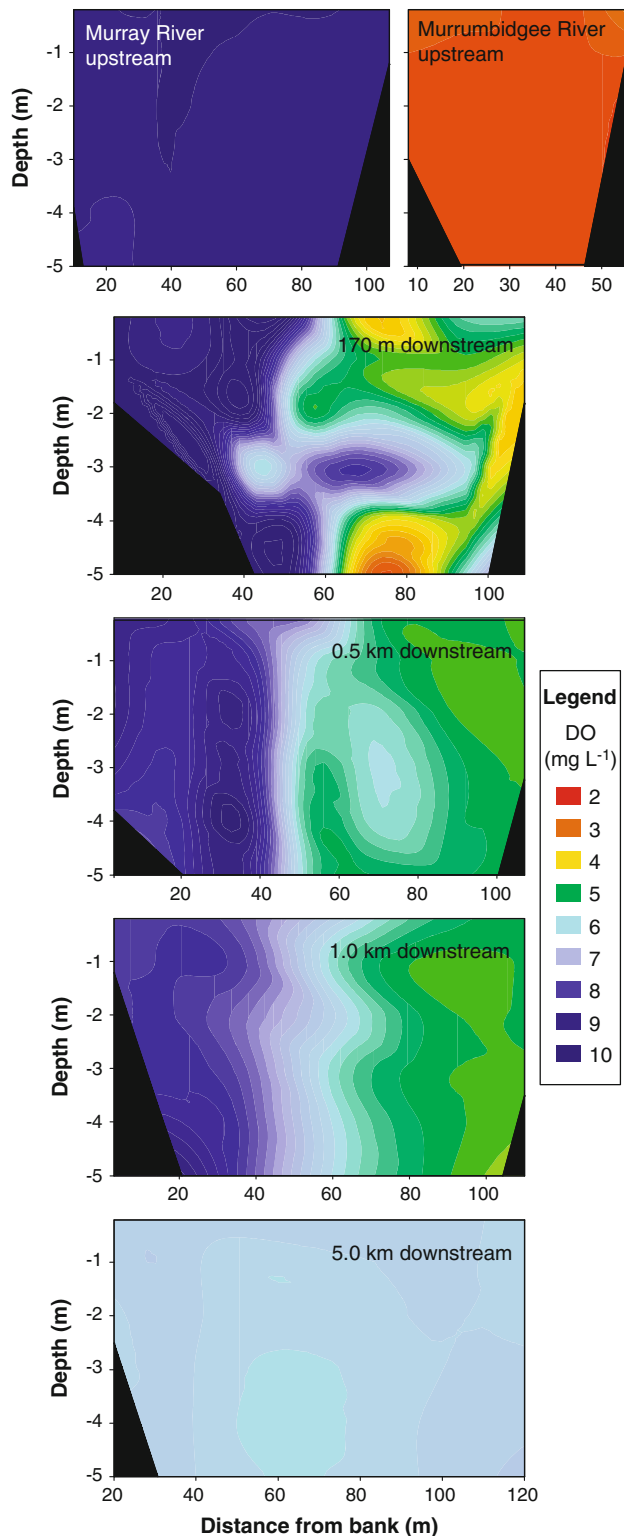
A detailed survey of mixing processes at the confluence of the hypoxic Murrumbidgee and oxygenated Murray Rivers also revealed a delay in horizontal mixing for several kilometers downstream (Fig. 2). A corridor of oxygenated water from the Murray River persisted past the junction (left side of Fig. 2), maintaining connectivity to oxygenated upstream refuge zones.

The monitoring data and fish observations suggest that oxygenated inflows, even if not of sufficient volume to adequately dilute hypoxic flows, may provide refuge points or connectivity to refuges for aquatic biota during hypoxic events, assuming other aspects of influent water quality are suitable.

### Dilution by Increasing Flow in a Hypoxic Reach

In the Murrumbidgee River system, DO as low as  $2 \text{ mg L}^{-1}$  had been recorded upstream of the Lowbidgee floodplain during December 2010, but during the environmental flow release period in early 2011, DO was generally above  $5 \text{ mg L}^{-1}$  (Fig. 1c). Downstream of the floodplain, DO was approximately  $0.5 \text{ mg L}^{-1}$  at the flood peak and generally increased as the hypoxic floodplain discharge decreased and dilution flows from upstream increased.

The expected impact of the dilution flows can be calculated from Eq. 1. For this calculation, the increase in



**Fig. 2** Mixing of hypoxic and oxygenated water at and downstream of the confluence of the Murrumbidgee and Murray Rivers. Flow direction is into the page for each profile

flow between Redbank (with 3-day offset to account for travel time) and Balranald during this period was used to estimate the volume of floodplain return water entering the

river channel between the two sites. The DO in the floodplain return water was estimated to be  $0.5 \text{ mg L}^{-1}$  (based on the measured DO at Balranald at the peak of the flood return flows; Fig. 1c).

The predicted DO based on Eq. 1 is generally higher (by an average of  $0.9 \text{ mg L}^{-1}$ ) than the measured value, but the general trend in DO is well represented by the model results (Fig. 1c). This suggests that the simple mixing model can also be used to provide an indication of the potential impact of increasing upstream releases on hypoxic blackwater dilution. The reduced model accuracy compared to application at channel junctions (Fig. 1a, b) is likely due to less precise estimates of floodplain return flow volumes and quality.

### Physical Re-aeration

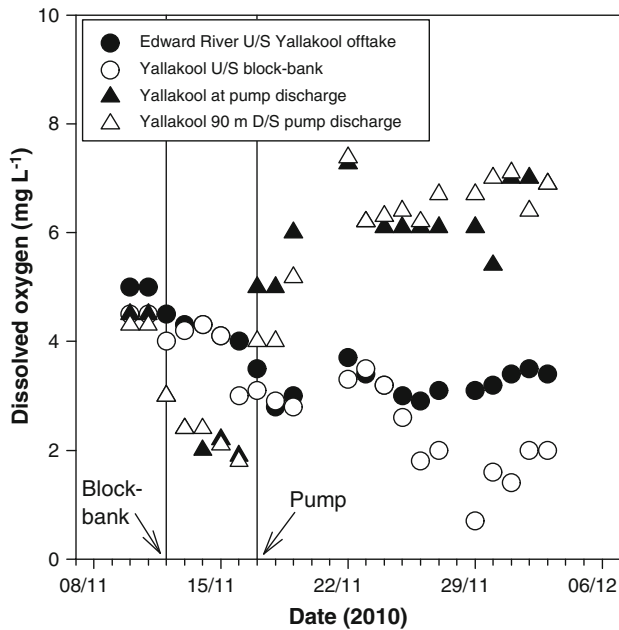
#### *Mechanical Aeration Using Paddle Wheels*

During the period of paddle wheel operation in the Swan Hill marina, DO values of  $0.1\text{--}3 \text{ mg L}^{-1}$  were recorded in the main Murray River channel at Swan Hill (data not shown). On the single occasion of DO measurement in the marina (3 February 2011), DO was  $0.1 \text{ mg L}^{-1}$  in the main channel,  $1.3 \text{ mg L}^{-1}$  in the center of the marina, and  $3.3 \text{ mg L}^{-1}$  at sites within 100 m of the operating paddle wheels in the marina. This degree of local aeration represents a substantial improvement in the aquatic habitat, raising DO to a level sufficient to enable many fish to survive (Gehrke 1988; McNeil and Closs 2007), although they may still experience stress. At the commencement of each paddle wheel operation period, cod that had appeared stressed by hypoxia regained their pigment and moved down from the surface within about 2 h. No fish deaths were recorded in the marina, despite the prolonged severe hypoxia in the main river channel.

#### *Mechanical Aeration Using Pumps*

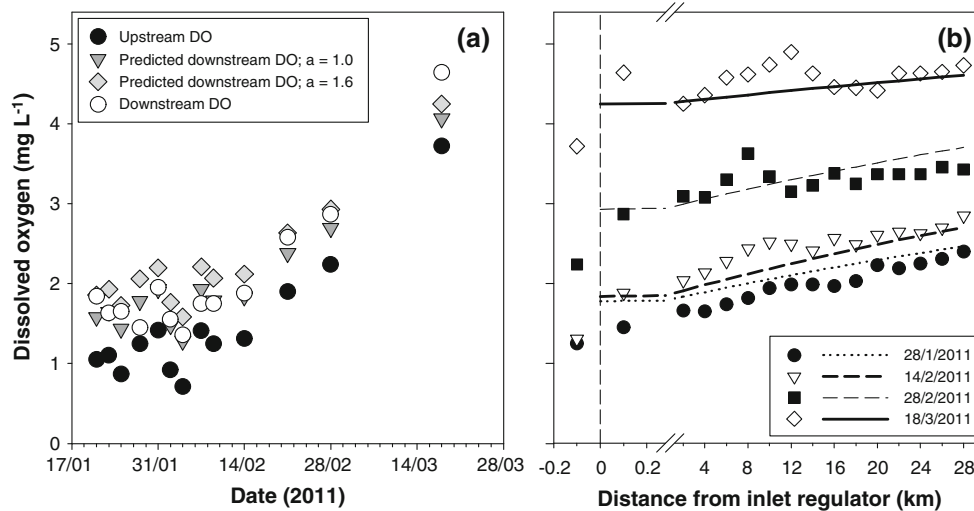
Prior to the installation of the block-bank on Yallakool Creek, the creek had been receiving flows above  $5.8 \text{ m}^3 \text{ s}^{-1}$  with DO levels above  $4 \text{ mg L}^{-1}$ . Upon cessation of flow, DO downstream of the block-bank dropped to below  $4 \text{ mg L}^{-1}$  within 1 day and to below  $2 \text{ mg L}^{-1}$  within 3 days (Fig. 3) and fish in downstream refuge pools were observed to be resorting to surface respiration. DO levels in the Edward River also fell during this time, but were generally approximately  $2 \text{ mg L}^{-1}$  higher than downstream of the block-bank.

The action of the pump transporting water around the block-bank promoted re-aeration, either by entrainment of air or by turbulent flow in the discharge stream. DO in the pump discharge water was approximately  $5\text{--}6 \text{ mg L}^{-1}$  and



**Fig. 3** Dissolved oxygen in the Edward River and Yallakool Creek upstream (circles) and downstream (triangles) of a block-bank. Reference lines show the date that the block-bank was installed and the date that a pump was installed to divert water around the block-bank

DO in the refuge hole 90 m downstream increased to 5 mg L<sup>-1</sup> on the first day of pumping and to >6 mg L<sup>-1</sup> within 4 days, despite a decrease in DO in the source water (Fig. 3). The refuge hole remained oxygenated (DO > 6 mg L<sup>-1</sup>) for the duration of the monitoring period and no fish kills were observed at this site.



**Fig. 4 a** Dissolved oxygen concentrations in Frenchmans Creek immediately upstream and downstream of the inlet regulator, compared to the predicted downstream concentrations based on Eq. 5 with two different *a* values (see main text for details). **b** The

*Use of Regulatory Structures for Aeration*

Dissolved oxygen levels in water entering Frenchmans Creek from the Murray River were below 2 mg L<sup>-1</sup> during January and February and below 4 mg L<sup>-1</sup> during March 2011 (Fig. 4a; see also Whitworth and others (2012)). Turbulence introduced by fall over the inlet regulator resulted in a mean increase in DO of 0.6 mg L<sup>-1</sup> over all monitoring occasions (*n* = 13, range 0.2–0.9 mg L<sup>-1</sup>) (Fig. 4a). This small increase was maintained in flows within Frenchmans Creek and further increases in DO of approximately 0.8 mg L<sup>-1</sup> were observed over the 28 km reach between the inlet regulator and the control regulator at the entrance to Lake Victoria (Fig 4b).

The re-aeration effect of flow over regulatory structures can be modeled using a modified version of the Gason equation, as cited in Butts and Evans (1983):

$$r = 1 + 0.38abZ(1 - 0.11Z)(1 + 0.046T) \tag{5}$$

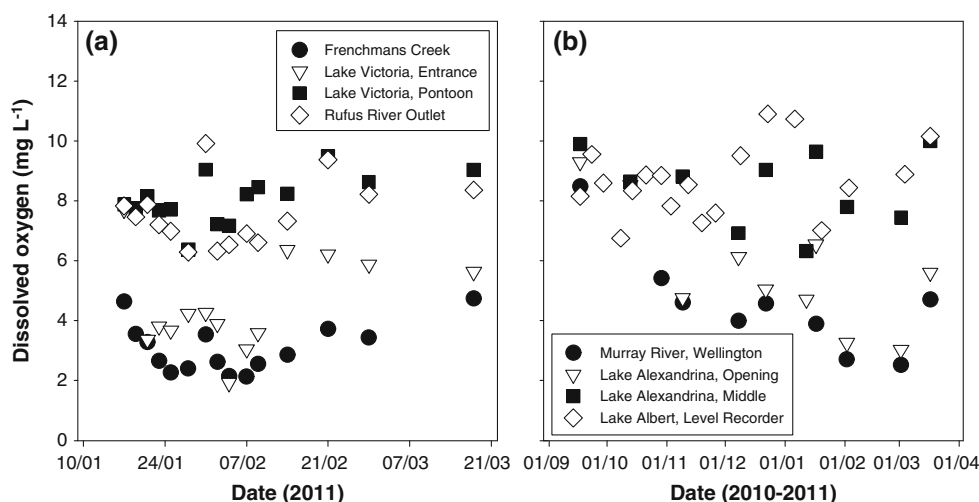
where *r* is the ratio of the oxygen deficit (difference from saturation) above and below the structure; *Z* is the distance of fall over the structure (m); *a* and *b* are empirical coefficients for water quality and structure type, respectively, as defined by Butts and Evans (1983); and *T* is the water temperature (°C). A model based on this equation is provided in Online Resource 2.

The re-aeration induced by fall over the inlet regulator is well represented by predictions based on Eq. 5 with *b* = 0.05 (structure type coefficient for sluice gates) and *a* = 1 (water quality coefficient for moderately polluted water) for data collected during the period of severe hypoxia (mid-January–mid-February 2011) and *a* = 1.6

measured (points) and predicted (lines; based on Eqs. 2 and 5) DO at 2-km intervals along the channel downstream of the inlet regulator on four monitoring occasions between January and March 2011



**Fig. 5** Dissolved oxygen concentrations in **a** Frenchmans Creek downstream of the control regulator, in the Frenchmans Creek inflow plume into Lake Victoria, in the center of Lake Victoria (Pontoon), and in the Rufus River between January and March 2011 and **b** the Murray River at Wellington, the entrance to the Lower Lakes and at sites near the centers of Lakes Alexandrina and Albert during the 2010–2011 hypoxic blackwater event



(slightly polluted) for data collected during the recovery period (mid-February–mid-March 2011) (Fig. 4a). Prediction of the downstream persistence of the re-aeration effect using Eq. 2 (estimating downstream channel width and depth of 60 and 3.2 m, respectively) also gives a good fit to the data (ignoring water travel time) (Fig. 4b).

Re-aeration and Dilution in Large Lakes

During the 2010–2011 hypoxic blackwater event, water quality at the entrance to Lake Victoria was impacted by a plume of hypoxic water from Frenchmans Creek (Fig. 4), particularly between mid-January and mid-February 2011 (Fig. 5a). Throughout the hypoxic blackwater event, DO remained high at other sites in Lake Victoria (Fig. 5a), including at the Rufus River outlet.

At the lower end of the MDB, hypoxic inflows from the Murray River between December 2010 and March 2011 resulted in a plume of low DO water at the entrance to Lake Alexandrina (Fig. 5b). However, DO at other sites across the lakes generally remained above 6 mg L<sup>-1</sup> (Fig. 5b).

During the blackwater event, daily inflows to Lake Victoria were less than 1 % of the storage volume of the lake (average storage volume January–March 2011 = 460 GL; average daily inflow 2600 ML day<sup>-1</sup>), but cumulative inflows over this period equate to exchange of approximately 50 % of the lake volume (assuming no hydraulic short-circuiting). Daily discharge in the lower Murray River was in the range of 2.2–4.5 % of the volume of the Lower Lakes between December 2010 and March 2011, with cumulative inflows totaling over 400 % of the average lake volume (average storage volume December

2010–March 2011 = 1,700 GL; average daily inflow 60,500 ML day<sup>-1</sup>; range 39,000–77,000 ML day<sup>-1</sup>).

Without re-aeration, this large hypoxic water input would have resulted in DO depletion in the lake water. Re-aeration and mixing due to wind shear over the surface of the shallow lakes and wave action at the lake margins evidently reintroduced sufficient oxygen into the water column on a daily basis to counteract low DO levels in inflows. Additionally, seiching—the movement of the entire water body with shifts in direction of the prevailing wind—would have promoted exchange of water into very shallow areas at the lake margins, further enhancing re-aeration. Many shallow (0.5–1.5 m deep) wetlands along the Murray River in South Australia also remained oxygenated despite being connected to hypoxic water in the main channel (data not shown).

The wind-driven re-aeration rate constant in standing waters can be modeled using an adaptation of the Wanninkhof equation (Chapra 1997; Gelda and others 1996):

$$k_a = 0.0986 \frac{U_w^{1.64}}{H} \times \theta^{(T-20)} \tag{6}$$

where  $k_a$  is the re-aeration rate;  $U_w$  is the wind speed (m s<sup>-1</sup>) at 10 m above the lake surface;  $T$  is the water temperature (°C); and  $H$  is the average water depth (m).

Equations 1 and 2 can be modified to predict oxygen dynamics in standing waters following the input of hypoxic blackwater, using lake water measurements as dilution water parameters and  $k_a$  as determined from Eq. 6 for the re-aeration rate constant. For continued hypoxic inflows, a batch model can be developed where a batch input of hypoxic blackwater and equivalent output of mixed lake water is assumed at each time step ( $s$ , days). The oxygen concentration at time  $t$  is:

$$DO_t = \frac{1}{V} \left\{ \left[ DO_s - \left( (DO_s - DO_{(t-s)}) e^{-k_a s} + \frac{k_d L_{(t-s)}}{k_a - k_d} (e^{-k_d s} - e^{-k_a s}) \right) \right] \times (V - F_{bw} \times 86400s) + (DO_{bw} \times F_{bw} \times 86400s) \right\} \quad (7)$$

where  $V$  is the total volume in the lake ( $m^3$ ),  $L_t$  (the oxygen demand term) is given by:

$$L_t = \frac{1}{V} \left[ L_{(t-s)} e^{-k_d s} \times (V - F_{bw} \times 86400s) + 2.664 DOC_{bw} \times F_{bw} \times 86400s \right] \quad (8)$$

and the other terms are the same as used in Eq. 2.

An electronic batch model based on these equations is provided in Online Resource 2. This model assumes complete mixing of the hypoxic inflows with the lake water at each time step, and no change in lake volume, average temperature, or wind speed during the analysis period. It is, therefore, difficult to fully verify this model using the current dataset. However, input of average and estimated values for these two sites during the hypoxic inflow period (Lake Victoria:  $F_{bw} = 30$ ,  $DO_{bw} = 3$ ,  $DOC_{bw} = 20$ ,  $V = 4.6 \times 10^8$ ,  $DO_{dil} = 8$ ,  $DOC_{dil} = 2$ ,  $H = 3.8$ ,  $U_w = 2.8$ ,  $T = 22$ ; Lower Lakes:  $F_{bw} = 700$ ,  $DO_{bw} = 2$ ,  $DOC_{bw} = 20$ ,  $V = 1.7 \times 10^9$ ,  $DO_{dil} = 10$ ,  $DOC_{dil} = 2$ ,  $H = 2$ ,  $U_w = 6$ ,  $T = 22$ ) reveals that over the period of hypoxic inflows, DO would not be expected to drop below  $6.8 \text{ mg L}^{-1}$  in Lake Victoria or  $7.5 \text{ mg L}^{-1}$  in the Lower Lakes, which compares favorably with the measured values at sites away from the blackwater inflow plume (Fig. 5).

## Discussion

Interventions targeted at reducing the severity or impact of hypoxic blackwater during the 2010–2011 and 2012 hypoxic blackwater events generally aimed to increase water column oxygen concentration on either a local scale or for some distance downstream. In some cases natural processes, such as wind and wave action and some instances of dilution, also served to increase the rate of re-oxygenation of hypoxic water. The effectiveness of these approaches varied in both the amount of net re-aeration achieved and the spatial extent of the re-aeration.

### Implications for Hypoxic Blackwater Management

Given that any single intervention may only result in a small improvement in water quality, a combination of management approaches may be required to reduce ecological harm

during a hypoxic blackwater event. Water management agencies in regions that may experience hypoxic blackwater events (particularly regulated river systems with forested floodplains) must develop event readiness plans which include regular monitoring activities and interventions (and community engagement) based on pre-determined trigger values (for example,  $DO < 4 \text{ mg L}^{-1}$  and  $< 2 \text{ mg L}^{-1}$  as approximate thresholds for fish stress and death; Gehrke 1988). To inform the development of such a plan, an action support flow chart for guiding the management of hypoxic blackwater, based on lessons from the case studies in this paper, is provided in Fig. 6. Excel versions of the models of the re-aeration potential of various interventions are provided as electronic supplementary material (see Online Resource 2). The suggested interventions focus initially on reach-scale re-aeration and then, if effective mitigation on this scale is not possible, progress down toward local refuge protection. Each intervention suggested in the flow chart may be undertaken in addition to the one prior. Any intervention should be accompanied by a rigorous monitoring program and the data used to further inform management direction and research both during and post-event. We discuss the suggested intervention approach below.

### Mitigation by Diversion to Shallow Off-Channel Storages

Observations from the 2010–2011 hypoxic blackwater event suggest that, with the exception of sites within inflow plumes, large shallow lakes are not likely to be severely impacted by prolonged inflows of hypoxic blackwater. Therefore, diverting hypoxic flows into large lake or wetland systems adjacent to the river channel (where these exist) is suggested on the flow chart (Fig. 6) as an initial intervention measure. After dilution and re-aeration has occurred, flow may be returned to the river as high-quality dilution water via a second channel, provided that the geomorphology of the lake does not encourage hydraulic short-circuiting between the two channels. Although this intervention decreases the benefit to riverine food webs of the return of floodplain carbon to the river channel (Junk and others 1989), it may be the best available option during a severe water quality event. Maintaining connection between the river and an off-channel lake or wetland system during a blackwater event may also allow aquatic biota to take refuge in the oxygenated lake water.

### Mitigation Using Dilution Flows

In many river systems, diversion to shallow off-channel storages is not possible or feasible. In this case, delivery of oxygenated dilution flows at channel junctions is the preferential management action for hypoxia mitigation.

We have demonstrated that the DO after mixing depends on the relative oxygen concentrations and discharge

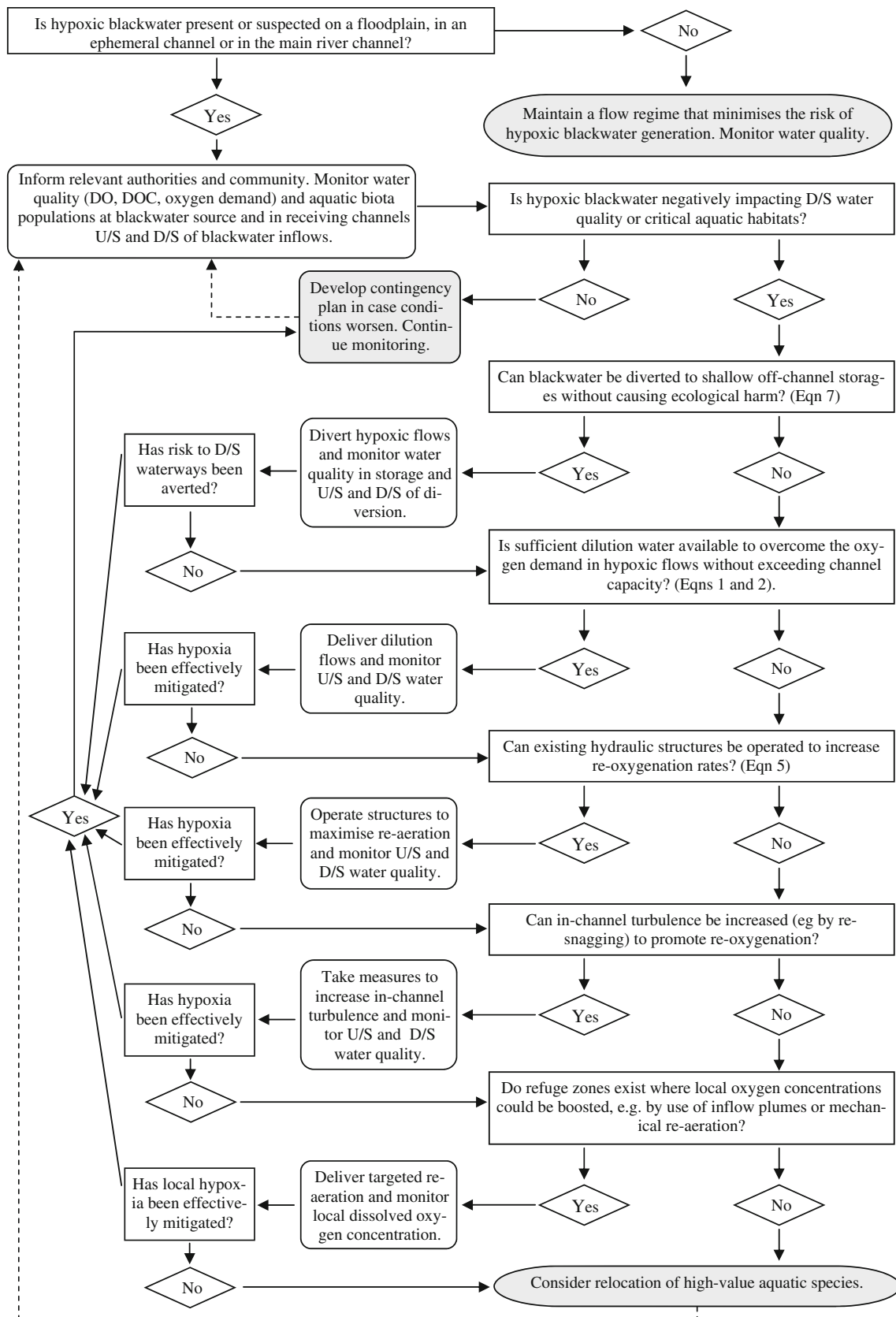


Fig. 6 Action support flow chart to inform the management of hypoxic blackwater

volumes of the blackwater and the dilution water and can be calculated using a simple mixing model (Eq. 1). When the dilution inflow is small compared to the hypoxic discharge or when the dilution water is not fully oxygenated, the benefit of dilution flows may only be minor. The persistence of any DO increase will depend on the oxygen demand remaining after dilution relative to re-aeration processes and can be estimated using an extension of the simple mixing model (Eq. 2).

In addition to delivery at channel junctions, increasing flows in hypoxic river reaches using environmental water delivery from upstream sources may be a beneficial mitigation strategy in some instances. However, accurate assessment of the degree of benefit provided by this strategy is hampered by limitation to the precision with which volumes and quality of the dilution and blackwater components of flow can be calculated. Additionally, care must be taken to ensure that flooding is not exacerbated by such an intervention; this strategy is best implemented on the falling limb of the hydrograph.

#### *Mitigation Using Physical Re-aeration*

If insufficient oxygenated dilution water is available to adequately dilute hypoxic flows or if the dilution effect is of limited duration, use of physical re-aeration methods may be necessary. Interventions designed to promote turbulence (e.g., a pump that entrains oxygen or discharges above the water surface, a paddle wheel aerator, fall over a regulatory structure, channel modifications such as re-nagging or introduction of flow obstructions) increase the surface area to volume ratio of the water body, enhancing oxygen diffusion across the air/water boundary. Maintaining sufficient flows to prevent water column stratification will also promote oxygenation of the entire water column (Bormans and others 1997).

For the case of fall over a regulatory structure, the expected re-aeration can be modeled using Eq. 5 and the downstream persistence can be predicted using Eq. 2. New structures on river systems prone to blackwater events can also be designed to provide optimum re-aeration benefits using these equations.

#### *Local Refuge Protection*

Where oxygen is being actively consumed at a high rate, as is often the case in hypoxic blackwater (Hladyz and others 2011; Whitworth and others 2012), turbulence needs to be maintained in order to achieve significant increases in DO. It would be prohibitively expensive to attempt to use mechanical means to re-oxygenate a large water body for several months. However, we have demonstrated that re-aeration can be used in a targeted manner to create

oxygenated refuges for aquatic biota. Small increases in DO, even if only in localized areas, may be sufficient to prevent fish deaths for the duration of the hypoxic event. We have also shown that dilution flows, even if not of sufficient volume to adequately dilute hypoxic blackwater, can create oxygenated refuge plumes or maintain connectivity to oxygenated upstream refuges.

#### *Other Considerations for Ecosystem Protection*

If all options for raising oxygen concentrations to a level sufficient to support biota are unsuccessful or not feasible, relocation of high-value species may be considered. Given the risks associated with extreme hypoxia and the physical or economic limitations to the implementation of many mitigation strategies, flow management (including appropriate floodplain wetting and drying regimes) to reduce the risk of hypoxic blackwater events occurring in the first instance is paramount (Hladyz and others 2011; Kerr and others 2013; Whitworth and others 2012).

#### **Conclusion**

Case studies from recent hypoxic blackwater events show that diversion of flows to off-channel storages; delivery of oxygenated dilution flows; and in-channel re-aeration using regulatory structures or other mechanical means all have the potential to promote re-oxygenation, but that in many cases only small or localized improvements in DO may be expected. We have developed an action support flow chart to guide management decisions and a set of simple spreadsheet-based models to enable assessment of the likely effectiveness of the various re-aeration options. An adaptive management approach to these interventions will inform future blackwater research and add to our understanding of the drivers of and controls on these severe water quality events.

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