Evaluating Use of Environmental Flows to Aerate Streams by Modelling the Counterfactual Case

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ABSTRACT

This paper evaluates an experimental environmental flow manipulation by modelling the counterfactual case that no environmental flow was applied. This is an alternate approach to evaluating the effect of an environmental flow intervention when a before-after or control-impact comparison is not possible. In this case, the flow manipulation is a minimum flow designed to prevent hypoxia in a weir on the low-gradient Broken Creek in south-eastern Australia. At low flows, low reaeration rates and high respiration rates associated with elevated organic matter loading in the weir pool can lead to a decline in dissolved oxygen concentrations with adverse consequences both for water chemistry and aquatic biota. Using a one dimensional oxygen balance model fitted to field measurements, this paper demonstrates that increased flow leads to increases in reaeration rates, presumably because of enhanced turbulence and hence mixing in the surface layers. By comparing the observed dissolved oxygen levels with the modelled counterfactual case, we show that the environmental flow was effective in preventing hypoxia.

24 KEYWORDS

25 Environmental water, hypoxia, reaeration, dissolved oxygen, counterfactual case

26

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33

34 INTRODUCTION

35 Dissolved oxygen concentration in streams reflects the balance of oxygen added by both
36 reaeration at the water surface and photosynthesis, and lost through ecosystem respiration
37 and oxidation of contaminants in the water column and boundary sediments (Diaz, 2001).
38 When oxygen consumption exceeds supply, oxygen concentrations decline (Diaz, 2001).
39 Elevated dissolved or particulate organic matter loading often produces declining oxygen
40 concentrations by supporting heterotrophic microbial activity and hence oxygen
41 consumption. The additional organic matter may be contributed by allochthonous sources
42 including floodwater draining off floodplains where dissolved organic matter is leached from
43 leaf litter, and sewage spills (Hladysz et al., 2011; McCarthy et al., 2014); or from autochthonous
44 processes stimulated by eutrophication such as algal blooms (Mallin *et al.*, 2006). Hypoxia
45 refers to low dissolved oxygen concentrations which impacts on aquatic animals through
46 suffocation, typically at concentration below 2 mg/l (Diaz, 2001). Hypoxia in streams has
47 been shown to alter fish behavior (Dwyer et al., 2014); increase mortality of fish (Small et al.,
48 2014) and freshwater crustacean (McCarthy et al., 2014); and reduce richness and abundance of
49 zooplankton (Ning et al., 2015), but effects will vary depending on the duration of the hypoxic
50 event.

51 The reaeration rate, defined as the net mass flux of O₂ from air to water, can be larger than
52 either oxygen production by photosynthesis or consumption by respiration (Aristegi et al.,
53 2009), making it a critical control on trends in dissolved oxygen concentration. For reaeration
54 to occur, O₂ gas must be transported across the air and water-side boundary layers (Gulliver,
55 2011). For a poorly soluble gas like O₂, the processes regulating exchange on the water-side
56 limit reaeration rates (Gualtieri and Doria, 2008). The two models commonly applied to
57 represent water-side gas-exchange emphasize the role of water-side near-surface turbulence
58 (Gualtieri and Doria, 2008). In the classical two-film model, turbulence reduces the thickness of

the concentration boundary layer thereby increasing oxygen concentration gradients within the diffusive sub-layer and hence mass flux for a given molecular diffusion coefficient (Gulliver, 2011). In the surface renewal model, turbulent eddies deliver oxygen rich water close to the interface, displacing oxygen poor water (Vachon et al., 2010). High correlations between field measurements of near-surface turbulent energy dissipation and interfacial gas exchange rates in natural streams over a range of sizes and flow conditions provide empirical support for the important role of turbulence (Vachon et al., 2010).

Reaeration rates (R) are usually modeled as the product of a reaeration coefficient (K_a) and the oxygen deficit given by the difference between saturated oxygen concentration (C_{sat}), which occurs at the water surface, and oxygen concentration below the water-side concentration boundary layer (C_w) (Gualtieri et al., 2002). Estimation of the reaeration coefficient is a major challenge in modelling stream oxygen balance (Grace et al., 2015). Large variations are produced by complex interactions of flow with boundary roughness and the effect of wind shear on the water surface, including formation of surface waves, all of which contribute to water-side near-surface turbulence. Direct measurement of K_a is possible using a gas tracer added to water but such measurements need to be repeated for any change in flow or wind conditions. Empirical equations based on repeat measurements at multiple sites have related K_a to wind speed, flow velocity, water depth, boundary roughness and stream slope as proxies for flow turbulence (Aristegi et al., 2009; Vachon et al., 2010). However, such models perform poorly when transferred to different sites (Gualtieri and Gualtieri, 1999; Melching and Flores, 1999; Parker and DeSimone, 1992; Riley and Dodds, 2013; Wilson and Macleod, 1974).

Grace et al. (2015) favour an alternate method where reaeration coefficients are estimated indirectly by fitting an oxygen balance model to a time-series of dissolved oxygen concentration measurements. This is based on a method first proposed by Odum (1956) to

84 infer rates of gross primary production and respiration of streams from diel variations in
85 observed oxygen concentrations. Respiration rates are assumed constant with diel variations
86 in O_2 assumed to the result of photosynthesis decreasing to zero during the night.

87 Various management strategies have been proposed to mitigate hypoxia in streams including
88 delivery of dilution flows; mechanical reaeration using pumps, paddle wheels and overflow at
89 structure; and diversion of blackwater (with high dissolved organic matter concentrations)
90 into shallow off-channel storages (Whitworth et al., 2013). In this paper we evaluate use of
91 environmental flows to enhance the natural process of stream reaeration. We examine the
92 case of delivering environmental flows in the Broken Creek to avoid hypoxic conditions in the
93 warmer months when flows would otherwise be low.

94 As with many environmental flow monitoring projects (Webb et al., 2010) it is not feasible to
95 evaluate the effect of the environmental flow using an experimental design such as Before-
96 After-Control-Impact. Instead, we use a model of the oxygen concentrations within the water
97 column, modified from Grace et al. (2015), to estimate levels for the counterfactual case that
98 there was no environmental flow delivered in the river. Model parameters are fitted using
99 observations of oxygen concentrations in the river over several months. The effect of the
100 environmental flow is evaluated by comparing observed dissolved oxygen concentrations
101 with those modelled for the counterfactual case. The benefits and limitations of this
102 counterfactual modelling approach are discussed along with the results of this study
103 evaluating a novel use of environmental flows to reaerate streams and avoid hypoxia.

104 CASE STUDY

105 Broken Creek lies in North East Victoria, Australia, with a catchment area of 3,300 km² and
106 mean daily discharge is 230 ML/d. It flows inland to meet the Murray River at the
107 downstream end of the Barmah Forest. The creek was historically, an ephemeral creek but a

108 series of weirs constructed along lower Broken Creek and flow regulation maintain
109 permanent water for irrigation through the dry summer season. Despite these hydrological
110 disturbances, the Broken Creek has a diverse native fish population, which includes several
111 species of recreational angling value and/or conservation significance, in particular Murray
112 Cod (*Maccullochella peelii*) and Golden Perch (*Macquaria ambigua*) (Rees et al. 2007). More
113 recently, vertical-slot fishways have been constructed on these weirs to allow for native fish
114 movements.

115 The final weir on lower Broken Creek, Rices Weir, has been beset by water quality issues,
116 centered on low dissolved oxygen concentrations with associated effects including increased
117 risk of fish mortality, altered biogeochemical cycling and eutrophication as nutrients are
118 released from sediments. Major fish kills have become a serious problem, likely caused by
119 eutrophication and low dissolved oxygen concentrations (hypoxia) in conjunction with little
120 or no flow (Koehn 2005, Rees 2006). Eutrophication is a particular problem because it can
121 increase the biomass and the coverage of *Azolla*, a floating fern. As the *Azolla* dies and settles,
122 it is thought to form organic-rich sediment with a high sediment oxygen demand that
123 stimulates recycling of carbon and nutrients into the water column, contributes to
124 maintenance of low dissolved oxygen and thus perpetuates the conditions for *Azolla* to thrive
125 (Rees et al. 2007). In recent years, environmental water has been delivered to the lower
126 Broken Creek specifically targeted at maintaining dissolved oxygen above 5 mg/L. These
127 environmental flows are delivered, typically at magnitudes of between 200 Ml/day and 300
128 Ml/day, between October and March when water temperatures are high and flows would
129 otherwise be very low.

130 This paper reports on the development of a dissolved oxygen model to assess the impact of
131 environmental flows on the dissolved oxygen concentrations in the lower Broken Creek.

132 Model parameters were calibrated using environmental data collected during the summer of
133 2012-13.

134 METHODS

135 *Data Collection*

136 Environmental measurements were made in Rices Weir during the 2012-13 irrigation season.
137 The flow velocity profile was monitored in the thalweg of Broken Creek, 15 m upstream of
138 Rices Weir using an IQ-plus Acoustic Doppler Current Profiler (ADCP, SonTek, USA). This
139 instrument uses high-frequency acoustic pulses to measure the Doppler shift from suspended
140 particles flowing through the water column to estimate 2-dimensional water velocity in 2 cm
141 'cells' from 4 cm below the water surface to 8 cm above the sediment surface. The ADCP was
142 installed on 25 October 2012 and set to record profiles every 15 minutes. From 17 January
143 2013, the profiling frequency was increased to every 2 minutes in preparation for a possible
144 flow manipulation experiment that did not proceed. Higher frequency measurements were
145 taken for the remainder of the data collection period, until the 12 May 2013.

146 Temperature profiles were also measured in the thalweg, approximately 2 metres
147 downstream of the ADCP. HOBO temperature loggers were suspended at 6 depths below the
148 water surface (0 cm, 14 cm, 34 cm, 49 cm, 66 cm, and 87 cm). The loggers were set to measure
149 temperature profiles every 5 minutes. Four HOBO dissolved oxygen sensors were installed at
150 35, 65, 93 and 118 cm below the water surface to record dissolved oxygen concentrations
151 every 5 minutes. This high resolution of dissolved oxygen measurement was aimed at linking
152 water quality with changes to flow, rather than just looking at the diurnal changes.

153 Meteorological conditions, including wind speed and direction, air temperature, relative
154 humidity, rainfall and solar radiation were also monitored from 25 October 2012 using a
155 Campbell's Scientific Automatic Weather Station. From 17 January 2013 a net radiometer was

156 installed in Rices Weir Pool to assess the extent of longwave emission from the water surface
157 and thereby allow an estimation of the irradiance available for photosynthesis.

158 *Model Development*

159 A one-dimensional oxygen balance model is used to assess the specific contribution of
160 environmental flow to the maintenance of dissolved oxygen concentrations using modified
161 equations from Uehlinger et al. (2000). The model represents the three primary processes
162 controlling dissolved oxygen levels: (i) oxygen production through photosynthesis; (ii)
163 oxygen consumption through respiration and chemical oxygen demand; and (iii) reaeration of
164 the water column at the water surface. In this way, the model can be used to simulate oxygen
165 concentrations with and without environmental flow delivery in lower Broken Creek.

166 The rate of change in oxygen concentration associated with photosynthesis (P), oxygen
167 consumption (C) and reaeration (R) (in units of $\text{kgm}^{-3}\text{s}^{-1}$) are represented using equations (1),
168 (2) and (3), respectively;

169

$$170 \quad P = \frac{P_{\max} I e^{-k_1 T_u}}{(K_P + I) d} \quad (1)$$

$$171 \quad C = \frac{-E}{d} Q^{(T_b - 20)} \quad (2)$$

$$172 \quad R = (K_R + a_1 W_d^{b_1} + a_2 W_c^{b_2} + a_3 U^{b_3}) (C_{\text{sat}} - C) e^{k_3 (T_s - 20)} \quad (3)$$

173

174 In these equations, $P_{\max}$ is the light saturated photosynthesis rate ($\text{gO}_2\text{m}^{-2}\text{s}^{-1}$), I is the light
175 intensity at the water surface (Wm^{-2}), K_P is the half-saturation light intensity (Wm^{-2}), T_u is the
176 water turbidity (NTU), k_1 represents the strength of turbidity dependence on photosynthesis,
177 d is water depth (m), E is the ecosystem rate of oxygen consumption at 20 °C ($\text{gO}_2\text{m}^{-2}\text{s}^{-1}$), Q
178 represents the strength of temperature dependence in oxygen consumption, T_b is the water
179 temperature at the streambed (°C), K_R is the reaeration coefficient in the absence of wind and

180 flow effects (s^{-1}), W_d is speed of wind (ms^{-1}) in the downstream direction (i.e. direction of
 181 longest fetch and equal to zero if wind is in the upstream direction), W_c is the speed of wind
 182 (m/s) of the non-downstream component of wind, U is the depth-averaged flow velocity (ms^{-1}), the parameters a_1 , b_1 , a_2 , b_2 , a_3 and b_3 represent the effect of wind and flow velocity on the
 183 reaeration coefficient, C_{sat} is the saturation oxygen concentration (kgm^{-3}) at the mean surface
 184 water temperature T_s ($^{\circ}C$), C is the depth-averaged oxygen concentration (kgm^{-3}) and k_3
 185 represents the strength of temperature dependence on reaeration. We have assumed a
 186 constant algal population and the model does not reflect any impact of Azolla, which was not
 187 present during the study period. The photosynthesis equation was modified from that of
 188 Uehlinger et al. (2000) to account for the effect of turbidity on light availability, the oxygen
 189 consumption equation was modified to account for effect of water temperature, and the
 190 reaeration equation was modified to account for wind and flow effects.

192 This is a one-dimensional model representing vertical exchange of oxygen at the water
 193 surface and both the generation and loss of dissolved oxygen within the water column and
 194 bed sediments. This approach assumes oxygen is well-mixed through the water column. The
 195 model also assumes there is no net lateral exchange of dissolved oxygen within the weir pool,
 196 which is a reasonable assumption given oxygen concentrations downstream through the weir
 197 show little variation (Gavin Rees, CSIRO, unpublished data).

198 The model uses an hourly time-step. Each hour the model calculates the rate of each of the
 199 three processes: photosynthesis, reaeration and oxygen consumption. The sum of these gives
 200 the net rate of change of dissolved oxygen through the water column during each hour.

201 Photosynthesis increases with solar radiation producing a diurnal pattern in dissolved oxygen
 202 levels. These changes can be summed over each 24 hour period to obtain the net daily change
 203 in dissolved oxygen concentrations. During periods of low solar radiation and reaeration we

204 can expect this to produce a declining level of dissolved oxygen. Hypoxic conditions are
205 produced when there is a sequence of such days.

206 *Model Calibration*

207 The model was calibrated using the observed depth-averaged dissolved oxygen
208 concentrations. Calibration data was available for all model variables for two periods: 15
209 November to 4 December in 2012; and 22 January to 7 March in 2013. Parameters (listed in
210 Table 1) were calibrated using three hourly mean oxygen concentrations. Whilst the model
211 simulated hourly variations in dissolved oxygen, we calibrated the model to minimize the sum
212 of square of differences between observed and modeled 3-hour moving average dissolved
213 oxygen. We used the three hourly-dissolved oxygen concentrations because the specific
214 hourly fluctuations are not of particular interest in this study. Rather the focus is on
215 representation of trends in dissolved oxygen over multiple days.

216 The effectiveness of environmental flow delivery can be simulated over the monitoring period
217 by manipulating the flow input into the model. This allows a comparison between the
218 observed dissolved oxygen conditions and that of a hypothetical or counterfactual condition
219 where no environmental flow is delivered.

220 4. RESULTS

221 Calibrated coefficients and exponents used in this dissolved oxygen model are shown in Table
222 1. The calibrated model reproduced the diurnal variations in dissolved oxygen concentrations
223 (Figure 1). However, it is the net change in dissolved oxygen over a 24 hour period that is
224 particularly important for this study of multi-day dissolved oxygen trends. Our model
225 reproduced multi-day trends in dissolved oxygen (Figure 1) although there is some error in
226 net daily change in dissolved oxygen for individual days (Figure 2).

227

Table 1. Parameters calibrated for the Dissolved Oxygen Model

$P_{\max}$	6.85 gO ₂ m ⁻² s ⁻¹	K_R	0.003 s ⁻¹	b_1	1.13
K_P	17.17 Wm ⁻²	a_1	0.20	b_2	1.12
k_1	0.0015	a_2	0.14	b_3	1.11
E	3.76 gO ₂ m ⁻² s ⁻¹	a_3	3.15	k_3	0.017
Q	0.017				

The effectiveness of environmental flow delivery can be simulated over the periods that the dissolved oxygen balance model was calibrated by manipulating the flow input into the model. This allows a comparison between the observed dissolved oxygen conditions and that of a hypothetical or counterfactual condition where no environmental flow is delivered. Without environmental flows, depth-averaged water column dissolved oxygen concentrations decrease to zero over both periods of simulation. In November 2012, simulated dissolved oxygen concentrations fell to zero after 11 days (Figure 3a), suggesting that photosynthesis and reaeration without flow were not sufficient to offset high respiration and sediment oxygen demands. Similarly, between the 21 January and 7 March 2013, modeled dissolved oxygen concentrations reached zero on the 1 February (Figure 3b). Modeled dissolved oxygen concentrations remained low in both simulations for the duration of the simulation with only brief periods where the minimum dissolved oxygen concentration during each diel cycle did not reach zero. As the rate of photosynthesis was not a function of flow in this model, the declining dissolved oxygen concentrations resulted from the accumulated daily oxygen deficit caused by a decreased level of turbulence-driven reaeration, which is flow-dependent in the model.

Insert Fig1, Fig2 and Fig3 here

252 DISCUSSION

253 Environmental water made up the majority of flow through the lower Broken Creek between
254 October 2012 and March 2013. The available evidence suggests that without this
255 environmental flow, dissolved oxygen concentrations, in Rices Weir pool would have been
256 substantially affected with extended periods less than 2 mg/l. In the absence of the
257 environmental flow, modeled results indicate that dissolved oxygen concentrations would
258 have undergone rapid and sustained depletion of dissolved oxygen, well below the water
259 quality guidelines (ANZECC, 2000). This study provides strong evidence that environmental
260 flows have been effective in maintaining moderate to high dissolved oxygen concentrations.

261 As has already been indicated, flow maintains a mixed water column that prevents the
262 formation of an anoxic hypolimnion and generates turbulence at the water surface promoting
263 oxygen exchange with the atmosphere (Stefan and Fang, 1993). However, the contrary effect
264 is also possible with increased flow flushing suspended solids from the riparian zone into the
265 stream, maintaining higher concentrations of entrained sediments and hence increased
266 turbidity levels. This will reduce light penetration and photosynthetic production of dissolved
267 oxygen (Vervuren *et al.* 2003; Nilsson & Renöfält 2008). This effect is not evident in data
268 collected during this study. Flow-induced mixing also supports transitioning of phytoplankton
269 type from buoyant cyanobacteria towards those reliant on mixing, such as diatoms (Sherman
270 *et al.*, 1998).

271 While the counterfactual model simulation of conditions without environmental flows
272 suggests that the reduction in reaeration dominated the decline in dissolved oxygen
273 concentrations, low levels of photosynthetic production or relatively high levels of respiration
274 and sediment oxygen demand could also have exacerbated this effect. The highly turbid water
275 during the experimental period may have reduced light availability and inhibited
276 photosynthetic production of dissolved oxygen, however this is unlikely to affect the model

277 output significantly. It is evident that turbidity measured between November 2012 and March
278 2013 (above 225 NTU) was significantly higher than previous studies at Rices Weir (130
279 NTU) (Rees et al., 2007) and elsewhere in the Murray-Darling Basin including the nearby
280 Goulburn River (above 50 NTU) (Fletcher et al., 1985), the River Murray above the confluence
281 with the Darling River (~28 NTU) (Walker and Thoms, 1993) and at Lake Alexandrina (80 –
282 120 NTU) (Skinner, 2012). The turbidity levels were also significantly higher than the period
283 either side of the study presented here. However, modeled estimates of photosynthesis in
284 Rices Weir reached $4.704 \text{ g m}^{-3}\text{d}^{-1}$, which is consistent with estimates from the literature, with
285 Rees *et al.* (2007) measuring production rates between $1 - 3 \text{ g m}^{-3}\text{d}^{-1}$ in Broken Creek, and
286 Oliver and Merrick (2006) reporting summer oxygen production rates of $4.2 \text{ g m}^{-3}\text{d}^{-1}$ for a site
287 on the River Murray in the Barmah Forest, in the vicinity of Rices Weir.

288 As the model treated the entire water column as a single, uniform cell, both sediment oxygen
289 demand and community respiration rates were added together to give a total oxygen demand
290 of $3.1 \text{ g m}^{-3}\text{d}^{-1}$. This is comparable, but at the lower end of previously measured summer
291 oxygen demand in the Broken Creek that ranged between $2.3 - 12.9 \text{ g m}^{-3}\text{d}^{-1}$ (Rees et al.,
292 2007). If our calibrated rate of ecosystem oxygen consumption (E) was an underestimation of
293 reality then the role of reaeration is also underestimated, emphasizing its importance in
294 maintaining dissolved oxygen levels. We suggest that estimates of oxygen production due to
295 photosynthesis are the most reliable of the three components of the oxygen balance because
296 the rate of oxygen production can be isolated from the diurnal fluctuations of dissolved
297 oxygen.

298 The average reaeration rate (R) modeled for the study period was 0.51 m.day^{-1} . This rate is
299 consistent with values used in the literature. Stefan and Fang (1993) reported surface oxygen
300 transfer velocity between $0.5 - 1 \text{ m.d}^{-1}$ for average wind speeds over seven lakes. For their
301 experimental site at Barmah, in the River Murray, Oliver and Merrick (2006) reported an

302 average reaeration component of 0.61 m.d^{-1} and a maximum of 1.16 m.d^{-1} in 1999. The
303 maximum reaeration component used at Albury, on the River Murray, upstream of Barmah
304 where water velocities are higher, was 3.19 m.d^{-1} (Oliver & Merrick 2006).

305 We have shown that a one-dimensional, deterministic dissolved oxygen model successfully
306 simulates the diurnal and monthly changes to dissolved oxygen. A simulation of changes to
307 dissolved oxygen in the lower Broken Creek without Commonwealth environmental water
308 provisions shows a rapid and sustained reduction in dissolved oxygen concentrations,
309 highlighting the importance of this environmental water delivery. Flow-induced mixing also
310 maintained a thermally uniform water column, with only transient periods of weak
311 stratification. The combination of flow, well-mixed water and more stable dissolved oxygen
312 concentrations also appeared to prevent any development of *Azolla* blooms.

313 This study demonstrates how the benefits of an environmental flow intervention can be
314 assessed using a model of the counterfactual case. This can be a useful alternative approach
315 where it is not possible to make before-after comparisons or comparisons at sites with or
316 without the intervention, a common situation for experimental environmental flow
317 manipulation studies (Webb et al., 2010). It needs to be recognized that the evaluation relies
318 on a modeled result and will be susceptible to model errors, unlike a comparison based on
319 measurements alone. Although not applied in this case, an analysis of model sensitivity (e.g.
320 Stewardson and Rutherford, 2008) to alternate parameter values or assumptions could be
321 used to build confidence in the model result. An even better approach would be to use a
322 statistical model where modeled counterfactual case is presented with confidence intervals
323 indicating uncertainty in the modeled result. Although not applied in this case, this is a
324 relatively straightforward additional component, for example using a Bayesian approach to
325 model parameter estimation and prediction (Webb et al., 2010).

326 The oxygen balance model, developed in this study, can also be used to design environmental
 327 flows in the future to avoid hypoxia. Indeed, the model could be used to operationalize
 328 adaptive management of environmental water. Each year, environmental monitoring can be
 329 used to improve the model performance by updating parameter estimates and potentially
 330 adjusting model structure. The model can then be used both to: (i) evaluate environmental
 331 flows delivered in the previous season for reporting; and (ii) design the following years
 332 environmental flow strategy. However, the efficacy of the model to inform environmental flow
 333 releases in this particular case may be constrained by the long travel times (several days)
 334 between the flow release point and Rices Weir. Further analysis is required to assess whether
 335 predictions using the model can be used to improve environmental flow management in this
 336 case.

337

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428 FIGURE CAPTIONS

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430 Figure 1. Modeled and observed time series of dissolved oxygen concentrations for two periods
431 where data are available

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433 Figure 2. Modeled and observed daily net change in dissolved oxygen concentrations (line indicates
434 1:1 ratio)

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436 Figure 3. Comparison of observed dissolved oxygen concentrations with modeled dissolved oxygen
437 concentrations, representing condition in the absence of environmental flow (average discharge
438 reduced from 332.7 ML/day to 23.3 ML/day)

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