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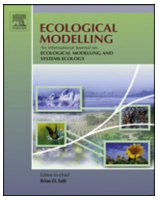

Effect of environmental flows on deep, anoxic pools

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ABSTRACT

A series of field surveys were carried out on two permanent pools of the upper Glenelg River in SW Victoria, Australia. One was representative of the wider and deeper pools while the other was representative of the more-narrow and shallower pools. Both pools showed a typical seasonal cycle of warm, brackish, oxygen-poor, summer conditions and cool, oxygen-rich, low-salinity, winter conditions. The summer salinity increases were larger than expected, suggesting possible saline groundwater inflow from unidentified springs. Both pools contained anoxic water in their deeper sections but this was permanent only in the deeper pool. A simple model of the flushing rate of such anoxic pools subject to flows, such as environmental flow releases, was developed, based on an energy balance between the potential energy required to lift the anoxic layer and the kinetic energy derived from the river flow. The results were tested against and in agreement with the field measurements. The model also suggests that the anoxic layers are resilient to all but the largest environmental flows.

1. Introduction

The Glenelg River in south-eastern Australia (Fig. 1) is typical of rivers in this region. It contains permanent pools whose deeper sections accumulate denser, saline water during periods of low flow that become anoxic and toxic to fish and other aerobic organisms. Anderson and Morison (1989) suggested that such stratified pools are ecologically important because they make a significant proportion of the river bed and banks unavailable to aerobic organisms, since branches and logs on the bed and banks that are a crucial habitat become inaccessible. A question faced by managers of these rivers is how environmental flows will affect the anoxic waters in these pools. However, identification of the formation and duration of extreme physicochemical conditions in rivers with reduced hydrological flow is critically important in being able to predict short- and long-term impacts of altered water quality on biotic communities.

Deoxygenation of the water column leading to hypoxic (<5 $mgO_2\ L^{-1}$) and anoxic (<1 $mgO_2\ L^{-1}$) conditions results in reduction in water quality. Rivers of south-eastern Australia exhibit well developed oxygen stratification associated with thermal stratification in summer (Turner and Erskine, 2005). Low environmental flows potentially intensify temperature and dissolved oxygen stratification leading to a reduction in suitable ecological habitat (Mulholland et al., 1997; Turner and Erskine, 2005). In addition to thermal and oxygen stratification, saline groundwater inflows produce salt stratification, which is also critically important to habitat viability in a freshwater system, particularly where freshwater discharge controlled salinity stratification results in an extended residence time (Turner and Erskine, 2005).

Anoxic conditions below the oxycline eliminate survival of all aerobic organisms and hypoxic conditions may impact on sedentary organisms unable to avoid hypoxic conditions and on native fish sensitive to low dissolved oxygen, such as *Galaxias* sp. and eel elvers (Landman et al., 2005). Hypoxia also elicits significant alterations in fish physiology (Pollock et al., 2007) and exposure reduces metabolic rate (Landry et al., 2007), elicits inhibition of gonadal development (Thomas et al., 2007), and inhibits embryo survival and hatch rates in native fish such as black bream *Acanthropagrus butcheri* (Hassell et al., 2008). Hypoxia also elicits inhibition of hatching, delayed embryonic development and mortality prior to metamorphosis in *Nassarius* gastropods (Chan et al., 2008), potentially found in the lower reaches of south-eastern Australian rivers.

Stratification is known to redevelop rapidly after having been overturned by wind mixing or increased environmental flow in south-eastern Australian rivers (Turner and Erskine, 2005). Such periodic hypoxia exposure represents a pulse disturbance that still has the potential to elicit deleterious response in aquatic organisms, and potentially restructure biotic communities (Jewett et al., 2005).

Sediment-bound phosphorus is released under reducing conditions, with order of magnitude increases in total phosphorus measured below the oxycline (Turner and Erskine, 2005). Effectively, this increases the nutrient loading available for P-limited cyanobacteria such as *Anabaena*, an anatoxin-a and saxitoxin-

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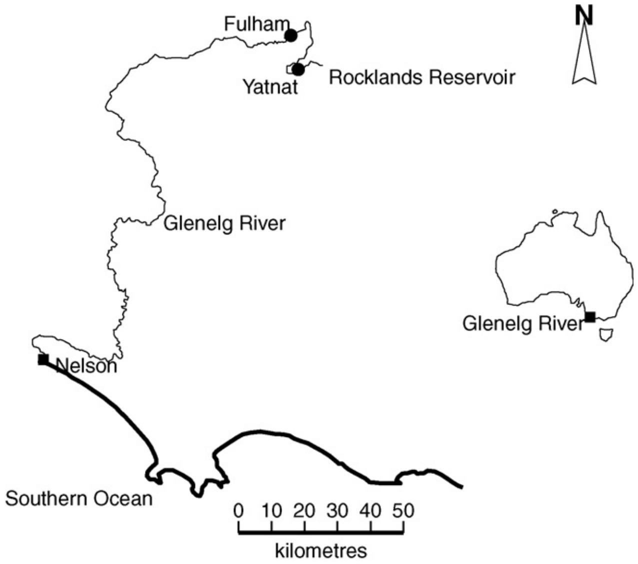

Fig. 1. A sketch map of the Glenelg River from the Rocklands Reservoir to its mouth at Nelson. The two field sites on the upper Glenelg River, the Fulham and Yat Nat pools, are marked.

producing species, present in rivers across south-eastern to south-western Australia (Hallegraeff, 1992; Ryan et al., 2008), representing significant health risks (Velzeboer et al., 2000; Haider et al., 2003).

Modelling observed oxygen profiles is a difficult task as it must incorporate highly coupled physical, chemical and biological processes that interact in complex ways. For example, Antonopoulos and Gianniou (2003) described a one-dimensional temperature–oxygen model to simulate a lake in northern Greece. It used a vertical-diffusion equation for temperature that was driven by solar radiation, with the turbulent eddy diffusivity calculated from the wind stress. A similar vertical-diffusion equation was used for oxygen transport and incorporated relatively simple terms for the biological consumption and production of oxygen. Solved numerically, the coupled equations showed diurnal and seasonal oxygen cycles linked to the duration of daylight, indicating the importance of solar heating. The model also showed the decrease in DO at depth, with a metalimnetic oxygen minimum due to the reduced physical mixing across the thermocline, but no anoxic conditions were observed.

Rather than solving coupled diffusion equations, Bell et al. (2006) used a one-dimensional, two-layer model with an empirical estimate for the diffusion parameter to simulate an English lake. The oxygen dynamics were more complex, though, using oxygen mass-balance equations with empirical relations for the oxygen consumption and production. Their results again showed diurnal and seasonal oxygen cycles linked to solar heating. The deeper oxygen concentrations were low in summer, when the stratification was present to limit vertical mixing across the thermocline, and, under suitable meteorological conditions, could lead to an anoxic deep layer. Such conditions were intermittent, however, and anoxia ended as soon as the stratification broke down and allowed oxygenated water to mix down into the deep layer.

The model of Hull et al. (2008) added additional complexity to the consumption and production terms in the one-dimensional, oxygen mass-balance equation, and used it to simulate DO profiles in Mediterranean coastal lagoons. The physical processes, however, were even simpler, with empirical estimates for the diffusive processes. The oxygen dynamics again showed solar-driven diurnal and seasonal cycles and the deeper oxygen concentrations were low in summer, with high probability of anoxic conditions.

These models are by no means an exhaustive list but they all demonstrated that anoxic conditions occurred only after the water column became stratified and prevented vertical mixing. However, they did not include the effects of salinity which is the dominant stratifying agent in the deep pools of the Glenelg River, nor were they intended to deal with the physical removal of the anoxic layer by flushing events. More complex, three-dimensional models, such as the coupled ERSEM (European Regional Seas Ecosystem Model) and POLCOMS (Proudman Oceanographic Laboratory Ocean Modelling System) combination, are required to model such flushing events, but these require very detailed data sets for the large number of ecological, chemical and physical parameters, and boundary and initial conditions, as well as considerable computing resources. Consequently, a simpler method to estimate the residence time and rate of erosion of the anoxic pools when subjected to environmental flushing flows is required. This is the intent of our paper.

The effect of flushing flows on dense-water pools has been discussed by Debler and Imberger (1996) and Debler and Armfield (1997). These authors performed laboratory simulations of the purging of saline pools of various sizes and bottom slopes in river beds, subject to both continuous and short-duration flows, and developed a relationship between the conversion of the kinetic energy of the freshwater inflow into the potential energy required to mix the fresh and saline waters. Western et al. (1998) also performed a laboratory simulation of the purging of saline pools in river beds, and observed that the dominant mixing process, when the pool was subject to higher velocity surface flows, was the removal of the saline water in a thin layer that flowed over the downstream slope of the pool. Such a feature was observed by Coates et al. (2001), who built a laboratory model to simulate many of the essential features of flushing flows, and measured the motion of a salt layer over a range of external forcing parameters. Using these data they demonstrated a direct relation between the depth of the salt layer and the forcing parameters that, like Debler and Imberger (1996) and Debler and Armfield (1997), was based on the conversion of the inflow kinetic energy into the potential energy required for mixing. They also demonstrated that the efficiency of conversion $k(t)$ was a strong function of time, although it did approach an asymptotic value.

Kirkpatrick and Armfield (2005) also performed a series of laboratory experiments on the purging of salt water from a rectangular cavity by an overflow of fresh water, and supplemented these with a series of two- and three-dimensional numerical simulations. They described the complex interactions between the fresh and salt water, with the resulting vortices driving significant mixing of fresh and salt water, and measured the flushing rate of salt water from the cavity. Their results were in good agreement with the predictions of Debler and Armfield (1997), once the conversion efficiency parameter had been calibrated against their data.

The results and functional relations of all these researchers, however, did not enable an easy estimation of the time of erosion of the anoxic layer under continuous and pulsed inflows that are typical of the regular water releases provided to establish environmental flows. However, Coates and Guo (2003) did develop such relations for the erosion of an estuarine salt wedge, and, in this paper, we follow their approach and develop a simple model to determine the flushing rate of the anoxic layer. We then present the field data from a year-long survey of the Glenelg River that were used to test our model before applying the model to some proposed environmental flows.

2. The model

It is convenient to analyse the field data in terms of the energy balance taking place as river water flows over the deeper anoxic