The role of bioirrigation in sediment phosphorus dynamics and blooms of toxic cyanobacteria in a temperate lagoon

Yafei Zhu [a, b, *], Matthew R. Hipsey [c], Andrew McCowan [b], John Beardall [d], Perran L.M. Cook [a]

[a] Water Studies Centre, Monash University, Clayton, Australia
[b] Water Technology Pty Ltd, 15 Business Park Drive, Notting Hill, Australia
[c] School of Earth and Environment, The University of Western Australia, Crawley, Australia
[d] School of Biological Sciences, Monash University, Clayton, Australia

ABSTRACT

A 3-D coupled hydrodynamic-biogeochemical/ecological model was developed and validated for the coastal Gippsland Lakes system, Australia, to explore the importance of bioirrigation on sediment phosphorus dynamics and the subsequent effects on the formation of summer blooms of *Nodularia spumigena*. Bottom water phosphorus concentrations and sediment phosphorus fluxes were most accurately simulated with bioirrigation implemented into the model. Further model simulations showed that bioirrigation selectively increased the flux of phosphorus relative to nitrogen leading to sediment N:P release ratios as low as 2. High summer phosphorus levels controlled the duration, size and severity of *N. spumigena* blooms; however, temperature and salinity were the primary factors that determined bloom formation and location. An assessment of sensitivity to model complexity identified that the model could only reproduce the observed *N. spumigena* bloom size when bioirrigation was implemented, highlighting the ecological importance of bioirrigation in phosphorus cycling and cyanobacteria bloom dynamics.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Cyanobacteria blooms are a common phenomenon in rivers, lakes and estuaries. Blooms in different systems can have very distinctive temporal patterns, for example, seasonal blooms that start in summer and last into autumn, persistent blooms that last across all seasons, or short-lived blooms that rapidly develop to a peak but collapse in just a few days or weeks (Havens, 2008). In general, warm temperatures, high solar irradiance, low turbidity, calm weather and vertical stratification are preferred by cyanobacteria (Perovich et al., 2008; Oliver et al., 2012; O'Neil et al., 2012). Wind- or flow-induced turbulence and destratification can remove the competitive advantage of cyanobacteria, and if such conditions persist, blooms may collapse rapidly (Paerl and Fulton, 2006; Liu et al., 2012).

It has been widely accepted that one of the main causes of

cyanobacteria blooms is increased nutrient loads derived from urban and agricultural sources (Carpenter et al., 1998). However, nutrient-rich sediment may prevent water quality improvement even if the external nutrient supply is reduced (Søndergaard et al., 2003; Jeppesen et al., 2005). Rapid phosphorus recycling at the sediment-water interface has also been found to be able to largely support the blooms of cyanobacteria in many systems around the world (Conley et al., 2009). In addition, a number of studies have shown that benthic fauna can contribute to a significant fraction of sediment phosphorus release (Gardner et al., 1981; Chaffin and Kane, 2010; Leote and Epping, 2015).

The Gippsland Lakes are one of the largest estuarine systems in Australia and suffer recurring toxic blooms of nitrogen-fixing *N. spumigena,* which are driven by major rain events during winter (Webster et al., 2001; Cook et al., 2010; Cook and Holland, 2012). Winter floods bring carbon and nutrients into the system, leading to intense vertical stratification and diatom and dinoflagellate blooms. The collapse of these blooms, as well as the high detritus input from the floods, can cause depleted bottom-water dissolved oxygen (DO), leading to an increase in the release of

phosphorus from the sediment that helps sustain blooms of *N. spumigena* when they are phosphorus limited. Recent work has shown that benthic fauna play an important role in phosphorus storage and release from the sediment in the Gippsland Lakes (Scicluna et al., 2015) yet the ecosystem scale relevance of this remains unknown.

It is increasingly understood the interplay of physiological processes in conjunction with hydrodynamic controls on environmental conditions is essential for simulating cyanobacteria blooms, with a number of studies now reporting the successful application of coupled hydrodynamic and ecological models (Cerco and Cole, 1994; Robson and Hamilton, 2004; Edelvang et al., 2005; Hu et al., 2006; Skerratt et al., 2013; Chung et al., 2014). An excellent example of such an interplay is the storage and release of phosphorus from the sediment which is tightly linked to water column stratification (Lukatelich and Mccomb, 1986; Cook et al., 2010). To capture these dynamics requires adequate simulation of sediment biogeochemistry across the system in order to capture the mass-balance of nutrients and the lag between nutrient accumulation and subsequent availability. However, many eutrophication models over-simplify or do not consider the dynamics of iron-bound phosphorus in the sediment or the effect of bioirrigation, which have been recommended to be included in water quality models by several authors (Chaffin and Kane, 2010; Thouvenot-Korppoo et al., 2012). The difficulty in capturing phosphorus dynamics in water quality models is highlighted by a previous study on the Gippsland Lakes, which failed to accurately model the release of phosphorus from the sediment in the Gippsland Lakes. One of the key recommendations of that study was that the factors controlling phosphorus storage and release in the Gippsland Lakes should be better understood and implemented into future models (Webster et al., 2001).

The main purpose of this study was to develop a 3-D coupled hydrodynamic-biogeochemical/ecological model for the Gippsland Lakes to investigate the impact of bioirrigation on the phosphorus cycle. A sensitivity analysis was subsequently undertaken to demonstrate that the changes to phosphorus dynamics brought about by bioirrigation could explain the size and distribution of a summer bloom of *N. spumigena*, even using a simple growth model without the need for parameterizing more complex life-cycle traits.

2. Study site

The Gippsland Lakes are the largest estuarine coastal lagoon system in Australia (Fig. 1). The system has a surface area of about 360 km^2 and is surrounded by a 20,000 km^2 catchment. It consists of three main lakes, which from the west to the east are Lake Wellington (138 km^2, less than 4 m deep), Lake Victoria (110 km^2, 3–10 m deep) and Lake King (92 km^2, 5–10 m deep). The deepest point is near Metung and can reach more than 16 m. Lake Wellington and Lake Victoria are connected by McLennan Strait which is a narrow channel about 10 km long, 80 m wide and up to 11 m deep. The lakes are connected to the ocean by an artificial entrance that was constructed in 1889. The entrance channel is 460 m long and 87 m wide at the south end. The average depth is about 6 m. There are more than 10 rivers delivering freshwater into the lakes but only 6 rivers contribute the majority of the fresh water inflow. The Avon, Thomson and Latrobe Rivers run into Lake Wellington; the Mitchell, Nicholson and Tambo Rivers into Lake King. The western rivers and eastern rivers each supply approximately 52% and 48% of the riverine freshwater inflows to the lake system respectively. The river flows can range from less than 0.1 m^3/s flow in the summer to 2000 m^3/s during a flood event. The system has suffered significant recurrent summer blooms of *N. spumigena* over the last few decades, making it a major

management concern since the blooms have caused substantial financial losses to the region.

3. Methods

3.1. Data collection

The model domain was constructed primarily based on the digital elevation model (DEM) developed by Wealands et al. (2002) for flood modelling, plus bathymetric survey data obtained for the entrance channel that was collected by Gippsland Ports (GP). LiDAR data covering the floodplain of the Gippsland Lakes was obtained from the Department of Sustainability and Environment (DSE). These datasets were used to compile the bathymetric input for the hydrodynamic model.

Meteorological data required by the model included hourly wind, mean sea level pressure, air temperature and cloud cover, daily rainfall, and solar radiation. These were obtained from weather stations at East Sale Airport and Bairnsdale Airport operated by the Bureau of Meteorology (BOM). Daily solar exposure from BOM was only available in MJ/m^2/day. However, the biological processes of the model require the input as Einstein (1E = 1 mol photons). A conversion factor of 1 E/m^2/day = 0.09783 MJ/m^2/day was therefore used, assuming photosynthesis can only use the visible light band (wavelength between 400 and 750 nm), which accounts for 45%–56% of the global radiation (Kirk, 1994). To convert the daily solar exposure to a time series of photosynthetic active radiation (PAR), a 5-min-interval time series of theoretical solar radiation was first generated using a MATLAB script developed by the Scripps Institute of Oceanography (http://mooring.ucsd.edu/). The time series was then scaled by the factors calculated by dividing the theoretical daily solar radiation by the observed.

A number of water level datasets were collected from various sources. A 4.5-year (May 2008 to October 2012) time series of the Lakes Entrance was measured by GP at a site located in the middle of Lakes Entrance inlet channel. A 21-year (1993–2013) simulated water level data offshore of Lakes Entrance was extracted from the Navy Coastal Ocean Model (NCOM) run by the Naval Oceanographic Office (NAVOCEANO). A 10-year (1992–2012) water level data set offshore of Lakes Entrance was simulated by the regional BLUELink model, jointly developed by CSIRO and BOM (Brassington et al., 2007). The above mentioned water level data were decomposed into tidal and non-tidal water levels using the MATLAB script developed by Pawlowicz et al. (2002) and was used to prescribe the offshore water level boundary condition for the hydrodynamic model. A tide water level time series was generated using the constituents analysed at Lakes Entrance GP with the replaced major constituents (O1, K1, N2, M2 and S2) predicted at the Lakes Entrance offshore by Hinwood and Wallis (Not Published). The non-tidal water levels were primarily formed by the residuals calculated at Lakes Entrance GP and extended by using the residual decomposed from the NCOM and BLUElink data. The ocean water temperatures and salinities were extracted from NCOM and BLUElink.

Daily river discharges and stream water temperatures were available from the Victorian Water Resource Data Warehouse and used to specify the river boundary conditions. For calculation of catchment nutrient loads, data from water samples taken by Water Ecoscience (WES) and Thiess Environmental (Thiess) on a regular basis since 1990 were used, which are also available from the Victorian Water Resources Data Warehouse.

Assessment of model performance was undertaken based on comparison with a range of hydrodynamic and biogeochemical datasets. In addition to the above data used for the ocean boundary, there was also a 36-year (March 1975 to December 2011) measured