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A modelling approach to determine systematic nitrogen transformations in a tropical reservoir

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ABSTRACT

The systematic nitrogen transformations were investigated in a tropical freshwater system using a three-dimensional Hydro-Eutrophication model, which simulated hydrodynamics, phytoplankton processes and nutrients cycling in Delft3D. The nitrification and denitrification processes were explicitly considered as the functions of water temperature and oxygen conditions in the model. The validated model was able to capture the thermal differences in vertical direction, reproduce the characteristics of nutrients cycles and primary productions across years with the forcing functions from the area-specific meteorological conditions, discharges and input loads. The modelled nitrification and denitrification process rates were verified by the lab process-oriented measurements.

The validated model preformed as a monitor, supplying the knowledge that sediment played an important role in nitrogen cycling, producing twice of the total external nitrogen load to water column. The water column bioactive nitrogen was controlled dominantly by phytoplankton assimilation, which had a nitrogen uptake rate of fifteen fold the external nitrogen loads. The bioactive nitrogen turnover rate by algal growth in this tropical water system was lower than the conditions in the other eutrophic lakes. Fifty-eight percent of the total external nitrogen load was retained via denitrification and burial processes in the Upper Peirce Reservoir.

The discovery of the systematic nitrogen transformations in tropical freshwater systems is proposed to be incorporated into future conceptual models of global nitrogen cycles.

1. Introduction

Excess nitrogen (N) from anthropogenic or internal sources has led to large changes in lake ecosystems, including water quality deterioration, shifts in biological species compositions and reduced biodiversity (Finlay et al., 2013; Galloway et al., 2008; Jeppesen et al., 2005; Moffat, 1998). During the past decades, great efforts have been made to understand the water quality of lakes impacted by external and internal nutrient loading (Forsberg, 1989; Jeppesen et al., 2005; Søndergaard et al., 2003). With advancement in the techniques for measuring microbial transformations, budgets of N transformations in water systems have become more detailed. It is reported that in-lake denitrification in combination with nitrification has the potential to remove substantial amounts of bioavailable N in aquatic ecosystems and thus provides valuable transformation pathways (Jensen et al., 1992; Jeppesen et al., 2005; Schlesinger, 2009). Benthic N loads and external N loads could contribute importantly to N contents in a water system (Burger et al., 2008; Jensen et al., 1992; Nilsson and Jansson, 2002; Rysgaard et al., 1995). Most current studies have focused on temperate lakes. There is great requirement to understand systematic N transformation rates in tropical waters to make effective management decisions to maintain or improve water quality.

Ecological modelling provides as an alternative research approach which has played a central role in biology and ecology for integration, prediction and understanding. It is clear that significant progress has been made over the last decades in the development of numerical process models (Jakeman et al., 2006; Jørgensen, 2010; Los and Blaas, 2010; Mooij et al., 2010). Among the series of current ecological models, a number of N-cycling models have been developed to focus on N transformations in the water system, including models specifically focusing on sediment-water inter-

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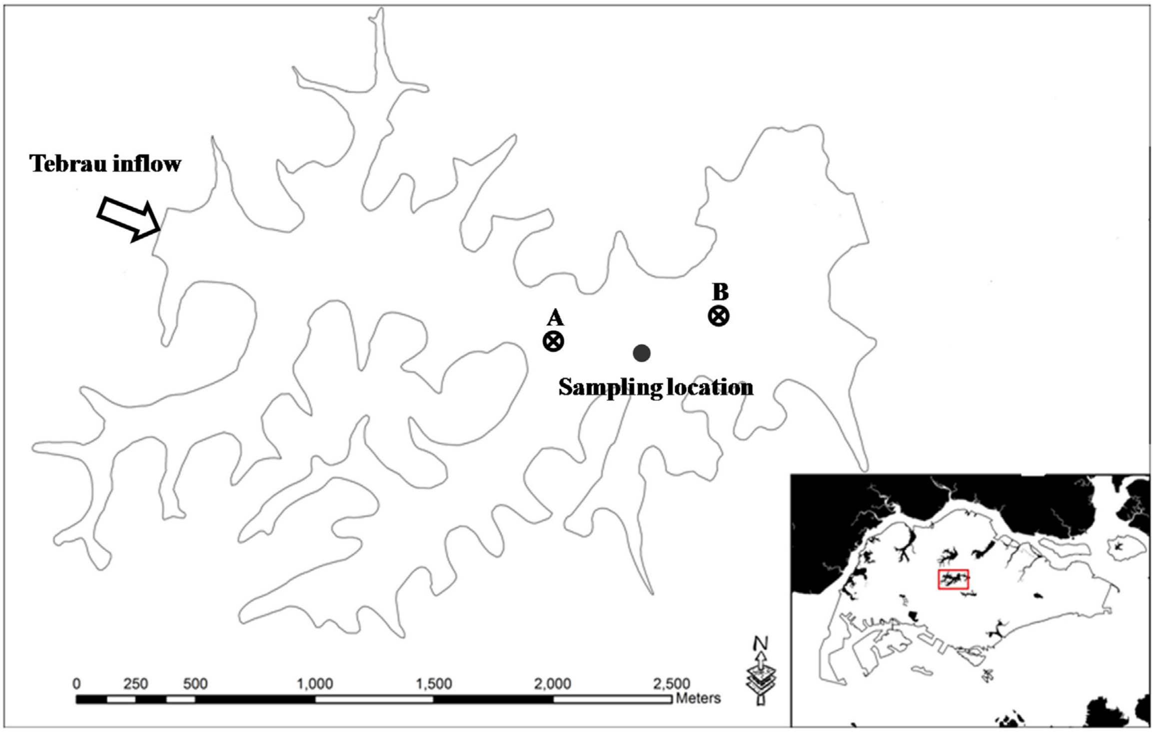

Fig. 1. The outline of the Upper Peirce Reservoir, Singapore. The map shows the water quality sampling location, the aeration system diffusers (A and B) locations and the external discharge point.

face interactions (Canavan et al., 2007; Robson et al., 2008; Testa et al., 2013) and subsequent impact on algal dynamics (Dørge, 1994; James et al., 2005). The former models considered more detailed N processes such as nitrification, denitrification and ammonification, burial and gaseous diffusion but only at sediment-water interface, excluding the effect from phytoplankton community such as N assimilation. The Lake Okeechobee Water Quality Model (LOWQM) described systematically the phytoplankton dynamics and sediment water nutrient interaction but this spatially-averaged model could not replicate spatial variability observed in the water column and sediments of the lake (James et al., 2005). A spatially explicit three dimensional system dynamic model is necessary to replicate the N transformations in a water system.

The purpose of the current study was to understand N transformation rates in a tropical freshwater system using a three-dimensional Hydro-Eutrophication modelling approach. The 3D Hydro-Eutrophication model was developed using Delft3D and validated by comparing the simulated physical and biochemical variables with the field observations. The quantifications of nitrification and denitrification rates obtained from small-scaled incubation experiments on the same system (Han et al., 2014) were used to compare with the modelled values. The model was consequently applied to understand the N transformations, N stocks and N retention in this tropical freshwater system.

2. Material and methods

2.1. Study site

Upper Peirce Reservoir is a tropical drinking water reservoir located in the center area in Singapore. Its surface area is 3.2 km^2 with a maximum depth of 22 m. The natural drainage area is comprised mostly of secondary tropical rainforest. An artificial aeration system was installed in the reservoir in 1990 to de-stratify the water column and prevent deoxygenation of the bottom waters (Sahoo and Luketina, 2006). An overview of the outline of the Upper Peirce Reservoir and the locations of the aeration diffusers is given in Fig. 1.

During the period studied here, the reservoir received a single point source inflow from the Tebrau River from Johor in Malaysia by way of a water transfer pipe (Fig. 1). This water discharge was stopped in 2011. The reservoir water was withdrawn for water treatment, irrigation as well as spilling to MacRitchie Reservoir and Lower Peirce Reservoir.

2.2. 3D Hydro-Eutrophication model description

The 3D Hydro-Eutrophication model was developed using the generic Delft3D model framework. This framework represents an integrated system containing several modules for simulation of wave transformation, near shore currents, sediment transport, morphology and water quality and ecology (Blauw et al., 2009; Lesser et al., 2004). In the current study, Delft3D-FLOW and Delft3D-ECO were applied to simulate lake hydrodynamic and eutrophication processes, respectively.

2.2.1. Hydro-submodel

The Hydro-submodel calculated the transport of dissolved substances in the water column as a function of advective and dispersive fluxes (Crank, 1975):

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} - \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right) + S + P \quad (1)$$

where C substance concentration (kg m^{-3}), u, v, w components of the velocity vector (m s^{-1}), x, y, x coordinates in three spatial dimensions (m), S source or sink of mass due to loads and boundaries (kg m^{-3} s^{-1}), P source or sink of mass due to physical, chemical and biological processes (kg m^{-3} s^{-1}), t time (s).

The hydrodynamic grid was developed using the orthogonal curvilinear grid generator Delft3D-Refgrid, consisting of a total of 1479 computational grid cells in the horizontal plane with a typical