Available online at www.sciencedirect.com
ScienceDirect
Estuarine, Coastal and Shelf Science 72 (2007) 690–702
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Nutrient and plankton dynamics in an intermittently closed/open lagoon, Smiths Lake, south-eastern Australia: An ecological model

Jason D. Everett [a,*], Mark E. Baird [b], Iain M. Suthers [a]

[a] Fisheries and Marine Environmental Research Lab, School of Biological, Earth and Environmental Science, University of New South Wales, Sydney, NSW 2052, Australia
[b] Climate and Environmental Dynamics Laboratory, School of Mathematics and Statistics, University of New South Wales, Sydney, NSW 2052, Australia

Received 16 August 2006; accepted 2 December 2006
Available online 21 March 2007

Abstract

A spatially resolved, eleven-box ecological model is presented for an Intermittently Closed and Open Lake or Lagoon (ICOLL), configured for Smiths Lake, NSW Australia. ICOLLs are characterised by low flow from the catchment and a dynamic sand bar blocking oceanic exchange, which creates two distinct phases − open and closed. The process descriptions in the ecological model are based on a combination of physical and physiological limits to the processes of nutrient uptake, light capture by phytoplankton and predator−prey interactions. An inverse model is used to calculate mixing coefficients from salinity observations. When compared to field data, the ecological model obtains a fit for salinity, nitrogen, phosphorus, chlorophyll *a* and zooplankton which is within 1.5 standard deviations of the mean of the field data. Simulations show that nutrient limitation (nitrogen and phosphorus) is the dominant factor limiting growth of the autotrophic state variables during both the open and closed phases of the lake. The model is characterised by strong oscillations in phytoplankton and zooplankton abundance, typical of predator−prey cycles. There is an increase in the productivity of phytoplankton and zooplankton during the open phase. This increased productivity is exported out of the lagoon with a net nitrogen export from water column variables of 489 and 2012 mol N d^{-1} during the two studied openings. The model is found to be most sensitive to the mortality and feeding efficiency of zooplankton.

Keywords: ICOLL; phytoplankton; zooplankton; model assessment; biogeochemical cycle; limiting factor; Australia; New South Wales; Smiths Lake

1. Introduction

Intermittently Closed and Open Lakes or Lagoons (ICOLLs) are a common type of estuary in south-eastern Australia. Of the 134 estuaries in New South Wales (NSW), 67 (50%) are classified as intermittently open estuaries (Roy et al., 2001). ICOLLs are characterised by low freshwater inflow, leading to sand barriers (berms) forming across the entrance preventing exchange with the ocean. Following a rise in the water level, these barriers are intermittently breached. Typically a narrow (<200 m), shallow (<5 m) channel forms, connecting the lagoon to the ocean, with reduced tidal velocities when compared to permanently open estuaries (Ranasinghe and Pattiaratchi, 1999).

The open/closed cycles of ICOLLs in south-eastern Australia are not seasonal due to the intermittent nature of rainfall (EPA NSW, 2000). The timing and frequency of the entrance opening are related to factors such as the size of the catchment, rainfall, evaporation, the height of the berm and creek or river inputs (Roy et al., 2001). Additionally, marine currents, wave activity, weather patterns and the strength of the initial breakout will determine how long the estuary remains open to the sea. As each of these processes is variable, open/closed cycles are rarely predictable and therefore, ICOLLs seldom reach any long-term steady-state (Roy et al., 2001). As an added complication, 72% of NSW ICOLLs

* Corresponding author.
E-mail address: Jason.Everett@unsw.edu.au (J.D. Everett).

0272-7714/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2006.12.001

are now artificially opened when they reach a predefined 'trigger' height (DIPNR, 2004). Reasons for this include flood prevention strategies and flushing in order to minimise pollution. Due to a lack of flushing, ICOLLs are particularly prone to pollution events such as nutrient or sediment runoff.

There are few published studies of ICOLLs in south-eastern Australia. Previous studies have focused on circulation (Gale et al., 2006), morphometric analysis (Haines et al., 2006), fish assemblages (Pollard, 1994; Jones and West, 2005) and benthic fauna (Dye and Barros, 2005). This study will focus on the water column nutrient and plankton dynamics of an ICOLL. Such studies have been undertaken in South Africa (e.g. Perissinotto et al., 2000; Froneman, 2004). However, South African estuaries typically open seasonally during the wet season, rather than intermittently like those in south-eastern Australia. In order to examine the open/closed cycles of an ICOLL, field data and the output of a process based model will be analysed.

Process based models of estuarine systems have been used with much success in the past (Madden and Kemp, 1996; Murray and Parslow, 1999). Recently, process based models of estuaries (Baird et al., 2003) and the open ocean (Baird et al., 2004) have included physical limits to key ecological processes. These limits include diffusion-limited nutrient uptake by phytoplankton cells or the grazing rates of zooplankton on phytoplankton. The latter incorporates an encounter rate calculation, based on the encounter rates of particles in a turbulent fluid, which places a maximum value on the rate of ingestion. The physical limits are used until a physiological rate, such as maximum growth rate, becomes more limiting. These physical descriptions provide an alternative methodology for the formulation of the key processes in the ecological model.

This paper presents an ecological model of an ICOLL, configured for Smiths Lake, and uses physical limits to describe key ecological processes. The aims are (1) to assess model performance using field data collected over two complete open/closed cycles, (2) to examine autotrophic growth limitation, (3) to assess model sensitivity to parameter selection and (4) to produce a nitrogen budget for each open/closed phase.

2. Methods

2.1. Field location

Smiths Lake (152.519E 32.393S) is located 280 km north of Sydney, on the mid-north coast of NSW (Fig. 1). It is classified as an ICOLL, with a catchment area of 33 km^2 (Webb McKeown & Associates Pty. Ltd., 1998) and a fluctuating lake surface area of 9.5–9.8 km^2. Over the course of the study, the lake height fluctuated between 0.15 m when open and 2.24 m Australian Height Datum (AHD) when closed. For a plot of Smiths Lake bathymetry see Figure 2 from Gale et al. (2006).

The Smiths Lake catchment remains relatively undeveloped. A population of 1100 people live within the catchment (Great Lakes Council, 2001). Due to low-lying development Smiths Lake is artificially opened by the local council when

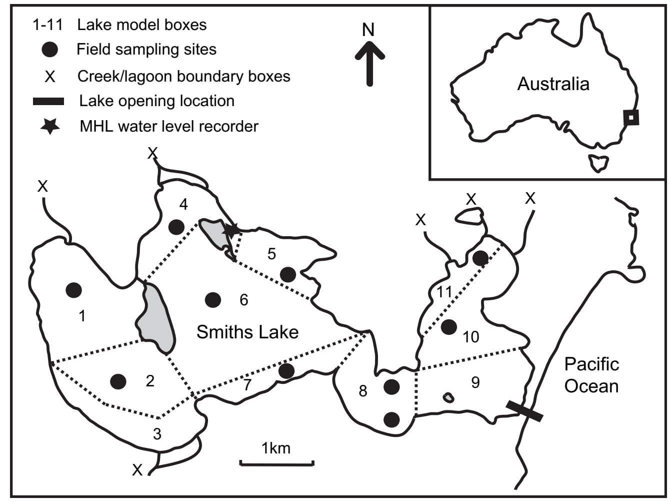

Fig. 1. Map of Smiths Lake with model boxes and sampling sites included. The ocean waters were sampled at Seal Rocks, approximately 4 km south of Smiths Lake.

it reaches 2.1 m AHD (G. Tuckerman – Great Lakes Council, personal communication, 2005).

2.2. Transport model

The model is spatially resolved to 11 lake boxes and seven boundary boxes (Fig. 1). The boundary boxes are representative of five small creeks, one small adjoining lagoon and an ocean box. The lake boxes were established to reflect subcatchment land use and topography, lake bathymetry, benthic habitat and sampling regime. The five creeks and one lagoon flow into boxes 1, 3, 4, 10 and 11, while exchange with the ocean only occurs at box 9 (Fig. 1). Boxes 3 and 9 do not contain field sampling sites.

The transport model is forced by evaporation (E), rainfall (R) and tidal exchange (TE). The influence of each of these physical forcings depends on the open/closed state of the lake (as outlined below). The transport of water column properties between adjacent boxes is modelled as a diffusive process. The equation for the change in concentration of a tracer in box i is given by:

$$\frac{dC_i}{dt} = \underbrace{\sum_{j=1}^{n} \frac{k_{ij}\left(C_j - C_i\right)}{V_i}}_{\text{Diffusion process}} - \underbrace{\frac{C_iE_i}{V_i}}_{\text{Evap}} + \underbrace{\frac{C_{cr}R_I}{V_i}}_{\text{Runoff}} + \underbrace{\frac{C_{oc}\mathrm{TE}}{V_i}}_{\text{Tidal exchange}} + \underbrace{\frac{C_i\,dV_i/dt}{V_i}}_{\text{Dilution}} \tag{1}$$

where C_i and C_j are the concentrations of box i and an adjoining lake box j (mol m^{-3}), V_i is volume of box i (m^3), k_{ij} is the transport coefficient between boxes i and j (m^3 s^{-1}), E_i is evaporation from box i (m^3 s^{-1}) and is negative, C_{cr} is the concentration of creek flow into box i (mol m^{-3}), R_I is the flow of water off the catchment into box i (m^3 s^{-1}), TE is the tidal flow into or out of the lake (m^3 s^{-1}), C_{oc} is the concentration in the ocean box (mol m^{-3}) and $n = 11$ is the number of lake boxes.