



## Potential effects of climate change and eutrophication on a large subtropical shallow lake

Carlos R. Fragoso Jr.<sup>a,\*</sup>, David M.L. Motta Marques<sup>b</sup>, Tiago Finkler Ferreira<sup>b</sup>, Jan H. Janse<sup>c</sup>, Egbert H. van Nes<sup>d</sup>

<sup>a</sup> Federal University of Alagoas, Center for Technology, 57072-970, Maceió, AL, Brazil

<sup>b</sup> Federal University of Rio Grande do Sul, Hydraulic Research Institute, CP 15029, Porto Alegre, RS, Brazil

<sup>c</sup> Netherlands Environmental Assessment Agency, P.O. Box 303, 3720 AH Bilthoven, The Netherlands

<sup>d</sup> Wageningen University, Aquatic Ecology and Water Quality Management Group, Department of Environmental Sciences, P.O. Box 8080, 6700 DD Wageningen, The Netherlands

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### ABSTRACT

In many aquatic ecosystems, increased nutrient loading has caused eutrophication, which is reflected in the trophic structure of the ecosystem. In Lake Mangueira, a large shallow subtropical lake in Brazil, nutrient loading has also increased, but it is still unclear what the effects of this increase will be and how this relates to climate change. To evaluate the effects of increased nutrient loadings in such large lake one would need to integrate hydrological and ecological processes into one model, an approach that has rarely been used before. Here, we apply different versions of a complex 3D ecological model, called IPH-TRIM3D-PCLake, which describes the integrated hydrodynamic, water-quality, and biological processes in the lake. First, the nutrient loadings from the watershed were estimated using a separate hydrological water quality model of the watershed based on field data. Second, we calibrated the 3D ecological model for a 6-year monitoring period in the lake using a simplified non-spatial version of the model. Finally, the calibrated ecological model was applied to evaluate the spatial explicit effects of different scenarios of land use, water pumping for irrigation, and climate change. On short term (1.5 year), the system seemed to be rather resilient, probably because of the lake size related to its high inertia. Our simulations indicated warming can increase water transparency in Lake Mangueira which may be related to two factors: (a) the current meso-oligotrophic state of the lake which may easily lead to nutrient limitation; and (b) submerged macrophytes grow during the whole season. The combined effect of climate change and increased nutrient loading, less strong than increased nutrient loading alone. The model can only be used for qualitative predictions of the effect of management scenarios, such as maintenance of water levels in the dry season, and water-pumping rules for irrigation in order to maintain the ecosystem structure and functions in the future under additional stress caused by increased use or climate change.

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### 1. Introduction

It is well-known that changes in external conditions such as climate, nutrient inputs, or management measures can lead to profound changes in the trophic structure and ecological functions of ecosystems such as coral reefs (Knowlton, 1992), deserts (Rietkerk et al., 1997), marine systems (Rahmstorf, 1997) and shallow lakes (Scheffer, 1998). Understanding the impact of nutrient loading on the trophic structure in ecosystems is difficult but important for ecosystem management. Often models are used

to estimate the combined effects of eutrophication and climate change. Due to a high complexity of ecological processes the results are often rather uncertain. An additional problem is that some processes may operate on very different time scales. An example of a system where the latter problem is especially relevant is a large shallow lake, where hydrological processes operate on a time scale of minutes, whereas their complex ecological processes operate on a much larger time scale.

Furthermore, the effects of climate change on the trophic structure in these lakes are significant and may interact with eutrophication (Straile and Adrian, 2000; Gerten and Adrian, 2001; Mooij et al., 2007). Most studies suggest that these changes will cause a decrease in water transparency due to several mechanisms, such as: (a) an expected increase of external nutrient loading by increase of net precipitation in the winter (Mooij et al., 2005); (b)

\* Corresponding author. Tel.: +55 5193181098.

E-mail addresses: [crubertofj@hotmail.com](mailto:crubertofj@hotmail.com) (C.R. Fragoso), [dmm@iph.ufrgs.br](mailto:dmm@iph.ufrgs.br) (D.M.L. Motta Marques), [tiagofferreira@hotmail.com](mailto:tiagofferreira@hotmail.com) (T.F. Ferreira), [jan.janse@pbl.nl](mailto:jan.janse@pbl.nl) (J.H. Janse), [egbert.vannes@wur.nl](mailto:egbert.vannes@wur.nl) (E.H. van Nes).

higher bacterial activity as a consequence of higher temperatures, increasing internal nutrient loading (Jensen and Andersen, 1982); (c) elevated temperature can favor the establishment of cyanobacteria, reducing the top-down control of zooplankton (Gliwicz, 1990); (d) resuspension may increase with the higher probability of the occurrence of strong winds (Schelske et al., 1995); (e) a different seasonal climate pattern might cause a mismatch between phytoplankton and zooplankton spring peaks, reducing the grazing pressure on phytoplankton (Winder and Schindler, 2004); and (f) fish predation on zooplankton can increase strongly (Mehner, 2000) and fish communities are expected to change dramatically (Jeppesen et al., 2010). However, these effects are far from certain, because opposite effects might also occur in other climates (Jeppesen et al., 2011). The dilution effect produced by increased inflow might for example attenuate nutrient concentrations. Increased temperature may also favor the spring clear-water phase caused by faster dynamics of both zooplankton and algae (Scheffer et al., 2001).

Simple models are often proposed to describe the effects of changes in external conditions on trophic structure of shallow lakes (Scheffer, 1998; Scheffer et al., 2001). Nevertheless, due to high non-linearity and the complex causal mechanisms found in freshwater ecosystems, a simple approach is not always adequate to evaluate the response of a system to such changes (Van Nes and Scheffer, 2005). Full-scale ecosystem models have been shown to be a good alternative to handle this complexity. Although such ecosystem models are widely used to evaluate the effects of eutrophication (Janse, 2005), recent work has demonstrated their usefulness concerning the effects of climate change in a temperate shallow lake (Mooij et al., 2007; Trolle et al., 2011).

In such complex full-scale models, it has usually been neglected that state variables are vertically and/or horizontally distributed in space, and that their distributions are profoundly influenced by local hydrodynamics (Mooij et al., 2010). Although the occurrence of patchiness has been known for a long time in marine systems (e.g. Steele, 1978), shallow lakes are often assumed to be horizontally and vertically homogeneous in modeling studies (e.g. Schindler, 1975; Thoman and Segna, 1980). It is well-known that horizontal spatial heterogeneity can be significant, especially for large shallow lakes (Fragoso Jr. et al., 2008). Wind-induced material transport is a dominant factor leading to both spatial and temporal heterogeneity of aquatic communities (Carrick et al., 1993), for instance by affecting the local nutrient concentration due to resuspended particles, or by resuspending algae from the sediment (Scheffer, 1998).

The purpose of this study is to model potential effects of nutrient enrichment and climate change on the trophic structure in a large subtropical lake. We use two integrated models to estimate (1) the nutrient loadings from watersheds and (2) the main ecological and hydrological components in the lake. We use different versions of the ecological model to cope with the differences in time scales of different processes.

## 2. Material and methods

### 2.1. Study area

Lake Mangueira (33°1'48"S 52°49'25"W) is a large freshwater ecosystem in southern Brazil, covering a total area of 820 km<sup>2</sup>, with a mean depth of 2.6 m and maximum depth of 6.5 m. Its trophic state ranges from oligotrophic to mesotrophic (annual average PO<sub>4</sub> concentration - 35 mg m<sup>-3</sup>, varying from 5 to 51 mg m<sup>-3</sup>). This lake is surrounded by a variety of habitats such as beaches, dunes, forests, grasslands, and two wetlands. This heterogeneous and productive landscape harbors an exceptional biological diversity, which motivated the Brazilian federal authorities to protect part of the entire hydrological system as the Taim Ecological Reserve in 1991 (Motta Marques et al., 2002). The watershed (c.a. 415 km<sup>2</sup>) is primarily used for rice production, with many associated water bodies used for irrigation, with a water withdrawal of approximately 2 L s<sup>-1</sup> ha<sup>-1</sup> on 100 individual days within a 5-month period and a high input of nutrients from the watershed during the rice-production period.

### 2.2. Description of the models

The nutrient loadings from the watersheds of the lake were estimated using a quality-hydrological model (IPH-II). These loadings were input for the ecosystem model (IPH-TRIM3D-PCLake) that was calibrated on monitoring data from a 6-year period considering the lake as completely mixed. We neglected spatial heterogeneity during this phase due to computational restrictions (six simulated years considering spatial heterogeneity took 5 days of running using an Intel Core 2 Duo 2.8 GHz) and because ecological processes have a slower temporal scale than the hydrological processes. After calibration, we applied the ecosystem model calibrated in scenarios of eutrophication and climate change, taking into account both horizontal and vertical spatial heterogeneity in the lake.

For the watershed analysis we developed a simple rainfall-runoff model (IPH2 model). Its mathematical basis is the continuity equation composed of the following algorithms: (a) losses by evapotranspiration and interception by leaves or stems of plants; (b) evaluation of infiltration and percolation by Horton (1937); and (c) evaluation of surface and groundwater flows (Tucci, 1998). We regard the drainage basin as a series of storage tanks, with rainfall entering at the top, and being split in a part that passes back to the atmosphere as evaporation, and a part that flows out of the basin as runoff (stream flow). Depending on the number of tanks and the number of parameters controlling the passage of water between them, the model can be made more or less detailed (it has a total of seven parameters per compartment). Nutrient loading was estimated by multiplying the simulated water discharge by the nutrient concentration measured during the rice-production period (i.e., surface wash-off from the rice crops). Thus, the contribution from each sub-basin was simulated with this model, which generated the time series of nutrient loadings for the lake for different land-use scenarios. The hydrological model output was used as boundary conditions (i.e. input) for the ecosystem model.

For the analysis of the lake ecosystem we used the IPH-TRIM3D-PCLake model, a complex ecosystem model (available to download at [www.peld.ufgrs.br](http://www.peld.ufgrs.br)). A detailed description of the model can be found in Fragoso Jr. et al. (2009). This model consists of a three-dimensional hydrodynamic module coupled with an ecosystem module. The model describes the most important hydrodynamic, biotic, and abiotic components of an aquatic ecosystem. The hydrodynamic model is based on the Navier–Stokes equations, which describe dynamically the three-dimensional flow. An efficient numerical semi-implicit Eulerian–Lagrangian finite differences scheme was used in order to assure stability, convergence, and accuracy (Casulli and Cheng, 1992; Casulli and Cattani, 1994). The chemical and biological dynamics in the open water and in the sediment is based largely on the PCLake model (for details see Janse, 2005). The IPH-TRIM3D-PCLake ecosystem model differs however from PCLake, as its form takes into account: (a) the horizontal spatial heterogeneity in the aquatic system at the cell level; (b) stratification over the water column for several state variables (temperature, water density, nutrients, phytoplankton, and zooplankton); and (c) more functional groups of fishes (which is needed to model the omnivorous fish species in subtropical regions).

In order to solve the advection-diffusion transport equation for each component in the water numerically, we implemented a flux limiting scheme that uses Roe's superbee limiter (Roe, 1985) with a second-order Lax–Wendroff scheme (Hirsch, 1990). Water temperature was modeled through a heat budget algorithm (Chapra, 1997). The closed boundaries of the modeled domain correspond to the shoreline, specifying a no-flux condition. No-slip boundary conditions were used for horizontal bottom boundaries, and free-slip boundary conditions were used for vertical land boundaries. Stress at the free surface due to wind was modeled as a momentum source distributed vertically over the surface wind-mixed layer (Hodges et al., 2000). The bottom drag coefficient was adopted as  $3 \times 10^{-3}$ , appropriate for a mud/sand bottom (Soulsby, 1983). The main inputs of the IPH-TRIM3D-PCLake model are: water inflow, infiltration or seepage rate (if any), nutrient loading, particulate loading, temperature, light, wind, rainfall and evaporation, spatial maps (including water body, bathymetry, bottom and surface stress coefficient, etc.), sediment features, and initial conditions.

### 2.3. Parameterization and model simplification

The inputs of the rainfall-runoff model (IPH-II) are some hydrological features of the watershed. A GIS program (ArcHydro/ArcGIS), was used to estimate the elevation, drainage-line definition, watershed delineation, and drainage-feature characterization from the Digital Elevation Model (DEM) provided by the Shuttle Radar Topographic Mission (SRTM), and adjusted by TOPODATA project (available at <http://www.dsr.inpe.br/topodata/>).

Most hydrological parameters of the ecosystem model (IPH-TRIM3D-PCLake) were determined by calibration on a time series of water level data of Lake Mangueira (2001–2006), seeking to close the water balance in the lake. Parameters related to infiltration were estimated *in situ* by infiltration tests using the double-ring infiltration method (ASTM, 1985). For the estimation of nutrient loading, we used the monitoring data from an extensive campaign carried out during an annual agricultural cultivation period (2005) in a representative rice field (watershed outlet No. 8, Fig. 1). We observed that the nutrient concentration had a distinct peak, Co, immediately after the fields were flooded in October, or after the young seedlings were set out (beginning of the cultivation period in November). From this time, the

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