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An integrated approach for urban water modelling, linking a watershed hydrological model and a cyanobacteria dynamics model in urban lakes

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ABSTRACT

In the future, the frequency and the intensity of cyanobacteria blooms in urban lakes are expected to increase in response to climate change and expanding urbanization. In order to study the impacts of watershed changes on cyanobacteria dynamics in urban lakes, a modelling approach, in which an ecological lake model is connected to a hydrological watershed model, is proposed. To validate this approach, the water quality (temperature, transparency, dissolved oxygen and chlorophyll-a) was monitored at high frequency (5-30 min) on two study sites in contrasted regions (climate, land-use…). In the first part of this paper, we show the advantage of using high-frequency data to simulate cyanobacteria dynamics in Lake Enghien (France), a temperate urban lake. In a second part, the methodology used, to link the ecological lake model and the hydrological watershed model is explained for Lake Pampulha (Brazil), a tropical urban lake. Some preliminary results of the ecological modelling of Lake Pampulha are also presented. The integrated modelling approach proposed, will allow us to study the lake response to different future scenarios of the watershed evolution. Furthermore, high-frequency data are expected to provide a better understanding of the lake functioning during extreme meteorological conditions (*e.g.* heavy rainfall events or drought).

KEYWORDS

Cyanobacteria, DYRESM-CAEDYM, high-frequency monitoring, urban lake, watershed modelling.

INTRODUCTION

Despite the importance of small shallow lakes in urban areas, research has mainly focused on large and deep lakes (Scheffer, 1998). Only recently, as the ability of aquatic ecosystems to provide services that benefit humans has been reduced, restoration projects have begun in many cities with the support of scientific teams who investigate the impacts of urbanization on lake functioning (Havens *et al.*, 2001; Ruley and Rusch, 2004). Furthermore, only recent studies have taken into account the impacts on urban aquatic ecosystems caused by global changes such as climate change and urbanization (Trolle *et al.*, 2010).

Meteorological forcing governs many of the physical aspects of lake ecosystems (e.g. lake temperature and its stratification) which affect the physiology, life history and development of phytoplankton and fish communities (Blenckner *et al.*, 2007). Phytoplankton communities, especially cyanobacteria, play a key role in aquatic environments since they are potential producers of toxic substances, which disrupt water uses and cause health problems (Huisman *et al.*, 2005). The effects of climate change on the physical and ecological dynamics in lakes can be diverse, each lake may respond in different way to the climate change (Tanentzap *et al.,* 2008). Although, it is generally expected that global warming will increase primary production in most lakes and favour cyanobacteria blooms (Paerl and Huisman, 2008): by (1) rising water temperature, since cyanobacteria usually grow better at high temperature than other phytoplankton species; (2) lengthening the growth period, i.e. earlier stratification in spring and later destratification in autumn; (3) affecting patterns of precipitation and drought which can intensify surface and groundwater nutrient discharge into water bodies and increase water residence time.

On the other hand, urbanization has intensified exchange of nitrogen and phosphorous between lands and surface water, which increases the input of nutrients in aquatic environments and contributes to accelerate their eutrophication (Zhang and Jørgensen, 2005). In urban regions, nutrient load traditionally comes from two sources: point sources, as municipal and industrial wastewater outlets and; non-point sources, as atmospheric deposition and drainage water. Point loadings are usually easy to characterise, since they do not depend on stochastic processes such as precipitation and temperature. On contrary, non-point loadings are difficult to estimate accurately due to the stochastic hydro-chemical processes and the heterogeneity of soil and vegetation properties (Nikolaidis *et al.*, 1998).

Actually, there is a strong need to investigate the links between the ecological lake functioning and watershed changes (land-use and climate changes). Recent studies have proposed modelling approaches to help in defining future scenarios, which can be very helpful to estimate lake response to different environmental management strategies or to different global changes (Hornung, 2002; Trolle *et al.*, 2010; Zhang and Jørgensen, 2005). This paper presents a modelling approach in which an ecological lake model is connected to a hydrological watershed model to study the impacts of future watershed changes on cyanobacteria dynamics in urban lakes. In the first part, we show the advantage of using high-frequency data to simulate cyanobacteria dynamics in a temperate urban lake. In a second part, the methodology used to link the ecological lake model and the hydrological watershed model is explained for a tropical lake and the first results of the lake ecological model are presented.

CYANOBACTERIA DYNAMICS IN A TEMPERATE URBAN LAKE

Study site. Lake Enghien-les-Bains is located in France, 11 km north of Paris (48°58'N, 2°18'E, see Figure 1). It is an urban shallow lake that plays a significant role in the stormwater management of its watershed by stocking up to 100,000 m^3 of stormwater. The main physical characteristics of the water body are listed in Table 1. Besides stormwater, the lake receives wastewater due to inappropriate connections in the stormwater network, resulting in the deterioration of lake water quality (SIARE, 2004). Water quality monitoring revealed that Lake Enghien is affected by blooms of *Planktothrix agardhii (*Quiblier *et al*. 2008).

Lake ecological model. In limnology modelling, hydrodynamic models are frequently coupled to ecological models: the former described the physical processes of transport and mixing in the water column, while the latter represent the main chemical and biological processes that affect phytoplankton and higher trophic levels (Hamilton and Schladow, 1997). The deterministic coupled model DYRESM-CAEDYM (DYCD, developed by the Centre for Water Research - CWR at University of Western Australia) is used in order to simulate water temperature and cyanobacteria dynamics in Lake Enghien.

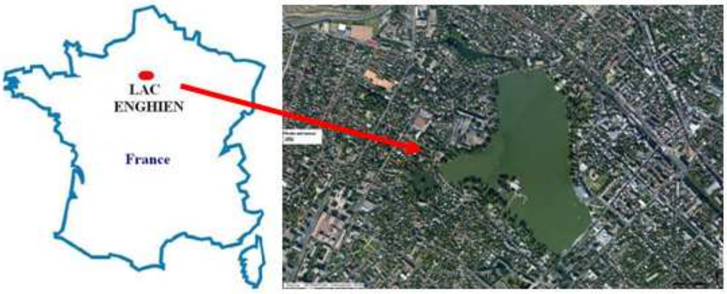

Figure 1. Lake Enghien-les-Bains location and its surrounding (IAURIF, 2008)

The input data required are: lake morphometry, inflows (water temperature and nutrient concentrations), outflows, meteorological forcing (wind speed, air temperature, solar radiation, rainfall, cloud cover and vapor pressure), and the initial conditions for cyanobacteria biomass, nutrient and dissolved oxygen concentrations and water temperature (see Figure 4).

Data collection. Most data necessary to run and validate DYCD were obtained from a measurement buoy installed on the lake in November 2008 within the PROLIPHYC research project (Monitoring system of phytoplankton blooms - application to cyanobacteria). This buoy was equipped with meteorological sensors and immersed probes which measured every 30 min, at a depth varying from 0.50 to 1.0 m, dissolved oxygen concentration, water temperature, pH, conductivity, total chlorophyll-a concentration and chlorophyll-a concentration associated to four different groups of phytoplankton: cyanobacteria, chlorophyceae, diatoms and cryptophyceae. More technical details about buoy sensors and probes are described in Proliphyc Group (2010), Silva (2010) and Le Vu *et al.* (2010). The hydrological data are very scarce and only allowed us to establish a linear relationship between rain and discharge rates based on 2004 measurements (SIARE, 2004). Inflow quality (NO_3, NH_4, PO_4^{3-} concentrations) was estimated from point measurements carried out in Spring 2008 (Marchandise, 2008). The initial set of parameters of the physiological characteristics of *P. agardhii* (maximum growth rate, optimum and maximum temperature) was based on *in vitro* experiments (Oberhaus, 2007; Post *et al.*, 1985). The maximum and minimum thicknesses of the Lagrangian layers were also calibrated.

*Simplified modelling approach***.** DYCD configuration was chosen in order to represent only cyanobacteria, the dominant phytoplankton group throughout the year 2009. Simulations were run on short time periods (about 15 days). DYCD was manually calibrated from 1 to 16 June 2009, period corresponding to the first cyanobacterial bloom of the year. The calibrated model was applied to simulate the period from 3 to 18 July 2009, in which cyanobacteria chlorophyll-a concentration reaches its maximum value over the year (360 μg chlorophyll-a.L^{-1}).

Results. Model results show good agreement with measurements (Figure 2). The goodness of fit is assessed through the correlation coefficient (r) and the root mean square error (RMSE). Water temperature evolution during the two periods is successfully described by the model, respectively r = 0.91; RMSE = 0.98°C and r = 0.95, RMSE = 0.65°C. Cyanobacteria dynamics is also well captured by the model (r = 0.97; RMSE = 15.8 μg chl-a.L^{-1} and r = 0.71; RMSE = 25.7μg chl-a.L^{-1}). The good fit of the temperature model enables a reliable modelling of cyanobacteria growth, whose prior control factor is water temperature.

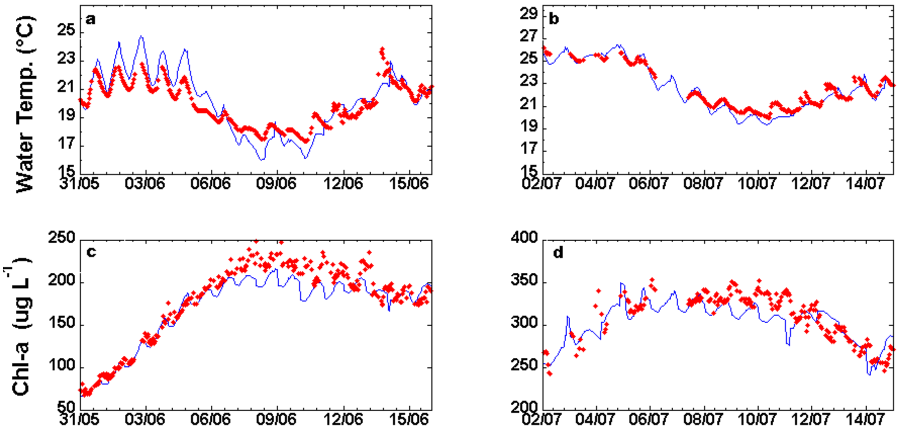

Figure 2: Lake Enghien (2009): model results at a depth of 0.75 m (line) and buoy data (dots) for water temperature (a, b) and cyanobacteria chlorophyll concentration (c, d).

The high frequency of data acquisition provides a thorough assessment of the model performance since its results were compared with buoy measurements at hourly time-step. Complementary high-frequency measurements of nutrient concentrations and inflow rates would enable us to improve model results.

Integrated catchment-lake modelling approach in a tropical urban lake

Study site. Lake Pampulha is a reservoir in Belo Horizonte city, Brazil (19°55'S, 43°56'W, see Figure 3). It is fed by eight small creeks, Sarandi and Ressaca creeks being the most important (70% of the inflow rate) and also the most polluted ones (Friese *et al.*, 2010). The main physical characteristics of Lake Pampulha are listed in Table 1. Originally, the reservoir was built to supply drinking water to the city, however, since the 1970s, the water quality has degraded as a consequence of the rapid watershed urbanization with neither sanitation infrastructure nor erosion control. Nowadays, lake silting and the reduction of its storage capacity, water eutrophication and the consequent increase of primary production with episodes of cyanobacterial blooms and excessive growth of macrophytes are the main problems to be tackled in Lake Pampulha. Despite its poor water quality, Lake Pampulha is an important tourist spot, a recreational and sportive area for inhabitants and it helps to prevent floods by storing stormwater.

Integrated modelling approach. DYCD will be used on Lake Pampulha whose catchment area is being equipped with measurement stations and described in a hydrological model. The results of the latter will be used to input inflow rate and quality into the lake model (Figure 4). Obviously, DYCD could be fed directly by inflow measurements on the tributaries, instead of simulated inflow; however, the purpose of our integrated approach is to help in predicting the impacts of watershed evolution (land-use changes, climate changes) on lake ecosystems: a watershed model will be necessary to simulate future scenarios.

Table 1. Main physical characteristics of Lake Enghien (SIARE, 2004) and Lake Pampulha (Resck, 2007)

	Lake				Watershed	
	Mean depth (m)	Max. depth (m)	Area (ha)	Volume (m^3)	Area (km^2)	Population (inh.)
Enghien	1.3	2.6	41	0.5×10^6	54	~200,000
Pampulha	16.2	5.1	197	10×10^6	98	~350,000

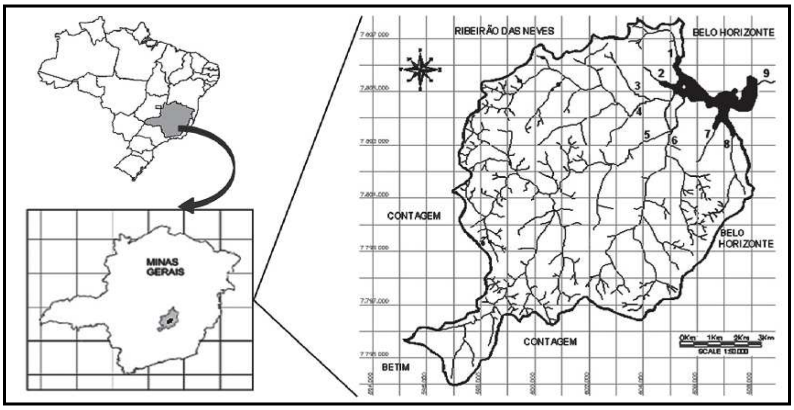

Figure 3: Lake Pampulha location and watershed map. Tributaries: (1) Olhos d'Agua; (2) AABB; (3) Braunas; (4) Agua Funda; (5) Sarandi; (6) Ressaca; (7) Tijuco and; (8) Mergulhão. Outlet: (9) Pampulha creek (Resck *et al.*, 2007).

Data collection. A measurement buoy similar to that used in Lake Enghien will monitor continuously water quality parameters on Lake Pampulha: temperature, conductivity, pH, dissolved oxygen and chlorophyll-a concentration. Meteorological forcing will be provided by a weather station located near the lake (National Institute of Meteorology - INMET). The municipality of Belo Horizonte is installing level sensors and rain gauges on the two main tributaries of Lake Pampulha (Ressaca and Sarandi creeks) and their outlet (Pampulha creek). Within the MAPLU 2 research project (Storm water management project 2), the flow rate, temperature, conductivity and turbidity of the creeks will be measured every 5 min at the same spots and automatic samplers will collect water for laboratorial analysis (BOD, TSS, VSS, NTK, NO_3^-, P_{tot}, PO_4^{-3}, metals and hydrocarbons). The data collection will be achieved over two hydrological cycles, from 2011 to 2013. It will be used to input, calibrate and validate the hydrological watershed model, as well as the lake ecological model.

Watershed hydrological model. The hydrological model is a dynamic rainfall-runoff model that computes flows and non-point source nutrients from watershed runoff. Briefly, the processes taken into can be described as follows (Figure 4): (1) during dry periods, pollutants are deposited over the land surface (2) during rain events, rain falls over the catchment area and washes off pollutants; (3) according to the characteristics of the catchment area (e.g. imperviousness, slope), it generates outflows in form of infiltration to the groundwater and/or in form of surface runoff; (4) this runoff and part of the groundwater reach the stormwater network and are drained to an outfall, Lake Pampulha, in our case (Rossman, 2010).

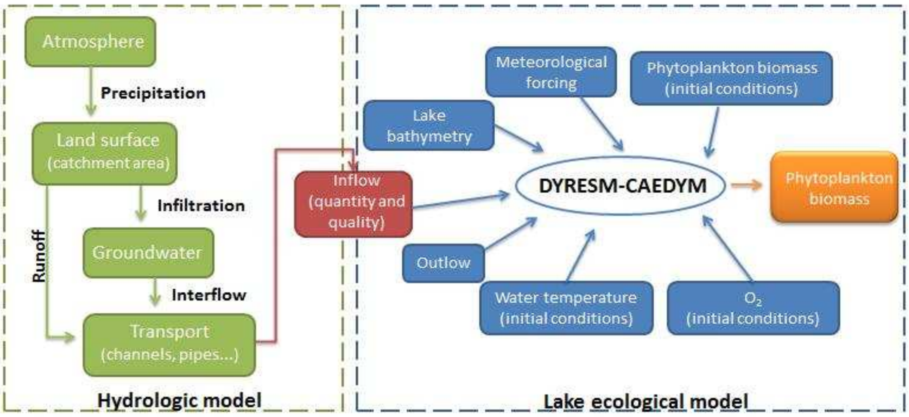

Figure 4: Integrated modelling diagram: hydrological model steps and DYCD inputs/output.

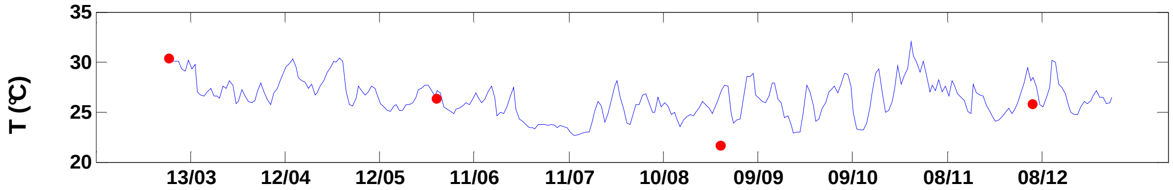

Figure 5: Lake Pampulha (2008): model results (line) and data (dots) for water temperature at depth of 1 m.

Lake ecological model. A preliminary attempt of modelling cyanobacteria dynamics in Lake Pampulha has been performed with an existing water quality data set. Belo Horizonte municipality is in charge of the seasonal water quality monitoring of the lake, including quarterly measurement of water transparency, temperature, nutrients and dissolved oxygen concentrations and phytoplankton counting. The lake data were collected in 4 dates in 2008: 6/3, 30/5, 28/8 and 5/12 (PBH, 2008) Mean monthly inflow rates and nutrient loadings (PBH, 2008) and hourly meteorological data from the INMET weather station provided the forcing data for DYCD. The calibration of the temperature model parameters was achieved through simulations running from 6 March to 31 December 2008. The model results of water temperature are presented on Figure 5. For cyanobacteria, the calibration step has been conducted during two different periods: a water cooling period from 06th Mars to 15th June and and a water warming period from 30th August to 05th December (Figure 6). The model gave the right orders of magnitude for both the water temperature and the chlorophyll-a concentration. Obviously, the data are too sparse to assert that the model is able to represent the dominant processes occurring in the lake throughout the year. Nevertheless, the applicability of DYCD on Lake Pampulha can be ascertained by the results of this first simulation.

Expected results. Once calibrated and validated, both models will be used to propose different scenarios of watershed changes: (i) meteorological changes such as air temperature increase, changes in rainfall regime and in wind speed; (ii) inflow rate and quality degradation due to the intensification of land-use, the expansion of impervious areas, or the opposite, improvements in the sanitary system in watershed. Thus, the lake response to these different scenarios will be simulated thanks to this integrated approach. Researches with similar goals have already been undertaken (Hornung, 2002; Trolle *et al.*, 2010; Zhang and Jørgensen, 2005), however, as far as we are aware, the continuous high frequency monitoring adopted in our approach was not implemented in previous works. Previous studies showed the low data frequency as an obstacle to model and understand the functioning of lakes, especially the small ones, during heavy runoff events (Trolle *et al.*, 2010).

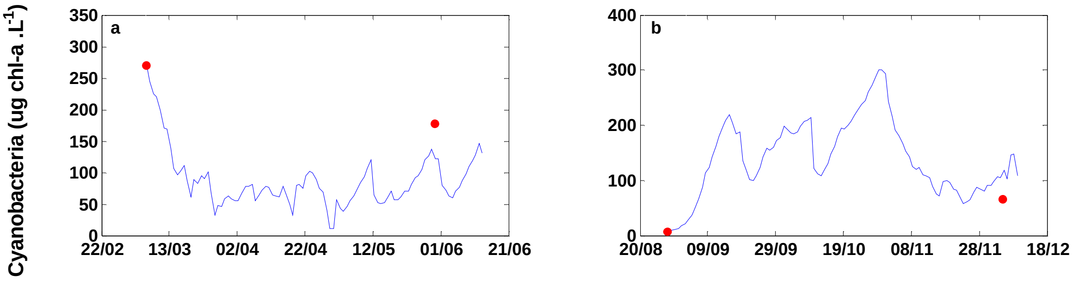

Figure 6: LakePampulha (2008): model results (line) and data (dots) for cyanobacteria at depth of 1 m: (a) from 06th March to 15th June and (b) from 30th August to 05th December.

We expect that the high-frequency monitoring proposed in this paper will allow us to improve the accuracy of the ecological model and the understanding of the lake ecosystem dynamics. Furthermore, we believe that a more accurate model could partially counteract the uncertainties in watershed global changes forecasts.

CONCLUSIONS

Our results on cyanobacteria modelling in Lake Enghien show the reliability of the ecological model whose performance has been thoroughly assessed against high-frequency data. The preliminary results of temperature and cyanobacteria modelling in Lake Pampulha also indicate that this model can be used for a tropical urban lake. Based on these outcomes, the coupling of the ecological model with the hydrological model will be performed in the next step of the project.

This integrated approach linking a watershed hydrological model and a cyanobacteria dynamics model in Lake Pampulha may not only help to guide its restoration and preservation, but also that of other water bodies in developing urban areas. Building scenarios to represent watershed evolution and simulating the lake response will highlight the processes the most likely to be affected by changes, and therefore support stakeholders' decisions.

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