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Abstract

Urban lakes performed several essential functions for the cities such as storing rainwater and providing recreation spaces. Blooms of cyanobacteria frequently occur in these lakes, disrupting water uses and decreasing ecosystem biodiversity. 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 hydrologic watershed model is proposed. To validate this approach, two study sites were selected: Lake Enghien (France) and Lake Pampulha (Brazil). In the first part of the paper, we assess the performance of a lake ecological model fed with high-frequency data collected in Lake Enghien. In the second part, we propose a methodology to connect the lake ecological model to a watershed hydrological model using data set from Lake Pampulha. Our results on cyanobacteria modelling in Lake Enghien (correlation coefficient = 0.71-0.97; RMSE = 15.8 – 25.7 µg chl-a L^{-1}) show the reliability of the lake model. In Lake Pampulha, the high-frequency data are expected to provide understanding about poorly known processes in lake functioning. Finally, as future steps of this research, the integrated modelling approach will be used to estimate lake response to different scenarios of the watershed evolution.

Keywords

Urban lake; cyanobacteria modelling; hydrologic watershed modelling; high frequency measurements

INTRODUCTION

Urban lakes are frequently man-made, small and shallow water bodies, highly influenced by land-use changes in their watersheds and by urban stress such as industry, traffic, waste and drainage systems (Friese *et al.*, 2010; Meyer and Likens, 2009). Worldwide, ponds and lakes located in urban regions performed several essential functions for the sustainable functioning of cities: storing rainwater; providing suitable aquatic and terrestrial habitats for a variety of wildlife; providing sport and recreation spaces; performing amenity and aesthetics function and often representing true heritage values. In addition, if examined within the context of global climate changes, these water bodies help to reduce the extremes of atmospheric temperature in the cities (Spronken-Smith & Oke 1999).

Despite the importance of small shallow lakes in urban centres, research has mainly focused on large and deep lakes (Scheffer 1998). Only recently, as the ability of urban aquatic ecosystems to provide services that benefit humans has been reduced, restoration projects have begun in many cities, supported by scientific studies that aim to investigate urbanization impacts in lake functioning (Stoianov et al. 2000, Havens et al. 2001, Ruley & Rusch 2004, Meyer & Likens 2009). Furthermore, only recent studies have taken into account the impacts on urban aquatic ecosystems caused by global changes as climate change (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 story and development of phytoplankton and fish communities (Blenckner et al. 2007). Phytoplankton communities, especially cyanobacteria, play a key role in urban 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, and individual lakes may respond very differently to changes in climate (Mooij *et al.*, 2005; Tanentzap *et al.*, 2008). Although, it is generally expected that global warming will increase productivity in most lakes and favour cyanobacteria blooms by (Paerl & Huisman 2008): (1) rising water temperature, since cyanobacteria normally growth better at high temperature than other phytoplankton species; (2) lengthening optimal growth periods, it means, 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, growth in population and urbanization has intensified exchange of nitrogen and phosphorous between lands and surface water, which increases the intake of nutrients in aquatic environments and contributes to accelerate their eutrophication (Meyer and Likens, 2009). Increasing impervious area in the catchment basin raises runoff in volume and speed, causing greater carrying capacity and greater nutrient load to aquatic receptors. This excessively availability of nutrients results in unnatural high primary productivity and phytoplankton blooms can be expected. In urban regions, nutrient load traditionally comes from two sources: point sources, as municipal and industrial wastewater and; non-point sources, as atmospheric deposition and drainage water. Point loadings are usually easy to determinate, since they do not depend on stochastic process like precipitation and temperature. By contrast, non-point loadings are difficult to estimate accurately due to the stochastic hydro-chemical processes and the heterogeneous of soil properties and vegetation (Nikolaidis *et al.*, 1998).

Problem statement. In order to define more appropriate strategies to restore the water quality in urban lakes, deeper understand of the links between the lake ecological functioning and its watershed is needed. Furthermore, the impacts of the urbanization expansion and the climate change in the water quality should be taken into account in the management strategies of these lakes and their watersheds. Modelling approaches are useful tools to better understand phenomena occurring into the lakes and to estimate their response to different environmental management strategies or to different watershed changes, such as land-uses changes, increase of the impervious area or improvements in the sanitation system.

This paper describes the first steps of a PhD research project that aims to evaluate the impacts of watershed changes on cyanobacterial dynamic in urban lakes using modelling approach and high frequency data. The main objectives of this paper are: (1) to assess the performance of an existing lake ecological model to simulate cyanobacteria dynamics in urban lakes using high frequency data as input; (2) to propose an integrated modelling approach, it means, a methodology for linking a hydrological watershed model and a lake ecosystem model. The first objective was achieved using data from Lake Enghien-les-Bains, France. The second objective was proposed to Lake Pampulha, Brazil, and its watershed. Thus, the methods and results sections of this paper are divided in two different parts: part I concerns the lake ecological model applied to the French study site and part II deals with the integrated modelling approach of the Brazilian lake.

METHODS

Part I - Lake ecological model

In limnology modelling, quite frequently, hydrodynamics models are coupled to water quality ecological models: the former take into account physical processes of transport and mixing in the water column, while the latter are responsible for representing the main chemical and biological processes that affect phytoplankton and higher trophic levels (Hamilton and Schladow, 1997). This type of coupled model was used in this study in order to simulate cyanobacteria dynamics in Lake Enghien-les-Bains.

Study site. Lake Enghien-les-Bains is located in France (Val-d'Oise), 11 km north of Paris (48°58’N, 2°18’E, see Figure 1). It is a small and shallow urban lake that plays a significant role in the stormwater management of its watershed by storing up to 100,000 m^3 of rainwater. The main physical characteristics of the water body and its watershed are listed in Table 1. Besides rainwater, the lake receives wastewater discharges from inappropriate connections in the stormwater network, resulting in water quality deterioration. According to Quiblier *et al*. (2008), water quality monitoring revealed that Lake Enghien is affected by blooms of *Planktothrix agardhii*, chlorophyll-a concentration (below chl-a) exceeding 350 µg chl-a.L^{-1} in midsummer (50 µg chl-a.L^{-1} is the threshold recommended by WHO for swimming prohibition).

Deterministic model. For simulating cyanobacteria dynamics in Lake Enghien, the deterministic model DYRESM-CAEDYM (below DYCD) was used. This model was developed by the Centre for Water Research at University of Western Australia. DYRESM (**DY**namic **RE**Servoir **S**imulation **M**odel) is a one-dimensional hydrodynamics model for predicting the vertical distribution of temperature, salinity and density in lakes and reservoirs. DYRESM can run either in isolation for purely hydrodynamics studies or coupled to CAEDYM (**C**omputational **A**quatic **E**cosystem **D**ynamics **M**odel), for investigations involving biological and/or chemical processes normally associated with water quality such as nutrient cycling studies; algal succession studies; food-web investigations; pathogen dynamics investigations; suspended solids studies; and toxic metal studies (Hamilton and Schladow, 1997). The input data required to DYCD are: initial conditions for cyanobacteria biomass, nutrient concentrations, dissolved oxygen and water temperature; lake morphometry; inflows (including inflow water quality); outflows and; meteorological forcing. The latter is represented by wind speed, air temperature, solar radiation, rainfall, cloud cover and vapour pressure (see Figure 3).

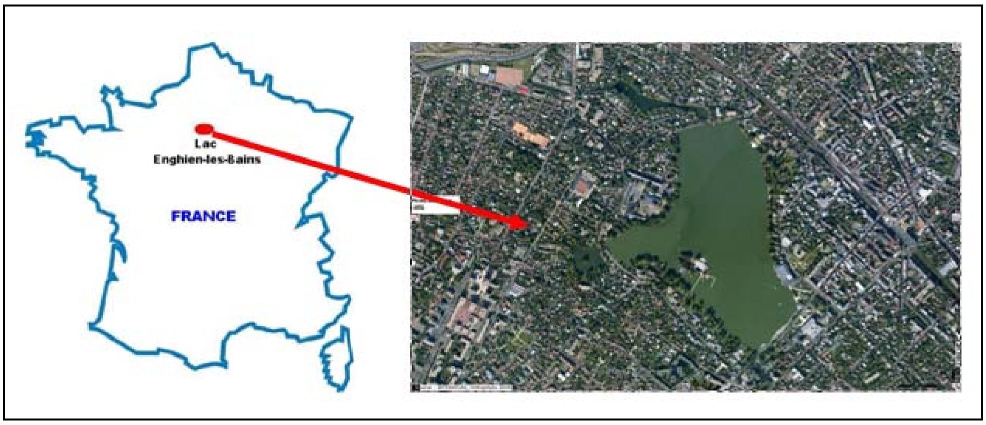

Figure 1. Lake Enghien-les-Bains location (Enghien-les-Bains city, France) and its urbanized surrounding.

Table 1. Main physical characteristics of Lake Enghien-les-Bains

Lake				Watershed	
Mean depth	Max. depth	Area	Volume	Area	Population
1.3 m	2.65 m	41 ha	534,000 m^3	54 km^2	~200,000 inh.

Data collection. Most data necessary to run DYCD were obtained from a freshwater-adapted measurement buoy installed on the lake in November 2008 within the PROLIPHYC research project (Monitoring system of phytoplankton blooms - application to cyanobacteria, funded by the French National Agency for Research, ANR-PRECODD). This buoy was equipped with meteorological sensors and immersed probes for measuring water quality parameters such as dissolved oxygen, water temperature, pH, conductivity and chl-a. The latter corresponds to the total chl-a and the chl-a related to four different groups of phytoplankton: cyanobacteria, chlorophyta, diatoms and cryptophyta. The measurements were performed in every 30 min at a depth varying from 0.50 to 1.0 m (for water parameters) and daily transmitted through GPRS protocol to a database. More technical details about measurement buoy sensors and probes are described in Silva (2010).

*Modelling approach***.** DYRESM was coupled to CAEDYM in order to simulate only cyanobacteria, the dominant phytoplankton group throughout the year 2009. DYCD has been successfully applied and validated since its development in many lakes/reservoirs around the world (Gilboa *et al.*, 2009; Hornung, 2002; McDonald and Urban, 2010), however, as far as we are aware, DYCD has been employed only in multi-year simulations (3 to 20 or more years) to provide means of predicting seasonal and inter-annual variability of lakes. In this paper, DYCD was used to simulate cyanobacteria dynamics throughout short time intervals (about 15 days).

Part II - Integrated modelling approach

The methodology applied to implement the integrated modelling approach in Lake Pampulha is described below. The few data available for Lake Enghien watershed do not allow us to use this modelling approach in the French study site. Instead, in Lake Pampulha, a complete data set will be available from 2012, since its watershed will be equipped with rain gauges, flow rate sensors and automatic samplers. Furthermore, Lake Pampulha catchment is located in a peri-urban area with a potential for urban expansion greater than Lake Enghien catchment. The latter is located in an urban region already highly densified and hence, few changes in the watershed are expected for the next years.

Study site. Pampulha dam (also called Lake Pampulha) is an artificial lake located in north-eastern part of Belo Horizonte city in Brazil (19°55'S, 43°56'W, see Figure 2). The main physical characteristics of Lake Pampulha and its watershed are listed in Table 2. Lake Pampulha is fed by eight small streams (Figure 2), Sarandi and Ressaca streams being the most important (70% of the total water income in the reservoir) and also the most polluted (Friese *et al.*, 2010).

Table 2. Main physical characteristics of Lake Pampulha

Lake				Watershed	
Mean depth	Max. depth	Area	Volume	Area	Population
5.1 m	16.2 m	197 ha	10×10^6 m^3	98 km^2	~350,000 inh.

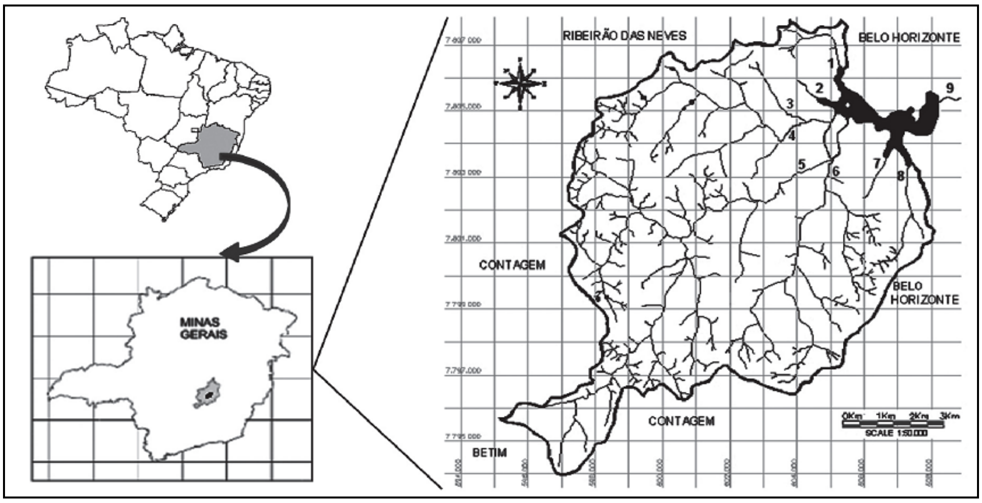

Figure 2: Lake Pampulha location and its watershed (Resck *et al.*, 2007). Tributaries: (1) Olhos d'Agua; (2) AABB; (3) Braunas; (4) Agua Funda; (5) Sarandi; (6) Ressaca; (7) Tijuco and; (8) Mergulhão. Outlet: (9) Pampulha.

Originally, Lake Pampulha was built to supply drinking water to the city, however, since the 70s, the water quality has been impaired as consequence of the rapid watershed urbanization with neither sanitation infrastructure nor erosion control. Nowadays, lake silting and reduction of its storage capacity, water eutrophication, cyanobacterial blooms and excessive growth of macrophytes are the main problems to be faced in Lake Pampulha. Despite the degraded water quality, Lake Pampulha is an important tourist hot spot and it helps in flood control by storing rainwater. The municipality of Belo Horizonte is very interested in improving the lake water quality, so it could be used to recreational and sportive activities.

Integrated modelling approach. DYCD will be used on Lake Pampulha whose catchment area runoff will be simulated by a hydrological model. The results of the latter will be used to input inflow rate and quality into the lake model (Figure 3). Obviously, DYCD could be fed directly by inflow measurements of the tributaries, instead of simulated inflow; however, the purpose of this integrated approach is to help in predicting the impacts of watershed changes on lake ecosystems. Therefore, a hydrological watershed model that takes into account catchment characteristics such as land-uses and impervious area rate is necessary to simulate runoff of future scenarios representing watershed evolution.

Watershed hydrological model. For the moment, the choice of the hydrological watershed model to be applied in the integrated modelling approach is ongoing. In general, hydrological models are dynamic rainfall-runoff models which compute flows and non-point source nutrients from watershed runoff. The processes taken into account in this type of model are described as follows (Figure 3): (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). Concluding, the hydrological watershed model will use rainfall data, catchment and stormwater network characteristics to simulate the quantity and quality of the runoff produced in the Lake Pampulha watershed.

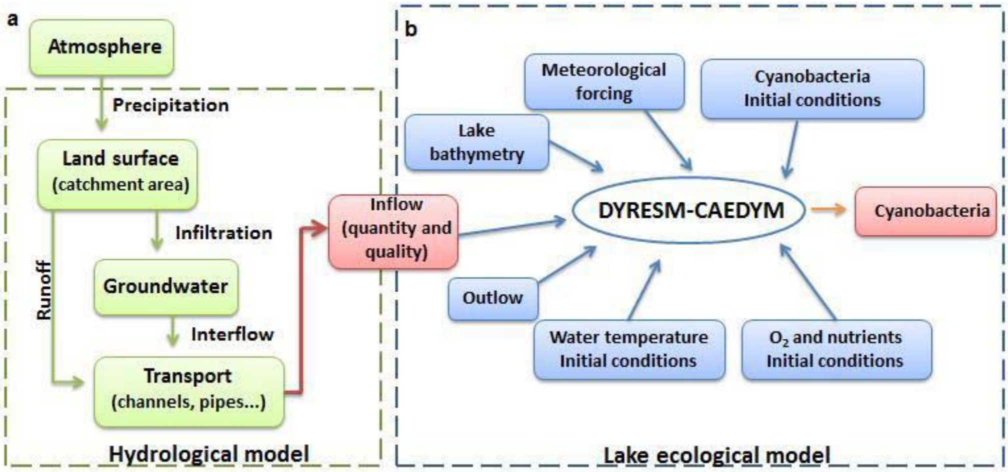

Figure 3: Integrated modelling approach diagram: (a) hydrological watershed model type and the process taken into account to compute runoff from the catchment area (model output) using precipitation and catchment characteristics (model inputs). (b) DYCD inputs and output. The link between the models is held by the inflow data which are simultaneously an output from the hydrological model and an input to DYCD.

Data collection. A measurement buoy similar to this one used in Lake Enghien will be installed on Lake Pampulha for monitoring water quality parameters every 30 min: temperature, conductivity, pH, dissolved oxygen and chl-a. Meteorological data at hourly time step will be provided by the Brazilian National Institute of Meteorology, INMET. Concerning the watershed, the municipality of Belo Horizonte will implement on the two main tributaries of Lake Pampulha (streams Ressaca and Sarandi) and its outlet (stream Pampulha) measurement stations equipped with level sensors and rain gauges. Within MAPLU 2 research project (Storm water management project, funded by the Brazilian Agency for Funding Study and Projects - FINEP), probes to measure at high frequency (5 min) flow, temperature, conductivity and turbidity of the streams will be installed on the same stations mentioned above, as well as automatic samplers to collect water for laboratorial analysis (BOD, TSS, VSS, NTK, NO_3^-, P_{tot}, PO_4^{-3}, metals and hydrocarbons). Data set will be obtained over two hydrological cycles, from 2012 to 2013.

RESULTS

Part I - Lake ecological model

Results. The thermal and ecological model was manually calibrated from 1st to 16th June 2009, period corresponding to the first cyanobacterial bloom of the year. The calibrated model was then applied to simulate the period from 3rd to 18th July 2009, in which cyanobacteria chl-a concentration reaches its maximum value over the year (358 µg chl-a.L^{-1}). Model results for calibration and validation simulations show good agreement with measurements (
Figure 4). 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 high frequency of data acquisition provides a very rigorous assessment of model performance since its results were compared with buoy measurements at hourly time-step. Comparing the results of this modelling with other lake studies carried out with DYCD supports this assertion (Burger *et al.*, 2008; Gal *et al.*, 2009). DYCD model can be considered validated for simulating cyanobacteria dynamics in a shallow urban lake, for short-term simulations (few weeks).

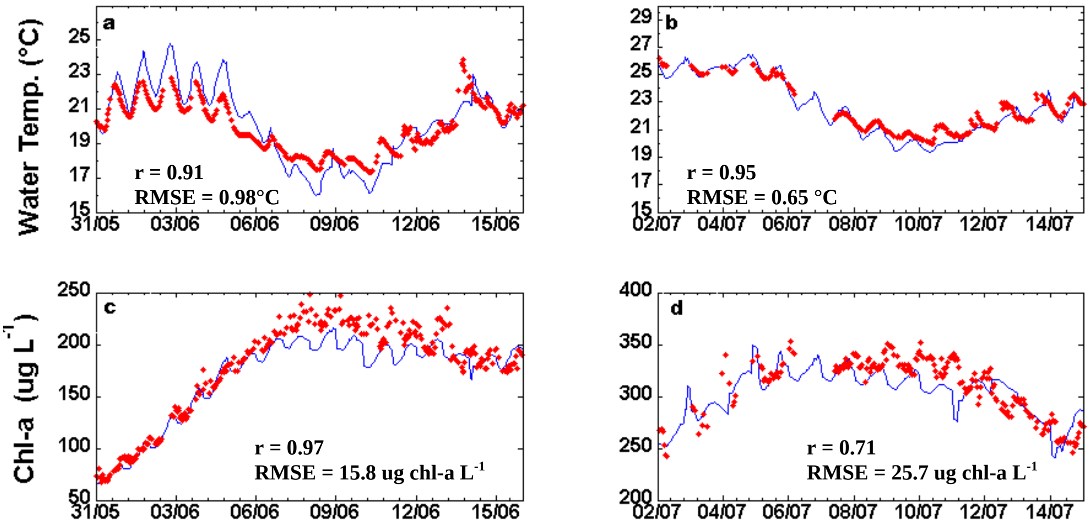

Figure 4: Simulated (lines) and buoy measures (dots) for water temperature (a, b) and cyanobacteria chl-a concentration (c, d). Simulation period: 1st to 16th June (a, c) and 3rd to18th July (b, d).

Part II - Integrated modelling approach

Expected results. The installation of the water quality monitoring devices in Lake Pampulha and in its watershed is being carried out throughout 2011. The first data needed to input the models will be available from the beginning of 2012. Once calibrated and validated, the hydrological watershed model and the lake ecological model will allow us to better understand the factors controlling cyanobacteria dynamic and its link with the watershed. Furthermore, both models will be used to propose different scenarios of watershed evolution: on the one hand, meteorological changes such as increasing in air temperature and changes in rainfall regime; on the other hand, intensification of land-use and expansion of impervious area leading to an increasing of the external loading of nutrients into the lake. Improvements in the sanitary system of the watershed will be also taken into account, since they can result in a decrease of external nutrient loading into the lake. Thus, lake response to these different scenarios will be simulated thanks to this integrated approach. Research with similar goals have already been undertaken (Hornung, 2002; Trolle *et al.*, 2010), however, as far as we are aware, high frequency data were not used until now. Thus, we hope that the continuous high frequency monitoring adopted in our approach will improve the accuracy of the models and provide hitherto temporal resolution of phenomena occurring into the lake.

CONCLUSIONS

Water bodies inserted in urban areas represent a key role to overcome the challenge of the coming decades in urban centres: harmonize economic growth, social development, biodiversity conservation and preservation of ecosystems. Water managers need to take into account the effects of watershed changes and climate change in their strategies to restore lake water quality. 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 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. Finally, 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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