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URBAN STORMWATER RUNOFF IMPACTS ON THE ECOSYSTEM OF A TROPICAL LAKE

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ABSTRACT

Rain events cause large changes in physicochemical and biological conditions in lakes. Stormwater may modify water conductivity, increase pollutant and sediment input and promote flushing effects, turbulence and mixing of the water column due to water inflow, air temperature decrease and strong winds. In turn, changes on physicochemical conditions have an effect on the dynamics of primary producers and higher trophic levels. In the urban context, catchment response to rain takes place in a few tens of minutes and the monitoring of urban runoff impacts on lakes should take advantage of high frequency monitoring technologies, which provide appropriate time resolution for analysing these phenomena. Improving our understanding of stormwater runoff impacts on lake ecosystems is critical to define strategies for water resources and catchment management and to cope with land use changes due to population growth and increasing urbanization as well as climate change impacts on hydrological processes. Lake Pampulha in Brazil (mean depth: 5.0 m, 197 ha) is an urban water body that has been monthly monitored since September 2011. Water temperature, conductivity and pH were measured every 0.5 m in a middle site in the lake. Flow of Lake Pampulha main tributaries are monitored every 10 minutes since October 2011 using automatic sensors. The General Lake Model (GLM) was used to model water temperature and mixing in the lake. Simulated water temperature showed good agreement with observed water temperature (rmse = 0.70℃). Model results and moni toring data showed that stormwater runoff are responsible for mixing the water column and disrupting algal growth during wet summer.

Keywords: High-frequency monitoring, lake modelling, cyanobacteria

1. INTRODUCTION

Rain events cause large changes in physicochemical and biological conditions in lakes and reservoirs, which depend on rain characteristics, catchment hydrology, land use and lake features. Stormwater may modify water conductivity (Legesse *et al.*, 2004), increase pollutant and sediment input (Rueda *et al.*, 2007) and promote flushing effects, turbulence and mixing of the water column due to water inflow (Liu *et al.*, 2011), air temperature decrease and strong winds (Zhu *et al.*, 2014). In turn, changes on lake physicochemical conditions have an effect on the dynamics of primary producers and higher trophic levels. For instance, large stormwater inflow can reduce phytoplankton biomass due to increased turbulence and high flushing rates (Bouvy *et al.*, 2003) or in case of less intense rain events, it may favour algal growth by inputting nutrients (Shaw *et al.*, 2001).

In the future the main drivers of the hydrodynamics of lakes and reservoirs are hypothesized to change. On the one hand, the predicted climate warming is supposed to increase the frequency of extreme rainfall events (Reichwaldt and Ghadouani, 2012). On the other hand, urbanization process is expected to increase impervious areas in the catchment which will raise runoff volume and speed, causing greater carrying capacity and greater pollutant load to aquatic receptors. Understanding the impacts of stormwater runoff on lakes ecosystem is of primordial relevance to deal with the actual and the future challenges of lake water management. In this work we aimed at assessing the stormwater runoff impacts on the thermal structure and cyanobacteria dynamics of an urban tropical lake. Monthly and high frequency data and numerical modelling approaches are coupled in order to achieve this objective.

2. MATERIAL AND METHODS

2.1 Study site

Lake Pampulha (mean depth = 5.1 m, maximum depth = 16.2 m) is an urban and hypereutrophic reservoir in Belo Horizonte city, Brazil (19°55'S, 43°56'W). When full, it has a surface area of 196.8 ha and a storage capacity of 9.99 x 10^6 m^3 (Resck *et al.*, 2007). 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 catchment urbanization with neither sanitation infrastructure nor erosion control. Nowadays, the area around the lake is used for recreational and sportive activities and it contributes to reduce flood risk in the neighbourhood. Lake silting and frequent episodes of cyanobacterial blooms are the main problems to be tackled (Figueredo and Giani, 2001). Despite the degraded water quality, Lake Pampulha is an important tourist spot and the municipality is currently investing in the improvement of its water quality.

The climate in the catchment area of Lake Pampulha is characterized by a dry cool season between April and September and a wet warm season from October to March when 90% of the total annual rainfall occurs (mean rainfall = 1 500 mm.year-1). Minimum monthly mean of air temperature is 18℃ in July and maximum monthly mean is 23℃ i n February (Nascimento *et al*., 2006). Lake Pampulha is fed by eight small creeks, Sarandi and Ressaca creeks are the most important (70% of the inflow rate) and also the most polluted ones (Tôrres *et al*., 2007). Lake Pampulha catchment has the area of 98 km^2 and 424 000 inhabitants.

2.2 Lake and catchment data

Lake Pampulha has been monthly monitored since September 2011 within the Brazilian research project Management of Stormwater (MAPLU Project). Temperature, conductivity, pH and dissolved oxygen are measured every 0.5 m in a central site (point P1) into the lake using 556 MPS multiparameters probe (YSI, USA). From March 15th to June 02nd 2013, the SMATCH buoy equipped with automatic sensors was installed in point P1 and carried out hourly measurements of water temperature and fluorescence related to chlorophyll-a at a depth of 0.8 m (nke, France). Chlorophyll-a fluorescence was used as an indicator of cyanobacteria biomass, which is the dominant phytoplankton group in Lake Pampulha. Hourly meteorological data were provided by a weather station of the Brazilian National Institute of Meteorology located 3 km far from the lake. The bathymetry of the lake was obtained from Resck *et al.* (2007). Belo Horizonte municipality operates a hydrometric network in Pampulha catchment. Water level data in Sarandi and Ressaca creeks are measured by two discharge stations installed just upstream their inlet into the lake. Rainfall data are provided by seven precipitation stations located in or around the catchment. Rainfall depths and water levels are automatically measured every 10 minutes since early October 2011. The hydrological model Storm Water Management Model - SWMM 5 (Rossman, 2010) was used in order to cover periods of gap in flow data. SWMM calibration and validation for Pampulha catchment was described in details in (Silva, 2014).

2.3 Lake modelling

The General Lake Model (GLM, version 1.4.0, Hipsey *et al*., 2013) was used in order to supplement data obtained from monthly surveys and one-depth hourly measurements carried out by the SMATCH buoy. GLM is a one-dimensional deterministic hydrodynamic model used to predict the vertical distribution of temperature and salinity in lakes and reservoirs. The input data required to GLM are bathymetry of the lake, daily inflow volume and temperature, daily outflow, meteorological forcing (wind speed, air temperature, solar radiation, rainfall, cloud cover and relative humidity) and the initial profile of water temperature and salinity. At each timestep, GLM computes energy budget including radiation flux, sensible heat, latent heat of evaporative heat fluxes and surface mass fluxes which account for evaporation, rainfall and snowfall and vertical mixing. Once a day, GLM takes into account for inflows and outflows. Detailed information about the equations used in GLM is available in Hipsey *et al*. (2013).

Meteorological data were set at hourly timestep and the model results were obtained at daily timestep. Calibration of the GLM simulation for water temperature at point P1 was carried out from October 18th 2011 to June 04th 2013 using data from monthly surveys. An automatic calibration procedure using a Markov Chain Monte Carlo (MCMC) algorithm (Laine, 2003) was implemented by coupling GLM code to the computing software Matlab (The MathWorks®, version 2006a). The objective function used was the root mean square error (rmse, Eq. [1]).

$$rmse = \sqrt{\left(\frac{1}{n}\sum\left[\theta_{sim}(t_i, d_j) - \theta(t_i, d_j)\right]^2\right)} \qquad [1]$$

Where, θ_{sim} is the simulated temperature (ºC) at the depth *d* and time *t*, θ is the observed temperature (ºC) at the same depth *d* and time *t* and *n* is number of measurements.

3. RESULTS AND DISCUSSION

3.1 Lake modelling results

Simulated water temperature by GLM showed good agreement with measured water temperature at different depths throughout the simulation period (Figure 1). The performance of Lake Pampulha simulation (rmse = 0.70ºC) was very satisfactory compared to other studies using similar models to GLM, for instance, Burger *et al.* (2008) and Trolle *et al.* (2008) obtained a rmse of 0.97ºC and 1.4ºC, respectively, using the DYRESM model (Centre for Water Research, University of Western Australia). Figure 2 shows water temperature simulated profile during the simulation period. Lake Pampulha shows thermal stratification from October 2011 to April 2012 and from October 2012 to March 2013 which mainly corresponds to the wet warm season of both years. During thermal stratification, the lake water temperature ranged from 32ºC at the surface layer to 24ºC at the bottom layer. Although, one could note that the stratification of the Lake Pampulha during the warm season is not stable and there are moments when it is disturbed. As will be discussed in the following paragraphs, rainfall events which occur mostly during the warm season are responsible for partial, or even total, thermal de-stratification of Lake Pampulha. From May to September 2012 and from May 2013 until the end of the simulation period, which correspond to the dry cool season, the water column temperature is quite homogenous in the most of the time and ranged from 26ºC to 18ºC.

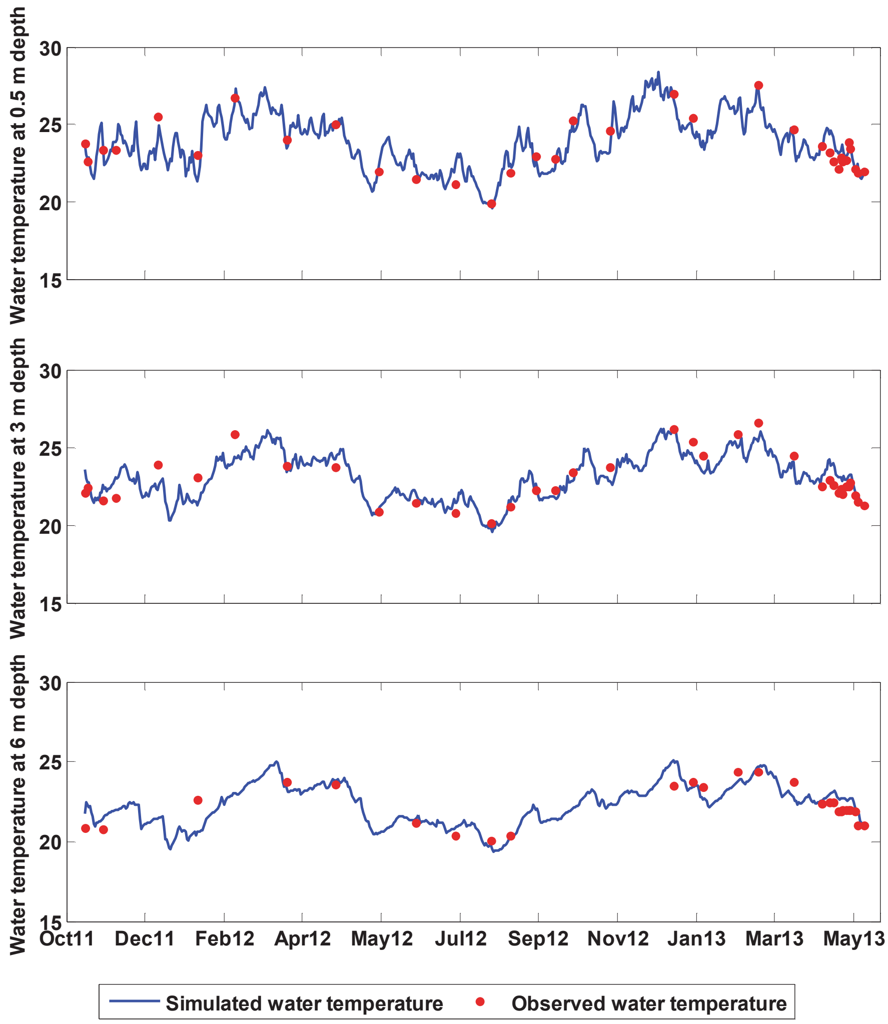

Figure 1 : Simulated (line) and observed (dots) water temperature in Lake Pampulha (point P1) at 0.5 m, 3.0 m and 6.0 m depth from October 18th 2011 to June 04th 2013.

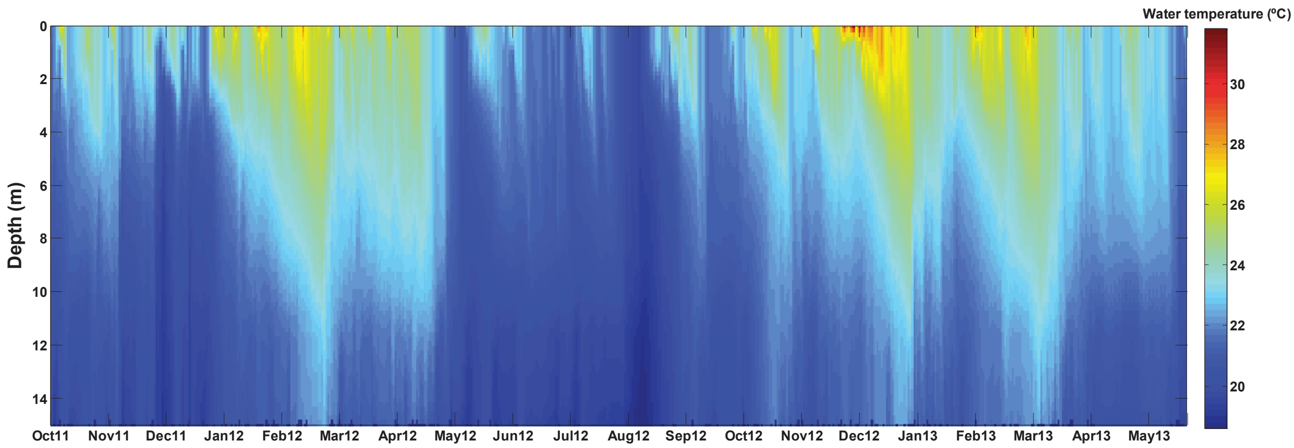

Figure 2 : Vertical variations of water temperature simulated by the GLM in Lake Pampulha (point P1) from October 18th 2011 to June 04th 2013.

3.2 Effects of stormwater runoff

The SMATCH buoy was installed in Lake Pampulha from March 15th to June 02nd 2013. Total rainfall recorded in this period was 347.6 mm distributed between six rain events. Figure 3 shows the effect of three rain events on the inflow volume into Lake Pampulha, its water temperature and cyanobacteria dynamics. Air temperature during the rain event is also plotted. The Lake Pampulha catchment is a very urbanized area and its response time to rainfall is very short and even small precipitations leads to stormwater runoff. On March 22th, it rained 50 mm and the daily mean inflow into the lake increased from 3.46 m^3s^{-1} to 8.03 m^3s^{-1}. Water residence time dropped from 60 days (mean residence time during dry season) to 14 days. On March 27th, the recorded rainfall was 29.6 mm, the mean daily inflow reached 11.25 m^3s^{-1} and the water residence time was 10 days. The most intense rainfall occurred on April 8th, it rained 34.4 mm in 30 minutes leading to a mean daily inflow of 17.31 m^3s^{-1} and a water residence time of 7 days.

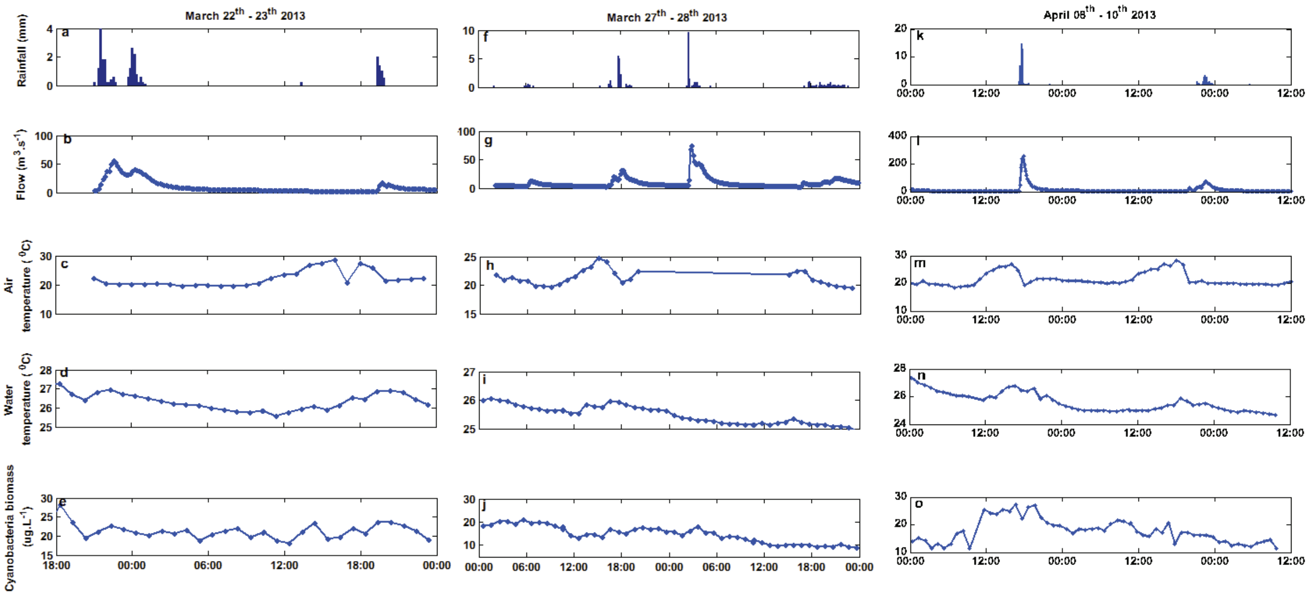

Figure 3: Stormwater runoff impacts on water temperature and cyanobacteria dynamics. a, f and k - Rainfall (mm); b, g and l – inflow into Lake Pampulha ($m^3.s^{-1}$); c, h and m – Air temperature (°C); d, I and n – water temperature from SMATCH buoy (°C); e, j and o – cyanobacteria biomass (µg chl-a. L^{-1}).

In general, during the rains, air temperature decreases and cloudiness increases leading to water surface cooling. If surface layer temperature drops below the adjacent layer temperature mixing starts. Lake water temperature will decrease in the following days, even if air temperature increases (Figure 3.i and n). GLM simulated this phenomenon on March 27th and April 8th(Figure 4.b and c). Although, less intense rainfall and smaller runoff volumes may not be able to cause lake de-stratification which was the case for the rain event of March 22th (Figure 3.d and Figure 4.a). In Lake Pampulha, thermal de-stratification during the wet season is closed linked to stormwater inflow into the lake. Stormwater inflows may disturb the thermal structure of reservoirs by inputting water with different density and by flushing (Huang *et al.*, 2014; Liu *et al.*, 2011).

SMATCH data showed that water temperature and phytoplankton biomass represented by fluorescence of chlorophyll-a are well correlated (r = 0.60, p = 0,04, n = 183). Water temperature decrease caused by mixing generally leads to a decreasing in cyanobacteria biomass (Figure 3.j and o) which is likely due to the dispersion of phytoplankton over the mixed depth and to inflow flushing effects. Both changes in hydrodynamics conditions and in cyanobacteria biomass occurred within few hours (Figure 3). The disruption effect of rain on cyanobacteria blooms in tropical reservoirs has already been reported previously (*Figueredo and Giani, 2001; Bouvy et al., 2003*). On the other hand, Shaw *et al.* (2001) stated that less intense rain event which does not lead to thermal de-stratification can immediately increase cyanobacteria biomass through nutrient enrichment. At least at short-term, it does not seem to be the case of runoff stormwater impacts on Lake Pampulha, nevertheless, in a medium-term this hypothesis need to be further investigated.

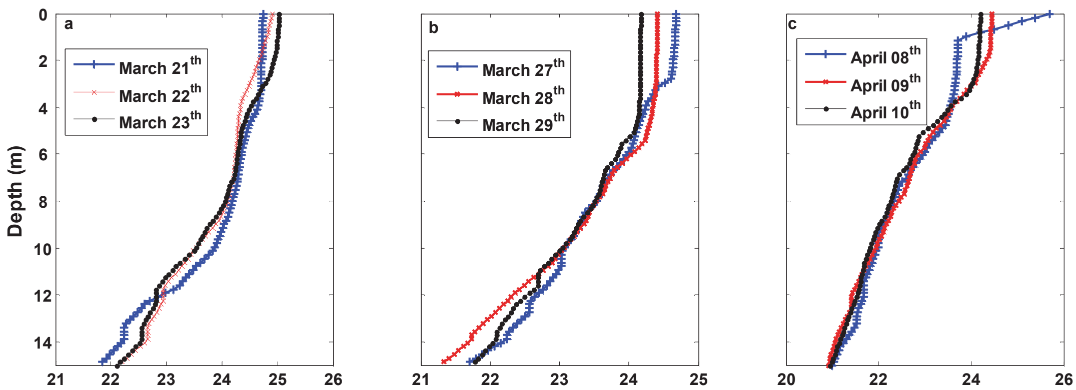

Figure 4: Vertical profiles of water temperature simulated by the lake model at Point P1. a – Rain event on March 22th; b – Rain event on March 27th; c – Rain event on April 08th.

CONCLUSIONS AND PERSPECTIVES

Improving our understanding of stormwater runoff impacts on lake ecosystems is critical to define strategies for water resources and catchment management and to cope with land use changes due to population growth and increasing urbanization as well as climate change impacts on hydrological processes. In the urban context, catchment response to rain takes place in a few tens of minutes and lake response to stormwater inflows may take place in few hours. We took advantage of high frequency monitoring technologies and existing numerical models to assess runoff effects on the water temperature and cyanobacteria dynamics of Lake Pampulha. In the next step, the hydrodynamic model GLM will be coupled to an ecological model to simulate cyanobacteria dynamics during rain events.

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