Coupling cyanobacteria dynamics and urban runoff modelling: an integrated approach for a tropical lake in Brazil

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Modélisation de la dynamique cyanobactérienne couplée à la modélisation du ruissellement urbain: une approche intégrée pour un lac tropical au Brésil.

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RÉSUMÉ

Dans les régions urbaines, l'expansion des surfaces imperméables conduit à une augmentation du volume et de la vitesse d'écoulement des eaux de ruissellement, à l'origine d'une capacité plus importante d'entraînement des polluants, dont les nutriments, aux milieux récepteurs tels les lacs. Une approche de modélisation intégrée où un modèle hydrologique est couplé à un modèle écologique est proposée pour le lac Pampulha (Brésil) afin d'étudier l'impact des changements du bassin versant sur la dynamique des cyanobactéries. Cet article décrit la méthodologie utilisée pour mettre au point les deux modèles ainsi que pour procéder à leur couplage. Les résultats du modèle pluie-débit ont montré un bon accord avec les mesures, le coefficient de Nash étant compris entre 0.71 et 0.90. Le modèle écologique alimenté par un débit d'entrée calculé par le modèle hydrologique représente correctement l'évolution de la température et des cyanobactéries, les valeurs de l'erreur quadratique moyenne étant respectivement, 0.71°C et 7.20 µg chla L^{-1}. Un nouveau jeu de données permettra de caler le module qualité du modèle hydrologique et de simuler différents scénarios pour le bassin versant.

ABSTRACT

In urban regions the increasing imperviousness of surfaces is responsible for rising runoff volume and speed reflecting in a greater capacity to drag nutrients into lakes. In order to study the impacts of catchment changes on cyanobacteria dynamics in urban lakes, a modelling approach in which a hydrological model is connected to an ecological lake model is proposed for Lake Pampulha (Brazil). In this paper we present the methodology used to prepare and to link both models.The rainfall-runoff model results show good agreement with measurements, the Nash coefficient ranging from 0.71 to 0.90. The lake ecological model fed with runoff water volume calculated by the previous model successful represents water temperature and cyanobacteria dynamics, the root mean square error value being respectively, 0.71°C and 7.20 µg chlaL^{-1}. Collecting new dataset will allow us to calibrate the water quality module of the hydrological model and to simulate different scenarios of catchment changes.

KEYWORDS

Runoff modelling, lake modelling, urban lake, cyanobacteria.

INTRODUCTION

Estimation of nutrient loading is a key information for environmental management and planning *e.g.* for the choice of the best strategies for improving and preserving water quality in receiving freshwaters. Among the many pollutants whose origin is the urban runoff, nitrogen and phosphorus are of particular concern for lakes which are especially vulnerable to nutrient enrichment because of their relatively lower retentions time (Zhang and Jørgensen, 2005). Eutrophication is responsible for decreasing the ecosystem biodiversity and disrupting water uses such as drinking water supply and fishing. Moreover, eutrophic lakes are propitious environments for cyanobacteria blooms, including potential toxic species (Paerl *et al.*, 2001).

The most reliable method to quantify nutrient loads from runoff is to establish a comprehensive monitoring of the catchment area; however this is rarely possible due to high involved costs. Furthermore, when it is necessary to perform prognostic studies, measurements are generally insufficient and modelling approaches are frequently applied (Chow *et al.*, 2012; Wu *et al.,* 2006). Numerical modelling has also been extensively applied to simulate thermal and algal dynamics in lake ecosystems (Huang *at al.*, 2012; Reynolds et al., 2001), especially in view of the complexity of the mechanisms involved in algae growth and in their toxin production.

Despite the interconnection between the catchment runoff and the nutrient load into the receiving water body, only recently these processes have been addressed in an integrated way. The link between the hydrological and the lake model consists in using the runoff output from the first model as forcing drive for the second one (Wu *et al.*, 2006; Xu *et al.*, 2007 and Norton *et al.*, 2012). The objective is to improve the reliability of the results and above all, to apply different scenarios of catchment changes and simulate the response of aquatic ecosystem. Because of the rapid and important evolutions of urban environments, namely, intensification of urbanization, climate change and increasing concern about water quality, this kind of integrated modelling approach offers numerous possibilities to be explored. Xu *et al.* (2007) and Norton *et al.* (2012) highlighted that such a coupled modelling approach is more easily accepted by managers and by the general public because it can be more readily seen as a representation of a natural linked system.

The researches mentioned above have dealt mainly with rural catchment areas while lakes and reservoirs in urban catchments are understudied. In urban regions, the increasing imperviousness of surfaces is responsible for rising runoff volume and speed, which is reflected in a greater capacity to drag nutrients into receiving water bodies (Zhang and Jørgensen, 2005). Actually, there is a strong need to investigate the links between the ecological lake functioning and urban catchment changes such as urbanization and improvements or degradation on sewerage systems and wastewater treatment facilities. This paper presents a modelling approach in which a hydrological model is connected to an ecological lake model which in a further stage will be applied to study the impacts of future catchment changes on cyanobacteria dynamics in an urban lake in Brazil.

MATERIAL AND METHODS

1.1 Study site

Lake Pampulha is a small and hypereutrophic reservoir in Belo Horizonte city, Brazil (19°55'S, 43°56'W, Figure 1). The climate in the region is a tropical mountain climate, with a dry season between April and September and a wet season from October to March when 90% of the total annual rainfall occurs (mean rainfall = 1 500 mm year^{-1}). Air temperature shows relatively small amplitude over the year with a minimum monthly mean in July of 18°C and a maximum monthly mean in February of 23°C (Nascimento *et al.,* 2006). Lake Pampulha is fed by eight small creeks (Figure 1), Sarandi and Ressaca creeks being the most important (70% of the inflow rate) and also the most polluted ones (Tôrres *et al.*, 2007). The main physical and chemical 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 catchment 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, the area around the lake is used for recreational and sportive activities by inhabitants and it helps to reduce flood risk in the neighbourhood.

On the left, Lake Pampulha subcatchments: (1) Mergulhão ; (2) Tijuco ; (3) Ressca ; (4) Sarandi ; (5) Água Funda ; (6) Baraúnas; (7) AABB; (8) Olhos d'água

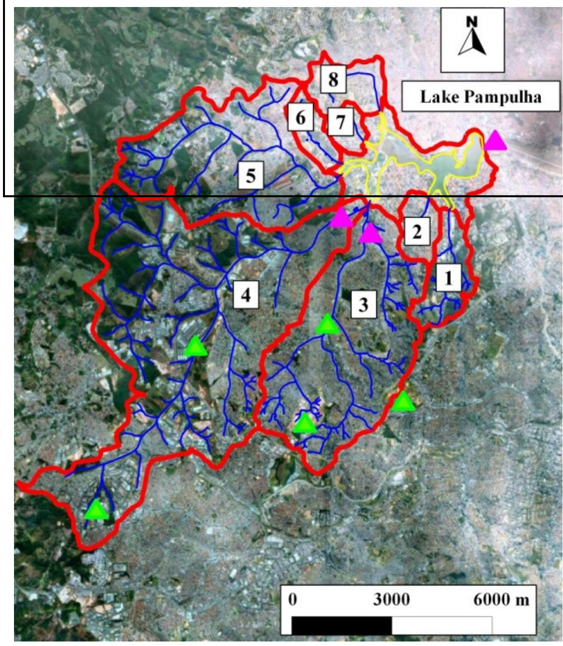

Figure 1 : Lake Pampulha (on the right) and its catchment (on the left). Triangles: green - rainfall stations; pink - rainfall and water level stations; blue – automatic samplers and sensors of temperature and turbidity. Red circles: points of sampling in Lake Pampulha (satellite imagery: © 2012 Google Earth, © 2012Digital Globe, © 2012 Geoeye)

Table 1 : Lake Pampulha main features

Pampulha Catchment	Population (inhabitants)	~350 000
	Total area (km^2)	98
	Ressaca catchment area (km^2)	20
	Sarandi catchment area (km^2)	49
	Ressaca+Sarandi mean flow dry weather (1) (m^3s^{-1})	0.651
	Ressaca+Sarandi mean flow wet weather (1) (m^3s^{-1})	1.632
Lake Pampulha(2)	Mean depth (m)	5.1
	Maximum depth (m)	16.2
	Area (m^2)	1.97×10^6
	Volume (m^3)	9.9×10^6
Water quality (3)	P_{total} (µg P L^{-1})	58 – 925 (207)
	PO_4 (µg P L^{-1})	1.7 – 113.1 (22.1)

	NH_4 (mg N L^{-1})	1.44 – 14.75 (5.71)
	NO_3 (µg N L^{-1})	3.61 – 460 (82.9)
	Chlorophyll-a (µg L^{-1})	19.5 – 322.0 (113.0)

(1) Tôrres et al. (2007), (2) Resck et al. (2007), (3) Min – Max (Mean value). Monitoring from December 2011 to July 2012 at 0.50 m depth (unpublished data)

1.2 Data collection

1.2.1 Catchment monitoring

Pampulha catchment is monitored by the municipality of Belo Horizonte and within the Stormwater Management Research Project – MAPLU 2. Rainfall data are provided by seven precipitation stations located in or around the catchment (Figure 1). Water level data in Sarandi and Ressaca creeks are measured by two stream discharge stations installed in their outlet. Rainfall depth and flow level are automatically measured every 10 minutes since early October 2011 for almost all stations. Water quality data are not available for the 2011/2012 rainy season and therefore modelling is still restricted to rainfall-runoff simulations.

By December 2012 sensors will be installed in the Lake Pampulha main inlet and in its outlet (Figure 1) to perform continuous high frequency measurements of water temperature and turbidity. At the same spots, two automatic samplers will collect water samples for laboratory analysis (TSS, NH_3, NO_3, P_{tot}, PO_4^{-3}) during rain events.

1.2.2 Lake monitoring

From mid-September to early November 2011, bi-weekly vertical profiles (eleven profiles in total) of water temperature and algae fluorescence were performed with a spectrofluorometer probe in three different points of the lake (Figure 1). Monthly samples were collected under the surface for nitrate, nitrite, ammonium, phosphate and total phosphorus analysis. Since flow measurements in the tributaries were not yet performed, inflows and outflows could be estimated from a water balance based on the measured water level of Lake Pampulha. Inflow water quality (nitrate, phosphate and ammonium concentration) has been assessed only from February 2012 by bimonthly punctual sampling. Meteorological variables (solar irradiation, wind speed, air temperature and atmospheric pressure) were provided at hourly timestep by a weather station of the Brazilian National Institute of Meteorology located 3 km from the lake.

By December 2012, in a mid-point inside the lake (point P2 in Figure 1), a buoy equipped with sensors to measure water temperature, dissolved oxygen concentration, conductivity and algal fluorescence will be installed. Measurements will be done every 30 min and transmitted daily through GPRS to a database.

1.3 Modelling approach

1.3.1 Hydrological model

The hydrological catchment model here adopted is the Storm Water Management Model - SWMM 5 (Rossman, 2010), a dynamic rainfall-runoff model that computes flows and associated wet weather non-point source pollutant processes. Briefly, the processes taken into account can be described as follows: (1) during dry periods, pollutants (nutrients in our case) are deposited over the land surface; (2) during rain events, rain falls over the catchment area and washes off nutrients; (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 sub-surface flow reach the stormwater network and are drained to an outfall (Figure 2, left hand side block).

SWMM represents the catchment in the form of three main objects: subcatchments, nodes and conduits. Subcatchments are the elements where runoff is generated. The rainfall-runoff transformation is modelled by a non-linear reservoir following the kinematic wave model (Singh, 1988). The outflow of a subcatchment can be routed to another subcatchment or to a node which is the entry point to the conduit network. The flow in the conduits, open or closed, is computed by Saint-Venant equations whose simplification degree can be selected by the user (dynamic wave, kinematic wave or steady flow). More details about SWMM can be found in Rossman (2010).

Since outflow was measured in two different points, *i.e.* Ressaca and Sarandi outlet, these subcatchments were simulated separately while the others were not represented in the model. Concerning model setup, infiltration was computed using the Curve Number method and dynamic wave was chosen as the flow routing model. Ressaca subcatchment is entirely in Belo Horizonte territory and detailed cadastre of the drains is available. In turn, most of the Sarandi subcatchment area is located in the neighbouring city, Contagem and available data of the storm water network only allowed a much less detailed spatial subdivision of the catchment. Thus Ressaca and Sarandi creek catchments were divided respectively into 54 and 10 subcatchments according to their land features and channel locations which were obtained from topographic maps and storm drain system cadastre (Bonnary, 2011). Maps were also used to provide subcatchment information, such as slope or impervious cover. Thiessen polygons method was applied to spatially distribute rainfall data from available raingages.

An automatic model calibration procedure based on a genetic algorithm was used to calibrate the most difficult to assess parameters. Genetic algorithms can be used for solving optimization problems inspired by natural selection. They have been used for hydrologic models calibration or optimization during the last 20 years and they are now well diffused in hydroinformatics applications (Savic and Khu, 2005). The main interest of these algorithms is their efficiency in finding close-to-optimal solutions of high-dimensional optimization problems, without strong hypotheses on the problem setting (*e.g.* linearity or continuity of the objective function).

The optimisation function adopted was Nash criterion (equation 1) and to achieve a compromise between model performance and computing time the maximum number of iterations was set equal to 100 for Ressaca subcatchment and 50 for Sarandi subcatchment.

Equation 1

Where F_{sim} is the calculated flow at timestep *i* (m^3s^{-1}) ; F_{mes} is the observed flow at timestep *i* (m^3s^{-1}) and $\overline{Fmes}$ is the mean measured flow over the simulation period (m^3s^{-1}).

1.3.2 Lake ecological model

Hydrodynamic models are frequently coupled to ecological models: the former describes the physical processes of transport and mixing in the water column, while the latter represents the main chemical and biological processes that affect phytoplankton and higher trophic levels. The deterministic coupled model DYRESM-CAEDYM (hereafter DYCD) is used in order to simulate water temperature and cyanobacteria dynamics in Lake Pampulha. DYRESM (DYnamic REServoir Simulation Model) is a one-dimensional hydrodynamic model based on variable depth layers used to predict the vertical distribution of temperature, salinity and density in lakes and reservoirs. DYRESM can be coupled to CAEDYM – (Computational Aquatic Ecosystem Dynamics Model) for investigating biological and/or chemical processes such as nutrient cycling studies and algal succession (Hamilton and Schladow, 1997).The input data required to DYCD are (Figure 2, right hand side block) : lake morphometry, inflows (water temperature and nutrient concentrations), outflows, meteorological forcing (wind speed, air temperature, solar radiation, rainfall, cloud cover and vapour pressure) and the initial conditions for cyanobacteria biomass, nutrient and dissolved oxygen concentrations and water temperature.

In our approach, cyanobacteria represented by the equivalent chl-a concentration are not submitted to vertical movements such as migration and settling. Zooplankton groups and higher trophic levels were not included in the simulation. Nitrate and phosphate limitations were simulated through the Michaelis-Menten equation. Half-saturation constants for nitrates and phosphates are set to 55 and 5 $\mu g.L^{-1}$, respectively. Chl-a concentration was converted into carbon by using a constant rate of 40 mg C.mg $chla^{-1}$. To assess model performance, the root mean squared error (rmse, Equation 2) between measurements and the simulated water temperature and cyanobacteria biomass at each timestep and each depth was computed where field data were available.

$$\text{rmse} = \sqrt[2]{\frac{1}{\sum_{i=1}^{m} n_m} \times \sum_{i=1}^{n} \sum_{j=1}^{m_i} \left[\theta_{sim}(t_i, d_j) - \theta_{mes}(t_i, d_j)\right]^2} \quad \text{Equation 2}$$

Where Θ_{sim} (t_i,d_j) is the water temperature (°C) or the cyanobacteria biomass (µg chla L^{-1}) simulated by the model at timestep *i* and depth *j* and Θ_{mes} (t_i, d_j) is the water temperature (°C) or the cyanobacteria biomass (µg chla L^{-1}) measured at timestep *i* and depth *j*.

1.3.3 Integrated modelling approach

Once calibrated and validated separately the rainfall-runoff and the lake models will be coupled by using the outflow volume and water quality simulated by the hydrological model as input to the hydrodynamic and ecological lake model, which in turn will simulate cyanobacteria dynamics (Figure 2). This coupled model could be used to evaluate different scenarios of catchment 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 the catchment.

As mentioned in paragraph 2.2.2, water quality data from the tributaries of Lake Pampulha are not yet available, only bimonthly punctual sampling were conducted in order to estimate the order of magnitude of nutrient and suspended solids concentrations entering the lake. However, an initial test of the coupled model functioning was undertaken by using outflow simulated by SWMM to replace inflow data in DYCD modelling.

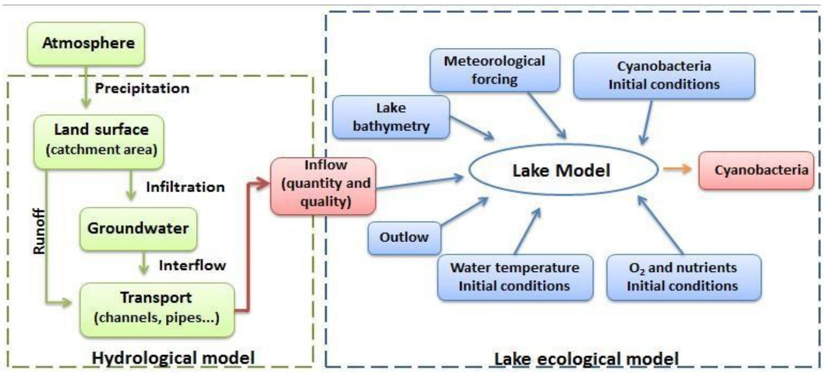

Figure 2 : Integrated modelling diagram: rainfall-runoff model steps and the lake model inputs and output.

RESULTS AND DISCUSSION

1.4 Rainfall-runoff modelling

Runoff from Sarandi catchment was firstly calibrated from 18th November 2011 to 13th January 2012 and then validated between 14th January and 13th March 2012. In a next step, runoff was calibrated during the latter period and validated over the former one in order to perform a cross-calibration. This approach was applied to confirm the results obtained by the model since available data correspond to only one rainy season. The same procedure was applied for Ressaca catchment from 1rst February to 18th March 2012 and from 19th March to 02nd May 2012, period in which data were available. For each catchment, eight parameters were calibrated (Table 2): (i) the Manning coefficient of conduits (n-cond), (ii) the time necessary for a fully saturated soil to completely dry (Dry time), (iii) characteristic width of the overland flow path for sheet flow runoff (w), (iv) Manning coefficient for overland flow over the impervious areas (n-imp), (v) Manning coefficient for overland flow over the pervious areas (n-perv), (vi) depth of depression storage on the impervious areas (s-imp), (vii) depth of depression storage on the pervious areas (s-perv) and (viii) the Curve Number parameter (CN). All parameters were calibrated to obtain a mean value representing each catchment, except CN parameter which was calibrated for each subcatchment in Ressaca and Sarandi catchment.

Runoff modelling from Sarandi catchment showed excellent results and its simulation periods comprised most of the rainy season (total rainfall during calibration and simulation = 1 348.8 mm). Nash coefficient ranges from 0.74 to 0.90 (Figure 3). The model successfully reproduced flow peaks intensity as well as the time they occurred (see example in Figure 3). The rainfall-runoff model of Ressaca catchment was less effective regarding the previous model, but still Nash coefficient values were higher than 0.70 which is a good agreement between measurements and simulation (Bennis and Crobeddu, 2007). In view of the results obtained for both catchments and taking into account that Sarandi and Ressaca catchments represents respectively 50% and 20% of Lake Pampulha contributing area, the models can be considered calibrated, validated and ready to be used in a coupled approach with Lake Pampulha model. To take into account the runoff produced by the others subcatchments which compose Lake Pampulha catchment, the sum of the daily water volume from Sarandi and Ressaca creeks was increased by 30% according to estimations carried out by Tôrres *et al.* (2007).

Table 2 : Rainfall-runoff model calibrated parameters

Parameter	Range value	Assigned value	
		Sarandi	Ressaca
n-cond	0.009 – 0.1	0.010	0.045
Dry time	2 – 7	2.02	6.12
Width	40 – 3000	2910	1398
n-imp	0.01 – 0.06	0.059	0.011
n-perv	0.009 – 0.05	0.02	0.0093
s-imp	0.1 – 3	2.98	0.44
s-perv	0.1 – 3	1.22	2.88
CN	50 - 98	Mean: 67.4	Mean: 88.8

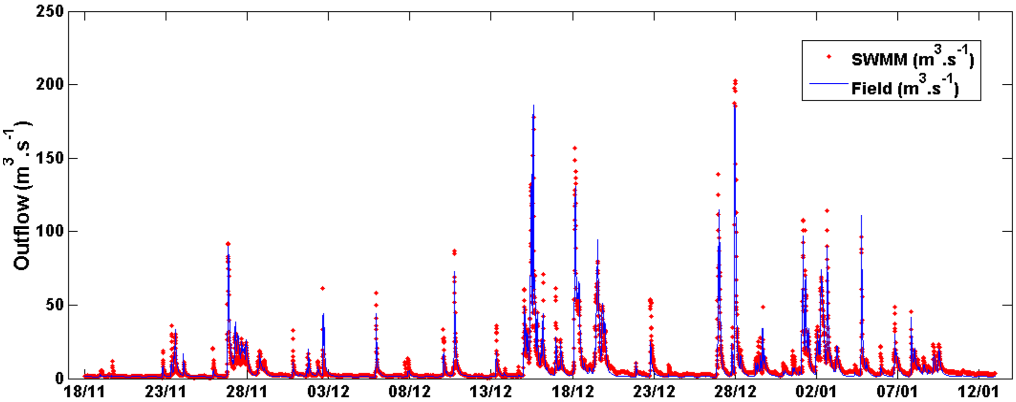

Figure 3 : Rainfall-runoff model results (blue line) and measurements (red dots) for Sarandi catchment during calibration period.

Table 3 : Rainfall-runoff model performance

	Sarandi catchment			Ressaca catchment		
Simulation	**Period (numbers of days)**	**Total rainfall (mm)**	**Nash coefficient**	**Period (numbers of days)**	**Total rainfall (mm)**	**Nash coefficient**
Calibration	18th November to 13th January (56)	1134.63	0.90	1rst February to 18th March (46)	169.65	0.74
Validation	14th January to 14th March (60)	214.13	0.74	19th March to 2nd May (46)	169.79	0.74
Cross-calibration	14th January to 14th March (60)	214.13	0.87	19th March to 2nd May (46)	169.79	0.79
Cross-Validation	18th November to 13th January (56)	1134.63	0.79	1rst February to 18th March (46)	169.65	0.71

1.5 Water temperature and cyanobacteria biomass modelling

The dataset obtained in 2011 was used to calibrate DYCD for simulating water temperature and cyanobacteria dynamics from 19th September to 10th November in the deepest point of Lake Pampulha (point P3 in Figure 1). DYCD was manually calibrated by adjusting layer thickness to ensure a good resolution of model results and then a multiplier factor of the wind speed was fit to take into account different conditions on the lake and at the weather station. In a next step, the most sensitive parameters to cyanobacteria growth were calibrated; their values are shown in Table 4. A retrocalibration of layer thickness and the wind factor was then carried out. Parameters related to phosphorus and nitrogen uptake by cyanobacteria were set as the model default values since nutrients are not limiting-growth to algae in Lake Pampulha during the simulation period.

Model results show good agreement with measurements for both water temperature (mean rmse = 0.61°C, mean temperature over simulation period = 21°C) and cyanobacteria biomass (mean rmse = 6.63 µg chl-a L^{-1}, mean biomass over simulation period = 30 µg chl-a L^{-1}). Figure 4 shows measured and simulated vertical profiles of water temperature. During the first days, water column was rather mixed. From 4th October, as the temperature on the lake surface rises, the water column becomes more stratified. DYCD model successfully represents this evolution except on 18th October which coincides with a failure in a water jet located near the sampling point. The water jet has an aesthetic function but it also plays a role on water mixing in this lake area.

Cyanobacteria dynamics follows the water temperature trend: vertical distribution is quite homogenous during the first two weeks and the biomass increases from early October as a result of favourable meteorological conditions (high light intensity and water temperature). Limitation functions calculated by the model for phosphorus and nitrogen are always greater than 0.97; this indicates that cyanobacteria growth is not limited by nutrient concentrations. The ecological model was able to catch these variations. Not surprisingly, the model fails to represent cyanobacterial biomass for the week of October 18th for the same reason described above for water temperature. Figure 5 shows measured and simulated vertical profiles of cyanobacteria biomass.

1.6 Preliminary coupled model

The calibrated and validated rainfall-runoff model was used to simulate runoff volume in Ressaca and Sarandi catchments from 04th October to 10th November 2011, which corresponds to a part of the calibration period for Lake Pampulha model. The inflow data obtained from the water balance computation were replaced by the runoff model output and variations in the simulated water temperature and cyanobacteria biomass were checked to assess the coupled model performance.

The change in inflow data has led only to a small degradation in the lake model performance since vertical profiles for water temperature and cyanobacteria biomass have remained rather unchanged. For water temperature mean rmse = 0.71°C and for cyanobacteria dynamics mean rmse = 7.20 µg chl-a L^{-1}. The lack of significant variation in the results is encouraging about the two models’ coupling. However, it could also stand for a lack of sensitivity of the lake model to the inflow volume model during this period. The study of this “inter-sensitivity” will be the object of further analyses on the coupled model.

Table 4: Lake ecological model calibrated parameters

Parameter	Unit	Range value	Assigned value
Minimum layer thickness	m	0.2 – 1.0	0.6
Maximum layer thickness	m	0.4 – 5.0	4.0
Wind factor	-	1 – 3.0	2.36
Maximum growth rate	day^{-1}	0.5 – 0.7	0.64
Optimum temperature	°C	31 – 33	33
Maximum temperature	°C	39 – 41	39
Light saturation	$\mu Es^{-1}m^{-2}$	100 – 600	290

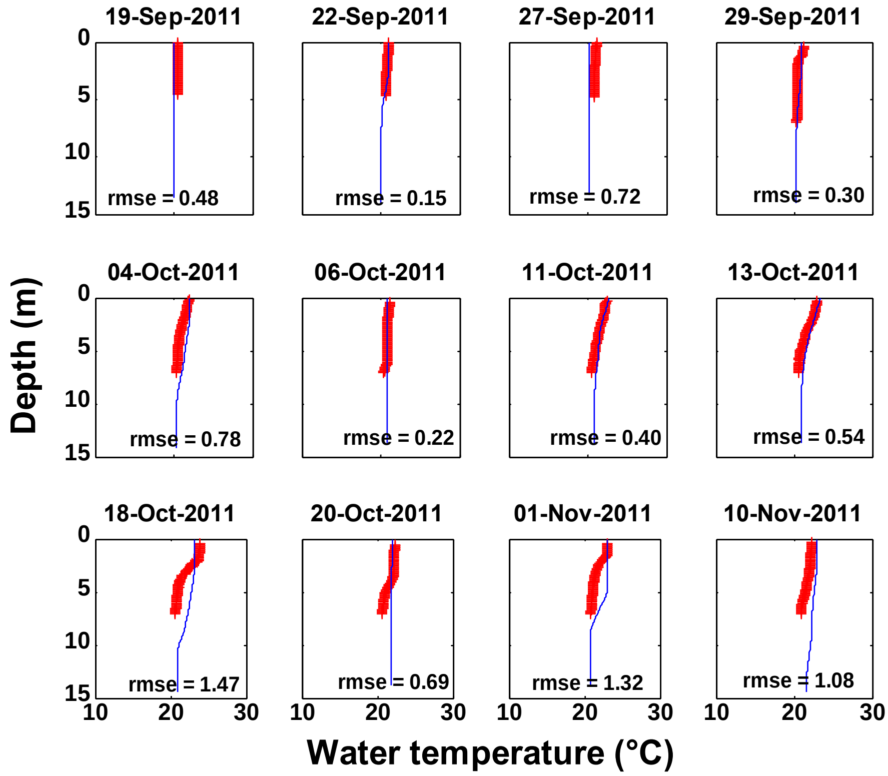

Figure 4 : Model results (blue line) and measurements (red dots) for water temperature at point P3. RMSE values are in °C units

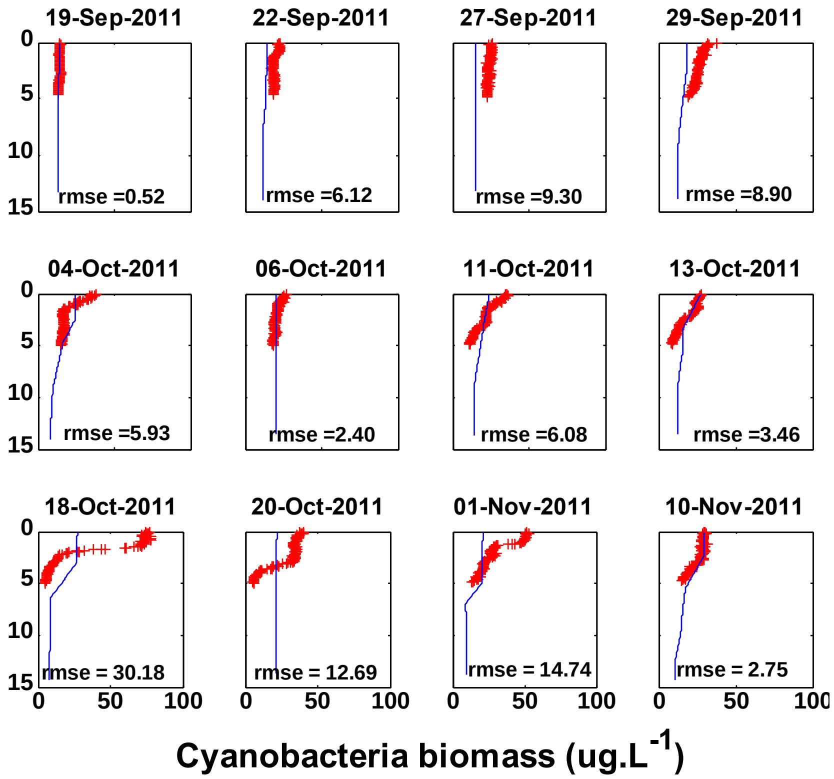

Figure 5 : Model results (blue line) and measurements (red dots) cyanobacteria biomass at point P3. RMSE values are µg chl-a.L^{-1}.

CONCLUSION AND PERSPECTIVES

An integrated modelling approach is proposed in which the urban runoff simulated by a hydrological model is used as input for a hydrodynamic-ecological model simulating cyanobacteria dynamics. Both models, SWMM and DYCD revealed a good ability to reproduce processes of the urban water cycle in the catchment and into the receiving water body. A first attempt to couple SWMM and DYCD for the moment concerning only water volume was promising. In the next steps, the lake model will be validated with another dataset and the SWMM water quality block will be used to simulate runoff water quality.

This integrated approach of the catchment and the lake will make possible to study Lake Pampulha as a water body that integrates and responds to changes that occur in its surroundings. The results obtained will help to determine in advance the impacts of a likely intensification of urbanization on this water body which has a great touristic, cultural and landscaping relevance to Belo Horizonte city. The assessment of positive impacts resulting from improvements in the sanitation system will be possible and thus management strategies for the lake and its catchment will be likely better guided. This integrated approach in Lake Pampulha may not only help to guide its restoration and protection, but also may be replicated to other water bodies located in urban areas.

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