Acta Scientiarum. Technology
ISSN: 1806-2563
eduem@uem.br
Universidade Estadual de Maringá
Brasil

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Acta Scientiarum. Technology, vol. 35, núm. 1, enero-marzo, 2013, pp. 59-67
Universidade Estadual de Maringá
Maringá, Brasil

Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v35i1.13670

Hydrodynamic modeling and morphological analysis of lake Bolonha: a water source in Belém, Pará State, Brazil

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ABSTRACT. Current paper's main contribution includes hydrodynamic modeling and morphological analysis of lake Bolonha which, along with lake Água Preta, makes up the Utinga watershed in Belém, Pará State, Brazil. Bathymetry of lake Bolonha was undertaken by digitalizing the data provided by COSANPA (the local Sanitation and Water Supply Company) dating back to 1983, and from a 2007 field study. Both bathymetries produced two terrain elevation models which were used for morphological analysis and hydrodynamic simulations. The morphological analysis showed that between 1983 and 2007, no significant relief changes occurred on the bottom of lake Bolonha, except for the formation of the outflow channels between the interconnecting channel and Bolonha Water Treatment Plant (WTP). The hydrodynamic model was able to simulate depths and velocities. The velocities, ranging between 1.8 and 9.0 cm s^{-1}, showed a subtle current between the outlet of the canal connecting the lakes Bolonha and Água Preta and the water intakes of the Bolonha and São Braz WTPs. This fact demonstrated that lake Bolonha reservoir is a passage for waters from lake Água Preta.

Keywords: bathymetry, terrain elevation model, water treatment plants.

Modelagem hidrodinâmica e análise morfológica do lago Bolonha: um dos mananciais de Belém, Estado do Pará, Brasil

RESUMO. As principais contribuições do artigo são a modelagem hidrodinâmica e a análise morfológica do lago Bolonha, o qual juntamente com o lago Água Preta, forma o manancial do Utinga em Belém, Estado do Pará. A batimetria do Bolonha foi obtida através da digitalização de dados provenientes da COSANPA que datam de 1983 e do levantamento em campo realizado em 2007. As duas batimetrias originaram dois modelos de elevação de terreno, os quais serviram para análises morfológicas e simulações hidrodinâmicas. A análise morfológica demonstrou que, entre 1983 e 2007, não houve nenhuma mudança significativa do relevo de fundo do lago Bolonha, a não ser a formação de um canal entre a chegada das águas do lago Água Preta e a tomada d'água da ETA Bolonha. O modelo hidrodinâmico mostrou-se capaz de simular as profundidades e as velocidades. As velocidades, na faixa de 1.8 a 9.0 cm s^{-1}, mostraram uma sutil correnteza estabelecida entre a saída do canal interligando os lagos Bolonha e Água Preta e as captações das ETA Bolonha e São Braz, demonstrando que o lago Bolonha serve de passagem às águas provenientes do lago Água Preta.

Palavras-chave: batimetria, modelo de elevação do terreno, estação de tratamento de água.

Introduction

Water is one of the vital basic inputs for the existence of mankind. It is a renewable, yet not inexhaustible natural resource of public domain. As such, water has to be allocated for different purposes and, in that case, water integrity may be endangered by factors such as industrial development, accelerated urbanization and population growth.

Water resources in Brazil play a decisive underlying role in the economic field, as the country has an extensive and dense hydrographic network. Water pollution in cities has been aggravated over the years due to an increase in the polluting loads from households and industries. These factors, such as increased sediment transports and organic and chemical contamination of waters, put at risk water resources.

Two artificial lakes, Bolonha (0.58 km^2) and Água Preta (3.12 km^2), supply water to the metropolitan area of Belém, Pará State, Brazil. These water reservoirs are interconnected and together make up the Utinga water source (Figure 1).

Since the water system of lake Bolonha and lake Água Preta has undergone several environmental aggressions due to constant encroachment, urban sprawl and land clearing at the lakes' water sources, the issue raises major concerns with the amount of pollutants that are discharged from households surrounding the water bodies. The population living in the surrounding area usually does not have proper sewage disposal resources so that wastes are disposed of near the lakes and hamper the water's use for other purposes, including supply for the population. Based on the above, current essay includes the development of a hydrodynamic model for lake Bolonha and other morphological analyses that may eventually inform studies on the dispersion of pollutants and measure the current pollution scenario.

Over the past few years, hydrodynamic modeling of lakes has become an important tool for managing water resources, especially in the dispersion of pollutants and for good water quality. Based on this context, Ferrarin et al. (2008) designed a model for both the hydrodynamics and morphology of Venice Lagoon, Italy; Ji et al. (2007) analyzed the quality of the water in lake Xuanwu, China; and Rajar et al. (1997) designed a model for the hydrodynamics and water quality of lake Bohinj, Slovenia.

Material and methods

The development of hydrodynamic modeling primarily required substrate and topobathymetric data. Whereas the latter were used to assemble the Terrain Elevation Model (TEM), the substrate composition data were employed to set the Manning coefficient. TEM coupled to the roughness model and boundary conditions provided the date for the Saint-Venant equations that were solved and provided the simulation of velocities and depths of lake Bolonha. Moreover, TEMs prepared for different periods of time were used in morphological studies of the lake.

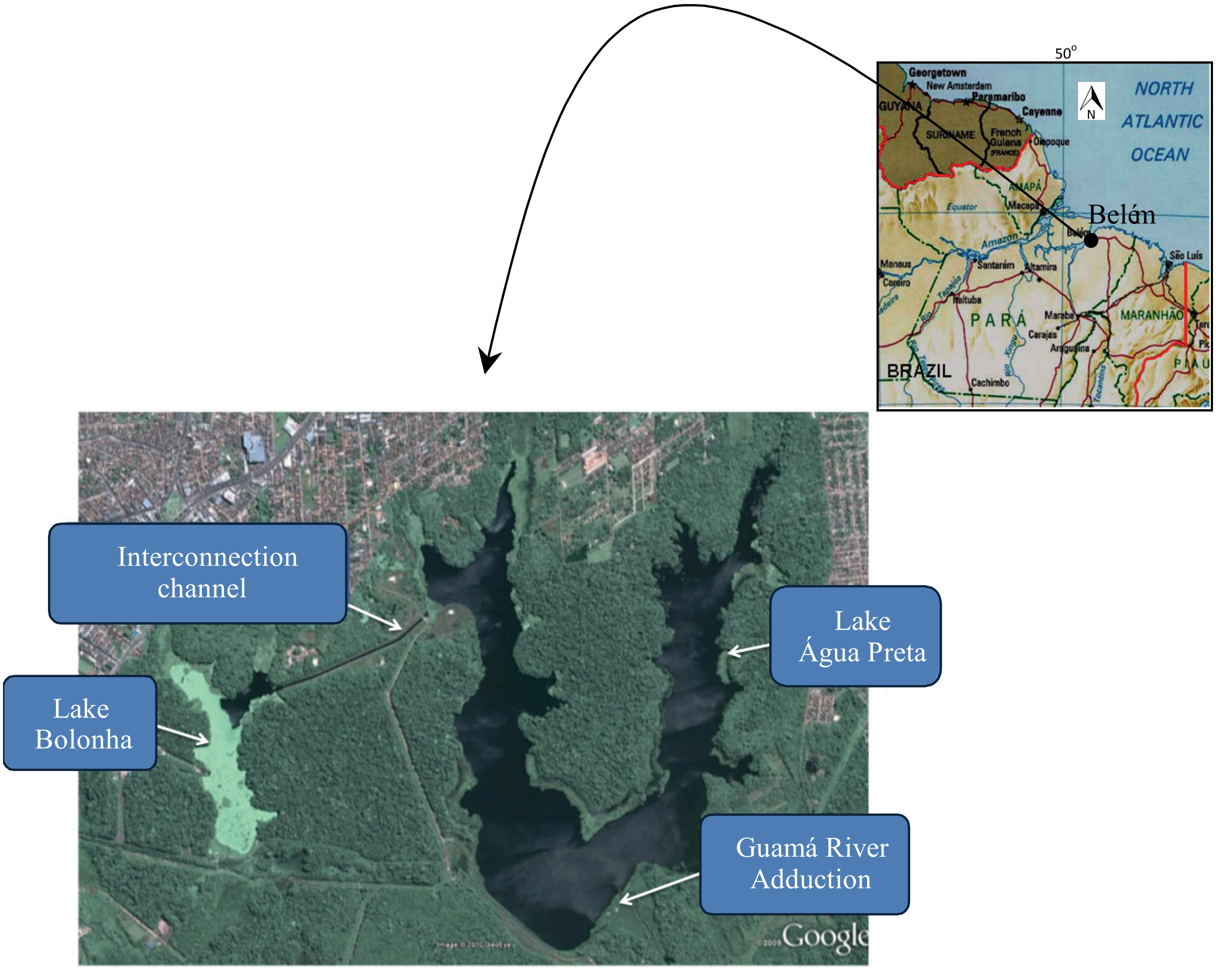


Figure 1. Belém location and satellite picture of lakes Água Preta and Bolonha (Source: Google Earth, 2009).

Modeleur and *Hydrosim* software have been used in current analysis. These were developed at INRS-ETE, a research center of the Université du Québec, Canada (HENICHE et al., 2000). *Modeleur* is a combination of Geographic Information System (G.I.S.) and a powerful pre- and post-processor Finite Element. It establishes Numerical Terrain Models (NMT) with information on topography, riverbed substrate, wind, ice and aquatic plants. The *Modeleur* also enables the division of the analyzed region into partitions with which data sets from the NMT are associated. An automatic procedure for data treatment in partitions' interfaces was used for the mesh generation of finite elements, which will be used to solve the 2-D Saint-Venant model with a drying/wetting capability to follow the shoreline evolution. Studies conducted by Blanco et al. (2009), Barros et al. (2011) and Holanda et al. (2011) corroborate the efficiency of the model and its application.

Topobathymetry data – 1983 and 2007

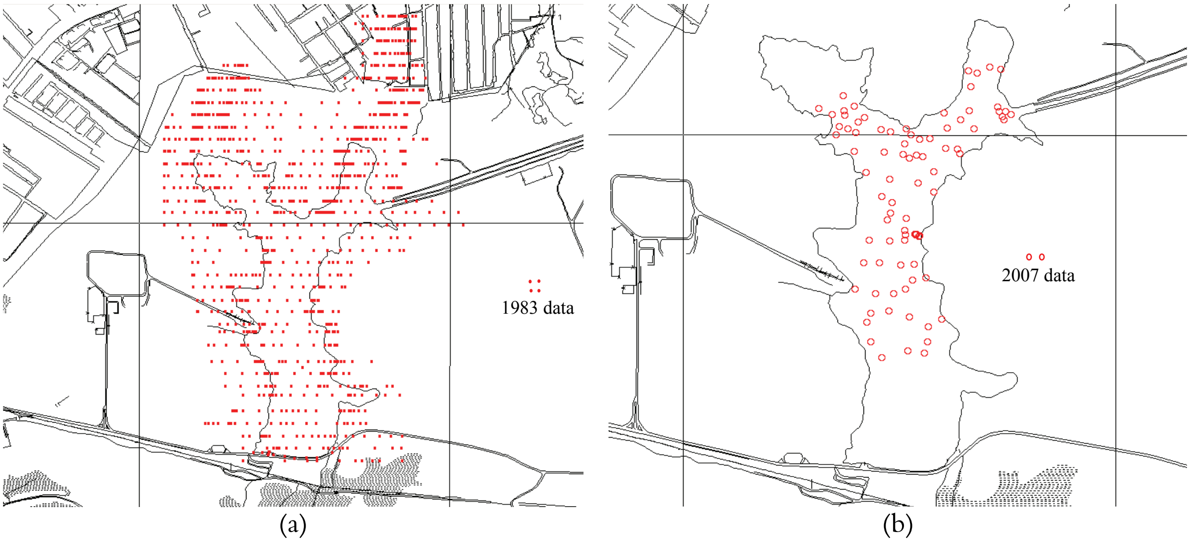
One of the main requirements for achieving satisfactory results through hydrodynamic models involves the quality of topobathymetric data. They should faithfully reproduce the underwater relief of the area under analysis.

Two sets of topobathymetry data were used in current assay. The 1983 set was obtained as a result of a search in the cartographic records at COSANPA (Sanitation Company of the State of Pará); and the second set of data was obtained through topobathymetry tests conducted in October of 2007. The former produced two terrain elevation models (Figure 2) since in 1983 the lake Bolonha and lake Água Preta interconnecting channel was still being constructed (Figure 1).

Thus, a 50 x 50 m regular square mesh was projected over the contour line map provided by COSANPA. Moreover, the x, y coordinates and the z elevation were determined for each point in the mesh cut by a contour line. Figure 2a shows the 1092 points generated by the digitalization of the topobathymetric map. The second set of data was obtained in the field from bathymetry conducted in October of 2007 (Figure 2b). In this specific case, bathymetry was limited due to the environmental conditions of lake Bolonha, significantly covered with macrophytes, as shown in an upstream view of the lake's south dam (Figure 3b). According to this scenario, the 2007 topobathymetric survey was limited since the use of an ADCP or an echobathymeter to automatize data measurement was impaired. Consequently, a weight tied to a metered rope was used to measure the depth of the lake. The 2007 topography was determined by subtracting the depth rates obtained from the lake's water level (N.A. = 7.0 m). In the area where the 2007 data were unavailable, the 1983 data were included (Figure 3a) and thus a mixed topobathymetry was constructed from data obtained in 1983 and 2007.

Terrain Elevation Model (TEM)

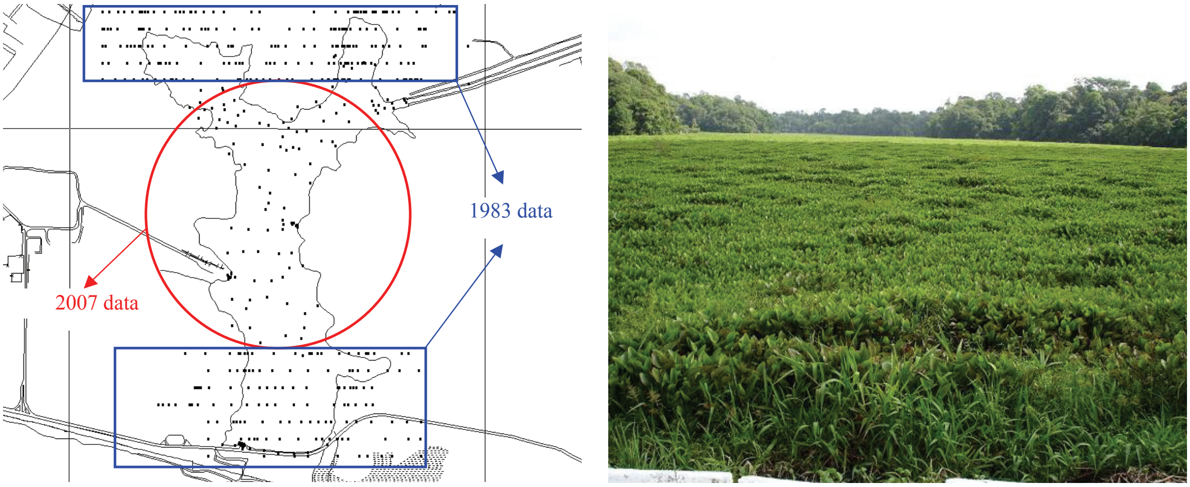
Figure 4 shows the 2007 and 1983 TEMs for lake Bolonha as contour lines from the set of raw data, without discarding the interpolation of Finite Elements Method (FEM) topography. It is important to highlight that the 2007 TEM is a mixed topobathymetry composition (Figure 3a).



(a) (b)

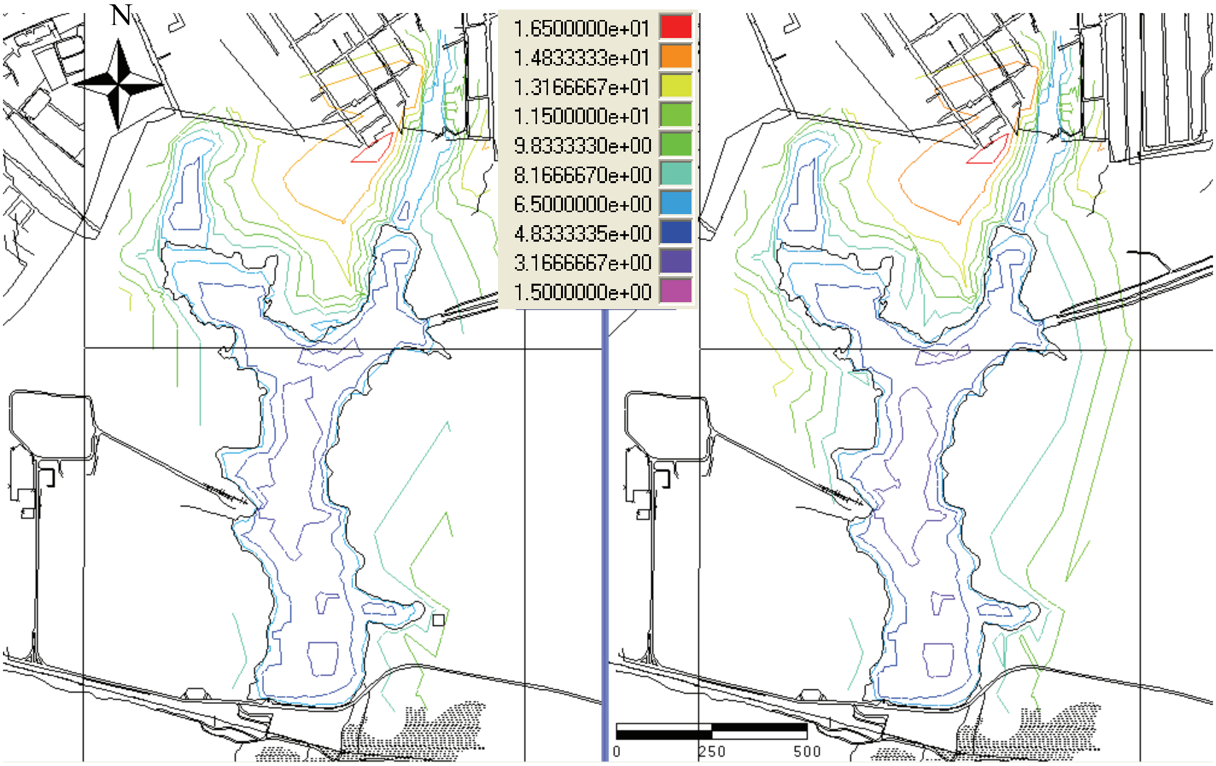
Figure 2. Topobathymetric data of 1983(a) and 2007(b).

As expected, Figure 4 reveals that the region further north of the lake has greater elevations, since the springs flowing to the creeks which make up the lake are located in that region. Such elevations reach up to 16.5 m. Further to the south, the elevations are approximately the same, reaching 8.0 m, since this is approximately the elevation of the lake's dam crest. The lowest elevations, between 1.5 and 3.0 m, are located in the central section of the lake. Figure 4 also reveals that the topographic elevations of lake Bolonha have not changed significantly over the past 24 years, or rather, between the TEMs of Figure 4a and Figure 4b. Thus, the feasibility of mixed bathymetry to fill the 2007 topobathymetric gaps is justifiable. Nevertheless, after the removal of the macrophytes, a new topobathymetric survey of lake Bolonha is required to update the lake's model and for other purposes.



(a) (b)

Figure 3. Mixed topobathymetric data (a) and a large area of lake Bolonha covered with macrophytes (b).



(a) (b)

Figure 4. Crude TEM for lake Bolonha: 2007 (a) and 1983 (b) in meters.

Lake's roughness

The hydrodynamic model should include a roughness model as well. The model used in this paper was determined on the assumption that the lake's substrate is a mean of its granulometry. A reference to types of granulometry may be found in the work of Holanda et al. (2011) from which data in Table 1 have been retrieved.

Table 1. Particles, granulometry and substrate percentage.

Particle	Particle diameter (mm)			%
Coarse Sand	2	to	0.2	47
Fine Sand	0.2	to	0.05	33
Silt	0.05	to	0.002	8
Clay		0.002		12

Since the entire lake bed is represented by the percentages above, the Manning friction coefficient (n) is calculated by the following expression,

$$n = \frac{1}{34.9[-\log(d_{med})]^{0.31} + 0.00017} \quad (1)$$

where:

d_{med} is the average diameter of the particles making up the substrate. Thus, the value of 'n' for the bed of lake Bolonha is equal to 0.019.

Boundary conditions

Another underlying element for formulating the hydrodynamic model includes the appropriate boundary conditions (free surface, bottom and closed, moving or open boundaries), comprising the rates of the entrance or output flows or properties, in accordance with the boundary typology. The following conditions are considered in this study:

Solid boundaries: impermeability condition;

Liquid boundaries: water levels and outflows.

Figure 5 shows the boundary conditions for maximum flow in lake Bolonha and are explained below.

A: Water intake through the connecting channel between lakes Bolonha and Água Preta: flow = 6.0 m^3 s^{-1} and water level = 7.0 m.

B: Water outlet through intake 1 (WTP/BOLONHA): Flow = 4.2 m^3 s^{-1} and water level = 7.0 m.

C: Water outflow through intake 2 (WTP/SÃO BRAZ): Flow = 1.8 m^3 s^{-1} and water level = 7.0 m.

Hydrodynamic model

A two-dimensional horizontal hydrodynamic model was adopted. In this case, mass conservation and momentum equations were integrated according to depth. Thus, the problem becomes two-dimensional and the velocity rates are mean rates in the vertical direction. These types of models are referred to as Saint-Venant, or shallow water models. The main conditions to be fulfilled for using this model (HENICHE et al., 2000) are:

water column is mixed in the vertical direction and the depth is small when compared to the width and the length of the water volume;

waves have low amplitude and long periods (tide waves). The vertical acceleration component is negligible, allowing for hydrostatic pressure approximation.

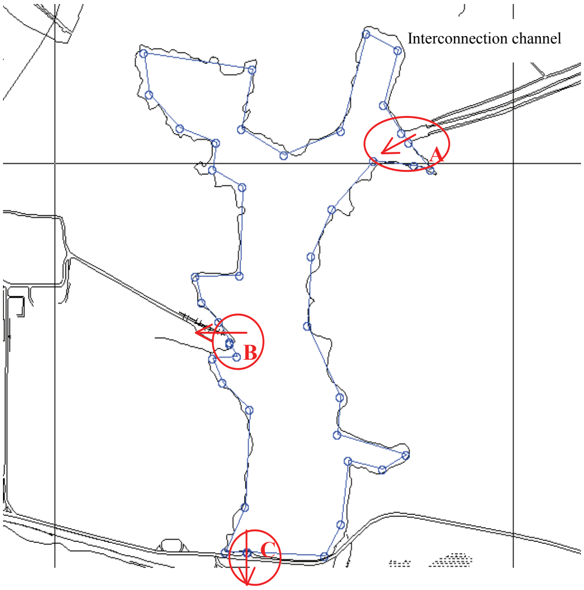


Figure 5. Boundary conditions applied to lake Bolonha.

Equations (2) to (4) are the conservative form of the Saint-Venant equations. The first is the continuity equation, whereas the other two are the momentum conservation equations for the fluid, in x and y directions, respectively.

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (2)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial q_x \frac{q_x}{H}}{\partial x} + \frac{\partial q_x \frac{q_y}{H}}{\partial y} = \sum F_x \quad (3)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial q_y \frac{q_x}{H}}{\partial x} + \frac{\partial q_y \frac{q_y}{H}}{\partial y} = \sum F_y \quad (4)$$

where:

q_x and q_y are the flow rates in the Cartesian coordinates x e y; t is time; h is the water level, H is the depth of the water column, and F_x and F_y are the volume forces in x and y directions.

F_x and F_y are given by equations (5) and (6).

$$\sum F_x = -gH\frac{\partial h}{\partial x} - \frac{n^2 g|\vec{q}|q_x}{H^{1/3}} + \frac{1}{\rho}\left(\frac{\partial(H\tau_{xx})}{\partial x}\right) + \frac{1}{\rho}\left(\frac{\partial(H\tau_{xy})}{\partial y}\right) + F_{cx} + F_{wx} \qquad (5)$$

$$\sum F_y = -gH\frac{\partial h}{\partial y} - \frac{n^2 g|\vec{q}|q_y}{H^{1/3}} + \frac{1}{\rho}\left(\frac{\partial(H\tau_{yx})}{\partial x}\right) + \frac{1}{\rho}\left(\frac{\partial(H\tau_{yy})}{\partial y}\right) + F_{cy} + F_{wy} \qquad (6)$$

where:

g is the acceleration of gravity; *n* is the Manning coefficient; $|\vec{q}|$ is the modulus of the specific flow rate; ρ is the water density; τ_{ij} is the Reynolds stress tensor;

$$\tau_{ij} = \nu\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right) \qquad (7)$$

where:

F_{cx} and F_{cy} are the Coriolis forces in *x* and *y* directions, respectively; and F_{wx} and F_{wy} are wind forces in the *x* and *y* directions, respectively.

The influence of the wind was not taken into account and will be studied in a subsequent stage. The Coriolis Effect was neglected due to the position of the domain close to the Equator.

The turbulence model employed was the mixing length (L_m) which is the distance between the wall and a point in the flow from which the wall itself no longer influences turbulence. This model assumes a balance between creation and dissipation of energy. In this case, the turbulence viscosity is given by:

$$\nu_t = L_m^2\sqrt{2D_{ij}D_{ij}} \qquad (8)$$

where:

ν_t is the turbulence viscosity;

D_{ij} is the *ij* components of the deformation tensor given by:

$$D_{ij} = \frac{1}{2}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right) \qquad (9)$$

where:

$\overline{U}_i$ is the mean velocity in the *i* direction.

Hydrodynamic mesh

Figure 6 shows the hydrodynamic mesh with finite triangular elements used in the simulations for lake Bolonha. The mesh stores all input variables required for the resolution of the Saint-Venant equations, as well as the resulting variables for the simulation of the two-dimensional flow (v_x, v_y and depth). In the case of the model considered herein, the input variables are: coordinates x, y and z, interpolated via TEM and transferred to the hydrodynamic mesh, the mean roughness rate calculated and the previously defined boundary conditions.

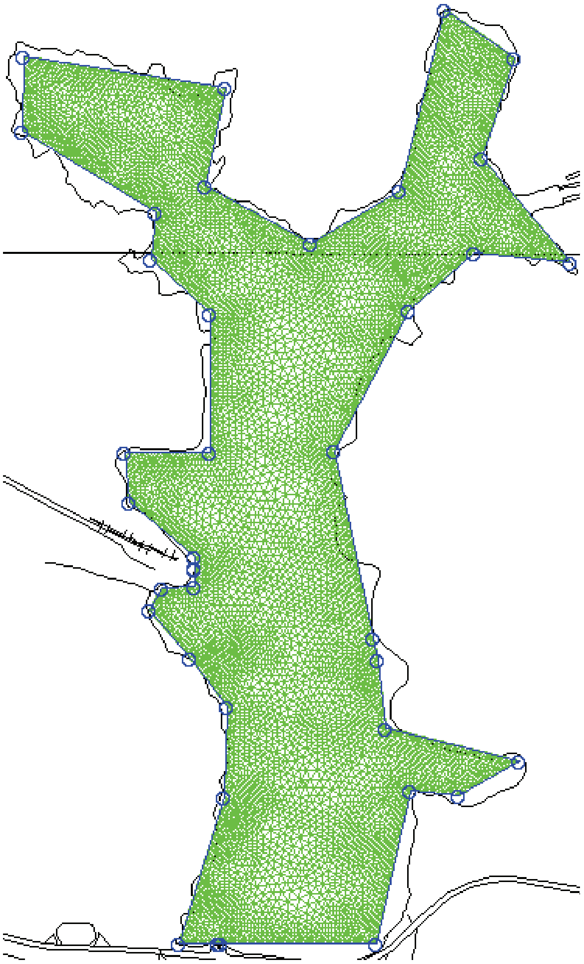


Figure 6. Hydrodynamic mesh of lake Bolonha.

Hydrodynamic meshes were used in the simulations with the larger edge of the triangles for the finite elements equal to 10.0, 5.0 and 2.5 m. The difference between the errors in the mass balance between the input and output of the domain for the 5.0 and 2.5 m meshes was small since the 5 m mesh takes a shorter computational time. Thus, the 5 m mesh (Figure 6), with 29,046 triangles and 59,411 nodes, was used for analyzing the results of the hydrodynamic modeling of lake Bolonha.

Results and discussion

Interpolated TEM

The terrain elevation models from the interpolation of the z elevation over the hydrodynamic mesh of Figure 6, such as raw terrain elevation models (Figure 4), are also presented as contour lines. Figure 7 shows the interpolated TEMs from 1983 and 2007.

By comparing the raw TEMs (Figure 4) to the interpolated ones (Figure 7), it may be seen that the interpolated TEMs adequately represent the topography of lake Bolonha, which is very important for the success of hydrodynamic simulations.

Depth

Depths are simulated by Eq. (10). However, in reservoirs such as lake Bolonha, water levels have little variation in relation with the water levels of boundary conditions and, thus, the water levels in the lake were equaled to 7.0 m.

$$\text{Prof} = \text{N.A.} - \text{Topo} \qquad (10)$$

where:

Prof is depth (m);

N.A. is water level (m);

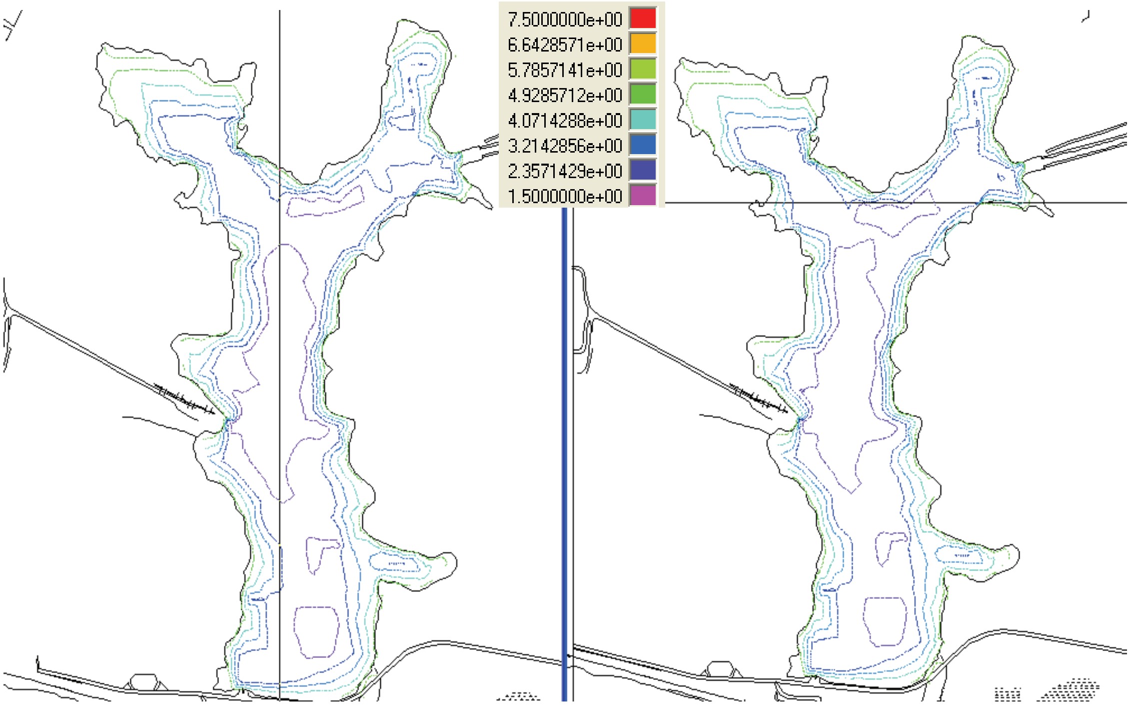
Topo is the terrain topography (m).

Figure 8 respectively shows the depth results for lake Bolonha for 1983 and 2007 in isosurfaces. The analysis of Figure 8 determined that the maximum current depth of the lake ranged between 4.5 and 5.0 m (Figure 8b), consequently differently from that in 1983 when the maximum depth was 4.5 m (Figure 8a). This depth difference has been detected in the outflow channel between the waters from Lake Água Preta and those collected by the WTP Bolonha (Figure 5). Erosion can be thus explained since the lakes were interconnected after 1983.

Velocity

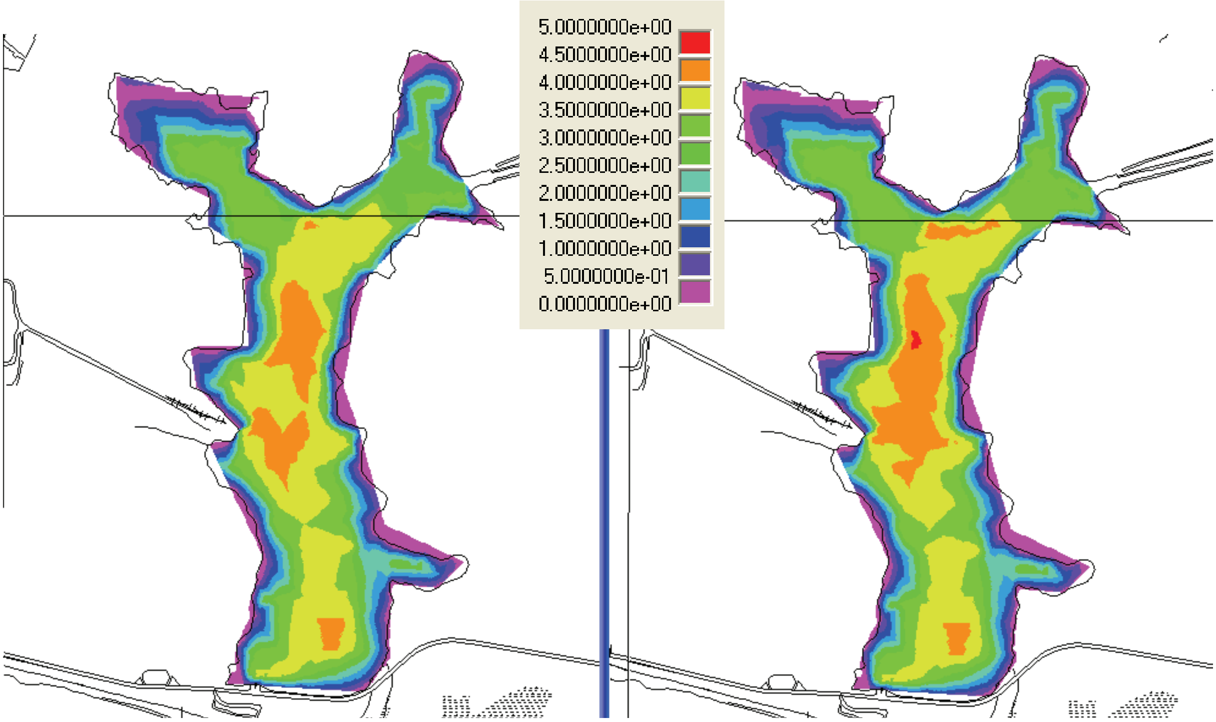
Figure 9 presents the simulated velocity field of lake Bolonha for 2007. In 1983 the dynamics of the lake were lower, as the interconnection channel between lakes Bolonha and Água Preta was still being executed.

Figure 9 shows a discreet current among the interconnection channel, the WTP Bolonha intake and the WTP São Braz intake. The current is not discreet only near the outlet from the channel and entrances to the WTPs (Figure 10). The flow is rather accelerated in these regions due to restrictions in the area. The other regions in the lake have reservoir characteristics, with velocities close to 0 (zero).



(a) (b)

Figure 7. Interpolated TEMs of lake Bolonha from 1983 (a) and 2007 (b) in meters.



(a) (b)

Figure 8. Depth isosurfaces of Lake Bolonha 1983(a) and 2007(b), in meters.

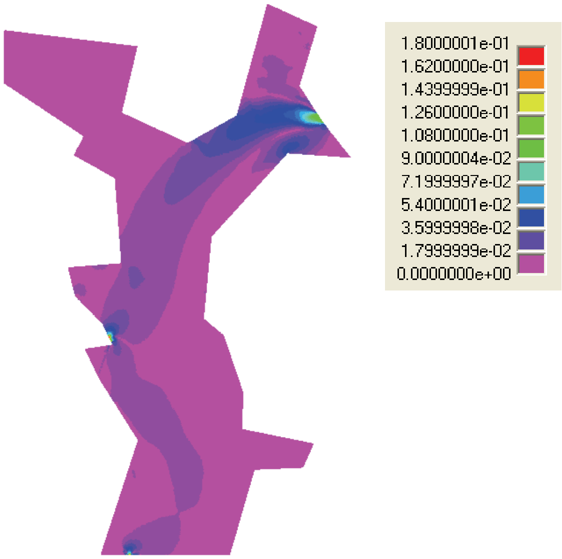


Figure 9. Simulated field for velocity modules in meters per second of lake Bolonha.

In current analysis it was not possible to calibrate the model that was developed due to the macrophytes floating in the lake at considerable velocities which hampered the velocity measurements required for model calibration.

Morphological analysis of lake Bolonha

Analysis included the interpolated 1983 and 2007 TEMs for Lake Bolonha (Figure 7) to represent the topography so that an investigation on the lake's morphological evolution may be undertaken. Since the topography rates were subtracted (2007–1983), the surface curves were produced and the relief differences after 24 years were revealed (Figure 11).

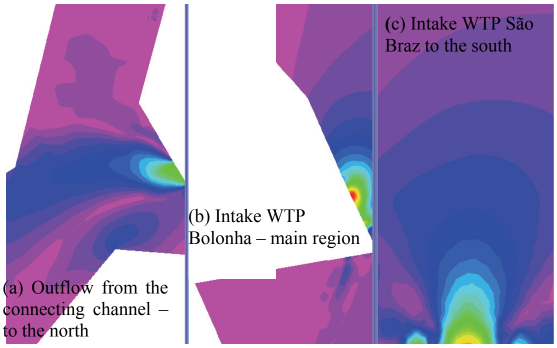


Figure 10. Zoom of the regions with accelerated outflow.

The negative rates for the topographic differences in lake Bolonha (Figure 11) point to erosion found in the outflow channel between the waters from lake Água Preta and those collected by WTP Bolonha (Figure 5). This may be explained by the fact that, after 1983, the lakes were interconnected. The negative differences are higher in regions where the velocities (Figures 9 and 10) are greater, e.g. the outlet from the interconnecting channel, where the difference reaches 0.50 m.

Negative differences also exist between the intake of the WTP Bolonha and that of the WTP São Braz. Nonetheless, since the velocities are lower, they do not exceed 0.20 m. The opposite effect is observed at the embankments of the eroded channel, where the differences are positive and reach up to 0.40 m. The appearance of outflow channels is the most conspicuous and predictable difference, since such outflow did not previously exist in the 24-year morphological evolution of Lake Bolonha, even with the limited 2007 topobathymetric data.

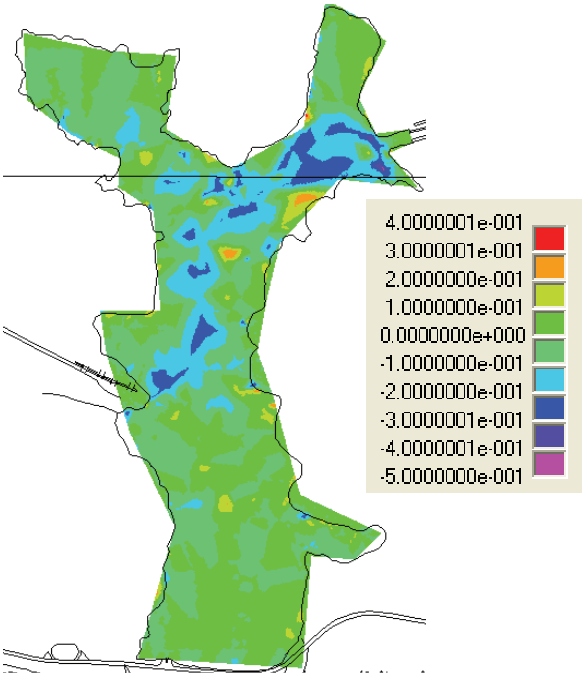


Figure 11. Isosurface for the topography differences, in meters, of lake Bolonha.

Conclusion

Simulation results for the outflow pattern from lake Bolonha revealed a discreet current with velocities ranging between 1.8 and 9.0 cm s^{-1} between the outlet of the interconnecting channel, the inlet to the WTP Bolonha and the inlet to WTP São Braz. This fact demonstrated that the Lake Bolonha constituted a passage for the water from lake Água Preta.

As for the morphological analysis, it may be observed that between 1983 and 2007, no significant relief change occurred on the bottom of lake Bolonha, except for the formation of the outflow channels between the interconnecting channel and water collection by the WTPs.

Acknowledgements

The authors wish to thank CNPq – “Conselho Nacional de Desenvolvimento Científico e Tecnológico”, of the Brazilian Ministery for Science and Technology, through the dossier 350398/2005-4 and 134597/2008-7; SEDECT - “Secretaria de Ciência e Tecnologia”, of the State of Pará, through the dossier 001/2006 for the financial support; COSANPA – “Companhia de Saneamento”, of State of Pará; and CPRM – “Serviço Geológico do Brasil”, for data and technical support.

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Received on June 7, 2011.
Accepted on January 20, 2012.