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Hydrodynamic Modeling and Morphological Analysis of Lake Água Preta: One of the Water Sources of Belém-PA-Brazil

The main contribution from this paper includes the hydrodynamic modeling and morphological analysis of Lake Água Preta in Belém city, Pará State, Brazil. The lake bathymetry was taken through the data provided by COSANPA (the local sanitation and water supply company) dating back to 1975, and from a 2009 field study. Both bathymetries produced two terrain elevation models, which were used for morphological analysis and hydrodynamic simulations. The morphological analysis has revealed that, from 1975 to 2009, the annual mean rate of sedimentation varies between 23,065 and 29,081 m^3/year. Through this result, the sedimentation time of Lake Água Preta, from 2009, has been calculated, which varies between 295 and 381 years, maintaining the same rate of sedimentation, water consumption and pumping. The hydrodynamic model simulated the depths and velocities, showing a slight flow with velocities ranging from 0 to 33 cm/s. This flow is established between water input and output of the lake, which is used as reservoir of Belém city.

Keywords: *hydrodynamic modeling, morphological analysis, Lake Água Preta.*

Introduction

In Brazil, water resources play an underlying, decisive role in the economic field, as the country has a vast, dense hydrographic network. Water pollution in cities has been aggravated over the years due to an increase in the polluting loads from both households and industries. These factors bring about damages to the water resources such as increased sediment transporting and organic and chemical contamination of the waters. In Belém, State of Pará, two artificial lakes are used for supplying water to the metropolitan area of Belém: Água Preta (3.12 km^2) and Bolonha (0.58 km^2). These water reservoirs are interconnected and together make up the Utinga water source (Fig. 1).

The hydro system of lakes Água Preta and Bolonha has experienced several environmental aggressions, whether through the constant encroachment, urban sprawl or land clearing taking place on the heads of the lakes. This raises major concerns with the amount of pollutants that can be added from the houses surrounding these water bodies. The population living in such surrounding area usually does not have proper disposal resources for their sewage, thus causing such wastes to be disposed of near the lakes and hampering the use of the lakes for other purposes such as water supply. Based upon that assumption, the objectives of this paper include the development of a hydrodynamic model and morphological analysis for Lake Água Preta that may subsidize studies on the dispersion of pollutants and measure lake management.

Over the past few years, hydrodynamic modeling of lakes, lagoons and rivers has become an important tool for managing water resources, especially in modeling the dispersion of pollutants and morphological analysis. For example, Ferrarin et al. (2008) designed a model to simulate the hydrodynamics and the morphology of Lake Venice, in Italy; Machado et al. (2008) described a three-dimensional Computacional Fluid Dynamics model to simulate the dispersion of effluents in rivers; Ji et al. (2007) analyzed the quality of the water in Lake Xuanwu, China; Gobbi et al. (2003) implemented a hydrodynamic and water quality model for the Lake Irai, in the metropolitan region of Curitiba, Brazil; Vargas et al. (2001) studied water circulation and pollutants dispersion in the south lakes complex of Santa Catarina State, Brazil; Rajar et al. (1997) designed a model for the hydrodynamics and water quality of Lake Bohinj, Slovenia.

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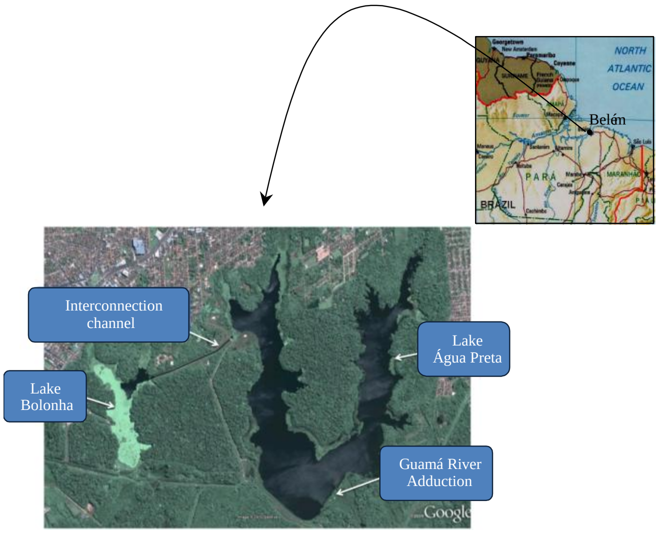


Figure 1. Belém location and satellite picture of Lakes Água Preta and Bolonha. Source: Google Earth, 2009.

Nomenclature

ADCP = *Acoustic Doppler Current Profiler*
D = *deformation tensor component, N/m*^{2}
d_{med} = *mean diameter, mm*
F = *volume force, N*
FEM = *Finite Elements Method*
g = *acceleration of gravity, m/s*^{2}
H = *depth of the water column, m*
h = *water level, m*
L = *mixing length, m*
n = *Manning coefficient, dimensionless*
N.A. = *water level, m*
Prof = *depth, m*
q = *specific flow rate, m*^{2}*/s*
$\left|\vec{q}\right|$ = *modulus of the specific flow rate, m*^{2}*/s*
T6L = *triangle of six nodes*
TEM = *Terrain Elevation Model*
TNM = *Terrain Numerical Model*
Topo = *Terrain topography*
t = *time, s*
U = *velocity relative to direction x, m/s*
V = *velocity relative to direction y, m/s*
x = *direction x of the Cartesian Coordinate System*
y = *direction y of the Cartesian Coordinate System*
z = *direction z of the Cartesian Coordinate System*
zf = *share fund*

Greek Symbols

∂ = *relative to partial derived*
ρ = *water density, kg/m*^{3}
τ = *Reynolds stress tensor, N/m*^{2}
υ = *viscosity*

Subscripts

cx = *relative to coriolis force in x*
cy = *relative to coriolis force in y*
i = *relative to plan of* τ *and to plan of D, and relative to direction of partial derived*
j = *relative to plan of* τ *and to plan of D, and relative to direction of partial derived*
m = *relative to mixing*
t = *relative to turbulent*
x = *relative to direction x*
y = *relative to direction y*
wx = *relative to wind force in x*
wy = *relative to wind force in y*

Data and Methods

The development of hydrodynamic modeling primarily requires obtaining substrate and topobathymetric data. The topobathymetric data are used for assembling the Terrain Elevation Model (TEM), whereas the substrate composition data are used for setting the Manning coefficient. TEM plus the roughness model and boundary conditions provided the data for the Saint-Venant equations (de Saint-Venant, 1871) that were solved, thus allowing for simulating the velocities and depths of Lake Água Preta. Moreover, TEM's prepared for different periods of time were used in morphological studies of the lake. In this analysis, the *Modeleur*/*Hydrosim* academic software has been used. It was developed at INRS-ETE, a research center of Université du Québec, Canada (Secretan et al., 2000; Heniche et al., 2000). *Modeleur* is a combination of a Geographic Information System (G.I.S.) and a powerful Finite Element pre- and post-processor. It allows for the creation of Terrain Numerical Model (TNM) with information concerning topography, riverbed substrate, wind, ice, and aquatic plants. The *Modeleur* also enables the division of the analyzed region into partitions. Data sets from the TNM are associated to the partitions. An automatic procedure of data treatment in the interfaces of the partitions is used for mesh generation of finite elements, which will be used in the solver *Hydrosim* to resolve the 2-D Saint-Venant model with a drying/wetting capability to follow the shoreline evolution. More details can be obtained in Secretan and Leclerc (1998). At that case, the Finite Elements are formed of triangles of six nodes, called T6L (Fig. 2). In this figure, the variables *h* (water level), *H* (depth), *zf* (share fund) and *n* the Manning coefficient are linearly interpolated, because their gradients are less pronounced that gradients of the velocities *U* and *V* and specific flow rates q_x and q_y, which are interpolated quadratically by generally having steeper gradients.

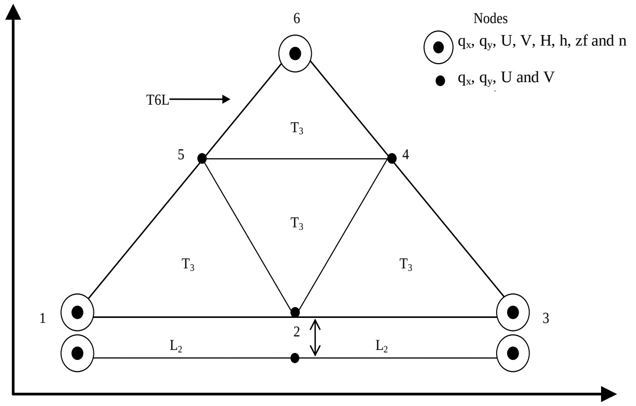
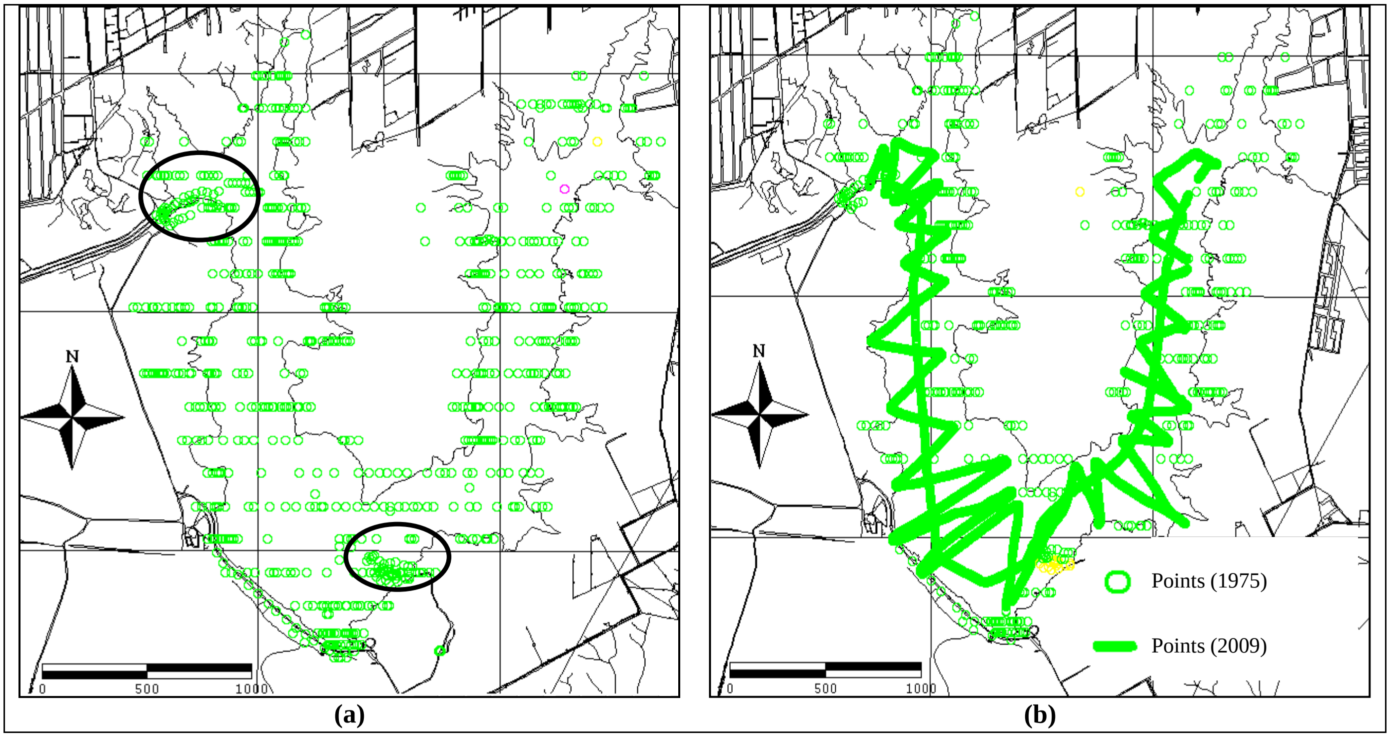


Figure 2. Triangulation used by Modeleur (adapted from Secretan et al., 2001).

Four works conducted by Blanco et al. (2009), Holanda et al. (2009), Barros et al. (2010), Holanda et al. (2010) showed the efficiency of the *Modeleur*/*Hydrosim*. The fisrt work allowed the simulation of the flow, and consequently the estimation of velocities before and after implementation of the new edge project of Belém. The second simulated the velocities and depths of Lake Água Preta with bathymetric data of 1975. The third studied the estuarine system Guajará Bay. The hydrodynamic model was calibrated using tidal levels. The results showed that the methodology has contributed to a better understanding of the system, and obtained a good representation of flow patterns of Guajará Bay, with results of water levels generally satisfactory. The fourth work treated the development of the terrain elevation models from 1975 and 2009, which allowed the variation determination of the depths and volumes of the Lake Água Preta.



(a) (b)

Figure 3. Topobathymetric data dating back to 1975 (a) and 2009 (b).

Topobathymetry data – 1975 and 2009

One of the main requirements to achieve satisfactory results through hydrodynamic models involves the quality of topobathymetric data. They should be able to reproduce well the underwater relief of the area being studied. In this paper, two sets of topobathymetric data were used. The first, from 1975, was obtained through a search of the cartographic records of COSANPA (Pará State Sanitation Company); and the second set of data was obtained through topobathymetry conducted in October 2009. And that originated two terrain elevation models (Fig. 3), considering that in 1975 Lake Bolonha and Lake Água Preta interconnection channel was still being designed (Fig. 1). Thus, a 50 x 50 m regular square mesh was projected over the contour line map provided by COSANPA. For each point in the mesh cut by a contour line, the x, y coordinates and the z elevation were determined.

Figure 3(a) shows the 750 points generated from digitalizing the topobathymetric map. In regions circled (Fig. 3(a)), points of topography were inserted, with the intention of representing Numerical Terrain Models more fully. It was made, because in 1975, there was no the adduction of the Guamá river and canal interconnection of the lakes.

The second set of data was obtained with an ADCP. It has a depht measure range from 100 to 0.30 m, with accuracy equal to 1%, adequate for most of the measured depths in Lake Água Preta. The ADCP sampling frequency equal to 1.00 Hz allowed a fast data collection with 12,716 topobathymetrics points. Despite the data collection being limited due to the environmental conditions of Lake Água Preta, which had considerable amount of macrophytes and tree trunks. Therefore, some areas of Fig. 3(b) show the inclusion of 1975 data to address the lack of data from 2009. This insertion did not cause damage to the flow analysis, since in the most dynamic region of the lake the data are from 2009.

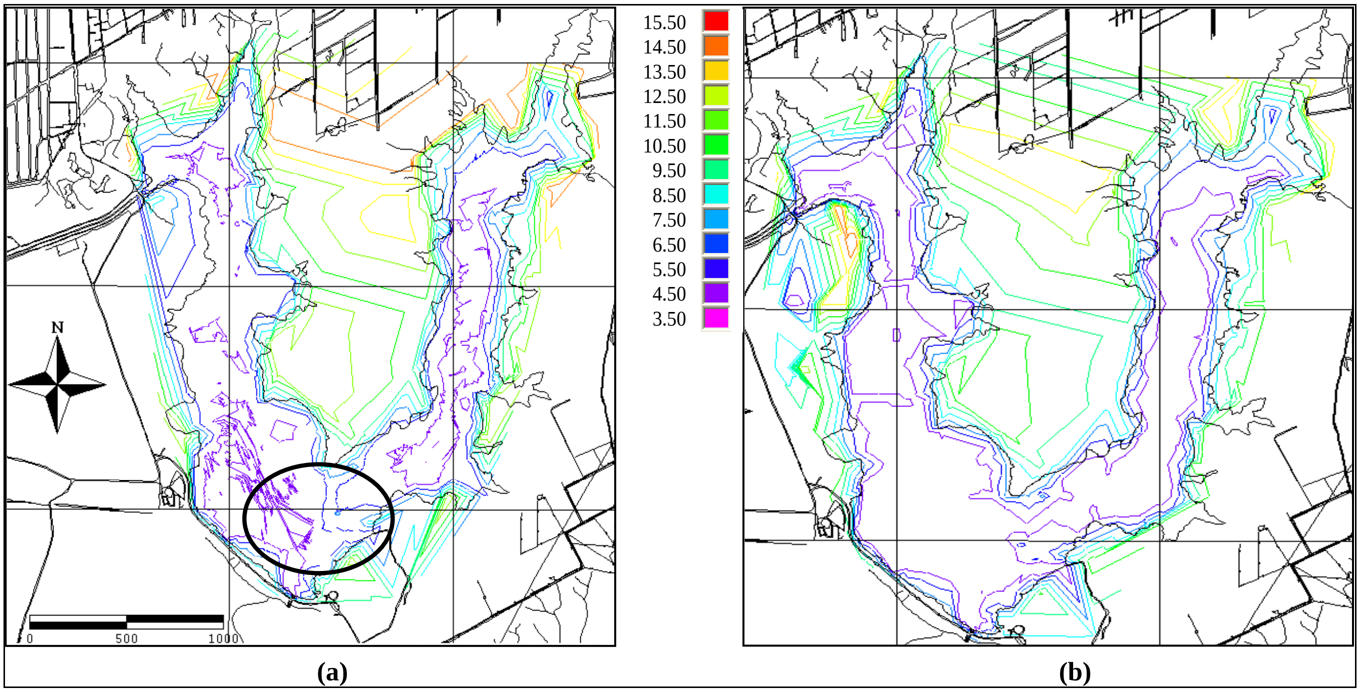
Terrain Elevation Model (TEM)

Figure 4 shows the 2009 and 1975 TEM's for Lake Água Preta as contour lines from the set of raw data without waiving the interpolation of Finite Elements Method (FEM) topography. It reveals, as expected, that the region further to the north of the lake has greater elevations, since the springs to the creeks making up the lake were located in that region. Such elevations reach up to 15.5 m. Further to the south, the elevations are approximately the same, at 9.5 m, since this is approximately the elevation of the lake's dam crest. The lowest elevations, between 3.5 m and 4.5m, are located in the central section of the lake.

Analysis of Fig. 4 also reveals that the topographic elevations of Lake Água Preta have not changed significantly over the past 34 years, between the TEM's of Figs. 3(a) and 3(b), except in the area circulated in Fig. 4(a), which TEM 2009 reveals a region of higher elevations, revealing the sedimentation caused by sediments from the river Guamá.

Table 1. Substrate compostion of Lake Água Preta.

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



(a)

(b)

Figure 4. Raw TEM for Lake Água Preta: 2009 (a) and 1975 (b), in meters.

Lake Roughness

The hydrodynamic model needs to 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 such granulometries can be found in the work of Dias et al. (1991). Table 1 shows the data compiled from their work.

Considering that the entire bed of the lake is made up by the percentages in Table 1, the Manning friction coefficient n is calculated by the following expression (Secretan et al., 2000):

$$n = \frac{1}{\left\{34{,}9\left[-\log\left(d_{med}\right)\right]^{0.31}\right\} + 0{,}00017} \tag{1}$$

where the mean diameter of the particles making up the substrate d_{med} is equal to 0.7 mm. Thus, the value of n for the bed of Lake Água Preta is equal to 0.019.

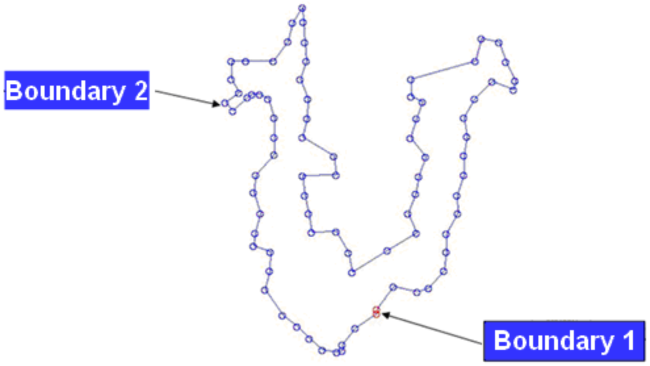


Figure 5. Applied boundary conditions to Lake Água Preta.

Boundary Conditions

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

Solid boundaries: imperviousness condition;

Liquid boundaries: water levels and outflows.

Figure 5 shows the boundary conditions imposed to Lake Água Preta. According to Greidinger (2000), such conditions are for the maximum flows and are explained as follows:

1: Water intake through the adduction of river Guamá: Flow = 6.0 m^3/s and water level = 8.9 m.

2: Water outlet through the connecting channel between Lake Bolonha and Lake Água Preta: flow = 6.0 m^3/s and water level = 8.9 m.

Hydrodynamic Model

A two-dimensional horizontal hydrodynamic model was adopted. In this case, the mass conservation and momentum equations are integrated with respect to the depth. Thus, the problem becomes two-dimensional and the values obtained for the velocities are mean values in the vertical direction. These types of models are referred to as Saint-Venant, or shallow waters. The main conditions to be fulfilled for using this model are as follows (Heniche et al., 2000):

- the water column is mixed in the vertical direction and the depth is small in comparison with the width and the length of the water volume;

- the waves are of small amplitude and long period (tide waves). The acceleration's vertical component is negligible, allowing for hydrostatic pressure approximation.

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

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

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

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

q_x are 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 Eqs. (5) and (6).

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

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

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 that is equal to 998 kg/m^3; τ_{ij} is the Reynolds stress tensor:

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

and ν is the kinematic viscosity that is equal to 1,3 x 10^{-6} m^2/s. F_{cx} and F_{cy} are the Coriolis forces in x and y directions, respectively; and F_{wx} and F_{wy} are the 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, near the Equator.

The turbulence model is mixing length (L_m) due to Rodi (1993). Where L_m is the distance between the wall and a point in the flow where the wall itself does not influence more the turbulence. This model assumes a balance between creation and dissipation of energy. In this case, the turbulent viscosity is given by:

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

ν_t is the turbulent viscosity and 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 and $\overline{U_j}$ is the mean velocity in the j direction.

Hydrodynamic Mesh

Figure 6 shows the hydrodynamic mesh with triangular finite elements used in the simulations for Lake Água Preta. The mesh stores all input variables required for the resolution of Saint-Venant equations, as well as the resulting variables for the simulation of the two-dimensional flow (U, V and H). For the model considered herein, the input variables are: coordinates x, y and z, interpolated via TEM and transferred to the hydrodynamic mesh; the Manning friction coefficient calculated value; and the boundary conditions defined previously.

Hydrodynamic meshes were used in the simulations with the larger edge of the triangles for the finite elements equal to 15.0, 10.0 and 5.0 m. The difference between the errors in the mass balance between the input and output of the domain for the 10.0 m and 5.0 m meshes was small (Table 2), taking into consideration that the 10.0 m mesh takes a shorter computational time. The simulations were executed on the Pentium 4-2.8 GHZ.

Thus, the 10.0 m mesh (Fig. 6) was used for analyzing the results of the hydrodynamic modeling and morphological Analysis of Lake Água Preta. In that case, the mesh has 33,288 triangles and 68,237 nodes.

Table 2. Error in mass balance and computational time for three meshes.

Mesh	Imposed discharge in boundary 1 (m^3/s)	Simulated discharge in boundary 2 (m^3/s)	Error %	Computational time
15 m	6.00	5.43	9,50	01h 01m 04s
10 m	6.00	5.69	5,20	01h 55m 06s
5 m	6.00	5.81	3,20	03h 37m 19s

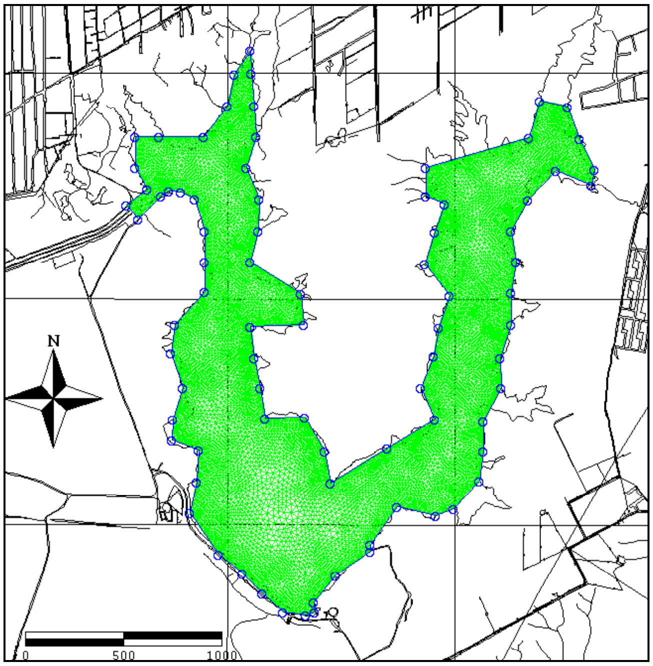
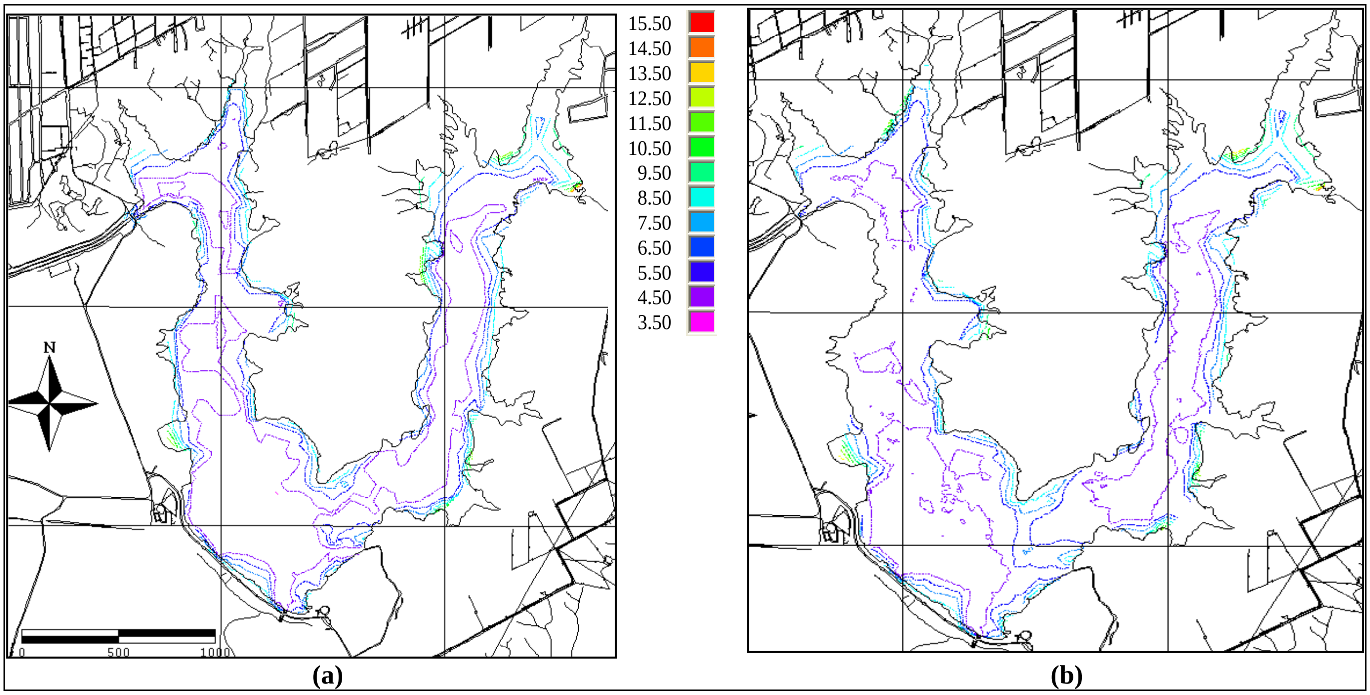


Figure 6. Hydrodynamic mesh of Lake Água Preta.



(a) (b)

Figure 7. Interpolated TEM's of Lake Água Preta of 1975 (a) and 2009 (b) in meters.

Results and Discussions

Interpolated TEM

The terrain elevation models resulting from the interpolation of the *z* elevation over the hydrodynamic mesh of Fig. 6, like the elevation models of raw terrains (Fig. 4), are also presented as contour lines. Fig. 7 shows the 1975 and 2009 interpolated TEM's.

By comparing the raw TEM's (Fig. 4) to the interpolated ones (Fig. 7), it can be seen that the interpolated TEM's represents the topography of Lake Água Preta well, which is very important for the success of hydrodynamic simulations.

Depth of Lake Água Preta

The depths are simulated by Eq. (10). Being that, in reservoirs such as Lake Água Preta, the water levels have little variation in relation to the water levels of boundary conditions and, thus, the water levels in the lake were equaled to 8.9 m.

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

where: *Prof* is depth (m); *N.A.* is water level (m); and *Topo* is the terrain topography (m).

Validation of the bathymetry of 2009

For comparisons with the simulated depths by Sodré (2007), it was applied a *N.A. = 7.9 m* in Eq. (10), together with the topography of the TEM from 2009.

Figure 8 shows that the maximum depth found in the lake is 4.40 m, which lies in the southern portion. In the northeast and northwest ends, depths range from 2.4 to 3.8 m. In the neighborhood of the adduction of the river Guamá, the depths range from 0.80 to 1.60 m. These shallow depths are associated with the settling of heavier particles that are deposited near this place, because the water that comes from the river Guamá is rich of sediments.

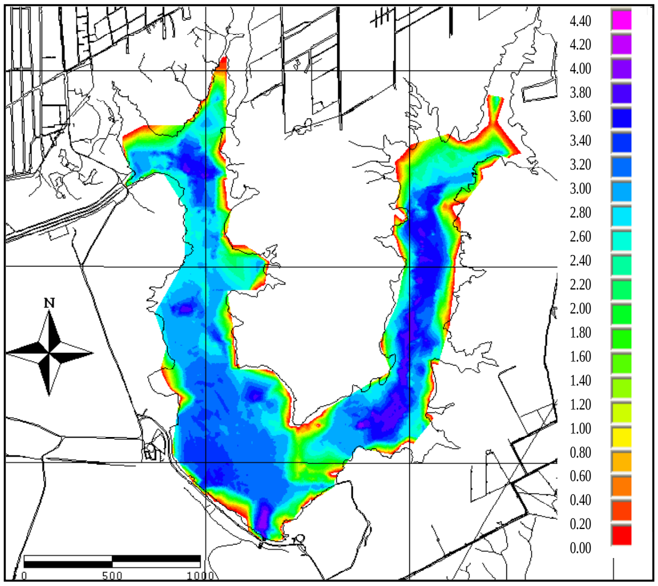


Figure 8. Depth isosurfaces in meters of Lake Água Preta 2009.

Figure 9 shows the simulated depths by Sodré (2007) with measured data in October 2006. In this case, the maximum depth was 4.40 m in the southern region of the lake. In the region of arrival of the waters of Guamá, Fig. 9 reveals depths range from 0.80 to 1.80 m. In the northeast and northwest edges were found depths ranging between 2.2 m, 3.2 m.

Comparing the simulated depth data for 2009 with Sodré (2007) data, it was found that there was little variation in the depths of the two studies, validating the bathymetry from October 2009, at least when compared to data available in literature. The bathymetrics data for 1975 were not validated because there are no data available in literature.

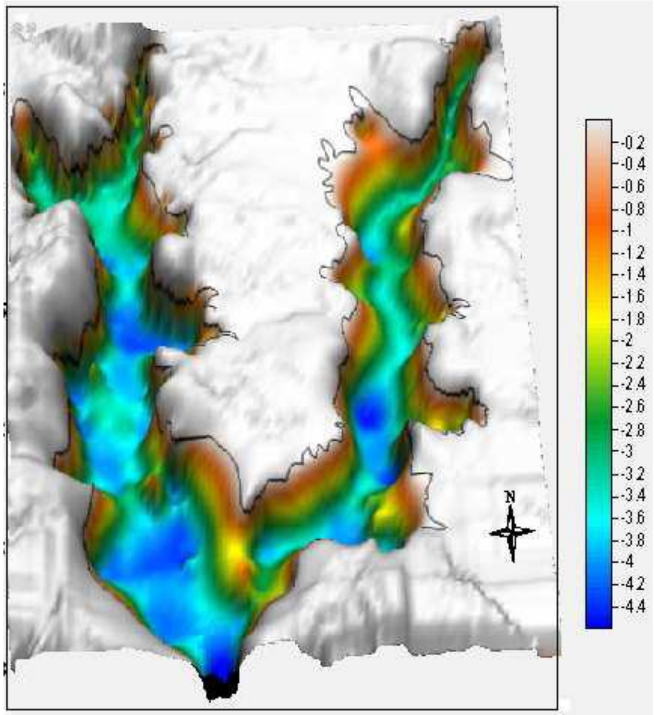


Figure 9. Depth isosurfaces in meters of Lake Água Preta 2006. Source: Sodré, 2007.

Velocity

Figure 10 presents the simulated velocity field of Lake Água Preta for 2009. The velocities vary between 0.00 and 0.33 m/s between the adduction of the River Guamá and the channel interconnection, while most of the lake velocity is close to zero. The maximum velocity was 0.33 m/s at the channel entrance of interconnection, which is explained by the change of section which passes from a larger to a smaller area, thus explaining the larger velocities.

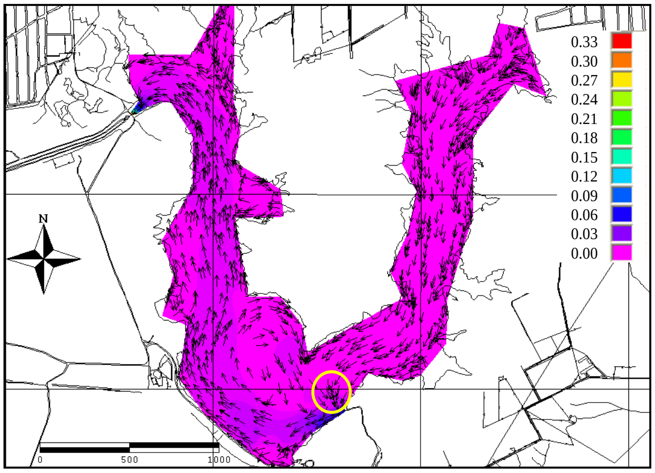


Figure 10. Simulated field for the velocity modules in meters per seconds of Lake Água Preta.

Figure 10 also shows near the adduction (area circled) a diversion of flow due to a region of lower depths, as shown in Fig. 8. Note also a recirculation zone in the central portion of the lake. In addition, water flows between the adduction of the river Guamá and the interconection channel of the Lakes Água Prtea e Bolonha (Fig. 1). The flow follows the higher depths shown in Fig. 8.

Morphological Analysis of Lake Água Preta

This analysis included the 1975 and 2009 interpolated TEM's for Lake Água Preta (Fig. 7) in order to represent the topography, thus performing a study on the lake's morphological evolution. For such, the topography values are subtracted (2009 – 1975), thus originating the surface curves, showing the relief differences after 34 years (Fig. 11).

Figure 11 shows a significant sedimetation in the arrival of water from the river Guamá, which can be explained for the flow expansion, causing the drop of heavier particles. Other important sedimentation takes place in the central area of the lake. At that case, it can be explained for the drop of lighter particles. However, the hypothesis of heavy or light particles can only be answered by sedimentological analysis. Figure 11 also shows that the silting up of the lake, during the 34 years separating the two bathymetric, reaches 2 m. Figure 12 shows a zoom in the central and adduction regions of Fig. 11.

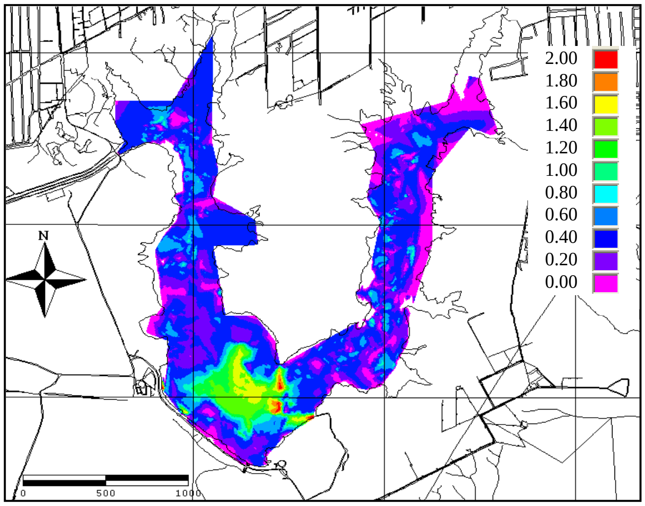


Figure 11. The Isosurface for the topography differences in meters of Lake Água Preta.

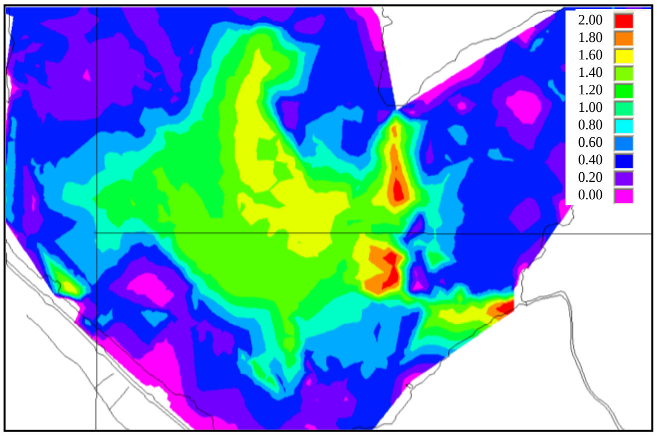


Figure 12. The Isosurface for the topography differences (zoom in).

In this analysis, the time of Lake Água Preta sedimentation was estimated with water pumping and consumption conditions, and sedimentation rate constants. Thus, the annual mean sedimentation rate ΔS (m^3/year) (Eq. 11) was calculated between 2009 and 1975.

$$\Delta S = \Delta V/\Delta t \tag{11}$$

where: ΔV (m^3) is the volume difference between TEM's from 2009 and 1975; and Δt (year) is the time analysed. It is considered the depht measures uncertainties equal to 1% (ADCP accuracy) for the TEM 2009. Accuracy data are not available for TEM 1975 and, in that case, the volume V (m^3) is equal to 9,580,824 m^3. Thus, ΔV varies between 784,195 and 988,768 m^3; and Δt is equal to 34 years. Therefore, ΔS varies between 23,065 and 29,081 m^3/year. For estimating the time of sedimentation, it was yet necessary to calculate V of the lake for 2009, which varies between 8,592,056 and 8,879,629 m^3. The calculated lake volume by Sodré (2007), equal to 8,847,061 m^3 for 2006, is within the calculated volume values range in this work. Through Eq. (12) the time of sedimentation of Lake Água Preta Ts (year) varies between 295 and 381 years.

$$Ts = V/\Delta S \tag{12}$$

The uncertainties of the values of ΔV, ΔS, V and Ts can be reduced if dephts were measured with an ADCP with more accuracy, for example, in the market; there are machines with acurracy minor than 1%. The uncertainties with which the volume of the lake is computed via *Modeleur*/*Hydrosim* calculator are those due to mesh uncertainties. However, the mesh has a good refinement (Table 2).

Conclusions

The hydrodynamic modeling and morphological analysis, presented in this paper, have added to a better physical understanding of what happens with the water from Lake Água Preta as well as the morphological changes in the lake.

Comparison between the raw terrain elevation models and those interpolated in the hydrodynamic mesh demonstrated that the interpolated models represent well the terrain being analyzed, thus allowing for using them in depth and velocity simulations for the lake.

The simulation result for the outflow pattern of the lake revealed a subtle current with velocities ranging from 0.00 to 0.33 m/s between the adduction of the river Guamá and water outlet channel by interconnecting Lakes Água Preta and Bolonha. Regarding the maximum velocities, top velocities reached 0.33 m/s and could be found in those regions near the water outlet channel by interconnecting Lakes Água Preta and Bolonha.

As for the morphological analysis, it could be determined an annual mean sedimentation rate of 23,065 to 29,081 m^3/year between 1975 and 2009. Through this result, it could be calculated the time of sedimentation of Lake Água Preta, from 2009, which varies between 295 and 381 years, maintaining the same rate of sedimentation, water consumption and pumping.

Hydrodynamic Modeling and morphological analysis presented in this paper can be used in the foreground, such as hydraulic engineering tools, supporting thus the management of water resources of lakes used as urban water reservoir.

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