FLOW ANALYSIS AND MODELING OF THE LAKE ÁGUA PRETA: WATER SOURCE OF THE BELÉM METROPOLITAN AREA

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Abstract. The natural conditions of water resources can be modified with the unsustainable use of them. For example, in Belém, capital of Pará State, Água Preta Lake has a history of degradation jeopardize the drinking water supply in Belém. Thus, the main contribution of this work is to develop a study on modeling hydrodynamic study of Água Preta Lake. Such study is carried through the bathymetric of 2009 performed with an ADCP. The bathymetry and substrate data that composes the Lake and its boundary. The bathymetry data are used to construct the digital elevation model, with the coordinates x, y and z in UTM; while the composition of the substrate is used for the determination of the Manning coefficient. The coordinates x, y, z and Manning coefficient are used in the hydrodynamic model. This one is the classic model of Saint-Venant. In this case, a vertical integration is applied to the three-dimensional equations of Navier-Stokes for incompressible flow with outline conditions, of bottom and of liquid and solid surface, included. Thus, the problem becomes two-dimensional (2D) and the values obtained for velocities are medium in the vertical direction. The velocities are the input data for the many models, such as pollutant dispersion sediment transport and aquatic fauna and flora habitats. Thus, besides of hydrodynamic model explains the patterns of flow in the lake, it can be employed for the others models of the Lake Água Preta.

Keywords: Digital elevation, Hydrodynamic modeling, Água Preta.

1. INTRODUCTION

In Belém, State of Pará, two artificial lakes are used for supplying water to the metropolitan area of Belém: Água Preta (3.12 km2) and Bolonha (0.58 km2). These water reservoirs are interconnected and together make up the Utinga water source (Figure 1).

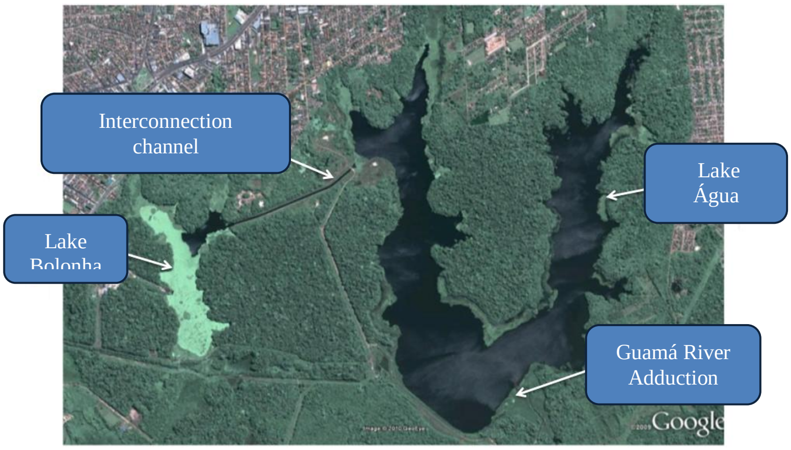

Figure 1 – Satellite image of Utinga water source.

The hydro system of the Lakes Água Preta and Bolonha has experienced several environmental aggressions, whether through the constant encroachment, urban sprawl, and 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 for Lake Água Preta that may subsidize studies on the dispersion of pollutants and measure lake management.

2. METHODOLOGY

The development of hydrodynamic modeling primarily requires obtaining substrate and topobathymetric data. The topobathymetric data are used for assembly the Terrain Elevation Model (TEM), whereas the substrate composition data are used for setting the Manning coefficient. The TEM plus the roughness model and boundary conditions provided the date for the Saint-Venant equations that were solved, thus allowing for simulating the velocities and depths of Lake Água Preta.

2.1. Numerical tools

In this analysis, the *Modeleur* and *Hydrosim* software have been used. These were developed at INRS-ETE, a research center of Université du Québec, Canada (Secretan and Leclerc, 1998; 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 Elevation Model (TEM) 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 TEM 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 to resolve the 2-D Saint-Venant model with a drying/wetting capability to follow the shoreline evolution. This solver is called *Hydrosim*. More details can be obtained in Secretan and Leclerc (1998). Studies conducted by, Blanco *et al*., (2009), Holanda *et al*., (2009 a), Barros *et al*., (2010) and Holanda *et al*., (2010 b) corroborate the efficiency of the model for the region of application, thus allowing the flow simulation and the consequent estimate of velocities.

2.2. Bathymetric Data

The topobathymetric 2009 was obtained with an ADCP. It has a depht measure range from 100 to 0.30 m, with a resolution equal to 10.0 cm, adequate for most of the measured depths in the 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 to have been limited due to the environmental conditions of Lake Água Preta, which had considerable amount of macrophytes and tree trunks. Therefore, some areas of (Figure 2) 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 of 2009.

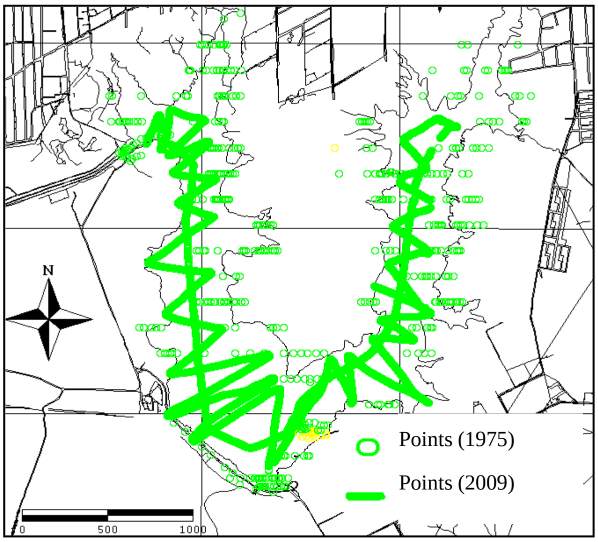

Figure 2 - Bathymetric data points.

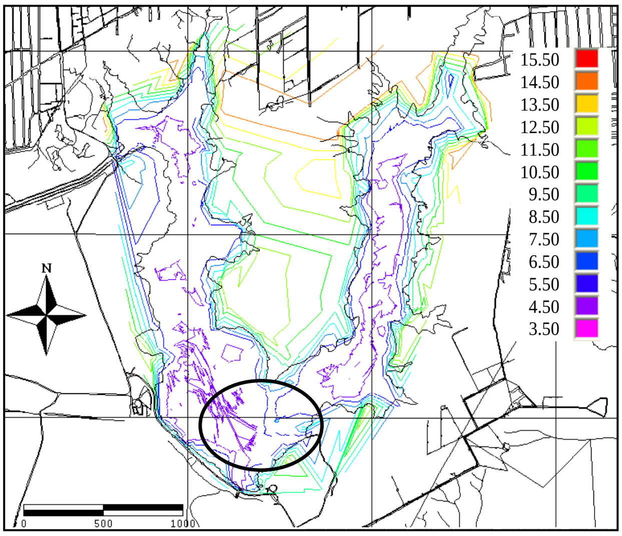

Figure 3 – Raw TEM of Lake Água Preta.

2.3. Lake roughness model

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.

Table 1 – Particle type, granulometry and substract percentile.

Particle type	Particle Diameter (mm)	%
Raw Sand	2 a 0,2	47
Fine Sand	0,2 a 0,05	33
Silt	0,05 a 0,002	8
Clay	0,002	12

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),

$$n = \frac{1}{34{,}9\left[-\log\left(d_{med}\right)\right]^{0{,}31} + 0{,}00017} \tag{1}$$

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

2.4. 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 entrance or output flows or properties, 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 4 shows the boundary conditions imposed to Lake Água Preta.

Boundary 1: Water adduction of the river Guamá: Flow = 6.0 m^3/s and water level = 8.90 m.

Boundary 2: Water outlet through the connecting channel between Lake Água Preta and Lake Bolonha: flow = 6.0 m^3/s and water level = 8.90 m.

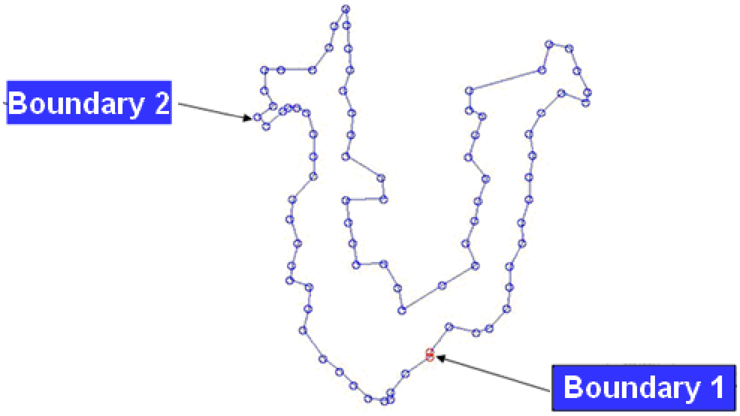

Figure 4 – Applied Boundary conditions applied to Lake Água Preta.

2.5. Hydrodynamic model

In the model, the mass conservation and momentum equations are discretized in the horizontal plane and integrated in the depth or vertical direction. The problem then becomes two-dimensional and the values obtained for velocities and elevations of water are averaged values in the vertical direction. These models are also called Saint-Venant models (Shallow Water) and are subject to the following hypothesis (Heniche *et al*., 2000):

- the water column is mixed in the vertical direction and the depth is small in comparison to the width and the length of the water volume;
- the waves are of small amplitude and long period (tide waves). The vertical acceleration component is negligible, allowing for hydrostatic pressure approximation.

Equations (2) to (4) are the conservative form of the Saint-Venant equations. The first one is the mass conservation equation while the other two are the equations for conservation of momentum for the fluid:

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

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

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

x and y are the directions of the Cartesian Coordinate System used; q_x and q_y are the flow rate in the x and y directions, respectively; t is the 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 the x and y directions, respectively. F_x and F_y are calculated by equations (5) and (6).

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

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

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;

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

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. The Coriolis effect was neglected due to the position of the domain, near the Equator.

2.6. Hydrodynamic Mesh

Figure 5 shows the hydrodynamic mesh with finite triangular 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 (v_x, v_y and depth). 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 value calculated 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 5.0m. The difference between the errors in the mass balance between the input and output of the domain for the 10.0m and 5.0m meshes was small, being that the 10m mesh takes a shorter computational time. Thus, the 10.0 m mesh (Figure 5) was used for analyzing the results of the hydrodynamic modeling of Lake Água Preta. In that case, the mesh has 33,288 triangles and 68,237 nodes.

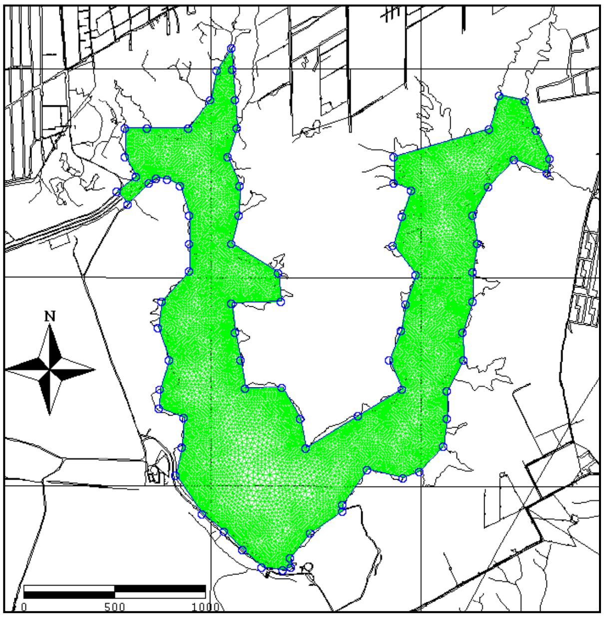

Figure 5 – Hydrodynamic mesh of Lake Água Preta.

3. HYDRODYNAMIC SIMULATIONS

3.1. Interpolated TEM

The first result of the application of the Modeleur/Hydrosim is the interpolated TEM by the Finite Element Method, using topography data. Figure 6 presents this information in the form of isosurface.

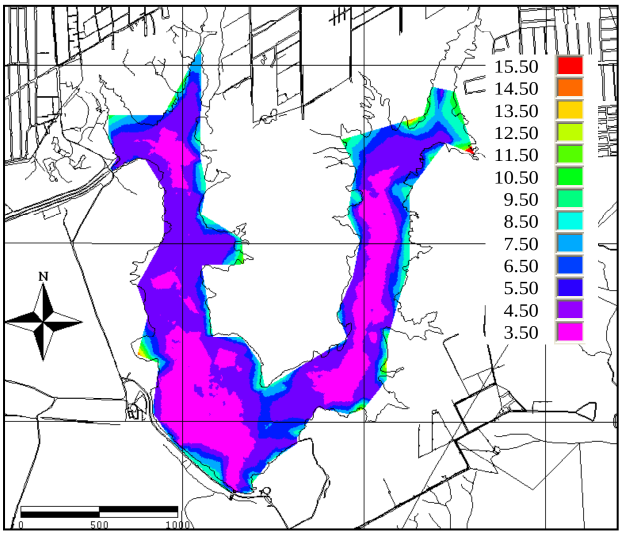

Figure 6 – Interpolated TEM's of Lake Água Preta of 2009 in meters.

By analyzing fig. 6, it can be observed that the terrain topography is in the range of 3.5 m to 14.5 m. However, most of the lake has altitudes between 3.5 and 10.0 m, only the north of the lake the altitude reaches 14.5 m. This was observed by Imbiriba Júnior and Da Costa (2003), which noticed that topographical characteristics of the basin wich low altitudes and in softly accidented terrain, typical of the Amazonian region. It originates floodplains in the boundaries of the lake that facilites the transport of domestic and industrial effluents for the lake.and domestic sewer.

3.2. Depth

The simulated results of water level associated to the interpolated TEM, originate the results of depth of the lake, through the following equation (Secretan *et al*., 2000).

$$Prof = N.A - Topo \qquad (8)$$

Where *Prof* is the depth (m), *N.A* is the water level (m) and *Topo* is the terrain topographic height (m). Figure 7 shows the lake depth field.

3.3. Depth 2009.

The isosurfaces of de depth presented in Figure 7, were simulated considering a N.A=8.9 m. In this case, a maximum depth of 5.0m was observed for Lake Água Preta Lake.

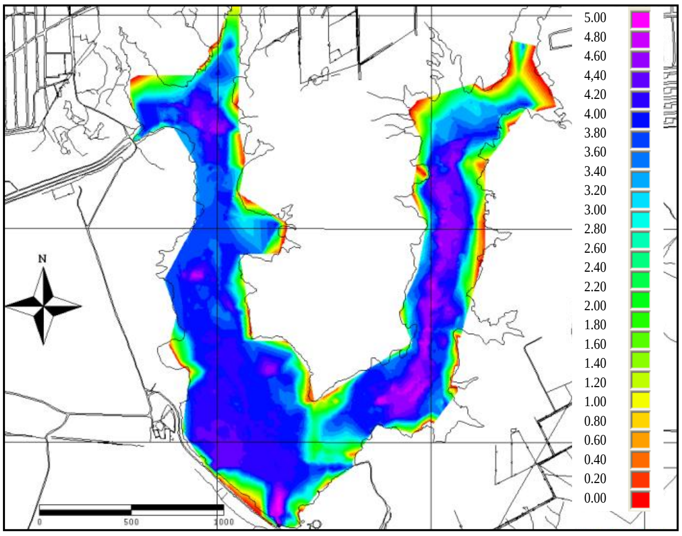

Figure 7 – Depth isosurfaces in meters of Lake Água Preta 2009.

3.4. Validation of the bathymetry of 2009.

For comparisons with the simulated depths by Sodre (2007), it was applied a N.A. = 7.9 m in Eq. (8), together with the topography of the TEM of 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 ranging 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 come from the river Guamá are rich sediments.

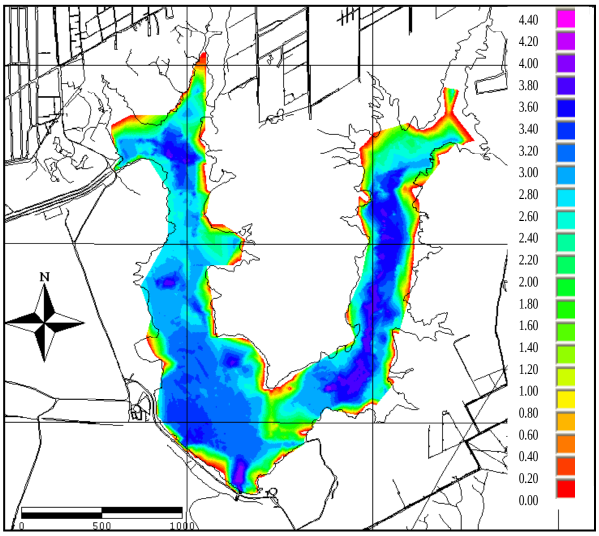

Figure 8– Depth isosurfaces in meters of Lake Água Preta 2009.

Figure 9 shows the simulated depths by Sodre (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. 8 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 data Sodre (2007), it was found that there was little variation in the depths of the two studies, validating the bathymetry of October 2009, at least when compared to data available in literature.

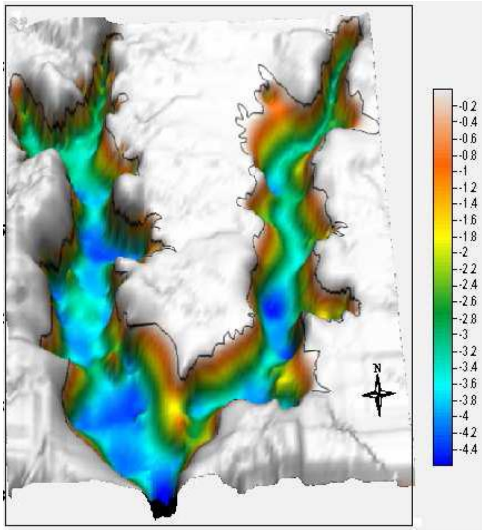

Figure 9– Depth isosurfaces in meters of Lake Água Preta 2009. Fonte: Sodré, 2007.

3.5. Velocity

Figure 10 presents the simulated velocity field of the 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 0.33m/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.

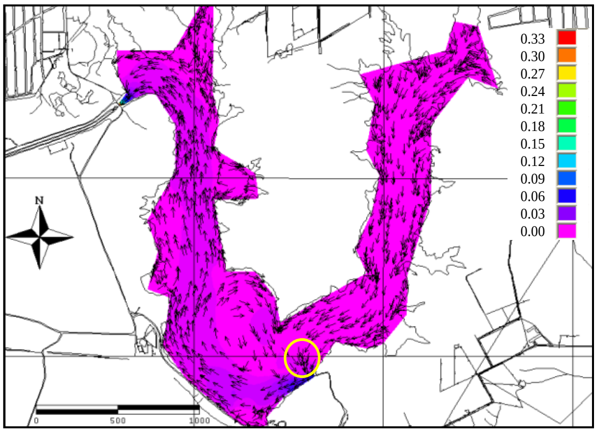

Figure 10 - Simulated field for the velocity modules in meters per seconds of Lake Água Preta.

Figure 10 also shows near the adduction (area circled in yellow) a diversion of flow due to a region of lower depths, as shown in Fig. 7. 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 interconnection channel of the Lakes Água Preta e Bolonha (Fig. 1). The flow follows the higher depths shown in Figure. 7.

4. CONCLUSION

The hydrodynamic modeling of Lake Água Preta, presented in this paper, has added to a better physical understanding of what happens with the flow pattern of Lake Água Preta. Comparison between the raw terrain elevation models from 2009 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.It was observed for the maximum calculated depth of the lake Água Preta is of 5.0 m.

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.

The hydrodynamics Modelling presented in this paper can be used in the foreground, such a hydraulic engineering tool, supporting thus the management of water resources of lakes used as urban water reservoir.

5. ACKNOWLEDGEMENTS

The authors wish to thank CNPq – "Conselho Nacional de Desenvolvimento Científico e Tecnológico", of the Brazilian Ministery for Science and Technology, through the dossiers 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 provided, and COSANPA – "Companhia de Saneamento", of State of Pará; and CPRM – "Serviço Geológico do Brasil for the data and technical support.

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