HYDRODYNAMIC MODELING OF THE LAKE ÁGUA PRETA: WATER SOURCE OF THE BELÉM METROPOLITAN AREA

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Abstract. The natural conditions of the water resources can be modified with unsustainable use of them. For example, in Belém, the capital of Pará State, Brazil, the used water is not treated. And it comes back to its source, i.e., to the Água Preta Lake, inherently polluted. This puts in risk the drinkable water supply of Belém. The main contribution of the present work is the hydrodynamic model construction of the Água Preta Lake. This model can be used to develop a model of pollutant dispersion, an important analysis tool to quantify the degradation of the water and to propose actions to control lake pollution. The modeling starts with the elaboration of a digital elevation model. This model also is used for the morphological study of the lake. The necessaries data to the model hydrodynamic are 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 model, morphological study, hydrodynamic modeling, Água Preta Lake.

1. INTRODUCTION

The water is one of the basic items for human life. It is renewable, but not inexhaustible. It is also of public management, needs to be allocated for different uses and has its integrity compromised by the industrial development, uncontrolled urbanization and demographic growth.

In Brazil, hydric resources have utmost importance in the economic planning. The country is endowed with a vast and dense hydrographic network. The water pollution has been continuously increased due to the urban and industrial polluting load increase, inadequate use of the ground and agrochemicals (pesticides and fertilizers), erosion, deforestation and mining. These factors have several negative impacts on the hydric resources; amongst then it can be cited the increase of the transport of sediments and the organic and chemical contamination of waters. This critical situation imposes more constraints in the location of the new industries plants, especially when they need to discharge of their disposals in effluent of rivers or lakes (Machado et al., 2008).

In the city of Belém, two Lakes are used in the water supply of the Metropolitan Region: Bolonha and Água Preta Lakes, which are located in the Belém Environmental Park, these water sources are linked between themselves and they form the Utinga reservoir, shown in fig. 1.

These Lakes have been objects of several environmental impacts. The people occupy its basins, generating deforestation that menace the lakes management. There is also in the region a yield of pollutants that are discharged directly or indirectly into lakes without adequate treatment. This fact increases treatment costs and it can became the system formed for the lakes unsutainaible.

Thus, the present work aims to develop an hydrodynamic modeling study of the Água Preta lake that can, later, to support studies of dispersion of pollutants and to survey the pollution currently presented.

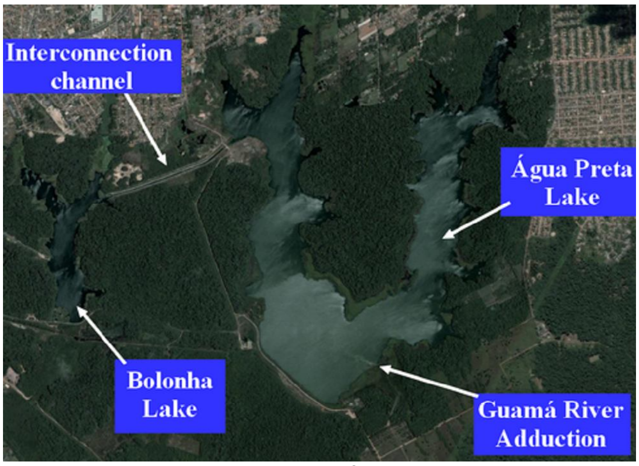

Figure 1 – Satellite image of Utinga water source.

2. METHODOLOGY

The development of the hydrodynamic modeling generally needs the acquisition of bathymetric data and substrate. The bathymetric data are used in the construction of the Terrain Elevation Model (TEM), whereas the composition of the substrate is used in the determination of the Manning coefficient. The TEM, roughness model and boundary conditions are used with the Saint-Venant equations, which are numerically solved using the Hydrosim/Modeleur software. As result, the flow velocity and depth field are obtained.

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; 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 Numerical Terrain Models (N.M.T) 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 M.N.T. 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).

2.2. Bathymetric Data

The special attention is given to the bathymetric data since they are used in the construction of the Terrain Elevation Model (TEM), which is used to discretize Saint-Venant equations. Thus, the TEM is key for a good hydrodynamic modelling ana it is function of bathymetric data that could describe with very precision the surface of the deep of the lake.

The detailed bathymetry was obtained through a isoligne map of the Água Preta Lake dated of 1975, supplied by COSANPA (Company of Sanitation of Pará). This map was designed during the construction of the interconnection channel between lakes (Figure 1). It was not met a map most recent, complete and avaliable of Lake. Thus, a square shaped regular mesh of 50x50m was projected on the map. The coordinates x, y and z were determined by the crossing of the isolignes with the mesh lignes. After this procedure, the coordinates x, y and the height z were digitalized, formatted and imported to the software Modeleur/Hydrosin1.0a07. Figure 2 shows the data of raw topography in the Modeleur platform.

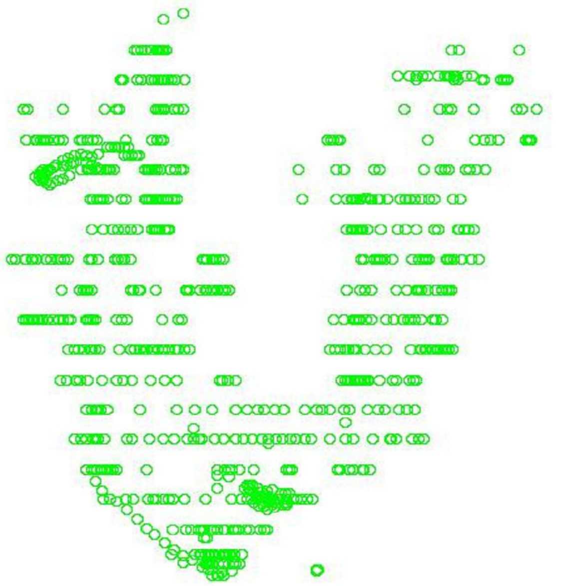

Figure 2 - bathymetric data points.

From this raw topography data set, topography isolignes can be created for the modeleur. Figure 3 shows the isolignes obtained using 750 coordinated points of x and y and height z, representing the raw TEM of the Água Preta Lake.

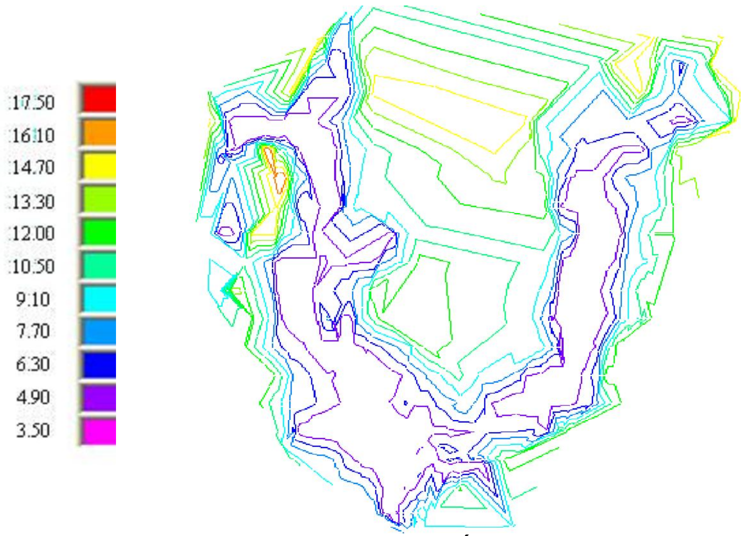

Figure 3 - Raw TEM of Água Preta Lake.

2.3. Lake roughness model

The hydrodynamic model could include a roughness model to determine Manning coefficient. In this paper, the model assumes that the lake substrate is an average of the granulometry that composes it. Raw data granulometry can be found in Dias et al. (1991). Table 1 presents those compiled data.

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 all the lake deep surface is composed for the percentages presented in table 1, the Manning 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 component particles of the substrate, which are presented in Table 1. Thus, apllicating the equation (1) to the data of the Table 1, the Manning coefficient is equal to 0,019 for the deep surface of Agua Preta lake.

2.4. Boundary conditions

Another hydrodynamic model basic element, is the boundary conditions that can be free and deep surface, closed, mobile or opened borders. In these boundaries, it can be imposed prescribed values for the velocity field, input and output flow. In this study, the following conditions had been considered. Solid boundaries: impermeability condition. Liquids boundaries: flow and water levels. Figure 4 shows these applied boundary conditions to hydrodynamic model of Água Preta Lake.

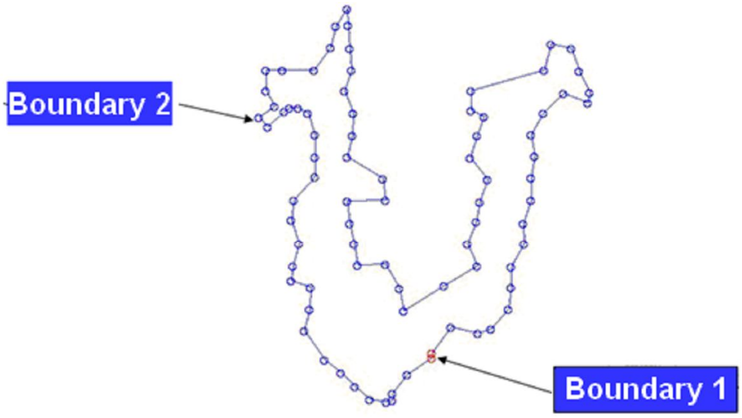

Figure 4 – Applied Boundary conditions.

The first applied condition was in the adduction of the Guamá river (boundary 1), in which the maximum inflow is equal to $6m^3/s$ and water level is $8m$. The second condition is the outflow for the interconnection canal, with an outflow of $6m^3/s$ and water level $8m$.

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;

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

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 presents the hydrodynamic mesh with triangular finite elements, used in the simulations of the present work. Each mesh node preserves the necessary input data to the solution of Saint-Venant equations, as well as the results of the model simulation (q_x, q_y, depth and water level). For the model considered here, the input data are: x, y and z coordinates, interpolated by Finite Elements Method (FEM) and transferred to the mesh hydrodynamics, the average value of roughness calculated and the boundary conditions of previously defined.

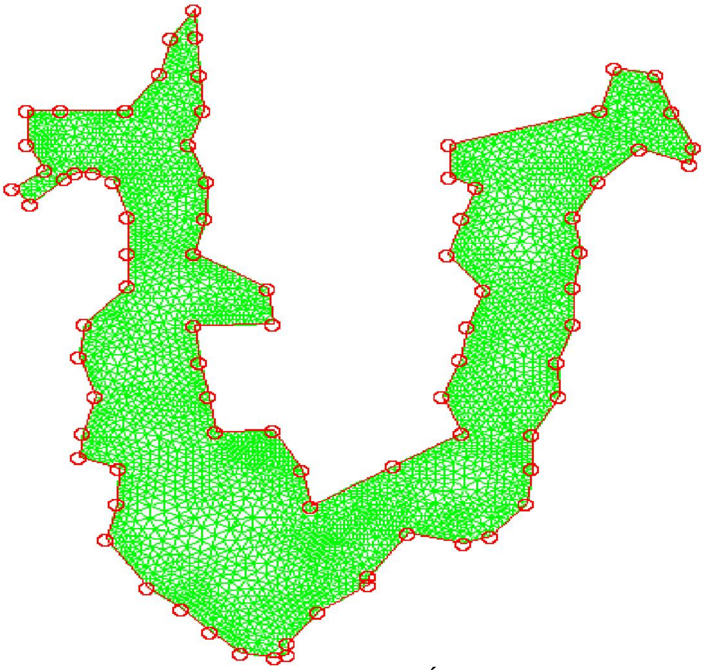

Figure 5 – Hydrodynamic mesh of Água Prtea Lake.

Three hydrodynamic meshes were used: the maximum triangle edge size in each mesh was 15, 10 and 5 meters. The difference between the errors in the mass balance of the domain for the mesh size of 5 and 10 was small and the mesh with 10 m consumes less computational time. Thus, the mesh size of 10 m (Figure 5) was used to analyze the results of the modeling hydrodynamic of the Água Preta Lake.

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.

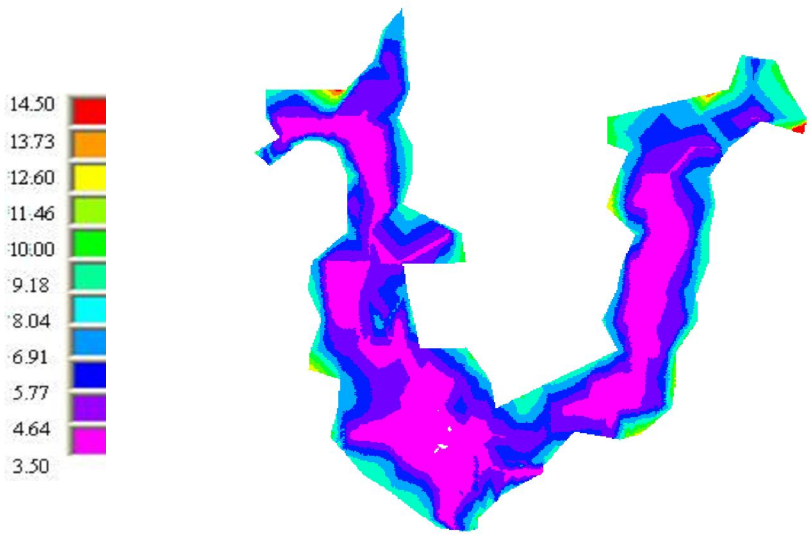

Figure 6– Interpolated TEM (m).

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).

$$Dh = w_l - s_l \tag{8}$$

Where Dh is the depth (m), w_l is the water level (m) and s_l is the terrain topographic height (m). Figure 7 shows the lake depth field.

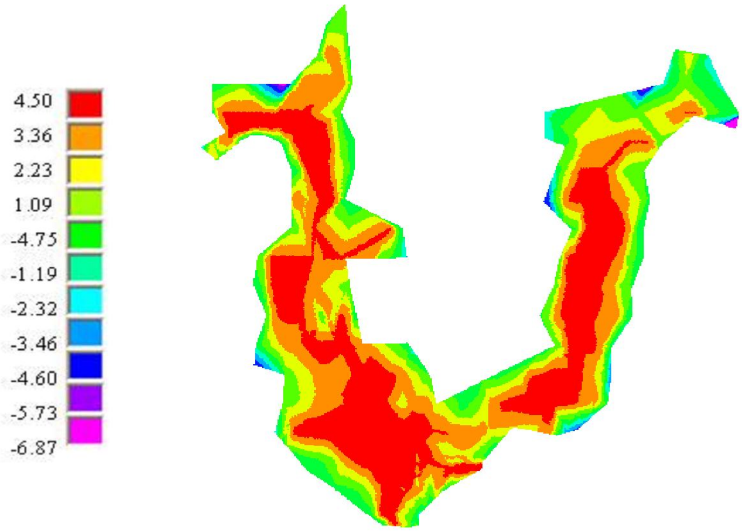

Figure 7 – Depth lake (m).

The data presented in Figure 7 shows that the maximum depth of the lake is of 4.5 m. The depths with negative values demonstrate the regions of the TEM that, in certains boundaries conditions, are not submerged by waters of the lake. Figure 8 presents the velocity fields simulated for the Água Preta Lake.

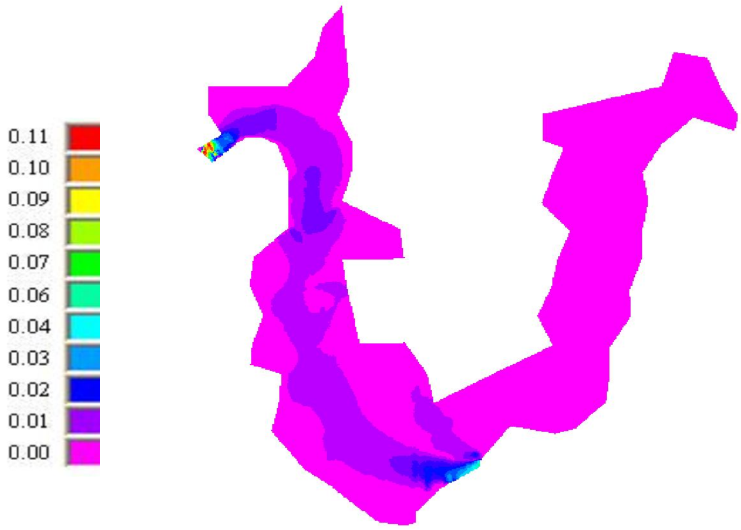

Figura 8 – Simulated Velocity Modulus Field (m/s).

In fig. 8 can be observed that lake flow dynamic is, as expected, much reduced. Only in the regions of the boundaries 1 and 2 (Figure 4) there are important gradients of velocity caused by the change of flow section. As shown in fig. 8, the maximum velocity is equal to 0,11 m/s and occurs in the boundary 2, while for the most part of the lake the velocity is approximately equal to zero. However, a minor flow is observed between the boundaries 1 and 2 of the Lake.

It should be noted that the velocity values had not been calibrated, as the calibration of model will be done by the use of an up to date bathymetry. In this study, the data used was collected at 1975 and are the only available at this moment.

The total computational time in the simulation was about 115 minutes in a personal computer with a Pentium 4 processor with 2.8 GHz.

4. CONCLUSION

The water is important natural resource. It constitutes essential element for the development of all the forms of life of the planet. The water is directly associated with the health and the comfort of the human populations. The irrational use and the pollution of important sources such as rivers and lakes can significantly increase the cost of water treatment.

In the Amazon region, it is necessary to develop studies that encompass all the associated parameters related with the deterioration of rivers and lakes. This is the main motivation of the hydrodynamic modeling of the Água Preta Lake, in order to stimulate the management of the hydric resources of this source of water supply of the city of Belém.

The starting point of this work was the analysis of the bathymetric data of 1975, the study of the roughness of the lake, the determination of the boundary conditions and the construction of the hydrodynamic mesh, the basic data needed to the simulations of depth and velocity field.

It was observed for that the maximum calculated depth of the lake is of 4.5 m. The negative values depths demonstrate the regions of the TEM that, for the given boundary conditions, is not submerged for waters of the lake.

The simulation of the lake Agua Preta flow pattern shows that the velocity gradient field is relevant only in the input and output regions, i.e. the adduction of the Guamá River and the interconnection channel of the two lakes. The maximum velocity is of 0.11 m/s that occurs in the interconnection canal, whereas for the most part of the lake the velociti is approximately equal to zero.

The hydrodynamic model is ready to receive new data from bathymetry to simulate the current flow pattern of the lake. With the up to date topographical and hydrodynamic data, will be possible to evaluate the dispersion of pollutants, transport of sediments, habitats analysis and ichthyofauna, aiming to the most complete and possible management of the hydric resources of this lake. Moreover, it will also be possible to carry a morphologic study, comparing relief the subaqueous differences of the year of 1975 and 2009. Such study will disclose trends of depositions of the lake, as the water proceeding from the Guamá River are rich in sediments.

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