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Hydrodynamic modeling of a reservoir used to supply water to Belem (Lake Agua Preta, Para, Brazil)

Maria Lourdes Souza Santos[1*], André Luis de Lima Saraiva[2], José Almir Rodrigues Pereira[3], Patrícia Façanha Rocha de Souza Marcio Nogueira[4] and Alex Costa da Silva[4]

*[1]Instituto Sócio Ambiental e Recursos Hídricos, Universidade Federal Rural da Amazônia, Av. Presidente Tancredo Neves, 66077-530, Belém, Pará, Brazil. [2]Programa de Pós-graduação em Engenharia de Recursos Naturais da Amazônia, Universidade Federal do Pará, Guamá, Belém, Pará, Brasil. [3]Faculdade de Engenharia Sanitária Ambiental, Instituto Tecnológico, Universidade Federal do Pará, Belém, Pará, Brasil. [4]Laboratório de Oceanografia Física, Estuarina e Costeira, Departamento de Oceanografia, Universidade Federal de Pernambuco, Cidade Universitária, Recife, Pernambuco, Brasil. *Author for correspondence. E-mail: lourdes.santos@ufra.edu.br*

ABSTRACT. Lake Agua Preta is used by the Sanitation Company of Para (Cosanpa) to supply water to the Belem Metropolitan Region. This study aims to use the Base System Modeling Program Environmental Hydrodynamics (Sisbahia) model to simulate seasonal hydrodynamic conditions in the lake and identify areas with the greatest silting. The model results revealed an identical distribution of the velocity module for each month of the year. However, at the outlet of the lake, a water channel variation speed of 0.28–0.32 m s^{-1} was observed. Furthermore, at the inlet of the lake, vortex silting tended to occur, as verified by bathymetry. Sedimentation mainly occurred during periods of low rainfall, which is when Cosanpa increases the inflow of water to maintain the reservoir level and this leads to an increase in sediments in suspension. With the model, it was possible to identify locations with higher rates of sedimentation, and in the future, such data can serve as an effective tool for managing this water resource.

Keywords: bathymetry, seasonality, siltation, water resource.

Modelagem hidrodinâmica em reservatório utilizado para fornecer água para cidade de Belém (Lago Água Preta, Pará, Brasil)

RESUMO. O lago Água Preta é utilizado pela Companhia de Saneamento do Pará (Cosanpa), para o abastecimento de água da Região Metropolitana de Belém. O objetivo deste trabalho foi utilizar o modelo hidrodinâmico do programa de Modelagem Sistema Base de Hidrodinâmica Ambiental (Sisbahia) para gerar simulações das condições hidrodinâmicas e determinar as áreas de maior assoreamento do reservatório, conforme a sazonalidade da região. O modelo mostrou que a distribuição do módulo da velocidade foi idêntica para cada mês do ano. Porém, próximo ao canal de saída de água do lago, foi observada variação da velocidade de 0,28 a 0,32 ms^{-1}. Além disso, a entrada de água no reservatório forma vórtice, tendendo ao processo de assoreamento, fato este verificado na batimetria. Os processos de assoreamento ocorrem, principalmente, no período de menor precipitação, pois a Cosanpa aumenta as vazões de entrada de água para manter o nível do reservatório, propiciando o maior aporte de sedimentos em suspensão. Também foi possível identificar os locais com maior deposição de sedimento, o que serve como uma ferramenta para gerenciamento desse recurso hídrico.

Palavras-chave: batimetria, sazonalidade, assoreamento, recursos hídricos.

Introduction

The use of models to assess changes in water resource quality serves to increase the predictive ability of researcher sand allows relevant authorities to respond to the essential needs of society. In Brazil, most water modeling studies have focused on flows in deep lakes, and relatively few studies on shallow lakes have been conducted to the best of our knowledge (CHRISTOFOLETTI, 2000).

Over the past few years, many advances have been made in the hydrodynamic modeling of lakes, ponds, and rivers, and such models have become an important tool for water resource management, especially in regards to modeling water quality, oil dispersion, and sediments. Cunha et al. (2006) developed a hydrodynamic model for water quality in Sepetiba Bay, Brazil; Machado et al. (2008) described a three-dimensional computational fluid dynamics model that can simulate dispersion in effluent streams an drivers; Machado and Vettorazzi (2003) simulated the production of sediments in the micro-watershed of Ribeirão dos Marins, Brazil; and Ji et al. (2007)

analyzed water quality in shallow lakes using a two-dimensional flow-sediment model.

This study conducts hydrodynamic simulations of Lake Agua Preta (PA, Brazil) over a year to verify the water quality behavior during periods of lower and higher rainfall in the region. Specifically, the Base System Modeling Program Environmental Hydrodynamics (SiSBAHIA) model was applied and measures of color and turbidity were analyzed. Then, the distribution and transport of suspended sediments within the lake were determined. The quantities of sediments that enter, exit, and remain in the lake were also calculated.

Material and methods

Lake Agua Preta (Figure 1), along with Lake Bolonha, are large surface water reservoirs that supply the metropolitan region of Belem. The size of Lake Agua Preta is 3.12 km^2, and the size of together make up the Utinga water source. The bathymetry map made by Holanda et al. (2011) shows that there is a minimum depth of 0.8 m in the area near the entrance of the Guama River and a maximum depth of 4.4 m in the central portion of the basin.

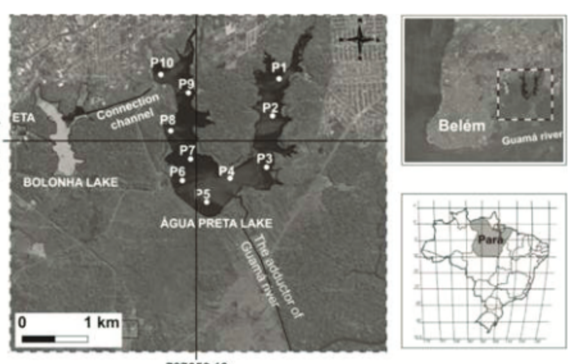

Figure 1. Locations of Lakes Bolonha and Agua Preta in Brazil.

Sampling and data compilation

Physical parameters were obtained at 10 points that were georeferenced using a GARMIN global positioning system (GPS) over Lake Agua Preta between February 2006 and January 2007. Water samples were transported to the Laboratory for Waste Control, Federal University of Para, and all analyses were conducted in accordance with standard guidelines of the APHA (2012).

In 2010, new data were collected to complement the information necessary for the development of the model. Specifically, averages of meteorological data for precipitation, wind intensity, and wind direction were obtained in 2010 from INMET (2010), and these data are shown in Table 1. The flow input (Table 1) was obtained from a calculation based on operational spread sheets for four model 24QL19 pumps that operate daily with 5.400 m^3 h^1 flow, 550 CV (cheval vapeur), and 24 MCA (minimum circuit amps) power. These pumps move water from the Guama River to Lake Agua Preta, which in turn maintains the level of Lake Bolonha by gravity through a connection channel. Seasonal variations in water levels are some what regulated by this artificial supply. All hydraulic information was obtained from COSANPA.

Table 1. Seasonal meteorological data for average precipitation, wind intensity, and wind direction, and average inflows and out flows from Lake Agua Preta for 2010.

Month	Precipitation mm month^{-}	Wind direction	Intense winds m s^{-}	Input Flow m^{3}s^{-}	Output flow m^3 s^{-}
January	455.2	N	3.2	4.45	3.88
February	362.4	N/NE	3.4	4.18	4.11
March	298.0	NE	2.8	4.60	3.94
April	453.3	E/NE	2.6	2.93	3.94
May	405.2	E/NE	2.2	3.14	3.95
June	164.3	E/SE	2	5.02	3.95
July	132.2	SE/E	2.1	5.33	3.89
August	189.2	SE/E	2.9	6.01	4.04
September	94.6	E	2.4	6.10	3.91
October	151.7	E/NE	3.2	5.49	3.86
November	135.7	N/NE	3.8	5.24	3.90
December	225.0	N/NE	3.5	4.67	3.90

Hydrodynamic model

In this study, we used a horizontal two-dimensional hydrodynamic circulation model (2DH) that was employed as part of the Environmental Hydrodynamics Base System (SiSBAHIA®; www.peno.coppe.ufrj.br/SisBahia). An earlier study demonstrated that this model has the potential to simulate the data set collected from the reservoir adequately (CUNHA et al., 2006). Based on the results of the hydrodynamic model, we noted that the wind has a significant influence on hydrodynamic circulation in the reservoir.

To obtain satisfactory results, the mesh input areas were chosen so as to comply with the contours of the domain boundaries to be studied, with the density of elements being determined in accordance with the degree of detail of the results. SiSBAHIA is a finite element numerical model that allows the use of numerical grids that follow the physical contour of the modeled region.

The mesh was constructed using quadrangular finite elements because quadratic mesh shows better results with higher stability and accuracy (ROSMAN, 2011). The domain was discretized into 591 elements and 2643 knots, of which 556 were part of the contour of the land and none were of the open boundary (Figure 2). A total of 1200 bathymetric points were used to better represent these results.

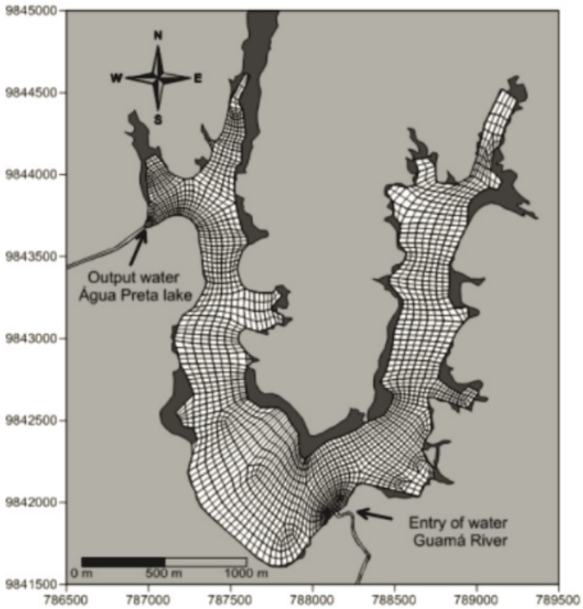

Figure 2. Modeled domain of Lake Agua Preta, with details show in the mesh discretization elements and knots. The axes represent distances in UTM coordinates.

During modeling, minor adjustments were made to the roughness coefficient of the bottom to better represent the simulations. Roughness amplitude values recommended by Rosman (2011) were used for these adjustments. The particle size of the most predominant size class found in Lake Agua Preta was the silt fraction (2–62 μm).The relevant model equations are as follows:

$$U(x,y,t) = \frac{1}{H}\int_{-h}^{\zeta} u(x,y,z,t)dz \;\; e \;\; V(x,y,t) = \frac{1}{H}\int_{-h}^{\zeta} v(x,y,z,t)dz \tag{1}$$

$$\frac{\partial\zeta}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\zeta} udz + \frac{\partial}{\partial y}\int_{-h}^{\zeta} \tag{2}$$

$$\frac{\partial\zeta}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \tag{3}$$

$$\frac{dF}{dt} = 0 \therefore \frac{d}{dt}\big(F \equiv z + h(x,y,t)\big) = 0 \therefore \left[w + \frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0\right] \quad (eq.4) \tag{4}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -g\frac{\partial\zeta}{\partial x} + \frac{1}{\rho_0}\left(\frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{xy}}{\partial y} + \frac{\partial\tau_{xz}}{\partial z}\right) + 2\emptyset sen\theta.v \tag{5}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -g\frac{\partial\zeta}{\partial y} + \frac{1}{\rho_0}\left(\frac{\partial\tau_{yx}}{\partial x} + \frac{\partial\tau_{yy}}{\partial y} + \frac{\partial\tau_{yx}}{\partial z}\right) - 2\emptyset sen\theta.u \tag{6}$$

$$\frac{\partial\zeta}{\partial t} + \frac{\partial UH}{\partial t} + \frac{\partial VH}{\partial y} = 0 \tag{7}$$

The model was calibrated with the averages of the 2010 meteorological data for wind intensity and direction (Table 1).

Mass balance

To estimate the mass balance of suspended sediments, stream data collected in the inlet and outlet tributaries were used (TORRES et al., 2007). Monthly estimates for the inlet and outlet (E/S, kg month^{-1}) were obtained by multiplying the flow of the tributaries (Q, m^{3}month^{-1}) with the nutrient concentration (C, g m^{-3}) at each collection point as follows:

$$(E/S) = 10^{-3}Q.C \tag{8}$$

The annual input of each tributary (*IA*, tyear^{-1}) was estimated from the sum of the monthly inflows (*IM*, kgmonth^{-1}) of the tributaries as follows:

$$IA = \sum\nolimits_{1}^{12} IM \tag{9}$$

and the results were expressed in tons.

The year was divided into two main seasons: the rainy season and the dry season. The averages of the rainy and dry months were determined as follows:

$$MEC = \frac{\sum_1^6 VMC}{6} \tag{10}$$

$$MES = \frac{\sum_1^6 VMS}{6} \tag{11}$$

where (i) *MEC*= average of the rainy season (kg month^{-1}); (ii) *VMC*= monthly values of the rainy season (December to June) in kg month^{-1}; (iii) *MES*= average of the dry season (kg month^{-1}); and (iv)*VMS*= monthly values of the dry season(July to November) in kg month^{-1}.

The mass balance (*BM*, t year^{-1}) was estimated by the difference between the annual input, IA (kg month^{-1}), and the annual output, SA (kg month^{-1}), as follows:

$$BM = \frac{\sum_1^{12} IA - \sum_1^{12} SA}{10^3} \quad (12)$$

Results and discussion

The simulation results were obtained from the topography, rainfall intensity, wind direction, flow, and output flow data, which make up the boundary conditions assigned to the model. The simulation time was 28,908,000 s.

In Lake Agua Preta, the highest water velocity values of 0.32 m s^{-1}occurred during the months of January and February and the lowest water velocity values of 0.28 m s^{-1} occurred during the months of June and December; the average velocity was 0.29 m s^{-1}.

In Figures 3 and 4, the maps show very similar velocity vectors for the different months. In these figures, the lengths of the vectors are not proportional to the magnitude of the velocity. The wind direction over the lake oscillated from north to southwest; these data were not presented every month because of the similarities between them.

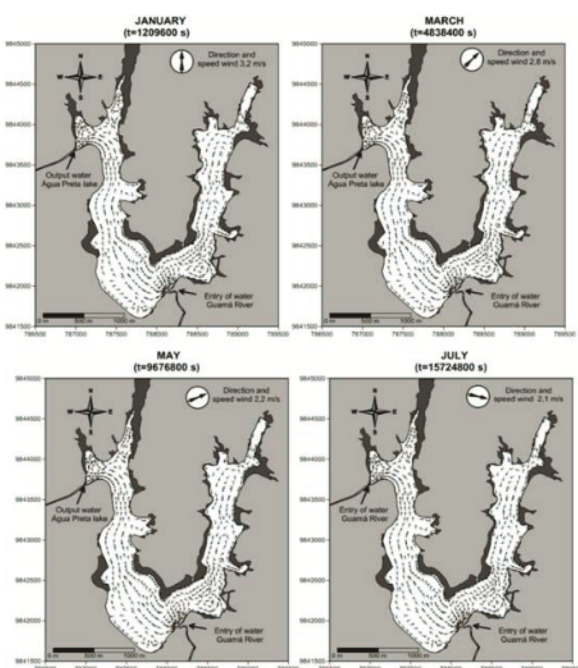

Figure 3. Velocity vectors of the flow in Lake Agua Preta for the months of January, March, May, and July.

The turbidity of Lake Agua Preta varied from 35 UNT at point 4 to 6 UNT at point 10. The highest value of the apparent color oscillated around 371 mg L^{-1}Pt Co, and this value was also detected at point 4; the lowest value of 58 mg L^{-1}Pt Co was detected at point 10. For suspended solids, the maximum value was 81 mg L^{-1}at point 4 and the minimum value was 1 mg L^{-1}at points2, 6, 9, and 10.

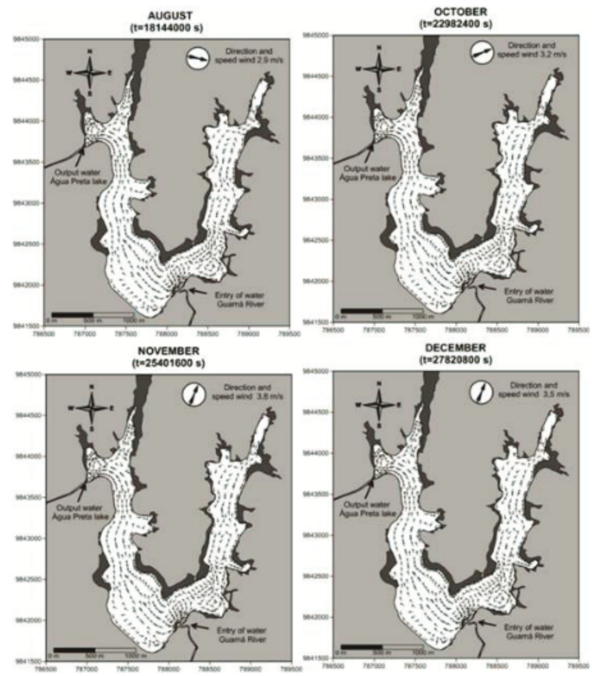

Figure 4. Velocity vectors of the flow in Lake Agua Preta for the months of August, October, November, and December.

In lakes, the surface boundary layer (SBL) is the most dynamic zone in many respects. Light and nutrients enable photosynthesis in phytoplankton, which serves as the basis of the food web and lays the groundwork for biological interactions. Physical and geochemical features undergo strong dynamics in the SBL owing to exchanges with the adjacent atmosphere and to photochemical and biological processes. Therefore, to understand the most relevant ecological phenomena, studying the atmosphere/water relationship is crucial. Depending on the properties of air, wind, water, and waves, the air/water interface creates a bottleneck for the exchange of physical quantities such as heat, kinetic energy, momentum, and matter (gases, vapor, aerosols, etc.). The most crucial parameter governing the wind-driven regime is the surface shear stress, i.e., force per unit area acting on the water surface as a result of wind (WÜEST; LORKE, 2003).

Water velocity variations may be related to the seasonality of the region because they often coincide with dry and rainy season weather patterns. Holanda et al. (2011) used Modeleur software and found seasonal differences in velocity of 0.33 m s^{-1}at the same location of a lake; although, the cause for such differences was difficult to determine because the authors did not examine the wind and rain fall data. Lima et al. (2013) used a hydrodynamic model and was able to simulate depths and velocities of Lake Bolonha; the velocities, which ranged between 1.8 and 9.0 cm s^{-1}, showed a subtle current between the outlet of the canal connecting Lake Bolonha and Lake Agua Preta to the water in takes of Bolonha and São Braz. This fact demonstrates that the Lake Bolonha reservoir is a passage for waters from Lake Agua Preta.

The spatial distribution of the module from the water flow velocity of each month was practically identical at different points of time regardless of the wind direction at the moment considered.

The action of wind has important effects on water circulation in Lake Agua Preta. However, in other studies of coastal regions, wind has a much greater effect on hydrodynamic models, as shown by Copeland et al. (2003), who applied a hydrodynamic model to Sepetiba Bay to study the dispersion of pollutants; Barros et al. (2011) revealed similar effects by applying a hydrodynamic model to Guajara Bay. Laval and Imberger (2003) employed a hydrodynamic model that considers the effects of spatiotemporal variability in the wind field on basin-scale motions in lakes and presented a description of the numerical methods used to reproduce the internal wave field in Lake Kinneret.

During our simulations, various observations were made regarding the standard water circulation patterns in the lake for the considered conditions near the water outlet of the lake by the canal connection and near point 4. This was done through the examination of the velocity vectors. The data revealed the formation of a small vortex that tends to deposit sediments and fine organic particles. In the right tributary of the lake, the velocity vectors showed almost stagnant north–south flow (Figure 3 and 4).

The vortex by the water inlet of the Guama River that tends to deposit sediments was verified by bathymetry, and this area tends to be silty. During periods with low precipitation, the water inlet toward the lake provides the largest contribution of suspended sediments (Figure 5a).

On the left side of the lake, the flow vectors were in the south–north direction and the flow speed wass low (Figure 5b). On the right side of the lake, the flow vectors were in the north–south direction and the flow was almost stagnant (Figure 5c). Areas with no flow dynamics tend to deposit silt, and this is common along the lake shore. In the Guama River water inlet to the lake, where a vortex is located, sediment deposition occurs (Figure 5d). During periods with lower rainfall ingress of water into the lake, higher amounts of suspended sediments were deposited. The sediments are considered pollutants depending on their concentration in the water because they can harm biota, impact water use, and affect the transport of pollutants through out the aquatic ecosystem (WU et al., 2001).

In general, the simulations revealed that runoff from the water inlet of the Guama River predominantly flowed to the left side of Lake Agua Preta toward the water outlet for the connection channel; the right side of the lake represents a more stagnant region.

The turbidity, color, and suspended solid data for the lake had similar distributions, i.e., the highest concentrations were found at point 4 and the concentrations decreased toward the outlet channel of the reservoir.

Factors responsible for the turbidity include inorganic suspended particles, bacteria, phytoplankton, organic detritus, and, to a lesser extent, dissolved compounds, which contribute to the true color of the water (MAIA-BARBOSA; BOZELLI, 2006). It is interesting to note that starting from the inlet of the Guama River and moving to the Lake Agua Preta reservoir, concentrations decreased owing to the sedimentation process.

The Agua Preta reservoir showed different seasonal patterns for the export and retention of suspended solids. These patterns were strongly influenced by periods of lower and higher rainfall. The suspended solids reached the highest concentration of 1298 t $year^{-1}$ during the dry season at the inlet and the concentrations were 251 t $year^{-1}$ at the outlet owing to the supply load of the sediment that is added to the reservoir. This seasonal trend is a result of the greater amount of water that flows in from the Guama River to maintain the level of the reservoir during the dry period. During the year, the reservoir retains 1370 t $year^{-1}$ of suspended solids; this material gradually makes the reservoir silty, thus decreasing its volume capacity (Figure 6).

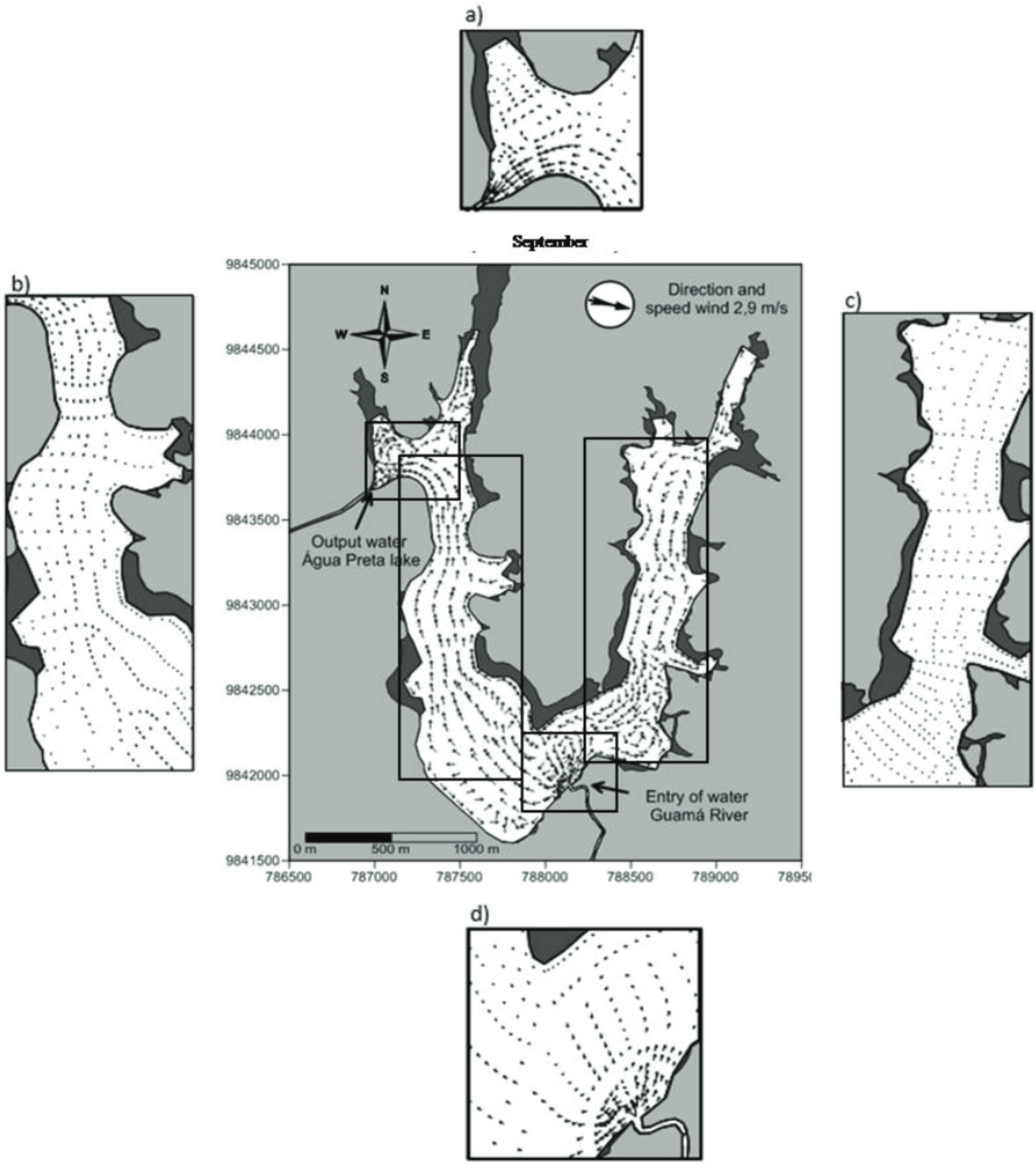

Figure 5. Velocity vectors of the details in Lake Agua Preta in September.

Figure 6. Annual mass balance of suspended solids (ton ano^{-1}) shown on a schematic drawing of the reservoir.

Conclusion

The use of hydrodynamic models plays an important role in the planning and development of alternative scenarios for reservoirs. In the case of the Agua Preta reservoir, the hydrodynamic model results showed that the velocity distribution of the module was identical for each month of the year, independent of wind direction. This pattern was mainly observed on the right side of the reservoir where the surface water becomes stagnant. However, the seasonal dynamics of the reservoir did influence the discharge water between the inlet and outlet flow through the connecting channel to lake Bolonha.

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