HYDRODYNAMIC MODELLING IN LARGE RESERVOIRS FOR WATER RESOURCES MANAGEMENT

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ABSTRACT - This paper deals with hydrodynamic modeling applied to storage estimate in the Sobradinho reservoir. In the hydrodynamic simulation, the model has as input discharge and stage time series from stream gages located in the São Francisco River, in the Grande River tributary and in the Sobradinho reservoir. Geometric information about the lake had been obtained from measurements carried out in the past (aerophotogrammetric survey) and complemented with data from the Digital Terrain Model SRTM-90 project. The period of simulations took place between 1978 and 2004. The comparison of calculated and measured stage series of the stream gages located in the Sobradinho reservoir shows that the hydrodynamic model MIKE 11 is appropriate for simulations at Sobradinho using existent data. The storage estimate using the model simulations was compared with the volume determined using the stage x storage curve. The stage x storage curve takes the water surface line as being horizontal, which can lead to error in calculating the volume of water in the reservoir. The model MIKE 11 was also used to analyze the dynamic of floodplain inundation and to evaluate the water budget in the reservoir.

Keywords: Hydrodynamic model, large reservoirs, water resources management.

1. INTRODUCTION

The Sobradinho reservoir is one of the major responsible by the discharge regularization in São Francisco River. This discharge is used in the power generation in the system of hydropower plants located in the basin. The reservoir is also used in flood control, irrigation, navigation and water supply.

Water resources planning requires precision in measuring accumulated volume, evaporation, reservoir inflow and floodplain area along the reservoir. For example, to define the firm energy of the system, it is essential to have an accurate determination of available water volume.

In most cases, storage estimate in reservoirs is carried out using stage x storage curves. This kind of curve is made using a topographic survey of the area of the lake. The use of these curves is appropriate for lakes where the water surface line is horizontal. In small and medium lakes, this hypothesis is correct and the margin of error is relatively low. In large reservoirs like Sobradinho, which is approximately 280 km long at maximum operation level, the water surface line exhibits a significant slope. In cases like this, stage x storage curves, which use only the stage closest to the Dam, can result in errors.

The objective of this work is to evaluate the potential of hydrodynamic modeling to furnish information related to storage volume and to determine the time variation of the flooded area in large reservoirs. In addition, the results obtained can help to determine the variables that make up the water budget in reservoirs.

Cirilo (1991) carried out hydrodynamic analysis in the Sobradinho reservoir and verified that the flood dynamic in São Francisco River affects the water surface slope and, consequently, the storage in the lake. Research using a hydrodynamic model to determine reservoir storage can be found in Castanharo & Mine (2006), at Foz do Areia reservoir in Paraná State, Brazil (138,5 km^2), and Tufford & McKellar (1999) at Marion Lake in the United States (330,7 km^2).

2. STUDY AREA AND DATA

2.1. Location

Sobradinho Lake is situated in a region called the Lower-middle São Francisco in the Northeastern of Brazil (Figure 1). The filling of the lake started in 1977 and the power plant began operation at the end of 1979. The region presents a typical semi-arid climate, irregular topography, mean annual precipitation varying between 800 mm over the hills bordering the State of Ceará to values below 400 mm in the Petrolina-Juazeiro region (Correia *at al.*, 2006), mean annual air temperature is 27 °C and the mean annual potential evaporation is 3.000 mm.

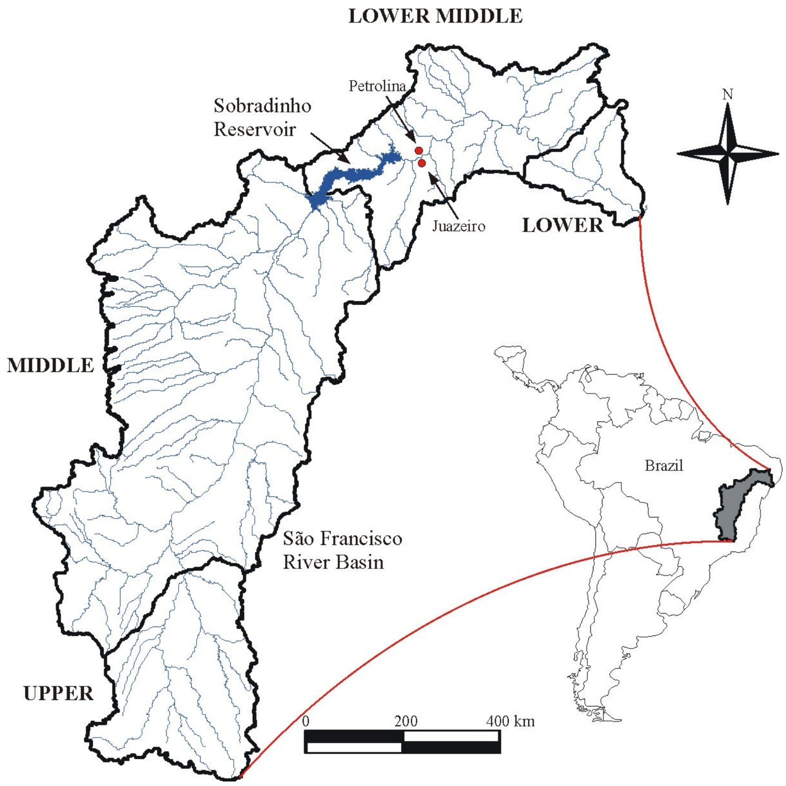

Figure 1 – Sobradinho location.

2.2. Data

The quality of the model simulation is related to the quality and quantity of data used. Information of hydrometric data, bottom profile, cross sections and bed roughness are necessary to implement the model.

2.2.1. Hydrometric Data

The choice of the hydrometric stream gages in the lake region was made using the Hydrological Information System of the National Agency of Water (ANA in Portuguese) and the Water Resources Management Division of the Hydroelectric Company of the São Francisco (CHESF is the Brazilian acronym). The list of stream gages is shown in Table 1. Figure 2 shows the spatial distribution of these gages.

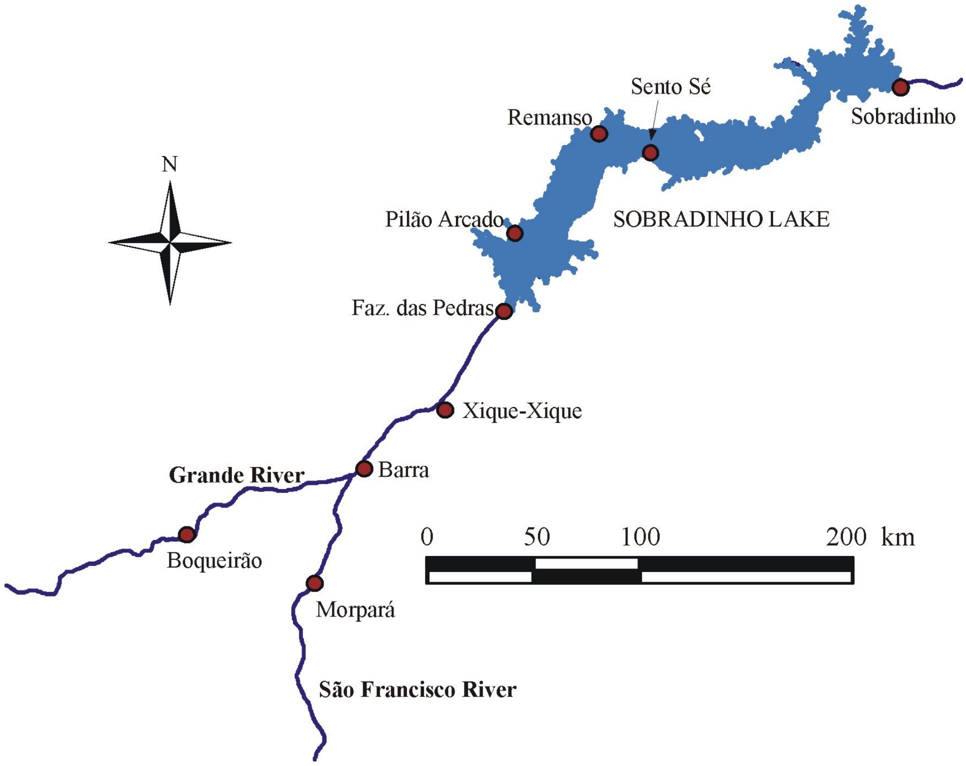

Figure 2 – Stream gages used in the study.

Table 1 – Stream gages used in the study.

Name	River	Collected Data
Boqueirão	Grande	Stage/Discharge
Morpará	São Francisco	Stage/Discharge
Barra	São Francisco	Stage
Xique-Xique	São Francisco	Stage
Fazenda das Pedras	São Francisco	Stage
Pilao Arcado	São Francisco	Stage
Remanso	São Francisco	Stage
Sento Sé	São Francisco	Stage
Sobradinho Dam	São Francisco	Stage

2.2.2. Physiographic data

Geometric data of the river and reservoir were used in the computation of unsteady flow equations. Two kinds of topographic data were used, an aerophotogrammetric survey carried out before the reservoir construction (early 1970's) and the Digital Terrain Model (DTM) from the Shuttle Radar Topography Mission (SRTM).

The SRTM is an international project spearheaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) of the United States. The mission obtained elevation data on a near-global scale to generate a high-resolution digital topographic database of the Earth. SRTM-90 is a DTM with 90 m resolution and it is available for the whole globe.

SRTM-90 was used to characterize the reach between the upstream boundary (Morpará and Boqueirão) and the Fazenda das Pedras stream gage. Fazenda das Pedras represents the beginning of the Sobradinho Lake. Figure 3 shows examples of cross sections obtained from the DTM.

Between Fazenda das Pedras and Sobradinho Dam, the region correspondent to the reservoir, the geometry has been characterized using aerophotogrammetric survey on a scale of 1:20,000. The aerophotogrammetric survey has level lines with 2.5 m interval and benchmarks.

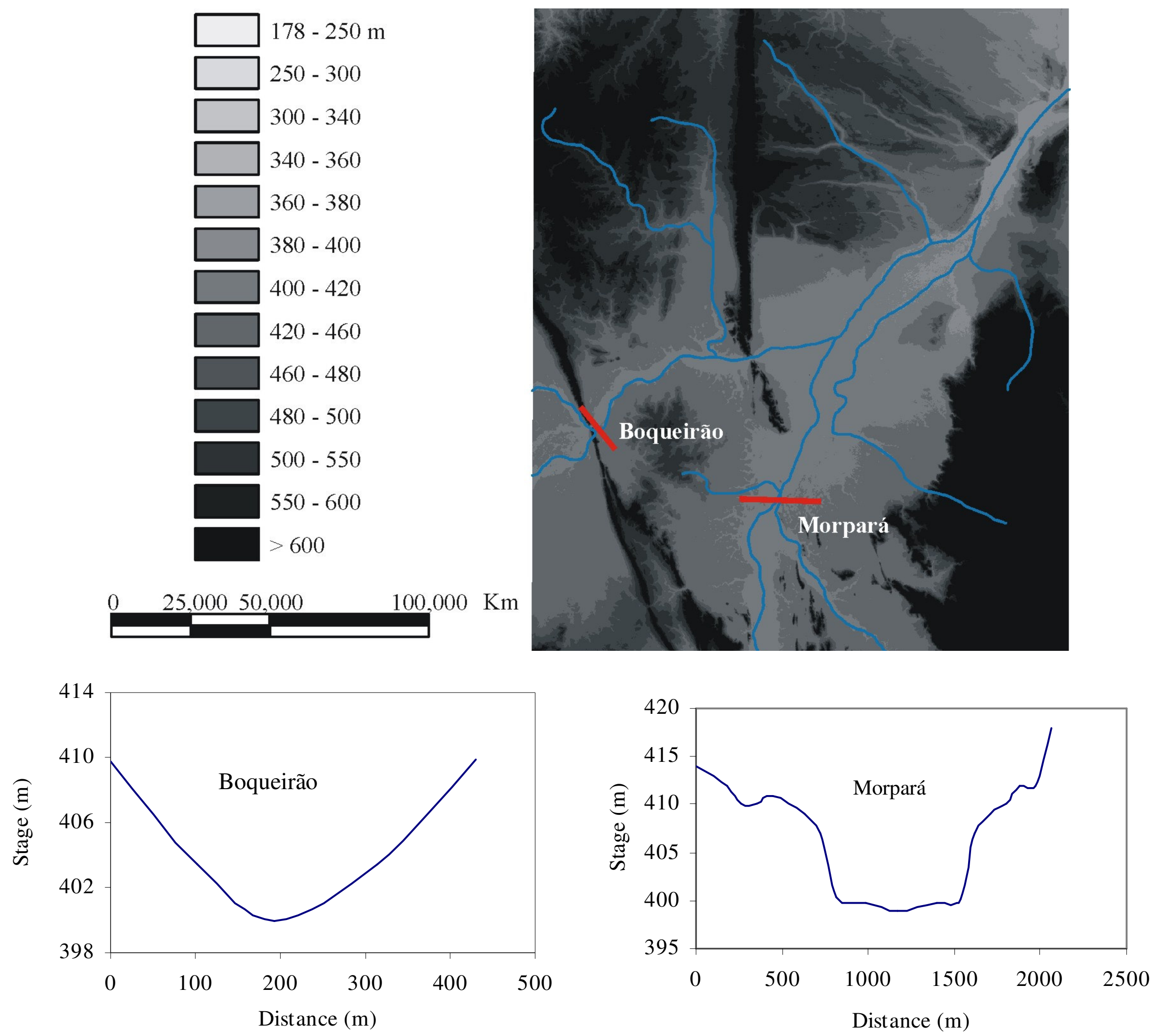

Figure 3 – DTM and cross sections extracted from it.

3. HYDRODYNAMIC SIMULATION

3.1. MIKE 11 Model

The hydrodynamic simulations were carried out using the MIKE 11 model developed by Danish Hydraulic Institute (DHI) Water & Environment. The MIKE 11 uses the complete Saint Venant equations (Equations 1 and 2) applied in one-dimensional unsteady flow in open channels (DHI, 2002). The MIKE 11 uses an implicit, finite difference scheme for the computation of unsteady flow. Details about this scheme are shown in DHI (2002).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + 2\frac{Q}{A} \cdot \frac{\partial Q}{\partial x} - \frac{Q^2}{A^2} \cdot \frac{\partial A}{\partial x} + \frac{\partial Z}{\partial x} + g \cdot A \cdot S_f = 0 \tag{2}$$

$$S_f = \frac{Q \cdot |Q| \cdot n^2}{A^2 \cdot R^m} \tag{3}$$

Where,

A ....flow area
Q ....discharge
q ....lateral inflow
S_f ....energy slope
g ....acceleration due to gravity
Z.........stage above datum
x ....space variation
t ....time variation
n ....Manning coefficient
R ....hydraulic radius
m ....parameter equal to 4/3 for steady flow

The length of the Sobradinho Lake is many times larger than its width. Owing to this characteristic, the lake has a hydrodynamic behavior similar to a large river and, for that reason; the flow can be considered one-dimensional (Cirilo, 1991).

The system modeled comprises two parts: river reach and lake reach. The beginning of the river reach is at Boqueirão in the Grande River and at Morpará in the São Francisco River. The end of the river reach is at Fazenda das Pedras. The lake reach starts at Fazenda das Pedras, the place where the backwater effect begins, and the Sobradinho Dam is at the end of the reach. Figure 2 shows the stream gages that define the boundaries of the reaches.

3.2. Water surface variation analysis in the Sobradinho Lake

The Sobradinho Lake has five stream gages along its 280 kilometers, as shown in Figure 4. Figure 5 shows the mean monthly stage in the lake for the period 1977-2006 and Figure 6 shows the same values in a longitudinal profile. As can be seen in Figure 6, the water surface slope in the lake is not negligible. The slope varies at different times (it is steepest during the drought season) and in different places (it is steepest between Faz. das Pedras and Remanso).

The water surface slope can be explained by the influence of the floodplain. Figure 4 shows the inundated area in two moments: dry season in 2001 and rainy season in 2004. As can be seen in Figure 4, between Faz. das Pedras and Remanso there are large floodplain areas, which contrast with the reach between Remanso and the Sobradinho Dam, where the water remains in the channel during the high water.

The floodplains also affect the time variation of the water surface. The maximum difference between high and low water at Pilão Arcado is smaller than the maximum difference at the Sobradinho Dam (Figure 6). During the falling water period, the volume storage in the floodplain returns to the main channel of the reservoir. Probably for this reason the water surface in Sobradinho stream gage and Pilão Arcado have different variations.

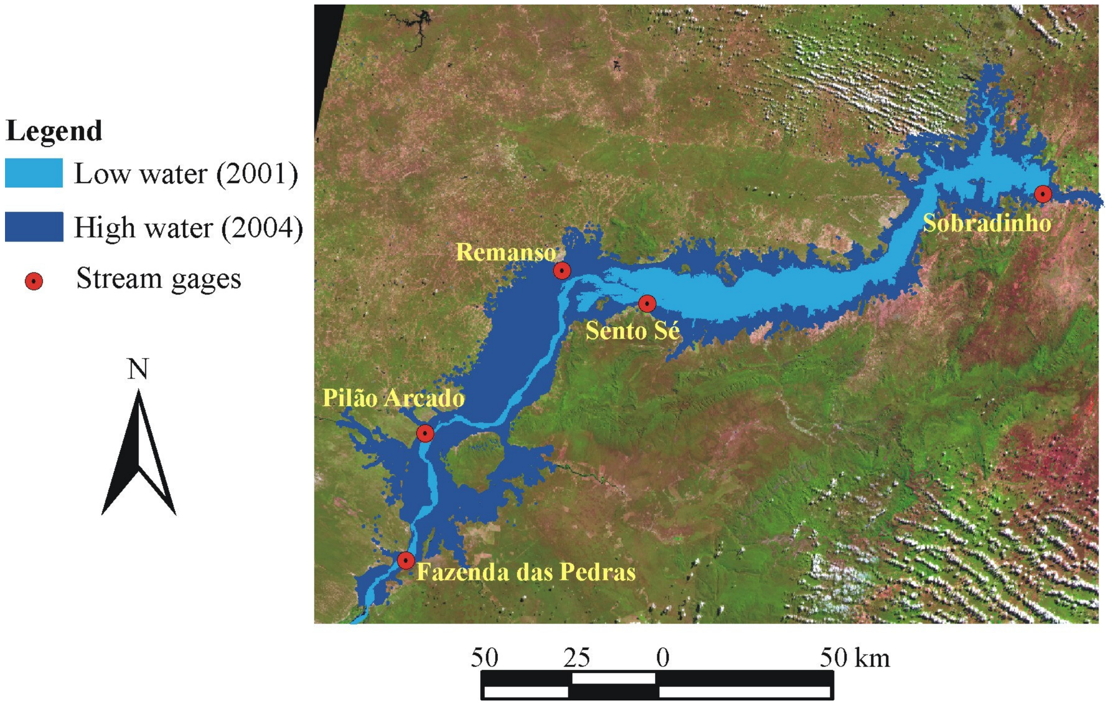

Figure 4 – Boundary of the Sobradinho Lake at low and high water.

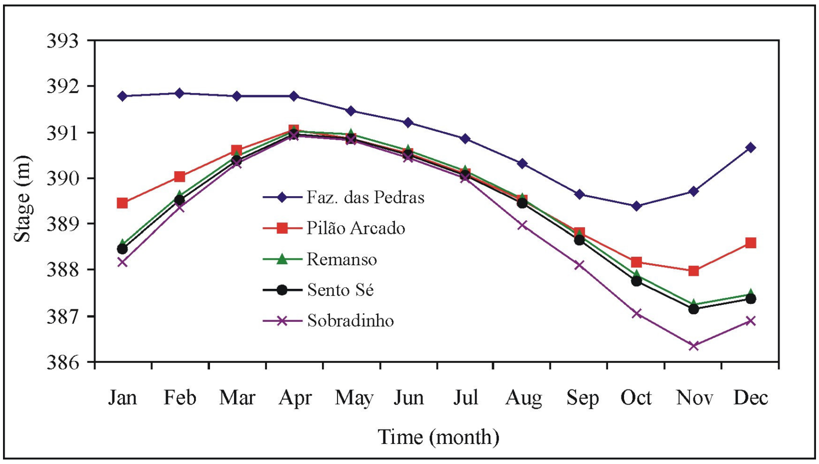

Figure 5 – Temporal variation of the mean monthly stage at the stream gages in the Sobradinho Lake.

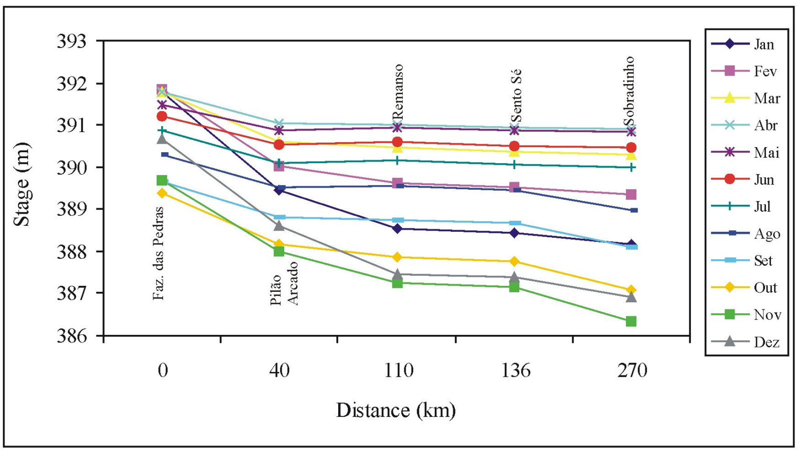

Figure 6 – Spatial variation of the mean monthly stage at the stream gages in the Sobradinho Lake.

The analysis of the stage variation in the Lake indicates that the floodplains influence the hydrodynamic of the Sobradinho Lake. Owing to this characteristic, the water line surface is not horizontal along the reservoir as it is in the smaller lakes, where the stage is unique for the same time step.

3.3. Hydrodynamic Simulation

The boundary conditions in the simulations are the discharge series at the Morpará and Boqueirão upstream boundary and the stage series at the Sobradinho Dam downstream boundary. In the simulations, Manning's roughness coefficient was equal to 0,033 for the whole system modeled. An example of result is shown in Figure 7 with the simulated and measured stage at Remanso stream gage. In all stream gages, the model performance was similar to the result showed in Figure 7.

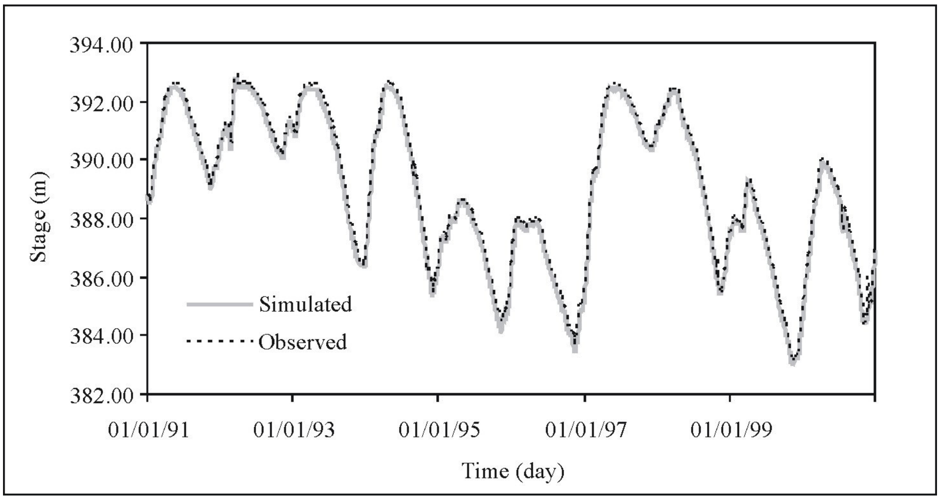

Figure 7 –Simulated and measured stage at Remanso stream gage.

4. STORAGE ESTIMATE IN THE SOBRADINHO LAKE

The storage in the Sobradinho Lake was calculated using both a stage x storage curve and the hydrodynamic model. The major geometric characteristics of the Lake are:

- Total volume: 34.1 billion cubic meters;
- Dead storage: 5.4 billion cubic meters;
- Normal maximum level: 392.50 m;
- Normal minimum level: 380.50 m;
- Length: 280 km;
- Total Area: 4,214.00 km^2.

The volume estimate in this work was carried out using three periods of rising water and three periods of falling water. In these periods, there is large variation in the water surface level, which represents the conservation storage.

The storage was obtained by summing the volume in all sections in the model. The volume is calculated multiplying the distance between the sections and the flow area. Figure 8 shows the variation of the storage in Sobradinho using the hydrodynamic model. The same Figure has the stage x storage curve.

The results indicate that the storage calculated using the stage x storage curve is lower than the value estimated by the model. According to the analysis presented in the section 3.2, the dynamics of the water surface level in the Sobradinho Lake must be taken into account.

Since the hydrodynamic model represents this dynamics in the water surface level, the storage determined using MIKE 11 will be considered as the reference value.

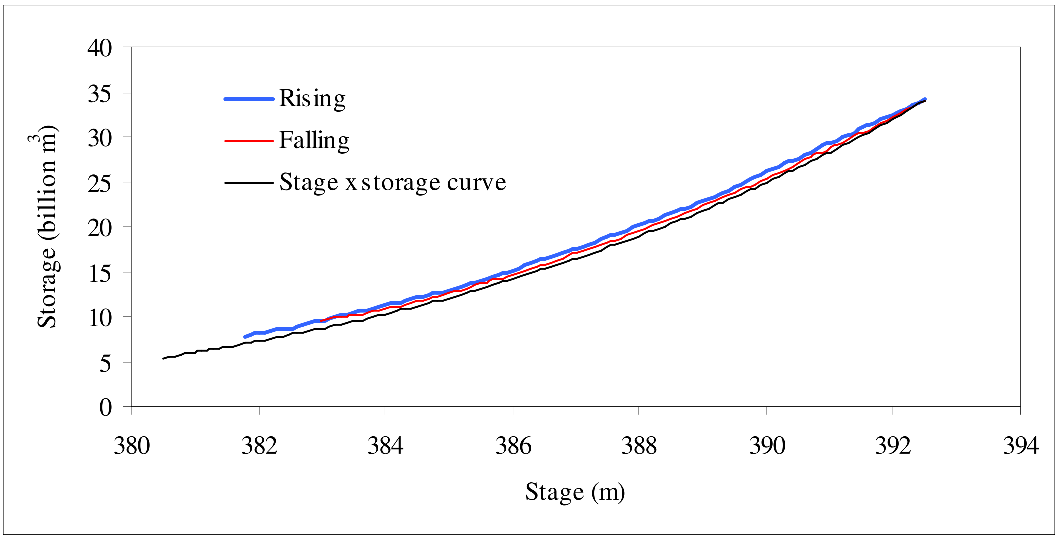

Figure 8 – Storage versus stage in the Sobradinho Lake.

The major difference between the storage estimates is verified when the water is low, which is the most critical period. Moreover, storage during the rising water tends to be greater than the falling water, as shown in Figure 8.

The difference in storage between the two methods corresponds to the volume of water that can be used either to increase the outflow discharge during the dry season or to generate more power. Table 2 shows the difference in volume and the correspondent values of discharge and power generation for the period 1978-2004. The values in Table 2 are the average of all years: falling period is from April to November and rising period is from December to March.

Table 2 – Difference of volume between the model and the stage x storage curve.

Period	Volume (hm^3)	Discharge ($m^3.s^{-1}$)	Power (MW)
Falling	456.13	23.8	66
Rising	675.62	63.5	177

During the rising water, the difference of storage corresponds to a mean discharge of 63.5 $m^3.s^{-1}$. This volume is available to be used to elevate the stage downstream from the reservoir and to improve the environmental conditions along the São Francisco River. The same volume can generate approximately 177 MW during the four months of rising water.

5. WATER BUDGET VARIABLES

Another application of the model is for the analysis of the water budget variables. The following equation corresponds to the losses based on water budget:

$$\overbrace{I - O +/- \Delta S}^{\text{losses}} = W + E - P - q \tag{4}$$

where ΔS is the change in reservoir storage, I is the reservoir inflow, O is the reservoir outflow, W is the water withdrawal, E is evaporation, P is precipitation over the lake and q is the lateral inflow. Evaporation, precipitation and outflow are measured. Reservoir inflow (I) and the change in storage (ΔS) are estimated using hydrodynamic model. The remaining variables (withdrawal and lateral inflow) correspond to:

$$W - q = (I - O +/- \Delta S) - (E - P) \tag{5}$$

The lateral inflow is close to zero during the dry season. Therefore, it is possible to determine the value of water withdrawal. The mean water withdrawal corresponding to the period 1978-2004 was 132.5 $m^3.s^{-1}$. The field measurement of this variable is very difficult because of the extension of the reservoir and the number of water users.

6. FLOODPLAIN SIMULATION

The temporal and space variation of the flooded area can be simulated by the MIKE 11. It is possible to obtain maps corresponding to the flooding at various time steps. Figure 9 shows the inundated area during the flood of 1992.

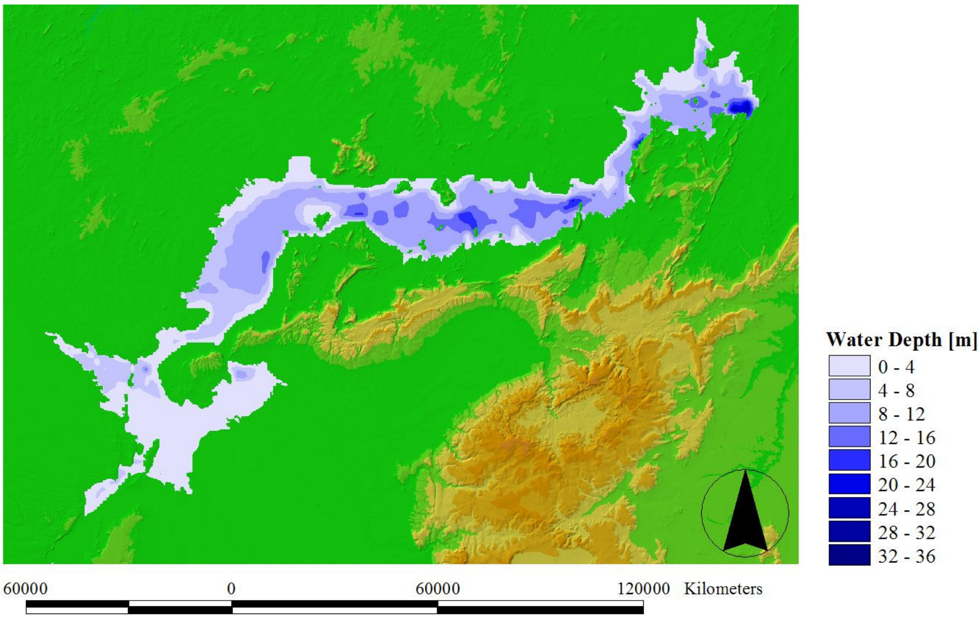

Figure 9 – Inundated area during the flood in 1992.

This MIKE 11 tool is able to help the understanding of the hydrodynamic processes and can also be used in the definition of the impact of the operation of the reservoir on the users located around it. About 700 hundred water users were identified along the shores of the lake. During the low water, many farmers use the land that is flooded by the lake during the high water. Hydrodynamic simulations can predict which areas will be flooded and avoid crop damage.

7. CONCLUSIONS

The results of the hydrodynamic simulations indicate that MIKE 11 is able to represent the flow routing in the Sobradinho reservoir using the geometric information available. The cross sections in the reservoir were obtained using the aerophotogrammetric survey. The DTM from SRTM-90 were able to overcome the lack of data about the river upstream the reservoir.

The water surface variation analysis in the Sobradinho Lake indicates that a hypothesis which considers that the water line along the reservoir is horizontal is not correct. Owing to the water surface slope, the use of the stage x storage curve could lead to errors in the storage estimate. Therefore, the storage estimate of the MIKE 11 model was considered as the reference value. Using the information from the MIKE 11 model, as opposed to the stage x storage curve, about 60 $m^3.s^{-1}$ is available for outflow and power generation.

Besides the storage estimate, the MIKE 11 can assist with other issues related to water management in the reservoir. The floodplain in the lake region can be simulated to forecast the impact of flood events that can cause damage to water users along the banks. In addition, a more accurate storage estimate can help to determine the volume of water withdrawn from the reservoir.

The more accurate the geometric data used in the model, the better the storage estimate in the reservoir. The next step in this work will be to carry out a bathymetric survey in the Sobradinho reservoir. Joining this information with the existent data will improve the storage estimate and the water resources management in the reservoir.

ACKNOWLEDGEMENT

The authors acknowledge to the Water Resources Management Division of the Hydroelectric Company of the São Francisco (CHESF), the Science and Technology Support Foundation of the State of Pernambuco (FACEPE) and the Brazilian National Council for Scientific and Technological Development (CNPq).

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