The Impact of an Extreme Flood upon the Mixing Zone of the Todos os Santos Bay, Northeastern Brazil

F. Genz †; G.C. Lessa‡ and M. Cirano‡

†Pós-graduação em Geologia
Universidade Federal da Bahia, Salvador
40170-115, Brazil
fgenz@uol.com.br

‡ Centro de Pesquisas em Geofísica e Geologia
Universidade Federal da Bahia, Salvador
40170-115, Brazil

ABSTRACT

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River dams, by impacting the discharge pattern of a drainage basin, may cause problems to the lower river course and associated estuarine areas, especially in relation to channel morphology and material exchange with the coastal environment. With the aim of investigating the effect a natural flood upon the hydrodynamics and mixing condition of an estuary (Paraguaçu River) inside Baía de Todos os Santos, a simulated 8-day flood event was released by Pedra do Cavalo Dam, located 20 km up the river, on November 2001. Peak discharge reached 1534 m^3s^{-1} (15 times the pre-dam average discharge) in the very first day of the simulation, and was reduced daily in a step-like fashion in the following 7 days. The flood had a major impact upon the water level of the closest monitoring station, 5 km downstream from the dam, but was not noticeable in the farthest station another 32 km downstream. Current measurements, performed at a fixed station 32 km downstream from the dam, registered velocities up to 1.8 $m.s^{-1}$ during the ebbing time, and an apparent inversion of the residual current vector between spring (ebb directed) and neap (flood direct) tides. The salt intrusion zone travelled 14 km up river during the spring-tidal cycle prior to the flood. With the onset of the event it was pushed 16 km downstream and was maintained out of the lower river course as the water column changed from well to partially mixed until the discharge dropped below 118 m^3s^{-1}.

ADDITIONAL INDEX WORDS: *Dam, freshwater, estuary.*

INTRODUCTION

The Baía de Todos os Santos (BTS) (Figure 1) is the second largest coastal bay in Brazil, with an area of 1223 km^2 and a catchment area of 60.000 km^2. About 95% of the catchment (56.300 km^2) is drained by Paraguaçu River, that discharges into a secondary bay called Baía de Iguape, in the western side of the BTS (Figure 1). The Paraguaçu estuarine zone has a total length of 40 km, comprising 16 km of the lower river course (4 m deep), 6 km inside Baía de Iguape and 18 km of a tidal channel (Paraguaçu Channel - 25 m deep) that connects Baía de Iguape to the main body of the BTS (Figure 1).

The Baía de Iguape has a total area of 76,1 km² and is divided into 3 sectors: north, central and south sector (CARVALHO, 2000). The tidal channels (depths between 5 to 10 m) along the northern and southern sectors of Baía de Iguape have an average width of 200 m and an extension of 11 km and 7 km, respectively. The central part of the bay, with a prograding fluvial delta fronting Paraguaçu River, is very shallow, with large longitudinal sand banks emerging at low water (LESSA *et al.*, 2000). The vegetated and non-vegetated intertidal area inside Baía de Iguape represent 37% and 21% of the total bay area, respectively. The most common mangrove species is *Laguncularia racemosa* (CARVALHO, 2000), that covers 81% of the total mangrove area of the estuary.

The Paraguaçu River had an average discharge of 102.7 $m^3.s^{-1}$ until 1985, when Pedra do Cavalo Dam (Figure 1), with a volume of 4,64 x 10^9 m³, was built 20 km upstream from Baía de Iguape. The original discharge, that accounted for 81% of the total fluvial input to the BTS, was reduced to 68.5 $m^3.s^{-1}$, or 60 % of its previous average. Water extraction for urban consumption, direct evaporation from reservoir surface area and the decline of the natural river discharge (due to climatic oscillations) are the causes for this reduction.

The impact of river damming upon the water and sediment dynamics of lower river courses and the estuarine areas can vary from channel shoaling (by marine and/or fluvial sediments) (KJERFVE, 1989; LEVINSEN and Van Dolah, 1997; EYRE *et al.*, 1998; COLLIER *et al.*, 2000; WOLANSKI *et al.*, 2001) to modification of the tidal assymetry and extent of salt intrusion along the estuary (WOLANSKI *et al.*, 1996; WOLANSKI *et al.*, 1998; GUILLÉN and PALANQUES, 1992; CARRIQUIRY and SÁNCHEZ, 1999; VIEIRA and BORDALO, 2000; WOLANSKI *et al.*, 2001). Channel shoaling, generally associated to a reduction of the magnitude of the river floods may cause i) morphologic instabilities of the outlets (GUILLÉN and PALANQUES, 1997; BARUSSEAU *et al.*, 1998; MORRIS and FAN, 1998; MEDEIROS *et al.*, 1999; OLIVEIRA, 1999; CAMPOS, 2001) and ii) environmental degradation as a consequence of impaired water circulation, degraded water quality and consequent impact upon the ictiofauna and intertidal vegetation (PATTY *et al.*, 1999; RUBIN *et al.*, 1998).

In July 2002 a research project financed by the Brazilian Research Council was initiated on three dammed rivers (Paraguaçu River as one of them) of different sizes, morphology and hydrological regimes, in order to evaluate the impact of dams upon the estuary morphodynamics. A proper assessment of the changes imposed by the dammed flow upon the estuarine hydrodynamics requests some knowledge of the flow and mixing patterns prior to the construction of the dam.

In the case of Paraguaçu River, no data exists on the water quality, mixing or hydrodynamics before 1985. A sole exception is the paper of WOLGEMUTH *et al.* (1981) that, with longitudinal profiles (water surface sampling), shows that stronger salt gradients occur by the river delta with river discharges varying from 21 to 130 $m^3.s^{-1}$. A way to bypass this limitation is to generate artificial flood events or use numerical modelling techniques. This paper deals with the impact of a simulated flood, with a return period of more than 1 year, on the whole extent of the estuary. The results will show that a flood wave with a return period of more than one year can only significantly change the circulation and water condition of the riverine sector of the estuary.

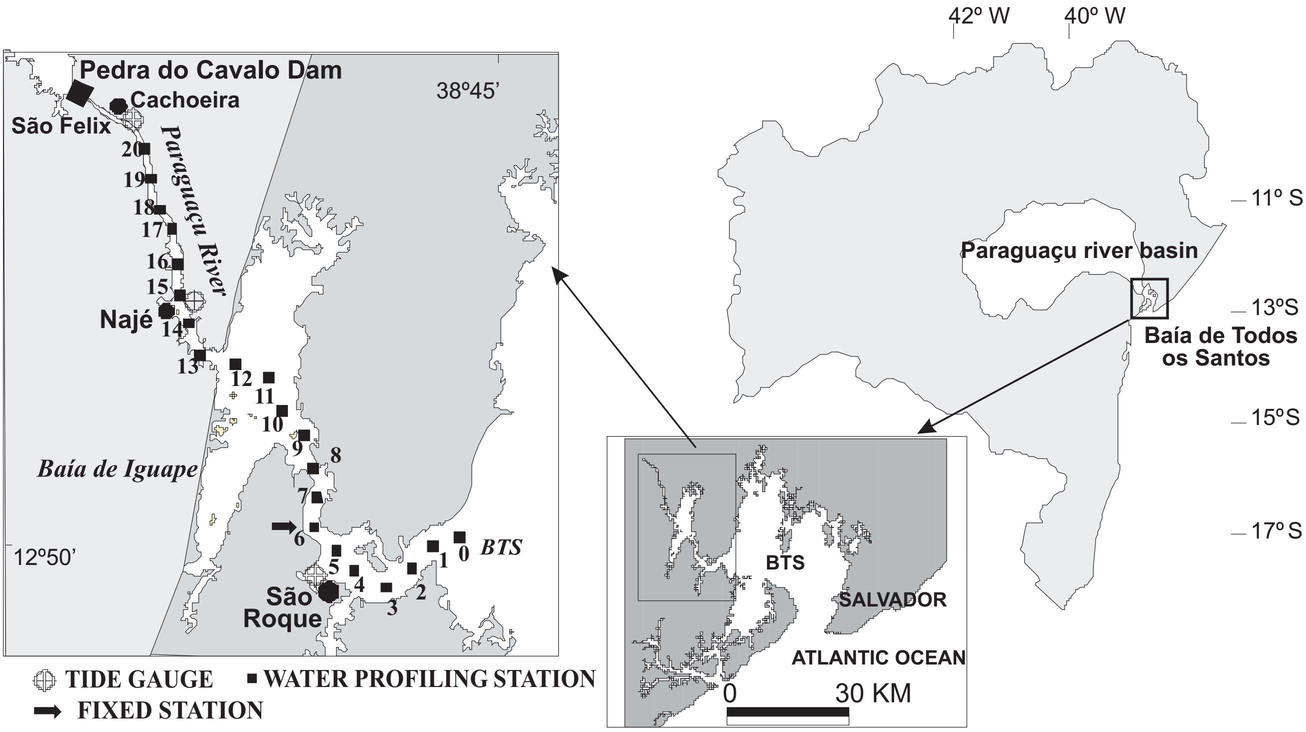

Figure 1. Location of study area and monitoring points.

METHODS

A flood hydrograph was established based on available discharge data (40 years before 1985). The dataset consisted of historical time series for the two major tributaries to the reservoir, namely Argoim station (at Paraguaçu River) and Ponte do Rio Branco station (at Jacuipe River). These two stations are located just upstream of the reservoir and can give a good estimate of the total inflow. Selected hydrographs, with peak discharges above 400 $m^3.s^{-1}$, indicate that the ascending sector of the curve, prior to the peak discharge, varied a few orders of magnitude (from 10 to 1000 $m^3.s^{-1}$) within a day interval. The descending sector of the hydrograph was much smoother, characterized by the following equation:

$$Q_{i+1} = Q_i\, e^{-k.\Delta t} \qquad (1)$$

where k is the decreasing coefficient, Δt is the time interval , Q_i is the discharge and i is a given time (starting from the peak discharge). The mean k value, based on 59 flood events with return periods larger than one year, was 0.28. The selection of the final hydrograph to be reproduced was also based on:

a) the volume of water available in the reservoir;

b) the tidal conditions;

c) the sluice operational guidelines.

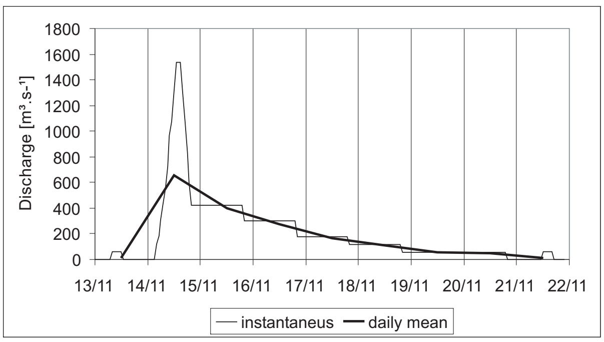

Figure 2. Hydrograph produced by the simulated flood event.

In order to avoid flooding of marginal cities (Cachoeira, São Felix and Najé), especially when discharges coincide with spring tides (that are up to 3 m high 5 km downstream of the reservoir LESSA *et al.* 2001), the peak discharge rarely exceeds 1500 $m^3.s^{-1}$. However, to avoid illegal occupation of the river bank, floods are generated at least once a year. Based on all these facts, the hydrograph was set to last 8 days (November 13 to November 21, 2001) and to provide a peak discharge of 1600 m^3s^{-1}, coincident with high water of a spring tide.

Tidal elevation was sampled along 3 different locations (Figure 1) using an analogic gauge, model LNG 7, made by Hidrologia. The tide gauges were deployed at distances of 4, 18 and 37 km from Pedra do Cavalo Dam (located 4 km upstream of the upper limit of the estuary). The water level records were digitized on a tablet and corrected for time and elevation offsets when necessary.

Vertical profiles of water quality (salinity, temperature, pH[1] and suspended sediment concentration) were executed with a Horiba multi-probe U-10 over 20 stations distributed along the mixing zone (40 km long) shown in Figure 1. The current field and the water quality were also monitored at a fixed station located 6 km downstream from Baía de Iguape, in Paraguaçu Channel.

The current field was measured with a Sensordata SD-30 in a fixed station, sampled every 0.5 hour during one complete tidal cycle at neap and spring conditions.

RESULTS AND ANALYSIS

The hydrograph for the monitored period is presented in Figure 2. The sluices were opened on November 14 (4 am), reaching a peak discharge of 1534 $m^3.s^{-1}$ at 1 pm. After 4 pm, the discharge started to be reduced hourly until it reached 423 $m^3.s^{-1}$ at 8 pm. From then on, the sluices were closed at an equal rate (based on the k coefficient) every day at 8 pm until the November 21, producing a step-like profile in the hydrograph. The daily average discharges between November 13 and 21 were 13, 656, 402, 278, 167, 108, 58, 48 and 13 $m^3.s^{-1}$.

[1]Not shown

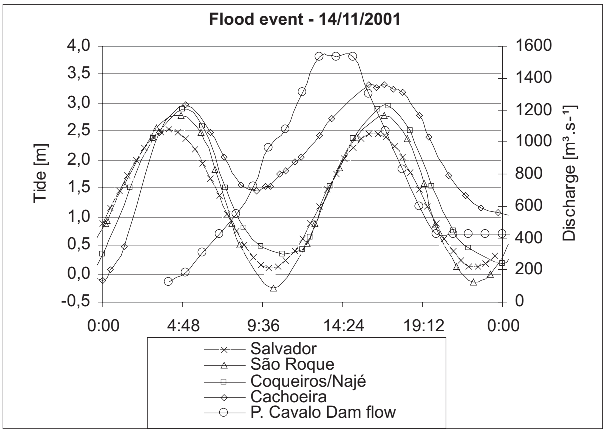

Figure 3. Tide and dam peak discharge - 14/11/2001.

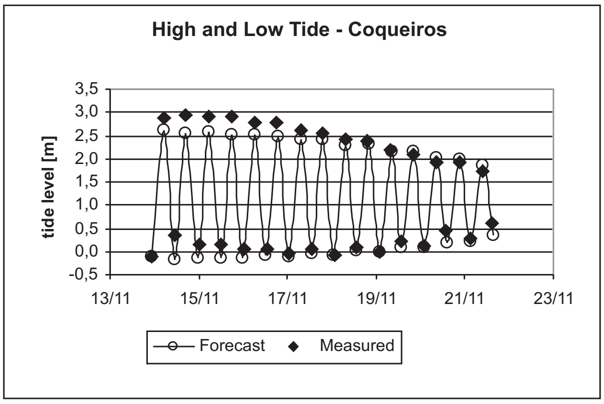

Figure 5. Predicted and observed high and low water elevations at Coqueiros.

Tide

The tide wave underwent amplification up the estuary, by a factor of 1.08 during spring and 1.19 during neap tides. On the spring tide of November 13, when the largest ranges were recorded prior to the flood, the tide range was 2.86 m at São Roque, 2.98 m at Coqueiros and 3.1 m at Cachoeira. During neap tides on November 21, when the flood hydrograph was over, tide ranges in those same locations were 1.33 m, 1.45 m and 1.59 m, respectively.

The tidal records at the three stations on November 14 are shown in figure 3 against the predicted tide level. Mean sea level was raised by about 1.5 m at the upstream most station (Cachoeira) during the flood peak on November 14. The high tide level reached an elevation 0.5 m higher than that predicted by the astronomical tides, but the tidal range was reduced in 1.2 m. At Coqueiros, the next downstream station, the river surge was only 0.5 m and tide range was reduced in 0.5 m.

Figure 4 shows that the effect of the flood at Cachoeira persisted until 19/11 (Figure 4), when the discharge was 58 $m^3.s^{-1}$. At Coqueiros (Figure 5), distortions of the tide level were observed only until 17/11, when the discharge was 177 $m^3.s^{-1}$. At the farthest station, São Roque, the river surge was not noticeable in the records. The predicted water levels used in figures 4 and 5 were obtained from harmonic analysis of a 15 day long water level record performed by the Brazilian Hydrographic Authority in 1976.

Without the flood, the tide wave distortions at Cachoeira and São Roque are opposing. In the former the rising tide is much shorter than falling tide, whereas in the latter falling tides are shorter. At Coqueiros, located between the above stations, the difference between flood and ebb periods is only of few minutes. During the flood, the original tide asymmetries were enhanced at all the stations, with rising tides becoming 30 minutes shorter at Coqueiros and Cochoeira, and 23 minutes longer in São Roque. An exception occurred in Cachoeira on the November 14, during the discharge peak, when rising tides became longer (Figure 3). Increased asymmetries caused longer time lags at low tide between the stations in the river and São Roque. Shorter falling tides in São Roque are ascribed to the large intertidal areas inside Baía de Iguape, that tend to retard the infilling of that section of the estuary (LESSA, 2000).

High and low water time lags during the flood were increased in relation to the predicted ones. Time lags between Cachoeira and Coqueiros changed from 0:07 hs to 0:23 hs at high tide, and from 1:06 hs to 1:26 hs at low tide.

Salinity

The longitudinal water quality profile (Figure 6) show that in the low tide in the pre-flood situation of November 13, the estuary was mostly well-mixed, with salinity values above 30 penetrating 16 km up the Paraguaçu Channel (station 8 in Figure 1). An intense longitudinal salinity gradient was observed after station 9 (before reaching Baía de Iguape), where salinity varied from 30 to 4 within 18 km. The farthest detectable salt concentration was at station 18, located 7 km

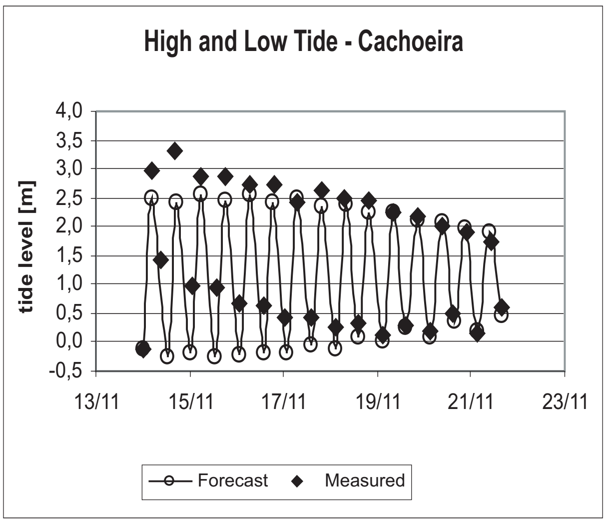

Figure 4. Predicted and observed high and low water elevations at Cachoeira.

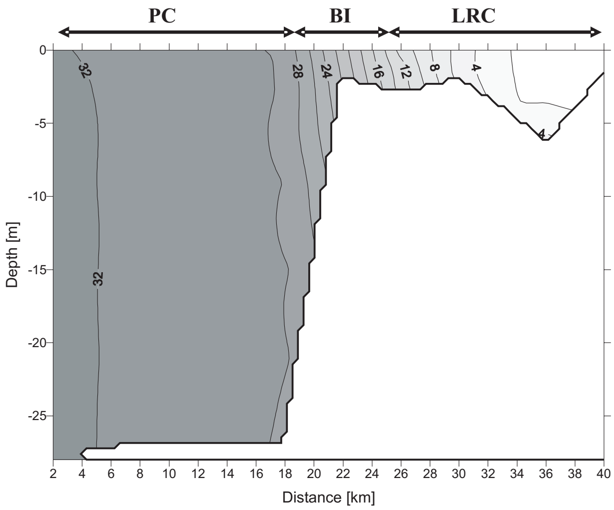

Figure 6. Longitudinal salinity profile at low tide on November 13 (PC Paraguaçu Channel; BI Baía de Iguape; LRC Lower River Course).

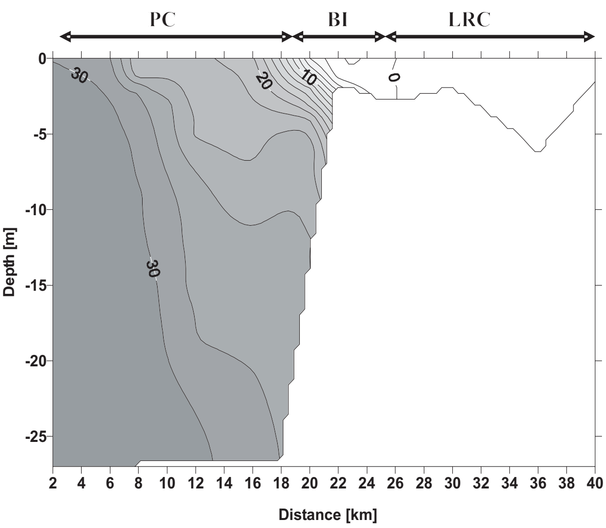

Figure 7. Longitudinal salinity profile at low tide on November 15.

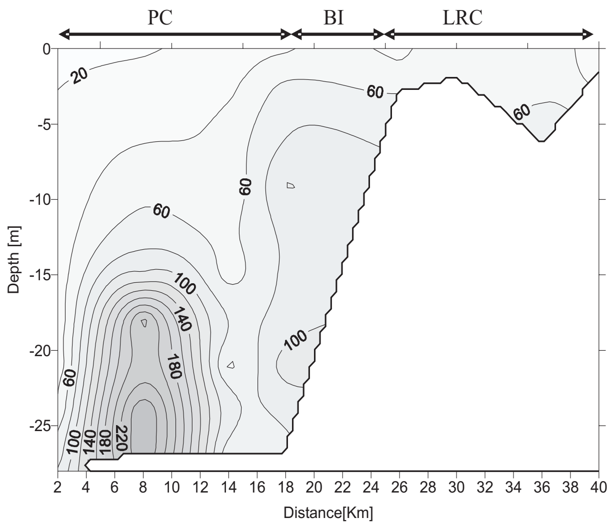

Figure 9. Longitudinal distribution of the suspended sediment concentration at the low tide on November 13.

downstream of Cachoeira, reaching 4 psu close to the bottom. This limit of salt intrusion may have moved farther upstream during the high tide.

With the onset of the flood the estuary gradually changed from a well to a partially mixed condition, with freshwater occurring along the whole lower river course (Figure 7). This mixing condition lasted until 18/11. At day 19/11, with discharges falling to 58 m^3s^{-1} and tides changing from spring to neap condition, salt intrusion along the lower river course is again observed. The maximum salinity gradients during the flood were generally found at the vicinity of Baía de Iguape, located either at end of the lower river course or at the beginning of Paraguaçu Channel. Figure 8 shows that the average salinity gradient was 2.6 psu km^{-1}, with maximum gradients reached up to 8.5 psu km^{-1}.

At the fixed station (Figure 1), where water properties were sampled over a complete tidal cycle (14/11), the influence of the flood was clearer during ebb tide, when the surface salinity dropped from 31.3 psu to 11 psu within one hour (from 18:30 to 19:30).

Currents and Suspended Sediment

The current field sampled at the fixed station (Figure 1) indicates that the tidal wave is stationary.

During spring tide and peak flood discharge (14/11) the depth-averaged velocity, here represented by its mean and the associated standard deviation, had a value of 0.31 0.57 $m.s^{-1}$ (the surface velocity had a maximum value of 1.80 $m.s^{-1}$ during ebb tide). On the other hand, with the discharge reduced to 58 $m^3.s^{-1}$ during neap tides (20/11), the depth-averaged velocity dropped to 0.05 0.17 $m.s^{-1}$ (the surface velocity had a maximum value of 1.11 $m.s^{-1}$), suggesting a reversion of the residual flow.

An increase of the suspended sediment concentration was observed along the estuary during the flood event. This was mainly caused by the higher turbulence and sediment resuspension in the lower river course (Figures 9 and 10). Turbidity maximum zones were found at the entrance of Paraguaçu Channel and at the entrance of Baía de Iguape.

A maximum concentration of 586 $mg.l^{-1}$ occurred at the bottom of station 3 on November 15 at high tide. After November 19, when the discharge was reduced to 58 m^3s^{-1}, measurements were performed during a high tide situation. For this scenario, a drastic reduction in the values of suspended matter was observed (generally below 20 mgl^{-1}).

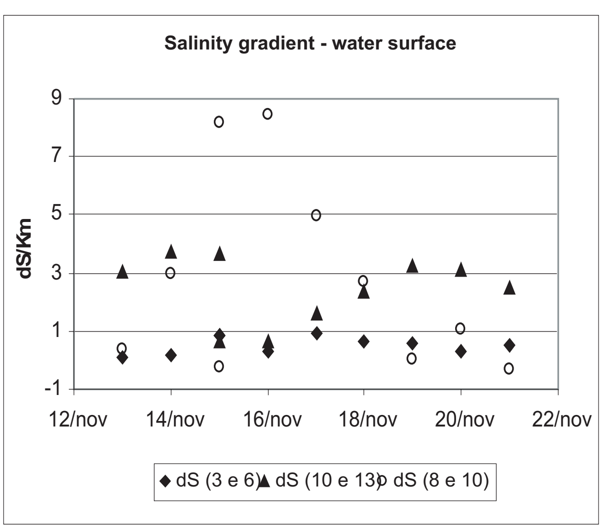

Figure 8. Daily variations of the surface water salinity gradient.

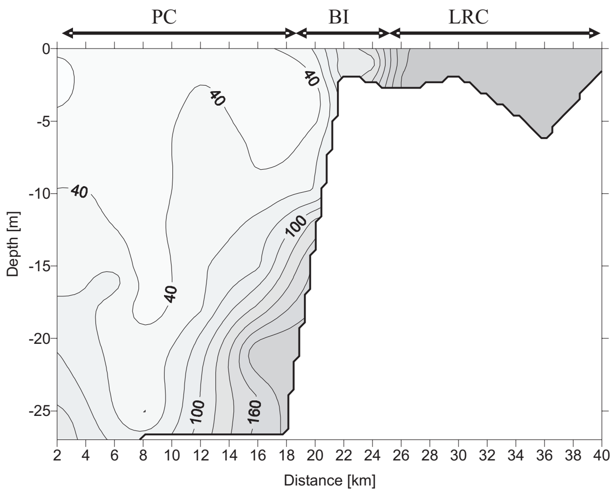

Figure 10. Longitudinal distribution of the suspended-sediment concentration at the low tide of November 15.

DISCUSSION AND CONCLUSIONS

This survey allowed for a preliminary characterization of the estuary dynamics under a flood hydrograph (based on pre-dam flow conditions) simulated by Pedra do Cavalo Dam. The flood magnitude reproduced an event with a return period of more than 1 year, and severely affected the water level at the closest station (Cachoeira), where mean sea level was superelevated in 1.2 m.

The surge waned out towards the second station (Coqueiros), still inside the more confined river valley, causing a superelevation of 0.5 m. This means a 68% reduction in the river surge height in 13 km, that is ascribed to a higher roughness coefficient of the river bed upstream Coqueiros. The surge must have been completely absorbed in Baía de Iguape, since it was undetected at the farthest station (São Roque). The highest discharge on November 14 also damped the tidal range in 1.2 m at Cachoeira.

Stronger flows along the lower river course impacted the propagation of the tidal wave upstream from Baía de Iguape. Tidal asymmetry was enhanced (even shorter rising times) and low-water time lags were increased by 0:30 hs. During the flood peak the normal tidal asymmetry at Cachoeira was inversed, as rising tide became longer than the falling tide**.**

Salt water intrusion became restricted to Baía de Iguape with river discharges higher than 118 m^3s^{-1}, or with the ratio of the integrated river discharge (R) over the tidal prism of the lower river course (P_{LC} - calculated through the hypsometric curve) higher than 0.05. The mixing pattern changed from well-mixed to partially-mixed with increasing river discharges. R/P ratios for the entire estuarine section (R/P_E - where P_E is the estuarine tidal prism) decreased from 0.09 on November 14 to 0.05 on November 20. It is observed that even with the highest river discharges, the ratio R/P_E was relatively small when compared with ratios from other partially mixed estuaries, and a well-mixed condition would be expected even on November 14. This situation is similar to that of Mersey River (DYER, 1973), where partially mixed conditions were identified with relatively low R/P ratios (0,01 and 0,02).

The suspended sediment concentration increased by 10 fold in the lower river course during a flood event, with two turbidity maximum zones occurring at both the exit of the Baía de Iguape and the exit of Paraguaçu Channel. Whereas the former was apparently caused by turbid waters coming down form the dam the latter was associated with sediment resuspension.

The occurrence of intense salinity gradients and the complete damping of the flood wave past Coqueiros, indicate the importance of Baía de Iguape in filtering the flood effects towards the BTS. While in the middle of Baía de Iguape the salinity changed from 22 to 6 psu between November 13 and 14, at the outlet of the bay the salinity dropped from 30, in the whole water column, to 28 at the bottom and 24 on the surface. At the most downstream station changes of only 2 psu was recorded (from 32 to 30psu).

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