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The fresh-water discharge in Todos os Santos Bay (BA) and its significance to the general water circulation

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Abstract - Fresh water discharge into Todos os Santos Bay is assessed on the basis of measured and estimated river discharge data. The average mean fresh water discharge amounts to 111.1 $m^3 s^{-1}$, and might be added to another 28.2 $m^3 s^{-1}$ that falls directly on the bay area as rainfall. The mean river discharge represents only 0.08% of the spring tidal prism, calculated by the means of a through analysis of the depth-area distribution.

Keywords - fresh water discharge, hypsometry, Todos os Santos bay.

INTRODUCTION

From an oceanographic viewpoint, estuaries are coastal indentations (river and glacial valleys, grabens and coastal areas embayed by spit/barrier growth), where salt water is measurably diluted by fresh water (Pritchard, 1967). The water circulation in the estuary is influenced both by variations in tidal range and river discharge. The influence of the tides on the estuarine environment is generally the easiest to assess, since it is basically astronomically driven and can be measured from a single point, during a relatively short term, at the entrance of the estuary. River discharge, on the other hand, relies on the still largely unpredictable weather, is much more stochastic in nature and far more difficult to measure because of its generally widespread discharge points. In addition, long term measurements are necessary in order to describe its statistics and allow for the construction of reliable rating curves.

More often than not we find estuaries with river discharges poorly characterized, or not characterized at all, and it is not surprising that estuarine studies often need to rely on estimates of water balance over the drainage basin to estimate the surface fresh-water inflow (see for instance Knoppers *et al.*, 1987; Ong *et al.*, 1991; Kjerfve *et al.*, 1996; Kjerfve *et al.*, 1997; Bonetti Filho, 1997). On the other hand, it is also observed that a reasonable amount of river discharge data may be available in State Institutions, stored in internal reports and data bases which are of difficult access, and therefore unknown to the general public.

The Todos os Santos Bay (TSB) (Fig. 1), in northeastern Brazil, is one example of a large and very important (socially, economically and environmentally) estuary where, up to date, no information was published in the scientific literature assessing its fresh-water inflow. With the aim to fill in this gap, this paper provides a comprehensive review and characterization of the fluvial water input to the bay by analyzing a series of unpublished long-term river discharge data from the main watersheds. In order to assess the importance of the fluvial discharge to the general bay hydrodynamics, a comprehensive hypsometric analysis will be presented, along with a dimensional analysis of the overall surface and meteoric fresh-water discharge.

ENVIRONMENTAL SETTING

Todos os Santos Bay is the second largest coastal bay in Brazil, with an area of approximately 1100 km^2 (Lessa *et al.*, 2001), and surrounded by 12 councils with an overall population of nearly 3 million people. The bay is located in a Lower Cretaceous rift system, delimited by the Salvador and Maragojipe faults (Medeiros & Pontes, 1981, Fig. 1), and therefore classified as a tectonic estuary by Lessa *et al.* (2000). Evidence of this tectonic bearing is observed, amongst other things, through the embrionary character of the drainage systems that debouch into the northern side of the bay. Only three major river systems flow towards the TSB, namely Paraguaçu, Jaguaripe and Subaé rivers, with highly different areas (Table 1). Other 93

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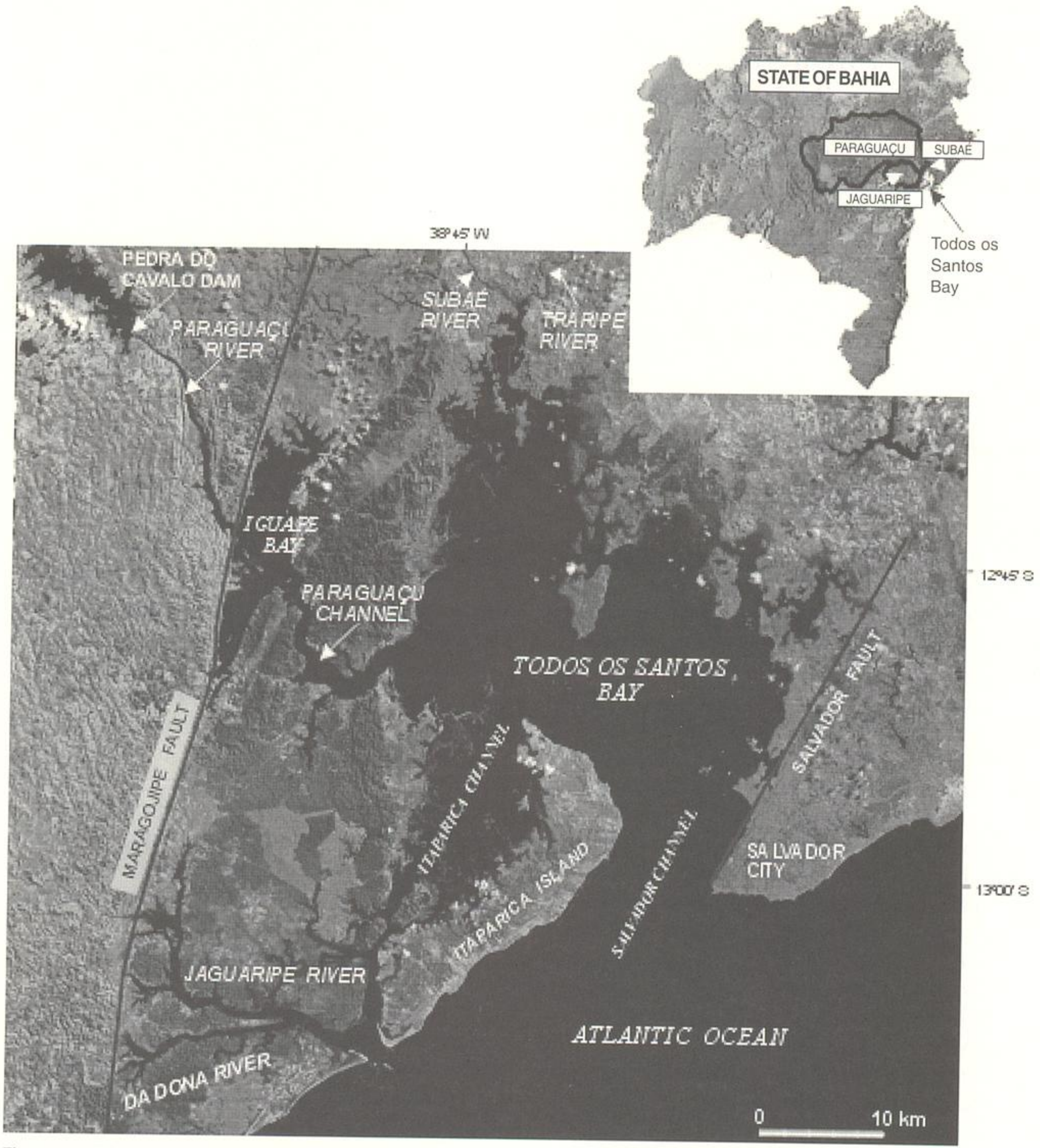

Figure 1 - Location of Todos os Santos Bay with its three main catchment areas (Paraguaçu, Subaé and Jaguaripe rivers) and the east and west limit of Recôncavo Basin (delimited by the Maragojipe and Salvador faults).

minor, peripheral drainage systems, with rivers longer than 1.5 km, can also be identified. In all, the total catchment area of the TSB exceeds 60,000 km^2. Total river discharge to the bay was greatly affected after the completion of Pedra do Cavalo dam (1980-1985) in Paraguaçu River (Fig. 1), which reduced the discharge in about 50% (Mestrinho, 1998).

The TSB has two entrances separated by Itaparica Island (Fig. 1). The most important is the Salvador channel, which provides for most of the water exchange between the bay and the ocean (Lessa *et al.*, 2001). Average and maximum depths in the Salvador Channel are 25 m and 102 m, respectively, in relation to the Navy Hydrographic Authority datum, herein

Table 1 - Area and time spans of the river discharge time series analysed from each catchment area.

Rivers	Catchment area (km²)	Time span
Paraguaçu	56,300	1949 - 2000
Jaguaripe	2,200	1949 - 1995
Subaé	660	1968 - 1989
Peripheral basins	1,950	–
Total	61,110	

adopted as a reference level (0 m DHN = 1.30 m below mean sea level (DHN, 1997).

The oceanographic characteristics of the bay, as indicated by published salinity measurements (33.0 to 36.7 - Wolgemuth *et al.*, 1981), are clearly marine. Estuarine characteristics are found only along the Paraguaçu Channel and Paraguaçu River (Wolgemuth *et al.*, 1981). The tides are semi-diurnal, with a mean spring range of 2.2 m in Salvador (Lessa *et al.*, 2001), and are amplified by a factor of 1.5 towards the northern end of the bay and along Paraguaçu Channel. Currents in the bay are mainly bi-directional and the water column appears to be well mixed in most part of the bay (Wolgemuth *et al.*, 1981; Barreto, 1993). The climate around the bay is tropical humid, with a ten-year average mean air temperature of 25.3°C close to Salvador city. A strong east-west rainfall gradient occurs in the catchment area, as the climate tends to become drier towards the semi-arid belt in the interior. A 30 year mean rainfall of about 1900 mm/year for the bay area changes to 500 mm/year in the middle of the Paraguaçu drainage basin. Opposing patterns of rainfall distribution are also observed, with higher precipitation rates occurring between December and February in most of the Paraguaçu river basin, and between March and June in the more coastal catchments (Fig. 2).

DATA SOURCES

Daily averages of river discharge were obtained from the National Energy Agency (ANEEL), the Bahia State Superintendence of Hydraulic Resources (SRH) and the State Water Board (EMBASA), who has been in charge of the Pedra do Cavalo dam operation since 1989. Time series length vary from a minimum of 21 years in Subaé River to a maximum of 51 years in Paraguaçu River. The discharge relative to the peripheral basins was estimated on the basis of the proportionality

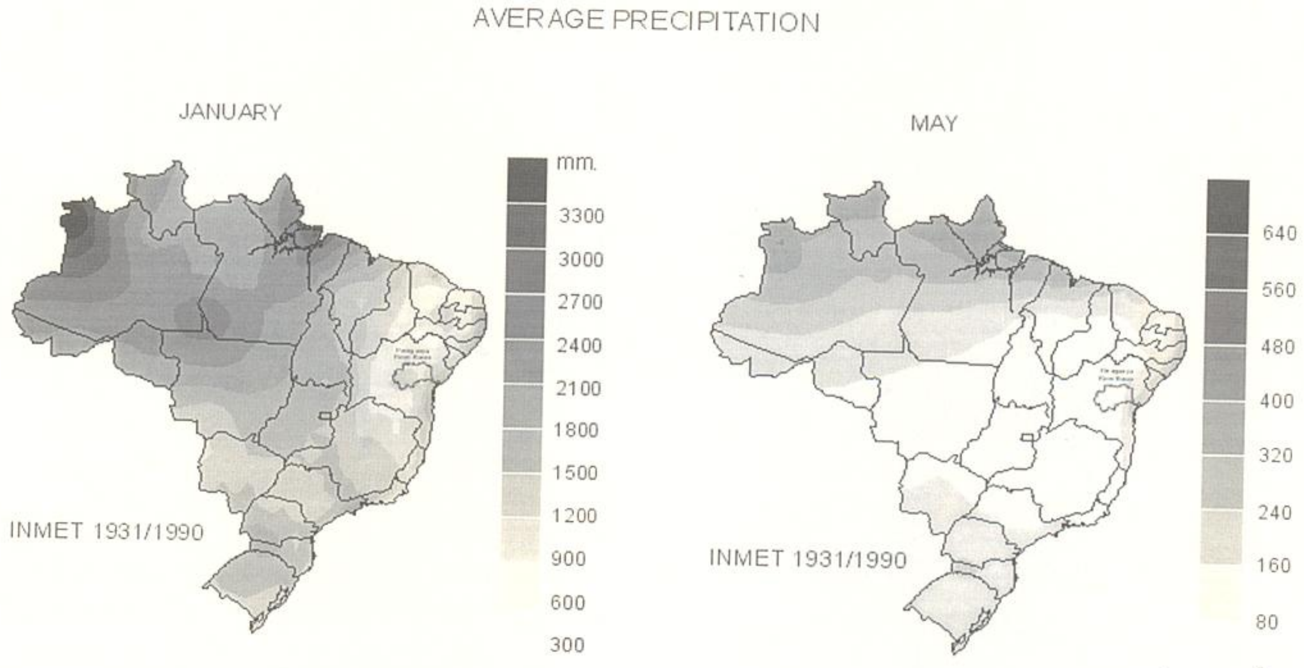

Figure 2 - Distribution of the month average rainfall in January and May, showing that higher rainfall rates occur in January at the headlands of Paraguaçu River (see the catchment area) and around the coastal region in May (source: www.inmet.gov.br).

of the catchment area in relation to the closest river discharge gauging station (CRA, 2000), also taking into consideration different types of vegetation and soil that can interfere with the surface runoff.

Bathymetric data was compiled from nine nautical charts published by the Navy Hydrographic Authority (DHN) with a 1:30,000 scale, except for the chart that covers the Itaparica Channel (Fig. 1), where scale was 1:100,000. All charts were digitized and georeferenced. Bathymetry of the lower Paraguaçu River course was surveyed in January 2000, and depths were corrected to the approximate DHN reference elevation. Depths along Jaguaripe river and the southern and northern extremities of Iguape Bay, where no bathymetric information exists, were estimated as 5 m, based on the depths observed in the surveyed neighboring regions.

The delimitation of the land boundary was perfected with the aid of LANDSAT 5 satellite images, since the nautical charts are notoriously mistaken in regard to this boundary in shallow regions. Image scale was 1:100,000 and resolution varied between 1:50,000 and 1:25,000. Data interpolation was executed through the Inverse Distance Weight (IDW method), with resolution set to 100 m.

The hypsometry of the bay was calculated between +3 m (the upper tidal inundation limit) and –85 m, because only a small portion of the bay reaches greater depths. Salinity measurements were obtained from a number of published and unpublished literature sources. A large quantity of data derived from unpublished reports from the State Environmental Center (CRA, 2000), covering spring and neap conditions during one week in summer and winter, in 8 stations inside the bay and 2 stations outside (Fig. 3). Vertical profiles in these stations were performed every hour, with measurements at 1 m interval with a SeaBird SBC19 mini CTD. Unpublished near-bottom salinity data was kindly provided by Orane Alves (Biology Department, UFBa) for 27 locations (Fig. 3) visited one time only between March and May 1997. Published salinity data was obtained from Moura (1979) and Wolgemuth *et al.* (1981), who measured salinity values in 98 stations (Fig. 3) between March and May 1977. Some of these stations were also with monitored vertically in 3 levels.

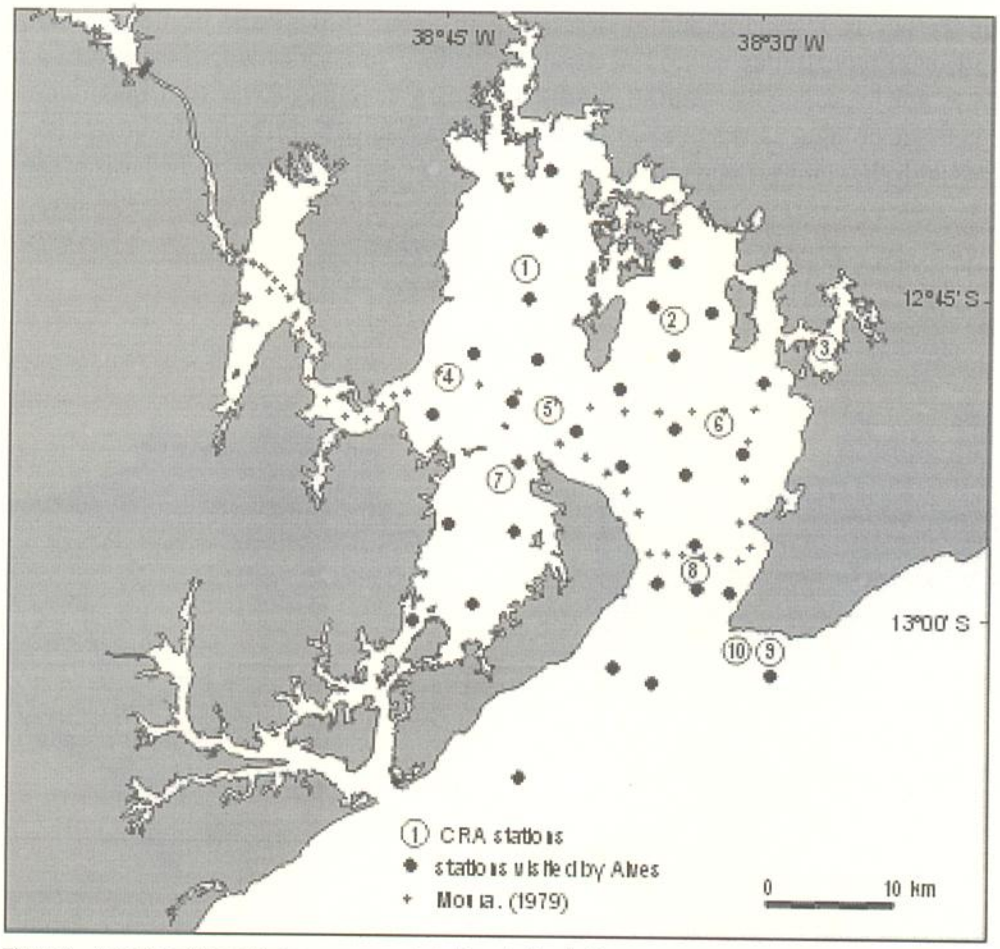

Figure 3 - Location of the salinity measurement stations inside the bay.

RESULTS

River discharge

Paraguaçu River

The Paraguaçu River has the largest drainage basin (56,300 km^2 - Table 1) and the highest water discharges to the TSB, with an annual mean of 52.79 m^3 s^{-1} that does not include an extraordinary flood event in 1989, when mean daily discharge reached 5726 m^3 s^{-1} – (Table 2, Fig. 4). Nowadays the discharge is regulated by Pedra do Cavalo dam, and total water discharge data in the past, prior to 1985, was calculated by the sum of the two last gauging stations in Paraguaçu (Argoin Station) and Jaguaripe (Ponte Rio Branco) rivers, the latter being the last downstream tributary. Both stations cover more than 95% of the total catchment area, and present a mean river discharge of 107.7 m^3 s^{-1} between 1949 and 1980 (Table 2).

Flow regulation by the dam has set maximum discharge values below 1700 m^3 s^{-1}, whereas the highest recorded discharge to date was 7100 m^3 s^{-1} in 1964. Although month-mean water discharges are evenly distributed along the year due to flow regulation (month mean of about 21 m^3 s^{-1}), the maximum discharges vary significantly, between 23.5 m^3 s^{-1} in September and 730.2 m^3 s^{-1} in December (Fig. 5), the wet season in the headwaters of the drainage basin.

Jaguaripe River

Two gauging stations were operative in Jaguaripe river, Nazaré and Coqueiro Grande. Nazaré station, which gauges the drainage of 1418 km^2, or more than 70% of the total Jaguaripe catchment area (Tab. 1), presents the longest time series of 46 years (Tab. 2 and Fig. 4). Mean daily discharge at the Nazaré station is 10.34 m^3 s^{-1}, with a recorded maximum of 300 m^3 s^{-1}. Data from Coqueiro Grande (1966 to 1970) shows a very small mean discharge of 0.85 m^3 s^{-1}, with a maximum of 6.5 m^3 s^{-1}. The total catchment area is 25 times smaller than Paraguaçu's (Table 1), but given the widespread aridity of the region where the Paraguaçu catchment area is inserted, the mean discharge for the whole catchment of 14.94 m^3 s^{-1}, including the estimated da Dona River discharge (Tab. 2) is only 3.5 times smaller than Paraguaçu's. The discharges have a clear seasonal pattern, being higher in June-July (month mean of about 28 m^3 s^{-1}) and lower around January (month mean of 12.5 m^3 s^{-1}, Fig. 5). Average month-maximum discharges are lower in October (33 m^3 s^{-1}) and higher in May (132 m^3 s^{-1}), but equally high values can also be observed in December and January.

Subaé River

Subaé River has the smallest catchment area, of only 390 km^2, or 85 times smaller than that of Paraguaçu River. The gauging station monitors the discharge of 60% of the total catchment area (Fig. 4), and indicate a mean daily discharge of 3.13 m^3 s^{-1} between 1968 and 1989. Most of the remaining catchment area, which is drained by Traripe River with an area 195 km^2, provides an estimated extra of 1.35 m^3 s^{-1}, totaling a discharge of 4.48 m^3 s^{-1}. Recorded maximum discharge for the gauging station is 129 m^3 s^{-1}, and maximum estimated discharge for the whole catchment is 140 m^3 s^{-1} (Table 2).

Likewise Jaguaripe River, month-mean discharges from Subaé River reach a maximum in May of 8.9 m^3 s^{-1} and a minimum in the summer months around 3 m^3 s^{-1}. Average month maximum attains the highest value in May (14.4 m^3 s^{-1}) and a second highest in December (Fig. 5).

Peripheral Catchment Areas

Estimated discharge values for all small catchments were obtained for dry, wet and normal climatic conditions (CRA 2000). The total area of these catchments amount to 1,950 km^2, about 5 times larger than the Subaé or 1.25 times larger than the Jaguaripe catchment areas. Total mean water discharge is 29.98 m^3 s^{-1}, whereas maximum discharges during wet periods reach 50.03 m^3 s^{-1} (Table 2). Total mean discharge during a dry season can be as low as 9.28 m^3 s^{-1}. Therefore, it is observed that although small as single entities, the total area and water volume discharged by the peripheral catchments together can be almost twice as large as the Jaguaripe and Subaé discharges combined.

The sum of the mean discharges from all catchments results in a mean surface fresh-water inflow rate to the TSB of 111.10 m^3 s^{-1}, and maximum discharge of 2222,13 m^3 s^{-1} (Tab. 2), assuming that maximum discharges from every catchment are

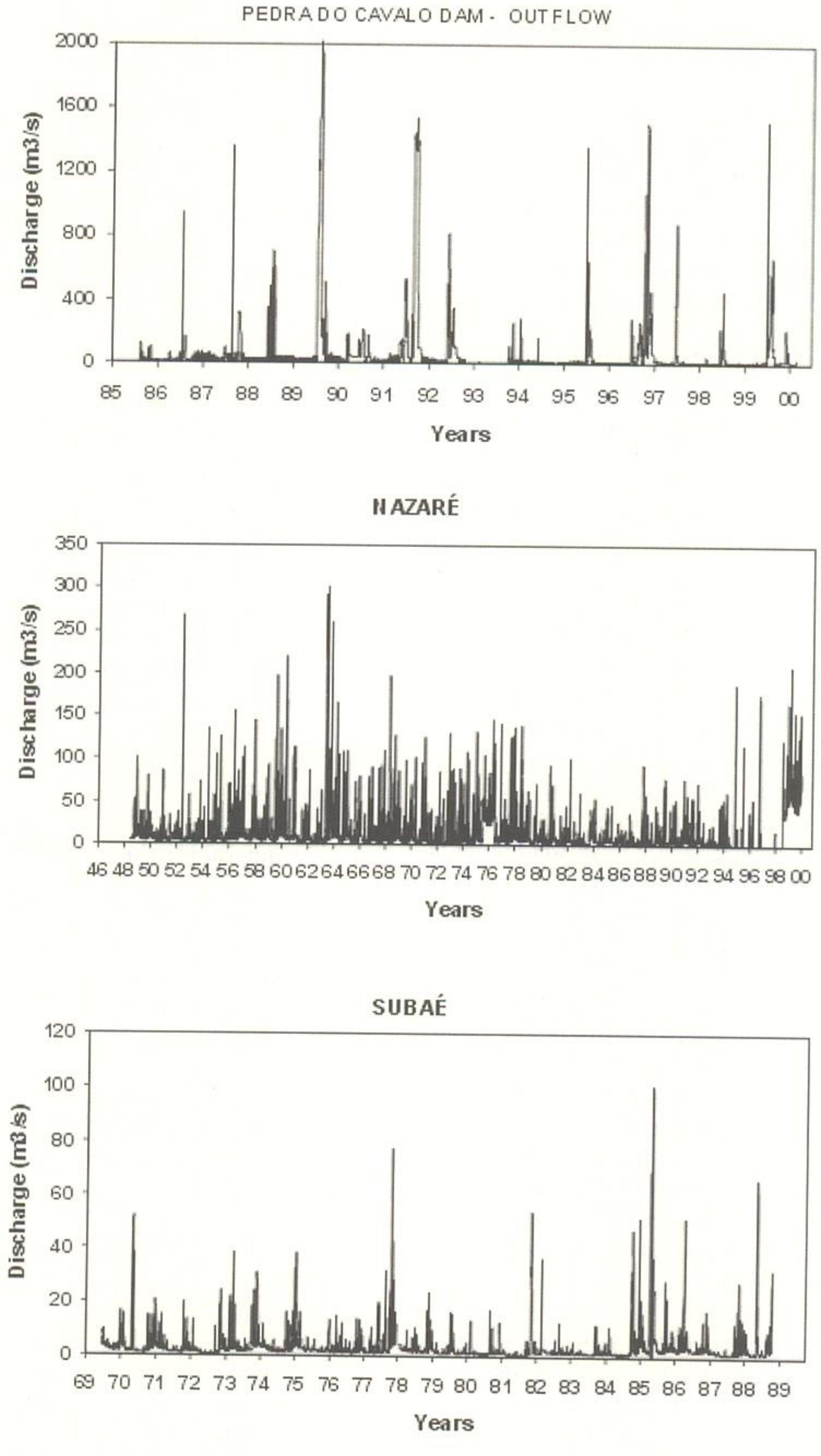

Figure 4 - Variation of the mean daily discharge of Paraguaçu River after Pedra do Cavalo dam (flood event in 1989 reached 5726 m^3/s), Jaguaripe River (Nazaré station) and Subaé.

Table 2 - Maximum and mean discharges, and the standard deviation of the mean, from the watersheds around TSB.

Rivers	Q max ($m^3 s^{-1}$)	Q avg ($m^3 s^{-1}$)	Q Standard Deviation ($m^3 s^{-1}$)	Time period
Paraguaçu (prior to 1985)[1]	7,100	107.7	206.18	1949 - 1980
Paraguaçu (after 1985)	1,700[5]			
	5,726[6]	52.79[7]	247.04[7]	1986/2000
Jaguaripe [2]	332.1	14.94	15.82	1949/1995
Subaé [3]	140	4.48	4.93	1968/1989
Peripheral basins [4]	50.03	29.98	-	-
Total	2,222.13	111.10	-	-

1 - sum of the discharge values from Argoin and Ponte Rio Branco stations

2 - considering estimated discharges from Coqueiro Grande Station and estimated discharges from da Dona River (Fig. 1). Standard deviation only considers real data.

3 - considering estimated discharges from Traripe River, (Fig. 1), excepting the standard deviation.

4 - estimated discharges.

5 - established maximum dam outflow.

6 - second highest river flood in the whole record.

7 - not considering the flood event.

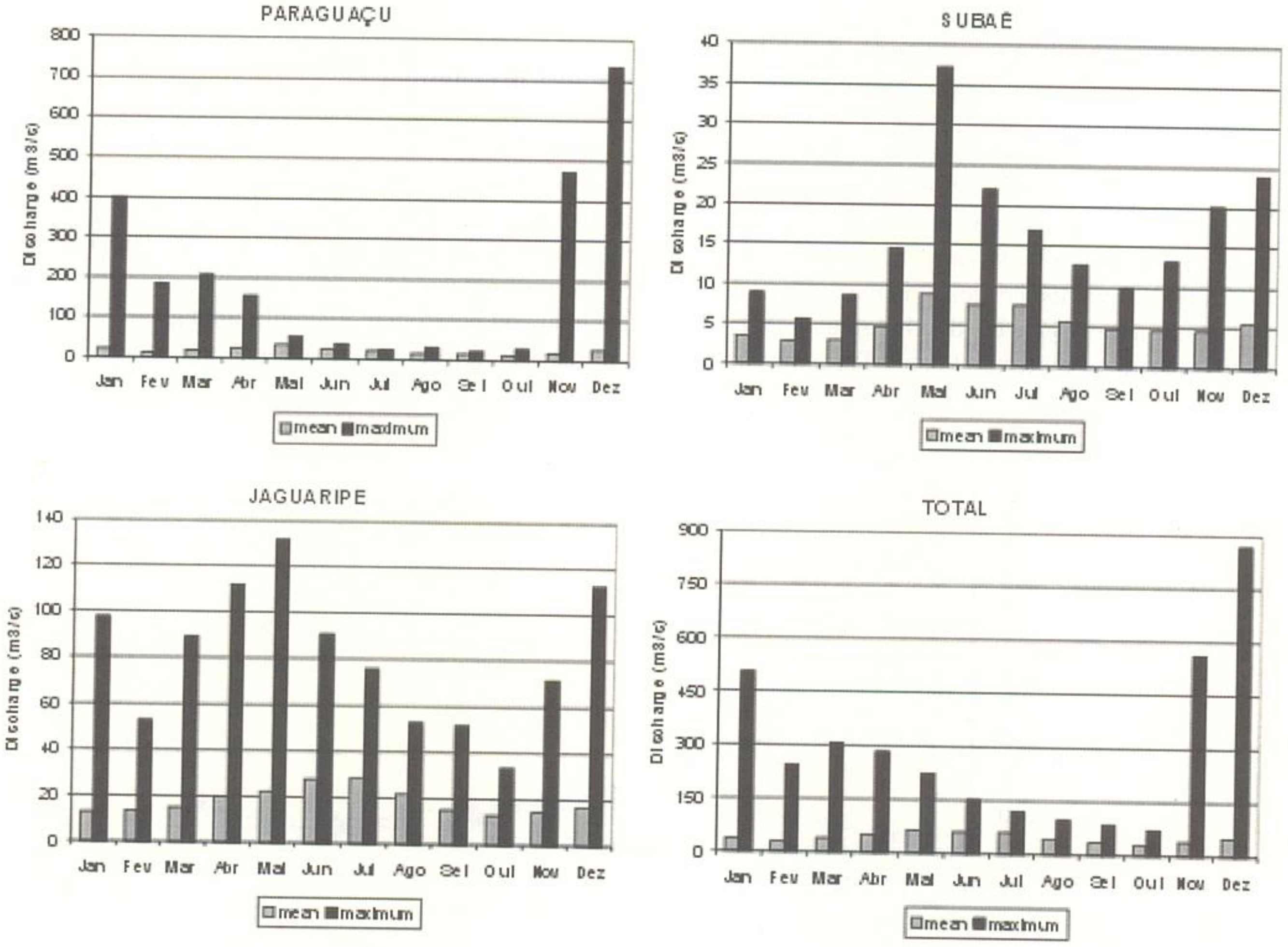

Figure 5 - Variation of the average month mean and maximum water discharges from the main watersheds. Data from Paraguaçu River reders to period 1985-2000 (after Pedra do Cavalo dam was built). Data from Jaguaripe and Subaé rivers include estimated discharge from da Dona and Traripe rivers.

simultaneous. Average month mean and maximum discharges from all catchments (Fig. 6) shows that the month mean surface fresh water inflow to the TSB reflects the discharge patterns of the coastal catchments, attaining a maximum of 115.7 $m^3 s^{-1}$ in May. The average month maximum discharges, however, reflects the highest discharges of Paraguaçu River in December, when the dam is partially emptied to wait for the headwater floods, diminishing then gradually until achieving a minimum that equals the mean discharge in October.

Hypsometry

The bathymetric map of the bay, which resulted from the depth sounding interpolation process, is shown in Fig. 7. The shallowest areas are located in the northern part of the bay, Itaparica Channel and Iguape Bay. The greater depths that define Salvador Channel bifurcate into three channels that run towards Aratu Bay, Madre de Deus Island and Paraguaçu Channel (Fig. 7), defining what appears to be a Pleistocene drainage path for the continental waters. The shallowest areas occur in the northern side, Iguape Bay and Itaparica Channel. Locally deep sections are observed at the entrance of Aratu Bay (-53 m) and between Frade and Madre de Deus islands (-63 m), and are likely tectonic controlled. Towards the west, the Paraguaçu Channel run along a canyon with depths greater than 20 m until it reaches an intertidal bank (Paraguaçu's River delta) in Iguape Bay (Lessa *et al.*, 2000). Other shallows worth mentioning are the ebb-tidal deltas outside Salvador and Itaparica channels, with elevations higher than –5 m.

The maximum bay area, associated with the farthest horizontal inundation during spring high tide, was calculated as 1,270 km^2, a value that is between 15% to 36 % larger than previous estimates (da Silva *et al.*, 1996, Lessa *et al.*, 2001). The hypsometric curve of the bay is shown in Fig. 8. More representative areas are those above 25m, that represents 87% of the bay area. The area-weighted depth of the bay is - 2.7 m if the intertidal area is considered, or - 5.2 m if only the subtidal area is taken into account in the calculation.

The total volume of the TSB, below near-maximum spring high-tide level (tide range = 3 m in the more internal sectors of the bay) is 12.5 x 10^9 m^3, where 3.36 x10^9 m^3 corresponds to the spring-tide intertidal zone (tidal prism). These values are about 10.9 x 10^9 m^3 and 2.92 x 10^9 m^3, respectively, under average spring-high tides, which are 13% smaller? 2.7 m).

Salinity distribution

The spatial distribution of the lowest salinity values observed in the TSB allows for the assessment of the likely maximum extension of the effects of river discharge in the dilution of saltwater. The distribution of the data obtained by CRA (2000) shows very small vertical and horizontal gradients amongst the stations in the central part of the bay, with a mean of 36 psu

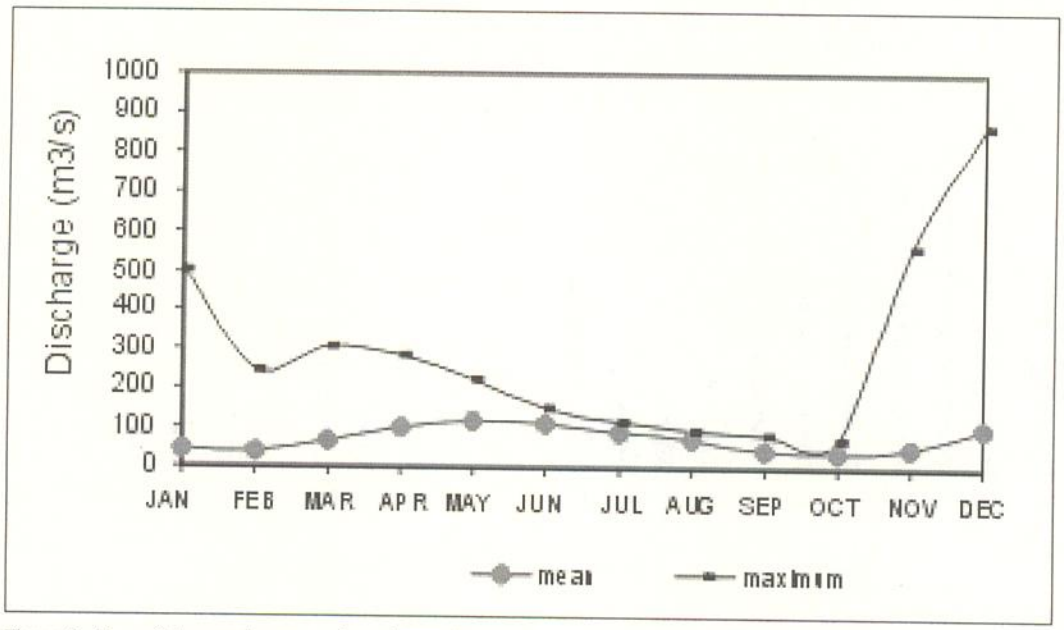

Figure 6 - Sum of the month mean and maximum discharges from all catchments around the TSB.

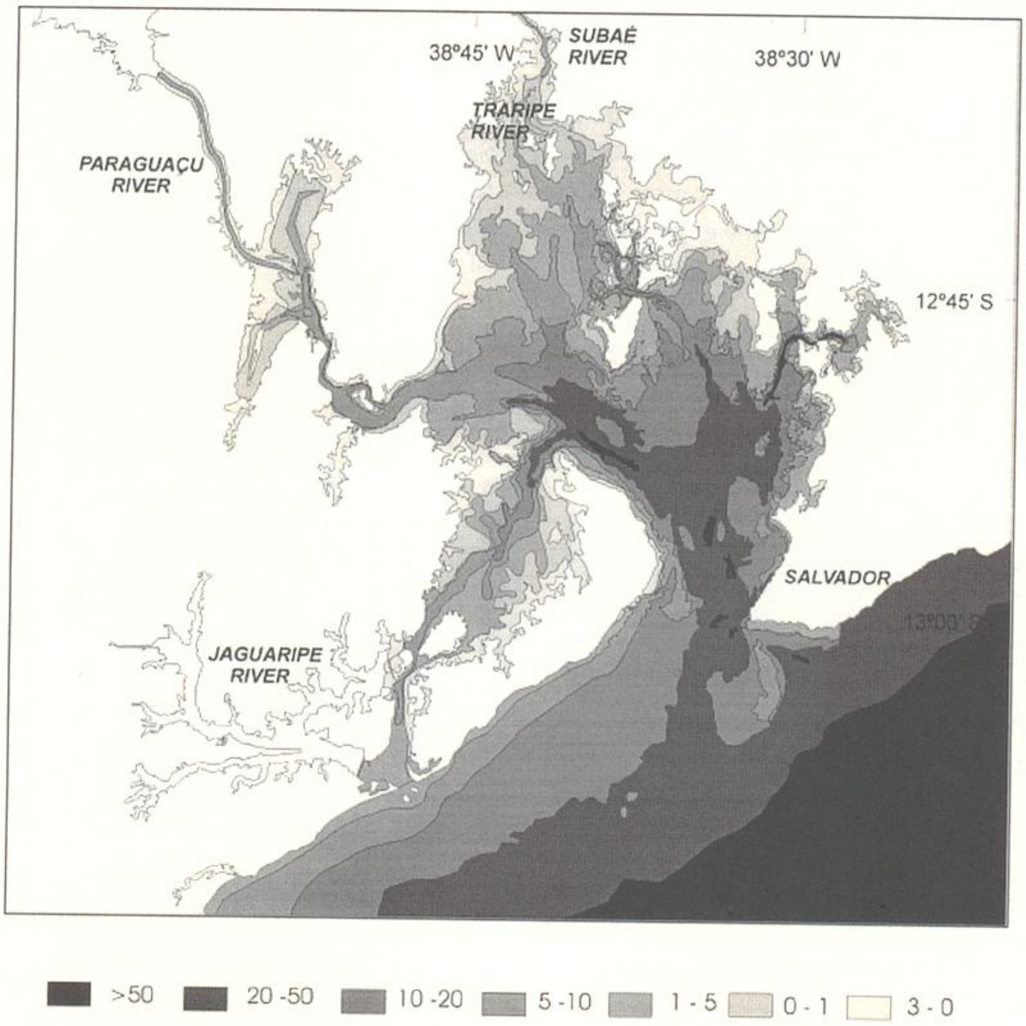

Figure 7 - Bathymetric map of the TSB that resulted from the interpolation of thousand of digitized depth soundings (depth in meters).

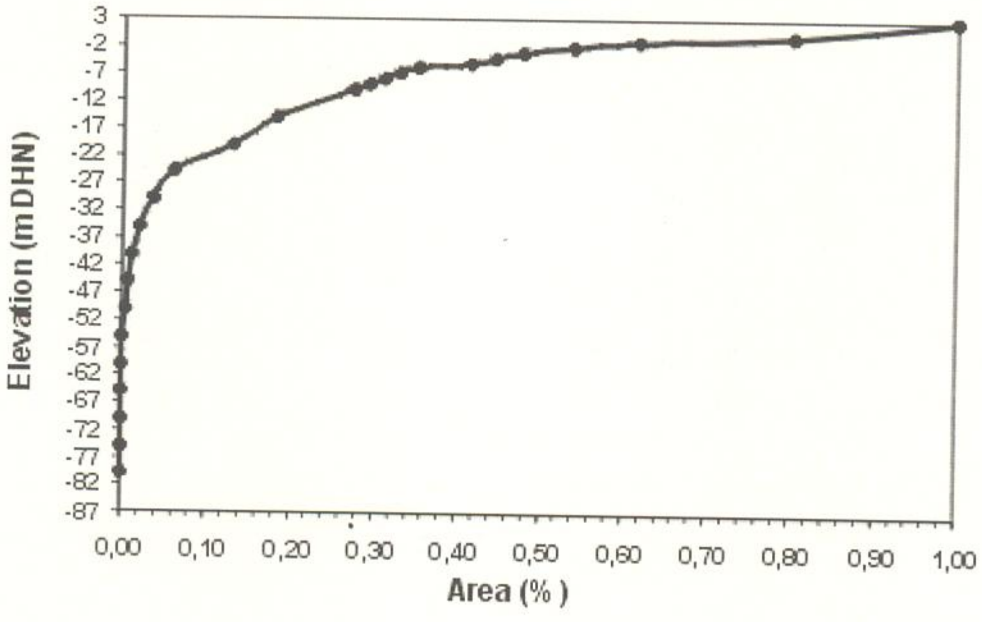

Figure 8 - Hypsometric curve of the TSB.

(Fig. 9). In fact, only station #4, close to Paraguaçu channel, presented a value smaller than the average (35 psu). Results from May show an overall reduction in the salt content, which attained an average of about 33 psu. During this monitoring period, outflow from Pedra do Cavalo was very small, just 11 m^3 s^{-1}. Hence, the dilution observed must be due the expected higher winter discharges from the smaller catchments.

The less systematic measurements made by Alves in the TSB show salinity minima of 27 psu close to Subaé River (northern most station in Fig. 3) and 28 psu close to the exit of Paraguaçu Channel (Fig. 3). Salt content in any other station was higher than that, topping up at 36 psu at the Paraguaçu Channel. These values show degrees of salt dilution during the winter of 1997 that are higher than those measured by CRA

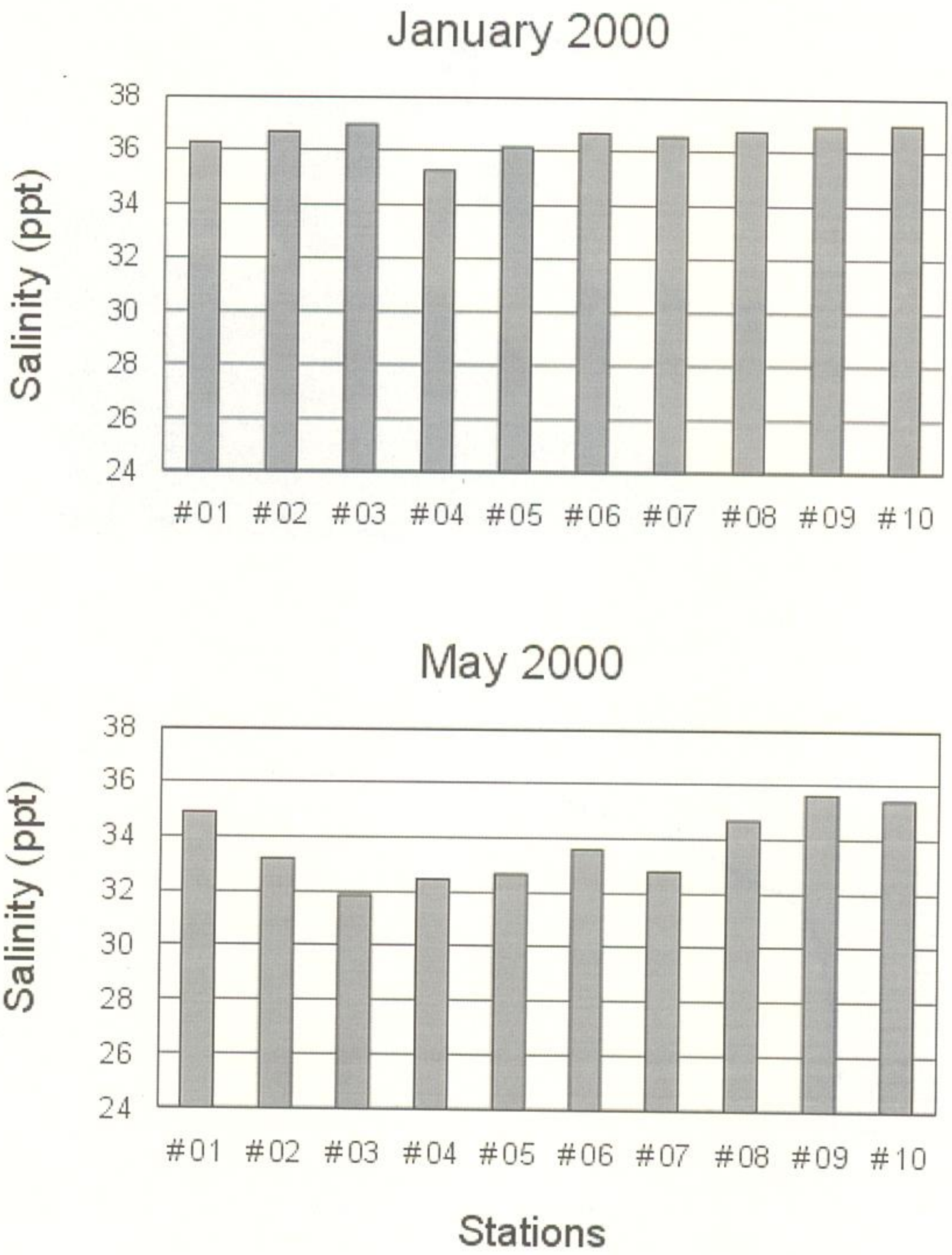

Figure 9 - Distribution of salinity values amongst CRA stations in January (dry season on the coast) and May (wet season on the coast) 2000 (see station's location in Fig. 3).

(2000). Well stratified water columns were also observed in this winter, as salinity differences between surface and bottom was below 1.3 psu. Only close to Paraguaçu Channel differences reached 2.7 psu.

Barreto (1993), when monitoring vertical salinity profiles in Paraguaçu Channel close to Iguape Bay, observed a minimum value of 28.2 psu coincident with a dam outflow of 13.8 m^3 s^{-1}. Prior to the dam, Moura (1979) and Wolgemuth *et al.* (1981) met fresh water 3 km upstream from Iguape Bay, coincident with a neap tide condition and river discharge of 36.9 m^3 s^{-1}. Under the same oceanographic conditions, salinity values along Paraguaçu Channel varied between 30 psu and 35 psu, pointing to a strong horizontal salinity gradient in the lower course of Paraguaçu River.

The distribution of the lowest salinity values measured in different sectors of the bay is shown in Fig. 10. Care must be taken not to interpret the map as the strongest salinity gradient one time observed, since measurements were not coincident. The map shows that salinity values below 35 psu have never been measured in the eastern half of the bay, and that brackish water (salt content < 25 psu) may be found only close to the major river outlets.

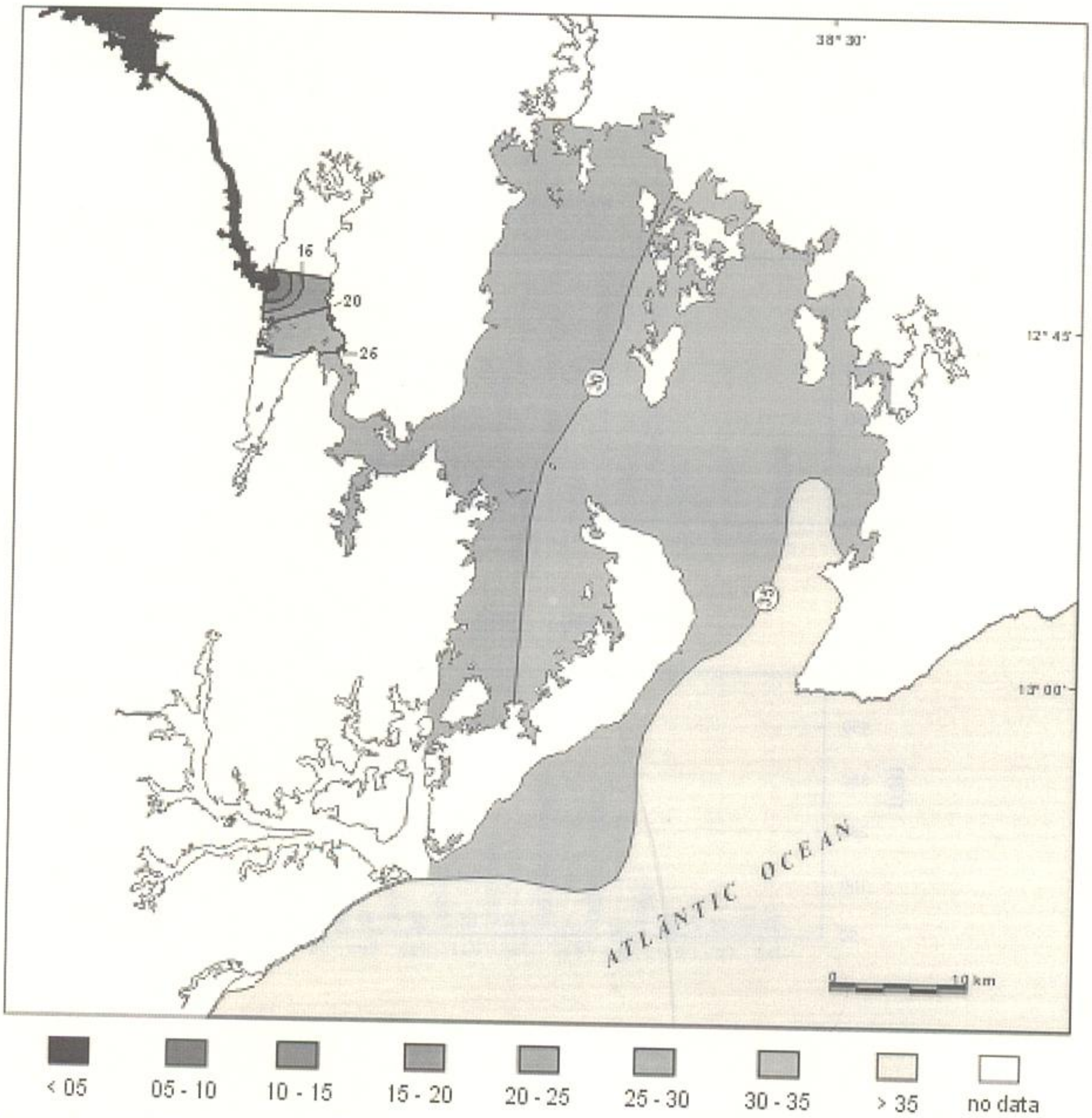

Figure 10 - Distribution of the lowest salinity values ever registered in the TSB (not coincidental). Salinity gradient observed in Iguape Bay refers to data published by Wolgetmuth *et al.* (1981) before the construction of Pedra do Cavalo Dam.

DISCUSSION AND CONCLUSION

With an intertidal area and volume that corresponds to 19 % and 27 % of the total, respectively, besides very shallow depths, mixing of the water column appears to be effective throughout the year. Maximum reported salinity difference between surface and bottom waters was 2.7 psu during fall (Moura, 1979, Wolgemuth, 1981). Horizontal gradients are also quite small, with salinity in the central bay area oscillating between 33 psu e 36 psu in the winter and summer, respectively.

The effects of the river discharges are only locally noticed, given that the discharge rate are rather small in comparison with the tidal discharge through Salvador and Itaparica Channels. Knowing that the tidal prism must be exchanged in half tidal cycle, tidal discharges through Salvador and Itaparica channels are expected to be 1.50 x 10^5 $m^3 s^{-1}$ and 1.30 x 10^5 m^3 s^{-1}, under maximum (3 m range) and average (2.7 m range) spring high tides, respectively. Calculated mean surface freshwater discharge to the TSB (111.10 m^3 s^{-1}) is therefore 0.08% of the average spring tidal prism. This value rises to just about 1.6 % if average maximum discharges, from all catchments, are considered to occur simultaneously.

In addition to the diffuse discharges around the bay, one also must take into account the direct fresh water input as rainfall. A 30 year mean rainfall for the bay area is about 1,900 mm/year, which multiplied by the bay area gives a total volume of approximately 2.4 x 10^9 m^3/year (rainfall gradients over the bay are not taken into account). A 30 year mean evaporation, estimated from Fig. 11, is 1,200 mm/year, which results in a loss of about 1.52 x 10^9 m^3/year. If the net volume (888 x 10^6 m^3/year) is evenly distributed along the year, average discharge of meteoric water would be 28.17 $m^3 s^{-1}$, about the same

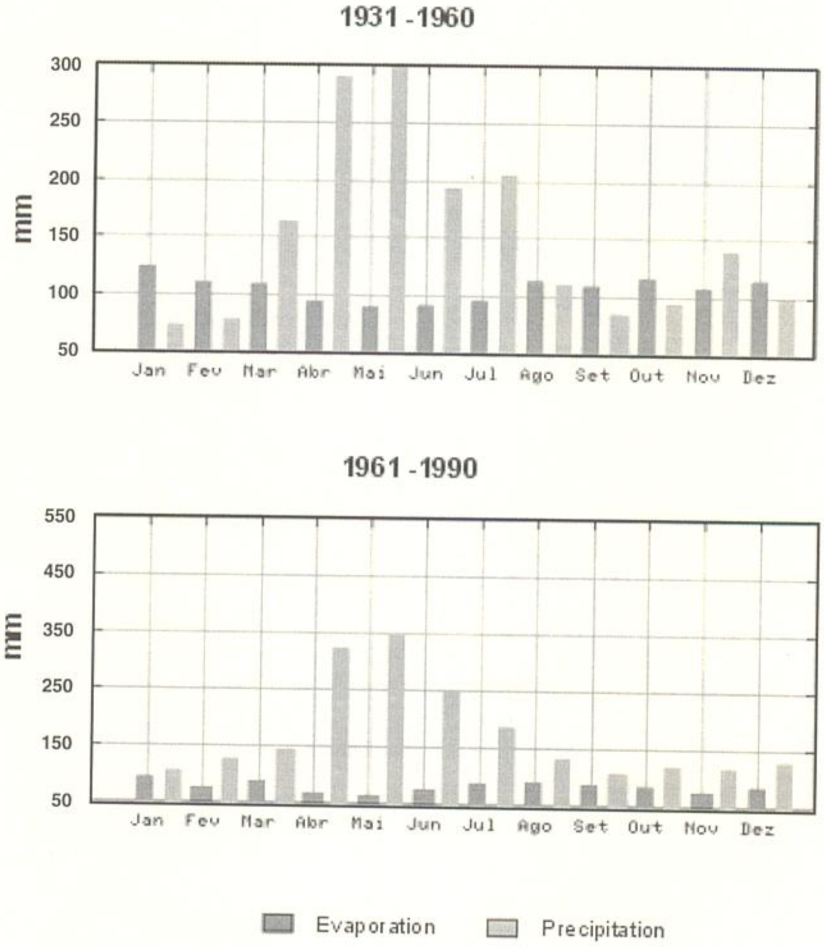

Figure 11 - Distribution of month average precipitation and evaporation for time periods: 1931-1960 and 1961-1990 in Salvador. (Source: Instituto Nacional de Meteorologia) – http://www.inmet.gov.br/climato/grafclim.htm)

amount of the estimated discharge of the peripheral catchments, and would increase the total mean surface fresh water discharge to the bay to 139.3 m^3 s^{-1}. However, rainfall and evaporation are not evenly distributed along the year (Fig. 11). If we consider only the wet season (March-July), when evaporation is low and precipitation is high, the net volume of meteoric water received by the bay would be 996 x 10^6 m^3, with an ensuing average discharge of 96.06 m^3 s^{-1}. This is more than half of the average discharge from all catchments (55.05 m^3 s^{-1}) in the same period.

Total river discharge was reduced after Pedra do Cavalo dam by an average 45.9 $m^3 s^{-1}$ (or 42.7 %), which is a fraction smaller than that reported by Mestrinho (1998). Besides causing an invasion of the lower river course by brackish water (mangrove vegetation is now close to the dam), this must have caused some slight increase in the salinity of the the TSB. To assess whether this hypothesis is sound, we can estimate the fresh-water volume needed to reduce the average salinity in the central part of the bay from 36 psu in the summer to 32 psu in the fall, or within a period of three months that separates the dry and wet season. To reduce this 4 psu in salinity, about 12.5% of the original water volume must have to be added. The water volume in the central section of the bay is approximately 817 x 10^6 m^3, and 12,5% of this equals 102 x 10^6 m^3. This volume corresponds to an average discharge of approximately 13 m^3 s^{-1} in three months, which is in the same order of magnitude of the discharge stolen from Paraguaçu River. The above mentioned dilution occurred at a time when Paraguaçu River had very small discharges, which averaged 11 m^3 s^{-1}. Therefore, the salinity decrease must have been caused by the discharge of all other smaller catchments and, more important, the rainfall.

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