

LONGITUDINAL SUSPENDED SEDIMENTS TRANSPORT IN THE JAGUARIBE RIVER ESTUARY, BRAZIL

Transporte longitudinal de sedimentos em suspensão no
estuário do Rio Jaguaribe, Brasil

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ABSTRACT

The Jaguaribe River estuary lies in a region characterized by climatic irregularities, inserted in semi-arid terrains. These storms associated with climatic and anthropogenic processes entailed by a barrage construction, shrimp farms, mangrove deforestation and the use and occupation of margins, caused significant changes in the processes of erosion, transport and deposition. These facts gave rise to economic losses and environmental impacts through the siltation of tidal channels and the less condition for navigability. Thus, it is important to know the mechanism of sediment production in order to contribute to the sustainable management of the activities to be developed. The study aimed to analyze the longitudinal transport of sediment in the river estuary based on data collection in situ through parameters of the hydrodynamic, morphodynamic and sedimentological conditions. Samples were collected in two tidal cycles (high/low tide). The analysis of longitudinal profile revealed retention of sediments in the estuary during the rainy season. The fine material comes from the suspended loads from the inside of the basin and the contribution of the sandy-mud sediments of the Barrier Formation which borders the west bank of the estuary.

Key words: sediment transport, estuary, Jaguaribe River.

RESUMO

O estuário do rio Jaguaribe está inserido em uma região caracterizada por irregularidades pluviométricas, características de regiões semi-áridas. Essas intempéries climatológicas associadas aos processos geogênicos e antropogênicos, como a construção de barramentos, fazendas de camarão, desmatamento de mangues e o uso e ocupação das margens, têm provocado alterações significativas nos processos de erosão, transporte e deposição. Isto leva a perdas econômicas e ambientais, representadas pelo assoreamento de canais de maré, dificultando a navegabilidade. Assim, torna-se importante o conhecimento do mecanismo de produção de sedimentos, a fim de contribuir com a gestão e manejo sustentável das atividades que ali se desenvolvem. O trabalho teve por objetivo analisar o transporte longitudinal de sedimentos no estuário do rio Jaguaribe com base na coleta de dados in situ dos parâmetros hidrodinâmicos, morfodinâmicos e sedimentológicos. As coletas foram realizadas em dois ciclos de maré (enchente/vazante). A análise do perfil longitudinal mostrou uma retenção de sedimentos na foz no período de chuva. O material fino é oriundo das cargas em suspensão do interior da bacia e da contribuição dos sedimentos argilo-arenosos da Formação Barreiras, que bordeja a margem oeste do estuário.

Palavras-chaves: transporte de sedimentos, estuário, Rio Jaguaribe.

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INTRODUCTION

Estuaries are corridors for the transition of sediments from rivers to the sea. This action depends directly on the mechanism of erosion, transport and deposition of sediments, which becomes an important component in the control of estuarine processes. The transport of suspended sediment is an important indicator of changes entailed by natural and anthropogenic processes, which leads to changes in marine and fluvial energy cycles. These cycles of energy are responsible for suspended sediments distribution and concentration. In semi-arid regions case studies, such as the estuary of the Jaguaribe River, the energy variations and the result of climatic changes together with anthropogenic actions, encompassing construction of dams, shrimp farms, deforestation, agriculture, tourism, margins use and occupation. This has a direct impact on transport patterns and sedimentation of estuaries. The sediment transport down the rivers is generally a heterogeneous mixture reflecting the variety of grain sizes available source within the catchment (Dyer, 1995). The deposition is the product of the relationship between the types of materials (clay, silt and sand) transported and the energy of the environment.

Upstream the estuary is located a wet passage or small dam in Itaíçaba town that amended the solid and liquid discharges into the system. Therefore, the load of suspended sediments is smaller and redistribution of this material depends upon the marine processes. Studies carried out by Marins *et al.* (2003) indicate that its effects accounted for the migration of mangrove forests and the replacement of local species by marine species. In dry periods, it has been observed the process of seawater intrusion along the estuary, which causes high salinities up to 28 km from the mouth, invading the fluvial plains, meadow areas and damaging indigenous crops (Morais *et al.*, 2009). Therefore, such actions have resulted in economic and environmental losses represented by the siltation of tidal channels and loss of navigability in some parts of the estuary taken by sandbanks that rise during low tide period. The knowledge of transport

dynamics of suspended sediments can help to understand the distribution of pollutants along the estuary, and to identify areas of maximum turbidity, usually associated with areas of environmental significance, and areas of sediment production. This study sought to analyze the transport of sediments throughout the estuary in different seasons.

STUDY AREA

The Jaguaribe River runs 610 km from its source at Joaninha Hill (Tauá - Ceará) down to its mouth in Fortim-Ceará. This river is located within the Northeast Atlantic Hydrographic Region, the area corresponding to the lower course spanning Fortim, Aracati and Itaíçaba cities (Figure 1). The estuary is 36 km in length and occupies an area of approximately 641.216 km², being physically limited landward by the Itaíçaba dam. From there, the Workman Channel, a 100 km channelization structure that carries freshwater to Fortaleza giving rise to *hydrografic basins water transposition projects* in the Ceará State.

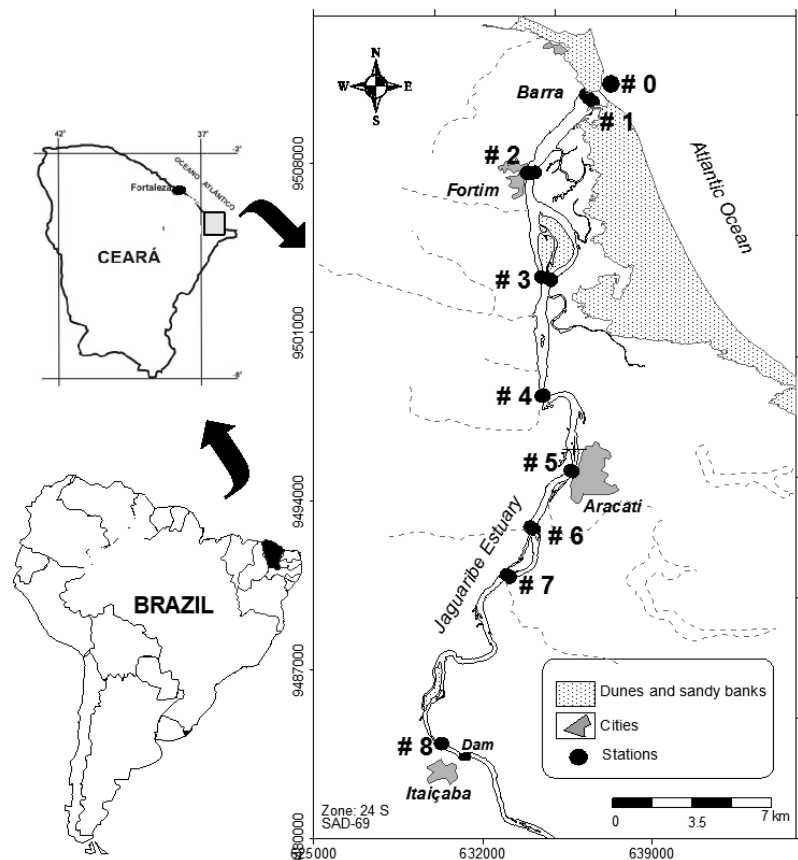


Figure 1 - Map of the study area.

The local geology comprises the Barreiras Formation Plio-pleistocene sediments, fluvio-marine plains, wind sediment deposits and Holocenic beaches (Paula, 2006). The presence of urbanization, trade and harboring activities spreads all over its margins. A 284 km² mangroves area is undergoing great environmental pressure (Meireles *et al.*, 2004).

The annual average rainfall over the last 30 years is 904.26 mm in Aracati (FUNCEME, 2009) from which 93% are concentrated from March to June period. Evaporation values are also quite high, reaching annually 180.00 mm, with maximum values from August to November, and the lowest from February to May. The medium temperature values varies from 25.7°C (June) up to 28°C (December). There is a real tendency towards a negative water balance in the estuary system under normal conditions. The predominant wind direction is from East over a SE-NW coastline alignment, which favors sediment bypass that leads to dunes and bars formation. There is an increasing wind speed from July to November, reaching higher values in September and October (7–11 m.s⁻¹), and gradually declining to May (3.5 m.s⁻¹). In dry seasons the strong winds allows mangrove silting, estuary mouth and channel drifting. (Morais *et al.*, 2008). The estuary has semidiurnal and symmetrical tidal regime with average period of 12.4 h and average discrepancy of 50 minutes (Pinheiro & Morais, 1999; Paula, 2006), characterized by two high tides and two low tides in a whole tide cycle. In this same season, the study area is dominated exclusively by marine action, classified as vertically well mixed with longitudinal stratification. On the other hand, in the rainy period is partially mixed with weak stratification and prevalence of advection in mixture processes (Morais *et al.*, 2005; Morais *et al.*, 2009, *in press*). The main economic activities in this estuary are fisheries, shrimp farm and tourism.

METHODOLOGY

Two legs were carried out during ebb and flood flows conditions spring tide at the rainy (July/2004) and dry seasons (September/03). The current measurement intensity and directions and flow water of the vertical profiles were conducted in the middle of the estuarine channel, in the eight stations in its longitudinal axis (Figure 01). In addition, details of the estuarine hydrological information's were used according to Morais *et al.*, (2005). The current intensify and directions were recorded with a SENSORDATA-SD 6000 and a Mini STD-3000 was used for the hydrological data

recorded. The material samplings in suspension were only performed in the ebb and flood tide cycles, as there is a strong relationship among current speeds, transport and concentrations of total suspended solids in these cycles (Dyer & New, 1986; Fernandes, 2001). It has been determined by gravimetry. The cross-section area was obtained and rectified with an echo-sounding and water level data. The daily water flow in Itaíçaba dam was taking from stored data at COGERH (Hydro Resources Management Company).

Fifty samples collect in the inner estuary have been used for textural characteristics of the bottom sediments and its possible interchange in the water column. In each station, three samples (margins and mid-channel) were collected with Van-Veen. There was one exception, in station 8, just one sample was collected due to the local morphology. The samples were mechanically analyzed using sieving and pipette techniques.

The water flow (Q) has been worked out in each section, as the product of the section of the area by the mean current velocity of the water column perpendicular to the cross-section (u) (Medeiros & Kjerve, 1986; Pereira Filho *et al.*, 2001; Schettini *et al.*, 1998, 2002; Miranda *et al.*, 2002). If it is considered that the Jaguaribe estuary is laterally homogenous and to obtain the suspended sediment transport ($C = T \cdot \text{dia}^{-1}$) the values should be correspondent to the product of the water flow by sediment concentration (c) in mg.l⁻¹ (Dyer, 1995; Miranda *et al.*, 2002).

In addition to reaching the calculation of the sedimentation estuary – ocean, there has been taken the imported and exported segmented balance hich is very important to sectors and processes that favor the sediment greater retention rate in the inner system. The bottom sediment was divided considering the textural point of view and sedimentary facies aiming to the identification of its origin.

RESULTS AND DISCUSSION

Hydrodynamic characteristics

The estuary current system presented considerable variability in relation to intensity, with minimum speed of 0.1 m.s⁻¹ and maximum of 0.61 m.s⁻¹ in the dry period. The speeds in this period indicated that the highest averages were observed among the stations 0 and 3 at the estuary mouth. The bottom speeds were greater than those at the surface in almost all sections with maximum variation of 0.06 m.s⁻¹ and minimum of 0.01 m.s⁻¹.

In the flood cycle, speed varied from 0.20 m.s⁻¹ to 0.57 m.s⁻¹, with the highest average in the water

column among all of the cycles being 0.388 m.s^{-1} . The highest speeds were recorded in stations 0 and 1 (0.57 m.s^{-1}), while in stations 4, 6, 7 and 8 current speed lessened of 61.5 % was observed. This reduction may be attributed to two factors: first, the storm silting process that causes shallower depths and, second, due to the estuary channel width decreasing. These factors consequently provided greater friction between the bottom and the mass of salt water that penetrates the estuary, reducing the effect of the tide in this area. In the ebb tide cycle, speed varied from 0.21 to 0.60 m.s^{-1} with an average of 0.39 m.s^{-1} . The highest speeds were recorded at stations 0 and 1 (0.61 m.s^{-1}). Furthermore, from section 3 to 8 an average reduction of 61.3% was found in the intensity of currents (Figure 2).

In the rainy period, current speed varied from 0 m.s^{-1} to 0.85 m.s^{-1} , with small vertical beddings. During the flood cycle, average speed varied from 0.08 m.s^{-1} to 0.60 m.s^{-1} , recording the highest average in all cycles, 0.33 m.s^{-1} . Greatest speeds were registered at stations 5 (0.40 m.s^{-1}) and 6 (0.60 m.s^{-1}). In this cycle, a reduction of 55% was observed in the intensity of the currents at station 7 in relation to the previous station. In the ebb tide cycle, average speed varied from 0.17 to 0.47 m.s^{-1} with a mean of 0.31 m.s^{-1} . The highest speeds were recorded at stations 0 and 1 (0.475 m.s^{-1}). It has been found differently when considering stations 3 to 8 that showed an average reduction of 41%. The difference in current intensity reduction between the two cycles was 12.5%, which very significant.

Bottom Sediment Characteristics

The estuary is predominantly formed by sediments of sandy texture (Figure 3). At stations 0 and 1, located close to the mouth, estuary substratum was formed predominantly by medium-grain sand. This section of the estuary is dominated by wave action that propitiates a higher energy level, preventing deposition of the finer fractions.

Stations 2, 3 and 4 were characterized by the presence of sandbanks at the west margin, originating from the degradation of the Barrier Formation hillside, medium-grain sand in the river channel and silt on the east swamp bank that presupposes mud or mud-sandy materials that could be explained by mangroves covered by dune field sediments. Due to decreasing transport capacity of the river and degradation of its margins due to shrimp farming, there is a predominance of coarse sediments in the rest of the stations.

Unstable sandbanks are concentrated at the estuary mouth between Aracati and Fortim counties. The depositional pattern of the estuary presented three different areas: the first one concentrates at the mouth and presents sandy sediments and a high energy level; the second area corresponds to the section that includes stations 2 to 4 and presents sandy mud and silty sand from 5 to 7 stations.

This sediment distribution qualifies the estuary as predominantly sandy, with domains of fine sediments (silt) close to mangroves and areas of low energy (I). The largest concentrations of sand occupy the areas of greater marine influence, being prolonged in the main channel within the estuary. The estuary could be considered into the ternary diagram Pjerup (1988) a very high hydrodynamic environment (IV).

In this study, the presence of clay was not identified. This may be explained by the construction

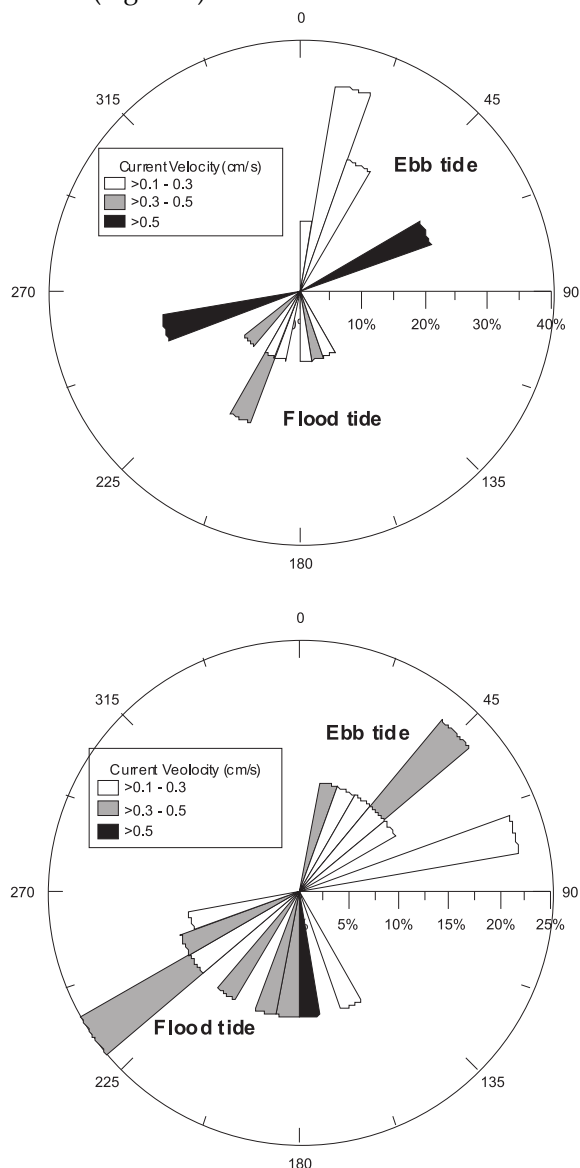


Figure 2 - Direction and intensity of estuary currents during spring tide in dry and rainy periods.

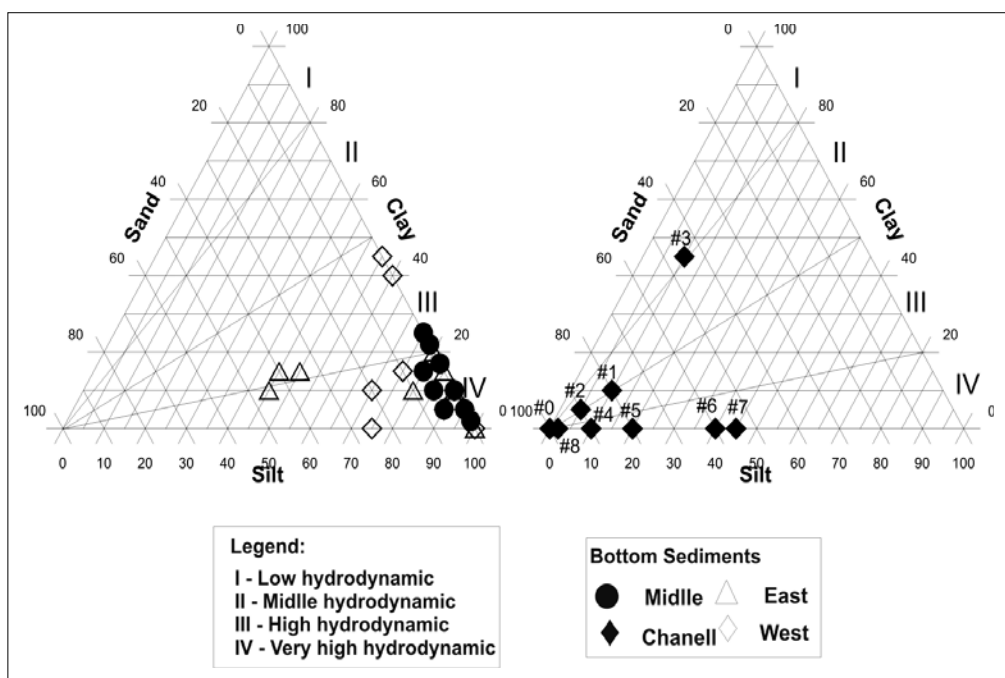


Figure 3 – Jaguaribe estuarie sand, silt and clay distribution as demonstrated by ternary diagram Pjerup (1988).

of dams upstream, which reduces solid discharges, subordinating the sedimentary dynamics of the estuary to the sea and wind action (Figure 3).

Sediment Transport

The circulation of sediments in an estuary is therefore a cyclical process, with bed erosion in the flood tide, deposition at high (full) tide, returning to erosion in the ebb tide and deposition at low tide (Dyer, 1995). The mass transport (total suspended solids), does not always occur in the same direction as the main flow of water, due to mixture processes (Kjerfve, 1986). Suspended sediment dispersal is better traced by means of clay mineralogy, since fine-grained sediments consist predominantly of clay minerals. Thus, it is commonly considered that variations in clay mineral associations allow one to identify sediment sources and transport pathways (Morais *et al.*, 2005).

The longitudinal distribution of SSC showed moderate behavior defined in relation to the estuary body, with larger concentrations close to the mouth, during the spring tide. Another well defined relationship of SSC involves salinity and temperature, as both showed similar variation, with higher values at the mouth and lower ones in the upper course (Whitehouse *et al.* (1960). In Jaguaribe estuary oceanic plume the suspended sediments are predominantly composed of clay minerals, with percentages of 38% smectite, 27% and 35% kaolinite to illite (Tintenolt, 1995).

In the dry period the highest concentrations of SSC were recorded in the flood tide, with a mean value of the longitudinal profile of 21 mg.l⁻¹. Among the stations 5 and 7 were found the highest concentrations, with maximum of 56 mg.l⁻¹ in season 6. In this sector, it is shallower sand-muddy ground, the effect of the tidal wave erosion of the substratum is more efficient, re-suspending the particles of finer sediments. In the ebb tide, the concentration of SSC was almost homogeneous throughout the estuary, with an average of 16 mg.l⁻¹. In the rainy period, the highest concentrations of SSC were found in the ebb tide, on average 44.0 mg.l⁻¹ with maximum and minimum values of 70 mg.l⁻¹ (station 4) and 28 mg.l⁻¹ (station 2) respectively. Between stations 3 and 4, the concentration of SSC tends to decrease with average values of 12.2 mg.l⁻¹. During flood tide, SSC tends to increase from station 4 to station 0 (mouth) due to the higher energy level of the currents in this section (Figure 4).

In the dry season the rate of import and export sediment to the ocean was 0.21 and 0.81 t.day⁻¹, respectively. In this case differently from what is expected for well mixed estuaries, the estuary exported sediment Jaguaribe. The dam of Itaiçaba contributed in this period with a rate of suspended sediment from 0.49 t.day⁻¹. In the longitudinal balance of sediments, it is observed that the sector between seasons 2 and 4 (between 10 and 19 km from the mouth) there is a tendency to retain sediment, with a positive rate of 0.85 t.day⁻¹. In this period the dam Itaiçaba contributed an average flow of 3.5 m³.s⁻¹.

Unlike what is expected in the rainy season and despite the high flow rates, the system showed a slight tendency for the importation of sediment represented by spatial stations 0 and 1 (mouth), with an average of 0.07 t.day^{-1} . The flow in Itaíba this period was $55 \text{ m}^3.\text{s}^{-1}$. The longitudinal profile in this period shows a condition sediment balance within the system and a small retention of material in the mouth and at station 07. Some material is muddy sediment in the southern sector, resulting from the failure in the load within the basin and the contribution of the

clayey-sandy sediments of the barriers which border the entire west bank of the estuary. To evaluate the increased flow of sediment in the middle estuary is important to undertake studies to assess in detail the contribution of the areas of disposal of effluent from shrimp farms throughout the estuary (Figure 5).

CONCLUSIONS

1. The highest current speeds were recorded at stations 0 to 4, because they correspond to a passage

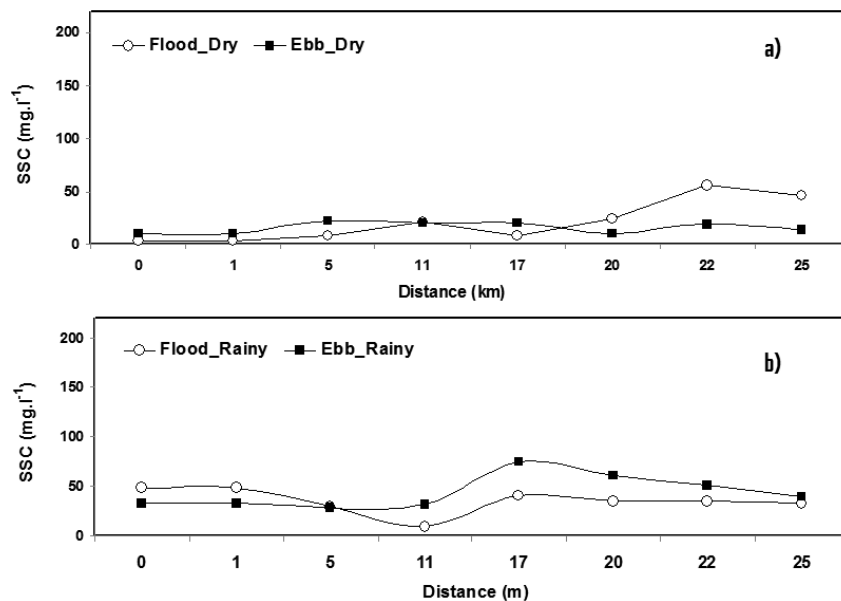


Figure 4 - Suspended solid concentration in longitudinal profile.

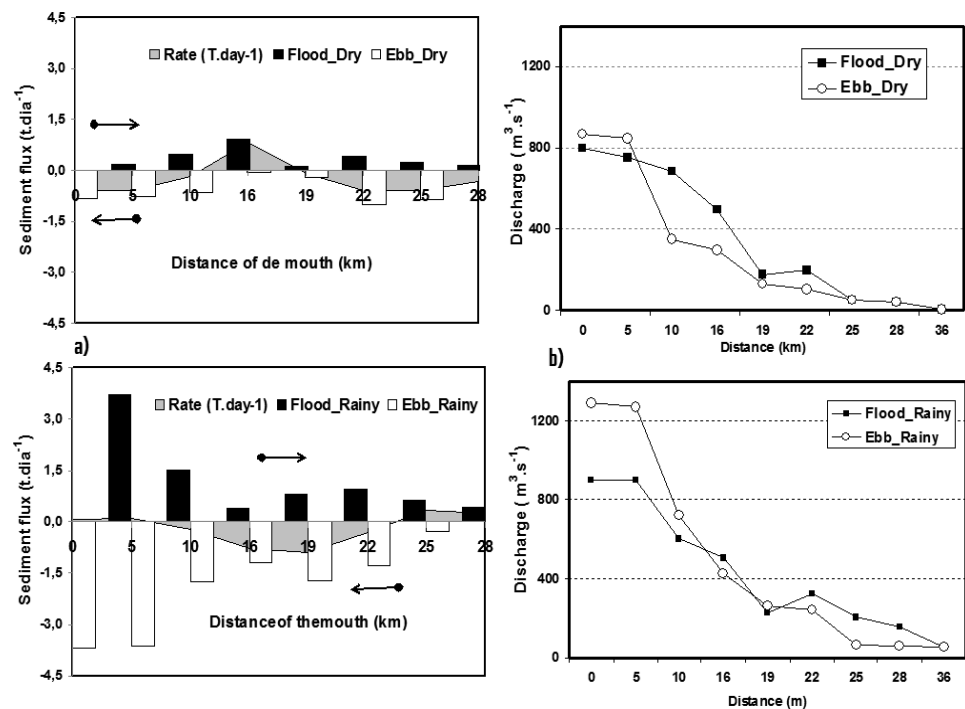


Figure 5 - (a) Suspended sediment transport; (b) liquid discharge in the longitudinal profile.

where the morphology of the channel propitiates greater circulation and lower bed friction, thus leading to higher speeds.

2. The estuary is predominantly formed by sediments of sandy texture. Bottom sediment textural characterization demonstrated that fine sediments were identified in deeper sections with low energy, usually close to the margins with the presence of mangroves, which are sheltered areas and with low agitation. The shallower, high-energy sections were characterized by the presence of sandy sediments.

3. SSC discharge balance indicates that, in the dry period, the tendency is the depositions happen to occur toward the river mouth, due to ebb tide discharge being greater than flood tide discharge. On the other hand, an inverse situation was displayed in the rainy period, favoring sediment accumulation, because flood discharges are higher than those of the ebb tide phase. There is a direct relationship between suspended concentrations of sediment and current speed, in that, as tide retreats, the particles in suspension are deposited at less agitated points.

4. The impact of the construction of dams along the Jaguaribe River is very active in both bottom and suspended sediment distribution in the estuary area. The estuary hydrodynamics is governed exclusively by marine influence in the dry period, altering SSC balance. Thus, in that period, the estuary behaves like an exporter, while the most lacking bar estuaries are importers.

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