



Fortnightly variability of total suspended solids and bottom sediments in a macrotidal estuarine complex on the Brazilian northern coast

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Abstract

Macrotidal estuaries are highly dynamic and complex environments that need to be understood in many aspects. In this context, the study of sediments is an important tool in the understanding of the processes in estuarine environments. The aim of the present study was to characterize the temporal and spatial distribution of total suspended solids (TSS) and bottom sediments of the Arraial Bay Estuarine Complex and their dynamics under different tidal conditions during different periods. Nine stations were selected within Arraial Bay Estuarine Complex, in Maranhense Gulf, where water samples were collected at two depths in different periods and tide conditions. The following parameters were analyzed: temperature, salinity, turbidity, total suspended solids (TSS), and bottom sediments for grain size analysis, in addition to cross sections to calculate the estuarine flow rate. Temperature, and pH, was within the expected range for the region, with little spatial or temporal variation. The precipitation and the hydrodynamics caused by tidal movements in the region are important controllers of salinity, estuarine flow, TSS and turbidity, which showed spatial and temporal variations. There is a predominance of fine material, mainly composed of silt, which suggests that mangroves are important in the supply and imprisonment of these sediments within the estuarine complex. In addition, tides play an important role in the distribution of suspended and bottom sediments, and in the dynamics of the resuspended one, controlling TSS concentrations and distributions of bottom sediments along the estuarine complex.

Keywords Estuary · Tide · Suspended solids · Grain size · Arraial Bay

1 Introduction

Estuaries are important regions regarding social, economic and environmental aspects. Estuarine regions are vulnerable water bodies, constantly subject to environmental variations of natural origin or even caused by human action (Eschrique

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2011). Environmental degradation may cause serious ecological, social and economic damage. Therefore, environmental monitoring is necessary to assist in decision-making in these areas, thus ensuring the integrity of the environment.

Among the tools used for the study and monitoring of estuaries are some physical, chemical, biological and geological variables, such as currents, physicochemical parameters, biodiversity and sediment dynamics. The sedimentological study allows the characterization and classification of the sediments, allowing inferences about their genesis, transport and deposition (Costa et al. 2010). Knowledge of sediment distribution is an important tool for understanding these processes.

The sediments that reach the estuaries can be deposited or transported by the currents, depending on the local hydrodynamic conditions. In macrotidal estuaries, tidal currents are of considerable importance when it comes to erosion, resuspension and deposition of sediments. In addition to tidal currents, waves also play a role in the transportation and maintenance of suspended sediments. Suspended sediments are an important component in studies of estuarine environments, since they carry adsorbed toxic substances, may limit the availability of light and photosynthesis, and cause sedimentation of port channels, which need to be dredged regularly (Park 2007).

The Arraial Bay Estuarine Complex (ABEC) is a macrotidal coastal environment, located southeast of the island of Maranhão. It is an environmentally sensitive and important area, once there is an extensive area of mangroves (de Menezes et al. 2008), and one of the most important rivers, which supplies a large part of the state capital São Luis, flows into that water body. Studies that aim the understanding of the sediment dynamics in estuaries have gained special attention, since these studies contribute to increase the knowledge on estuarine systems and their behavior regarding the distribution of sedimentary and physical characteristics.

Coastal environments such as estuaries have suffered major environmental impacts, mainly due to urban expansion (Purnachandra Rao et al. 2011; Rezende et al. 2010). Environmental degradation in these areas can cause serious ecological, social and economic damage. Thus, it is essential to understand the processes that occur in these environments, so that correct measures can be taken. Thus, the aim of the present study was to characterize the temporal and spatial distribution of total suspended solids (TSS) and bottom sediments of the Arraial Bay Estuarine Complex (ABEC) and their dynamics under different tidal conditions (Spring and neap tides) during different periods (Beginning and end of the rainy season).

2 Materials and methods

2.1 Study area

The present study was carried out in Arraial Bay Estuarine Complex (ABEC), located southeast of the island of Maranhão. Arraial Bay (AB) is one of the bays which forms a large and complex estuarine system known as Maranhense Gulf (Fig. 1). The estuarine complex comprises an area of about 23 km², including the Sampaio and Perizes rivers estuaries, and the Arraial Bay itself. The main access is by the highway BR135 that connects the Brazilian states of Maranhão and Minas Gerais. The Island of Maranhão, where the city of São Luis (capital of Maranhão) is located, occupies the central part of this estuarine system. The island is separated from the mainland by the Strait of Mosquitos that along with the Strait of Coqueiros connect the water masses of Arraial/São Jose Bay with those of São Marcos Bay.

ABEC is located in a region known as the macrotidal mangrove coast in the Amazon Region (Souza Filho 2005). The Maranhense Gulf has a semidiurnal tidal cycle, with a tidal height that can reach 7.2 m and current velocities of about 2 m.s⁻¹ (González-Gorbeña et al. 2015; Malheiro da Silva 2011; Samaritano et al. 2013). The climate is tropical humid, with two well-defined seasons: rainy season (December to July) and dry season (August to November).

The drainage basin is composed predominantly of low-relief groups (El-Robrini et al. 2006). Among the geomorphological features in the region are plateau, fluvial plain, mangroves and the Perizes field (Fsadu 2009). Regarding the type of soils, (de Alcântara 2004) observed in that area a predominance of soils of the class plintosols. In the Itapecuru River margin (São José/Arraial Bay), in the region of floodplain, known as Perizes Field, the tidal plain consists mainly of fine fraction (silt and clay), and it is basically colonized by mangroves. The mangroves in the study area are classified as *Rhizophora*-dominated “fringe forests”; however, the species composition may be very heterogenic (de Menezes et al. 2008).

Besides the environmental importance, the study area is a region that provides important resources for the local communities. Many people who live around the estuarine complex depend on this environment for their subsistence through fishing and other activities developed by those families. Therefore, the area is also socially and economically important.

Although the area of study is of relevant importance, environmental data about ABEC are still lacking, which makes it difficult to characterize the area in relation to some specific oceanographic variables. No studies were found on the morphological characterization of the channel

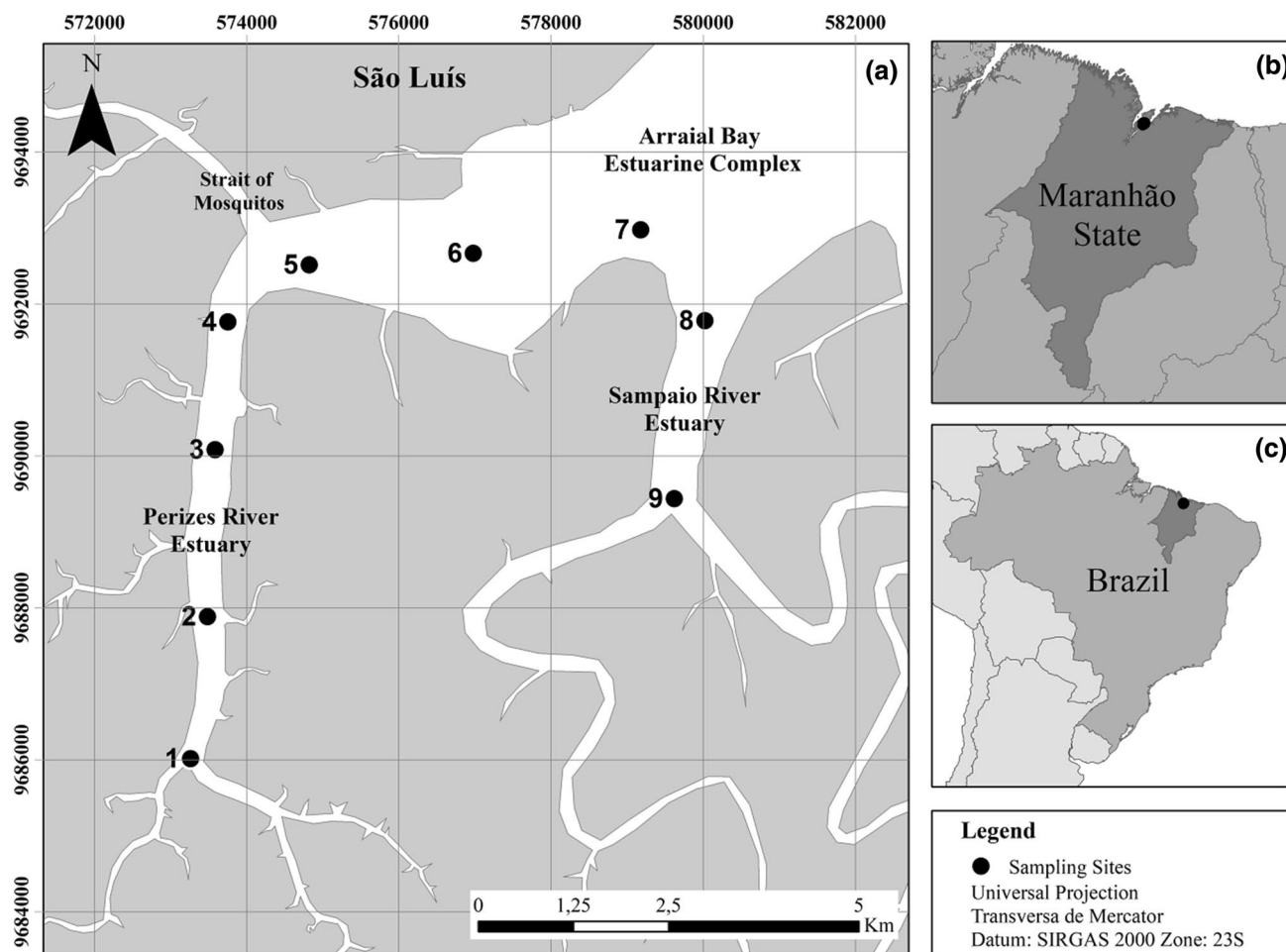


Fig. 1 Study area on the coast of Maranhão, Brazilian northern coast. Sampling stations (1–9) in Arraial Bay Estuarine Complex (ABEC), covering Perizes River Estuary (PRE), Sampaio River Estuary (SRE), and Arraial Bay. SMEC: São Marcos Bay Estuarine Complex

profiles. In addition, to date, no official study characterizing local bathymetry has been conducted.

2.2 Sampling and analysis

The water and sediment sampling were carried out in nine spatial stations in ABEC, covering the region of the Perizes River Estuary (PRE), Sampaio River estuary (SRE) and Arraial Bay (AB) (Table 1). Two campaigns were carried out (February and August 2015). For each campaign, two samplings were performed, one under spring tide and the other under neap tide conditions, totaling 4 samplings, being all of them carried out during ebb tide.

Samples of water and sediment were collected at each station. The water samples were collected with the aid of a *Van Dorn* bottle. After collection, the water was transferred to 500-ml polyethylene water bottles refrigerated at 2–5 °C until analysis. The bottom sediment samples were collected with a *Van Veen* grab sampler, homogenized, and stored in

plastic bags refrigerated at 2–5 °C until analysis. Salinity, temperature, pH, turbidity and TSS have been determined for two different depths (surface and bottom). Besides, volume transport and grain size data were also obtained.

The estuarine complex is relatively shallow. Local sampling depths were deeper in the rainy season, ranging from 3.0 to 28.0 m. During the dry season, the variation was between 2.0 and 23.0 m. Station 1 (located in PRE) had the lowest depths in both tides and in both periods. On the other hand, station 9 (Located in SRE) was always the deepest (Table 1).

Information about local rainfall was obtained from the National Institute of Meteorology (INMET), and information about the tide was provided by the Hydrographic and Navigation Department (DHN), for the tide gauge closest to Arraial Bay (MA), located in the Port Complex of Sao Luis.

The temperature and salinity parameters were analyzed in situ using a multiparameter Probe (Hanna HI-9828[®], Hanna Instruments Portugal Lda, Povoá de Varzim, POR)

Table 1 Stations, location, average depth, and sampling data of the selected stations in Arraial Bay estuarine complex (ABEC)

Station	Water body	Latitude (S)	Longitude (W)	Average depth (m)	Sampling
1	Perizes river estuary	2°50'00"	44°20'21"	2.7	Water; sediment; cross-section profile
2		2°49'35"	44°20'23"	3.6	Water; sediment; cross-section profile
3		2°49'18"	44°20'25"	4.4	Water; sediment; cross-section profile
4		2°48'12"	44°20'22"	4.8	Water; sediment; cross-section profile
5	Arraial bay	2°46'42"	44°19'58"	12.3	Water; sediment
6		2°46'28"	44°18'30"	3.3	Water; sediment
7		2°45'55"	44°16'51"	5.5	Water; sediment
8	Sampaio river estuary	2°47'57"	44°16'53"	11.0	Water; sediment; cross-section profile
9		2°47'51"	44°17'03"	23.5	Water; sediment; cross-section profile

with accuracy of $\pm 2\%$, and the turbidity was determined using a turbidimeter (Model TECNOPON TB-1000, Piracicaba, SP, Brazil) previously calibrated. The salinity data obtained for this study were converted into g kg^{-1} according to the International Thermodynamic Equation of SeaWater2010- TEOS 10 (<http://www.teos-10.org/>). The total suspended solids (TSS) in the estuarine waters were determined by gravimetric measurement according to the methodologies described in Strickland and Parsons (1972) and (APHA 2005), and the results were expressed as mg L^{-1} .

Instantaneous volume transport or estuarine flow was obtained using a towed Acoustic Doppler Current Profile (ADCP-Sontek/YSI) with frequencies of 1.5 MHz in cross sections at the flow. The velocity vector was decomposed in relation to the Orthogonal Cartesian coordinate plane Oxy, according to de Miranda et al. (2002). After decomposition of the velocity vector, for each hour, the components were delimited by the *ith* depth of each point. The volume transport (T_v) or estuarine flow in the cross sections perpendicular to the mean flow in area $A = A(x, z)$ was calculated through the numerical integration of the equation, according to (de Miranda et al. 2002):

$$T_v = \iint_A \vec{v} \cdot \vec{n} dA,$$

where $\vec{v} = \vec{v}(x, z, t)$ is the velocity vector, \vec{n} is the versor normal to section A, t is the instantaneous time interval, x is the horizontal distance of the section, and z is the depth.

The grain size analysis was performed according to the method proposed by Suguio (1973) using the technique of sieving and pipetting. The data were expressed as percentage of grains per text class defined in the Wentworth scale and the analysis was done through the R *software*, using the *Rysgran* package (Gilbert et al. 2012). The Pejrup Diagram (Pejrup 1988) was used to classify the sediments according to their hydrodynamic conditions.

Statistical tests were carried out to determine if there was a difference between the two depths of collection (surface and bottom), between the different tidal conditions (spring and neap) and between the two sampling campaigns (Rainy and dry seasons) for each parameter. To do that, Student's *t* test was used to compare means. However, before using the *t* test, two other preliminary tests were required: the Shapiro–Wilk test (to test the normality of the data) and the F-test (to test the homogeneity of the variances). Once the normality and the homogeneity of the data were tested, it was possible to perform the *t*-test.

In addition, Pearson's correlation coefficient (Rousseau et al. 2018) was used to evaluate the relationship between the parameters measured. This statistical method aims to understand the relationship between two variables, where the values (Correlation Index) vary from -1 to 1 . All statistical tests were performed using R 3.4.2 *statistical software* (The R Development Core Team).

3 Results

3.1 Meteorological and hydrological characterization

3.1.1 Rainfall

According to the analysis of the historical average regarding rainfall, it is possible to identify two distinct periods: rainy season (December to July) and dry season (August to December) (Fig. 2). The first campaign was carried out in February 2015 and the second one in August 2015. When comparing the historical average with the monthly precipitation registered for 2015, it was observed that except for March and May, the monthly precipitation was below average.

Regarding the sampling periods, February had precipitation values well below the historical average for that month

Fig. 2 Monthly average rainfall (mm) from 1961 to 2014 compared to the monthly rainfall for the year of 2015. Information taken from the nearest station from the study area (São Luís meteorological station)

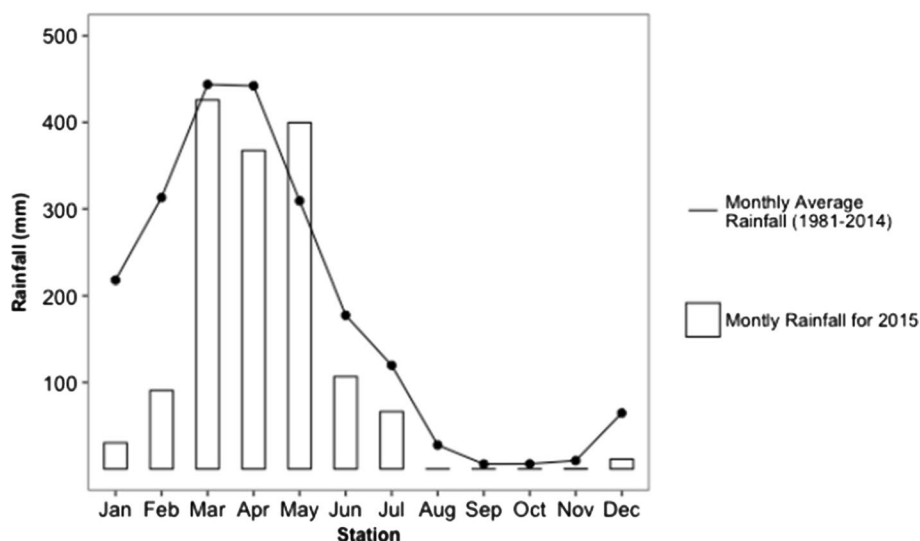


Table 2 Flow rates for February and August under different tidal conditions (spring and neap) in Arraial Bay Estuarine Complex (ABEC)

Station	February		August	
	Spring	Neap	Spring	Neap
	m^3s^{-1}			
1 Perizes river estuary	416.0	169.0	156.6	210.8
2	524.8	350.0	243.6	377.3
3	601.7	507.2	355.7	518.3
4	515.4	671.9	446.9	658.6
8 Sampaio river estuary	1799.2	633.8	2819.2	1005.1
9	378.7	1083.2	897.0	1224.9

(Fig. 2). According to the precipitation data, it rained 72.5% below the average. In August, it was also observed lower values compared to the historical average (Fig. 2), with rains 43% below the average. It is important to highlight that August is a transition month between the local rainy and dry seasons.

3.1.2 Volume transport

The flow rate values during the sampling campaigns for Perizes (PRE) and Sampaio (SRE) rivers estuaries are shown in Table 2. Considering the sampling campaigns, it is observed that the flow values registered in February were 20% lower than those observed in August. In August, the accumulated rainfall was higher in relation to the first campaign.

Regarding the tides, in February, during spring tide, the volume transport, per unit area, ranged from 378.7 to 1799.2 m^3s^{-1} , and during neap tide the variation was between 169.0 and 1083.2 m^3s^{-1} . Taking into account the minimum and maximum values between neap and spring

tides, it is observed that the flow rates under spring tide conditions were higher in 55% and 40%, respectively.

In August, during spring tide, the volume transport varied from 156.6 to 2819.2 m^3s^{-1} , and during neap tide, the variation was between 210.8 and 1224.9 m^3s^{-1} . Considering the minimum values between neap and spring tides, it is observed that during neap tide, the flow rates were 35% higher, and taking into account the maximum values, the flow rates during spring tide conditions were 57% higher.

Regarding the spatial distribution, the lowest flow rate values for both campaigns and both tide conditions were found in the stations located in PRE (Stations 1–4), in which during neap tide, flow rates ranged from 169.0 to 671.9 m^3s^{-1} , while in spring tide the variation was from 416 to 601.7 m^3s^{-1} . For SRE, flow rates varied between 633.8 and 1083.2 m^3s^{-1} during neap tide, and 378.7 and 1799.2 m^3s^{-1} during spring tide.

When comparing the average flows in both estuaries, it is observed that the flows in SRE were 47.2% higher in relation to PRE during spring tide, and 49.4%, during neap tide in February. Whereas, in August, the flows rate in SRE was 83.82% higher than the PRE, during spring tide and 60.43% during neap tide, in the dry season.

In PRE, during spring tide, the flow rates ranged from 156.6 to 446.9 m^3s^{-1} and during neap tide the variability was between 210.8 and 658.6 m^3s^{-1} . For SRE, during spring tide, the flow rates varied between 897 and 2819.2 m^3s^{-1} and during neap tide, the variation was between 1005.1 and 1224.9 m^3s^{-1} .

3.2 Physicochemical characterization

Table 3 summarizes the results obtained during the sampling periods, under different tidal conditions.

Table 3 Summary of the physicochemical parameters of the water collected in Arraial Bay Estuarine Complex (ABEC): Temperature (°C), Salinity (g kg⁻¹), pH, Turbidity (NTU) and TSS (mg L⁻¹). Min (minimum); Max (maximum); SD (Standard deviation)

Parameter		February		August	
		Spring	Neap	Spring	Neap
Temperature (°C)	Mean	30.5	31.3	29.2	29.7
	Min	29.8	30.9	28.4	29.0
	Max	31.0	31.7	29.8	30.4
	SD	0.4	0.2	0.4	0.3
Salinity (g kg ⁻¹)	Mean	31.8	31.2	26.3	18.7
	Min	31.0	31.1	26.1	18.2
	Max	32.5	31.4	26.6	19.4
	SD	0.3	0.1	0.2	0.4
pH	Mean	7.6	7.5	7.9	7.9
	Min	7.2	7.2	7.8	7.7
	Max	7.7	7.8	8.0	8.1
	SD	0.2	0.2	0.1	0.2
Turbidity (NTU)	Mean	484.4	33.5	540.5	212.4
	Min	16.5	14.7	11.8	15.6
	Max	2803.5	80.0	2662.0	2949.5
	SD	820.1	21.1	982.0	705.8
TSS (mg L ⁻¹)	Mean	368.3	133.9	276.2	152.7
	Min	81.2	47.3	39.7	24.3
	Max	1247.0	295.3	833.8	1037.3
	SD	332.2	74.6	307.6	235.8

3.2.1 Temperature, salinity and pH

Statistical analysis (*Student's t-test*) showed that there was no significant difference between the mean surface and bottom samples for temperature, salinity and pH. Thus, mean values between surface and the bottom for these parameters were considered for each tide condition, and for the different periods (Fig. 3).

In February, the temperature ranged from 29.8 °C to 31.0 °C (Fig. 3a). In August, the variation was from 28.4 °C to 30.4 °C (Fig. 3b). The *t-test* showed that there were no statistically significant differences ($p > 0.05$) when comparing the tidal conditions (spring and neap) and the two periods, characterizing the water temperature as typical of tropical regions.

Salinity varied significantly ($p < 0.05$) between the sampling campaigns, with lower values observed in August, mainly during neap tide (Fig. 3d). In February, the variation ranged from 31.0 to 32.5 g.kg⁻¹, showing no significant variation regardless of the depth or the tide conditions (Fig. 3c). In August, variations were larger, with values from 18.2 to 26.6 g.kg⁻¹. Unlike February, the *t-test* revealed a significant difference in the salinity mean values between neap and spring tides.

The pH values were, in general, slightly alkaline and also presented a small but significant variation between the means of the two periods (Fig. 3e and f). In February (Fig. 3e), pH ranged from 7.2 to 7.8, and there were no significant variations in the means between the depths or between the tide conditions. In August (Fig. 3f), the pH had a slight increase in relation to the first campaign, ranging from 7.7 to 8.1, and as in February, there was no significant variation between the sampling depths or between the tide conditions.

3.2.2 Turbidity and TSS

The turbidity values were higher in February (Fig. 4), mainly under spring tide (Fig. 4a and b). However, the means between the two sampling months (February and August) did not differ significantly ($p < 0.05$). In February, under spring tide, the turbidity varied between 16.5 and 2804.0 NTU. During neap tide (Fig. 4c and d), the turbidity values were lower when compared to spring tide, with values varying between 15.0 and 80.0 NTU. Regarding tide conditions, the means showed a significant difference. In August, during spring tide (Fig. 5a and b), the values fluctuated between 11.8 and 2662.0 NTU, and between 16 and 2949.5 NTU during neap tide (Fig. 5c and d). Likewise, during the first campaign (February), the highest values of turbidity were observed under spring tide condition.

Outliers were observed in some stations: bottom samples at the stations 2, 4, 5 and 8 during spring tide, in February; and the stations 2, 5 and 7 under neap tide in August. It is important to highlight that station 5 had values above 2000 NTU in both depths.

In February (Fig. 6), TSS ranged from 62.5 to 1247.0 mg.L⁻¹. In August (Fig. 7), the minimum TSS concentration was 39.7 mg.L⁻¹ and the maximum was 1037.3 mg.L⁻¹. Comparing the TSS means for the two sampling campaigns, the highest values were registered in February. However, the means did not vary significantly ($p < 0.05$) between the two periods.

Regarding tide conditions, the highest concentrations were always observed during spring tide, for both periods. In February, the variation in the TSS means between spring and neap tide was significant, unlike August, which did not present any variation between the means. When comparing the two depths, it was observed that the concentrations of the samples collected near the bottom were always higher comparing to the ones collected at the surface.

As well as turbidity, it was noticed that some stations showed some outliers regarding TSS concentrations. Station 2 had values above 1000 mg L⁻¹ on the bottom, for both periods, during spring tide, and in August under neap tide. Station 5, located in AB (Arraial Bay), also showed outliers during spring tides with values greater than 800 mg.L⁻¹.

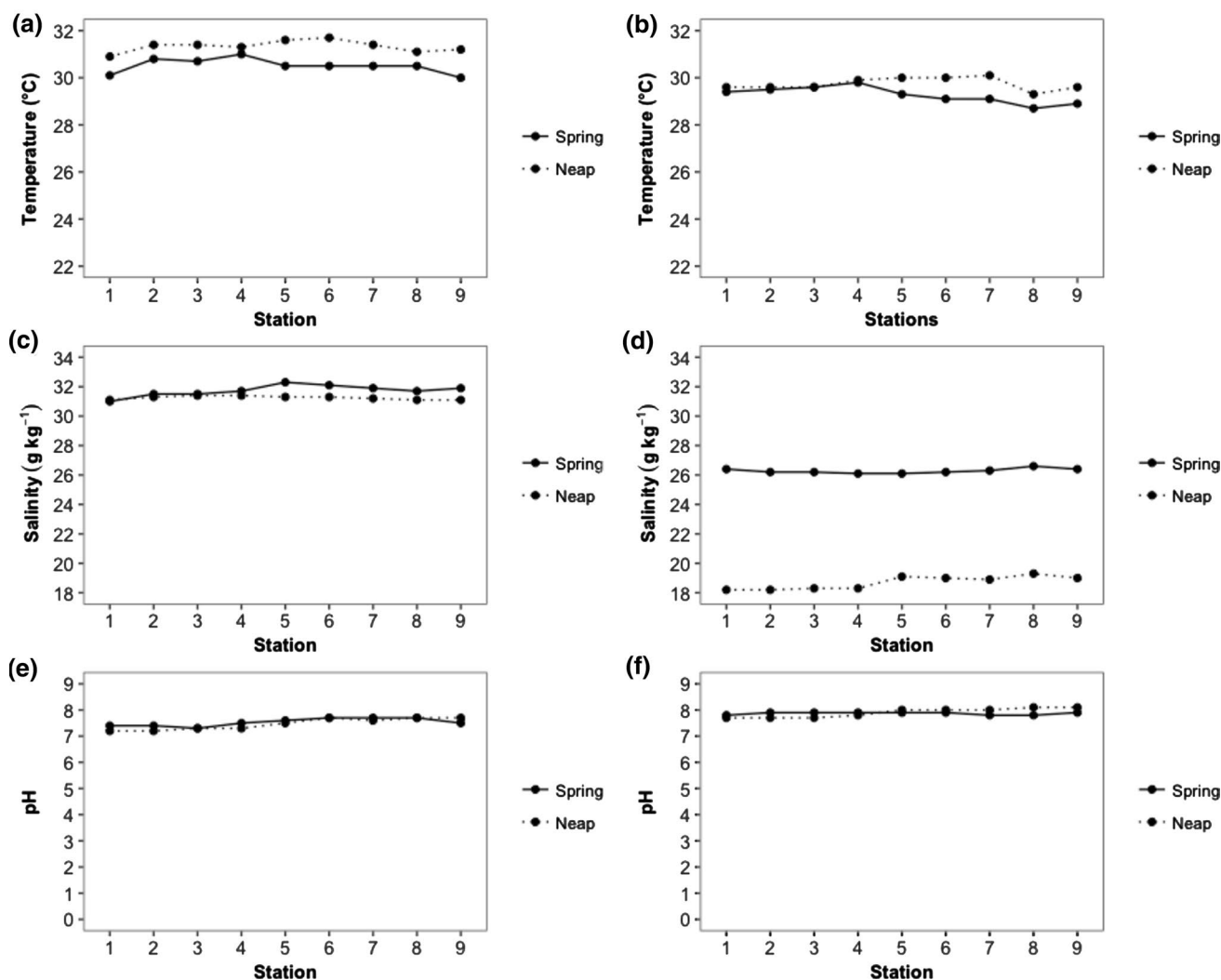


Fig. 3 Physicochemical parameters of the water collected in Arraial Bay Estuarine Complex (ABEC) under spring and neap tide conditions. First column (figures **a**, **c** and **a**): February; and the second column (figures **b**, **d** and **f**): August

3.3 Grain size characterization

The grain size analysis showed a predominance of fine sediments mainly composed of silt (clay being minor) (Fig. 8). In February, station 9 was the only one that presented a high percentage of sand (> 50%), under spring tide (Fig. 8a). The sediment sampled during the neap tide was rich in silt (> 80%) (Fig. 8b). In August (Fig. 8a and b), the only station that did not show a greater predominance of silt was station 5, which had a higher percentage of sand (95.77%). During neap tide, station 6 was the only one characterized by the predominance of sand (60.28%). The other stations showed a greater predominance of silt.

The results of the grain size analysis were plotted in the Pejrup diagram (Pejrup 1988) (Fig. 9). Initially, it is possible to observe that in both periods, under both tide conditions, the study area is characterized as a very high hydrodynamic

region, since all samples were grouped in area IV. However, spatial variations are observed as a result of the percentage of sand in the samples.

In February, during spring tide (Fig. 9a), the majority of the samples were within the group IV-C, which corresponds to the sediments that contain between 10 and 50% of sand, deposited under strong hydrodynamic conditions. During neap tide, in the same period, the majority of the samples were within the group IV-D, the group with samples that present smaller percentages of sand, but still deposited under strong hydrodynamics (Fig. 9b).

In August, most of the samples were concentrated in groups IV-C and IV-D, with one station (P5) classified in group IA, corresponding to the group with sand percentage between 90 and 100% deposited under low hydrodynamic conditions (Fig. 9c). During neap tide, the majority of samples were concentrated in group IV-D (Fig. 9d).

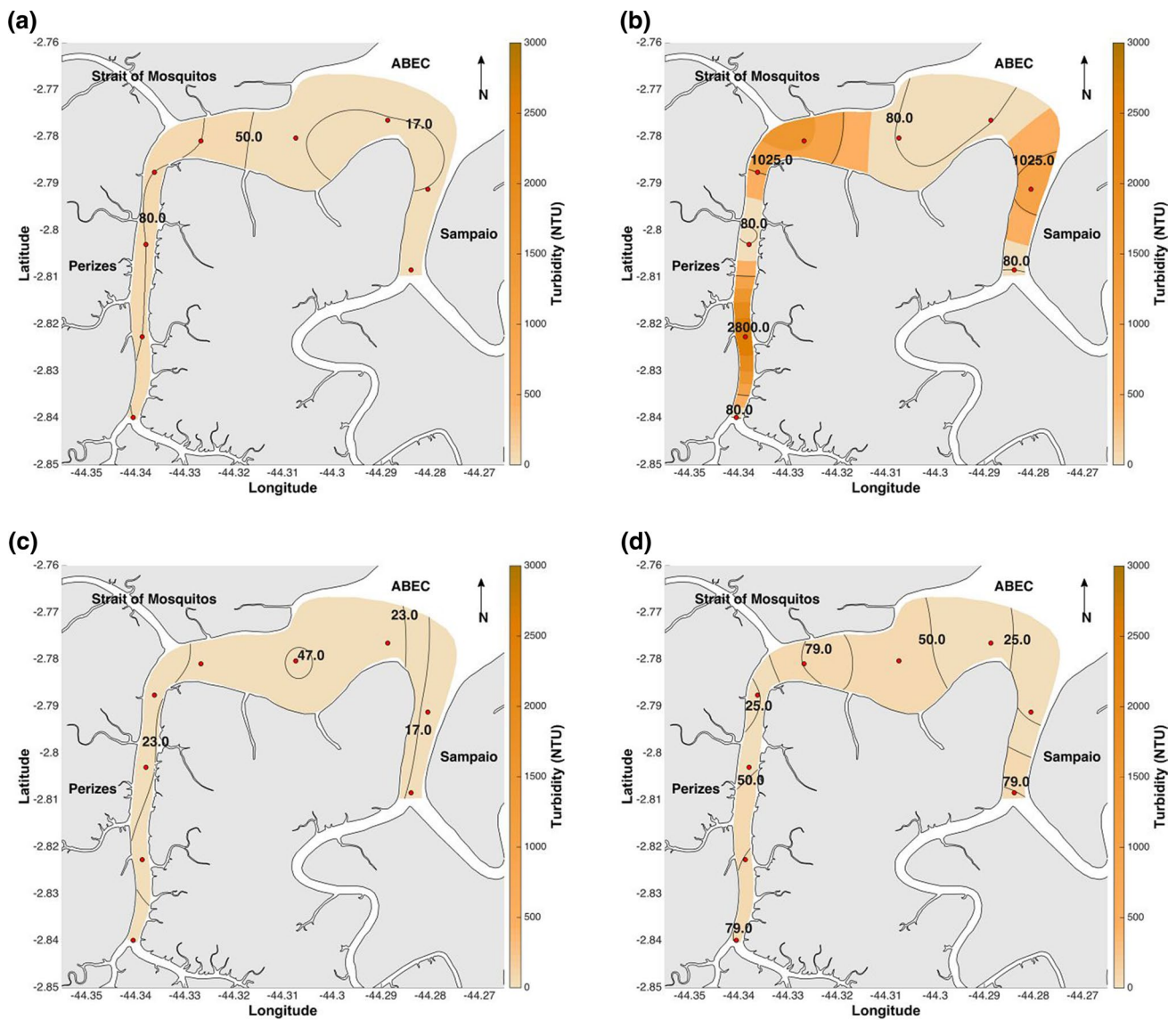


Fig. 4 Turbidity distribution in Arraial Bay Estuarine Complex (ABEC) in February. Spring tide: surface **a** and bottom **b**; and Neap tide: surface **c** and bottom **d**

4 Discussion

According to Infoclima (2015), in the Tropical Atlantic, sea surface temperature (SST) anomalies favored the southernmost position of the Intertropical Convergence Zone (ITCZ), but the weaker trade winds resulted in a weak performance of this system, which contributed to the rainfall deficit in most of the Northeast region.

The absence of events of the South Atlantic Convergence Zone (SACZ) contributed to the rainfall deficit in most of Brazil. The atmospheric blockade in the southeastern region of Brazil prevented a regular formation of atmospheric systems, important for the maintenance of the rainfall pattern in several regions of the country at this time of the year

(Infoclima 2015). The rainfall registered in this period is associated with the occurrence of High Level Cyclonic Vortices (VCAN) in the high troposphere, associated with the ITCZ (Nugeo 2015). The establishment of the *El Niño*-Southern Oscillation (ENSO) phenomenon and the low occurrence of Easterly waves disturbances were the main responsible for below-average rainfall in Maranhão. In addition, the ITCZ began to act north of its climatological position, accentuating the rainfall deficit in the north of the Northeast Region (Infoclima 2015).

Differences in flow values between campaigns are related to higher or lower rainfall rates. The correlation analysis indicated that the main factor contributing to the increase in volume transport was rainfall, since both presented a

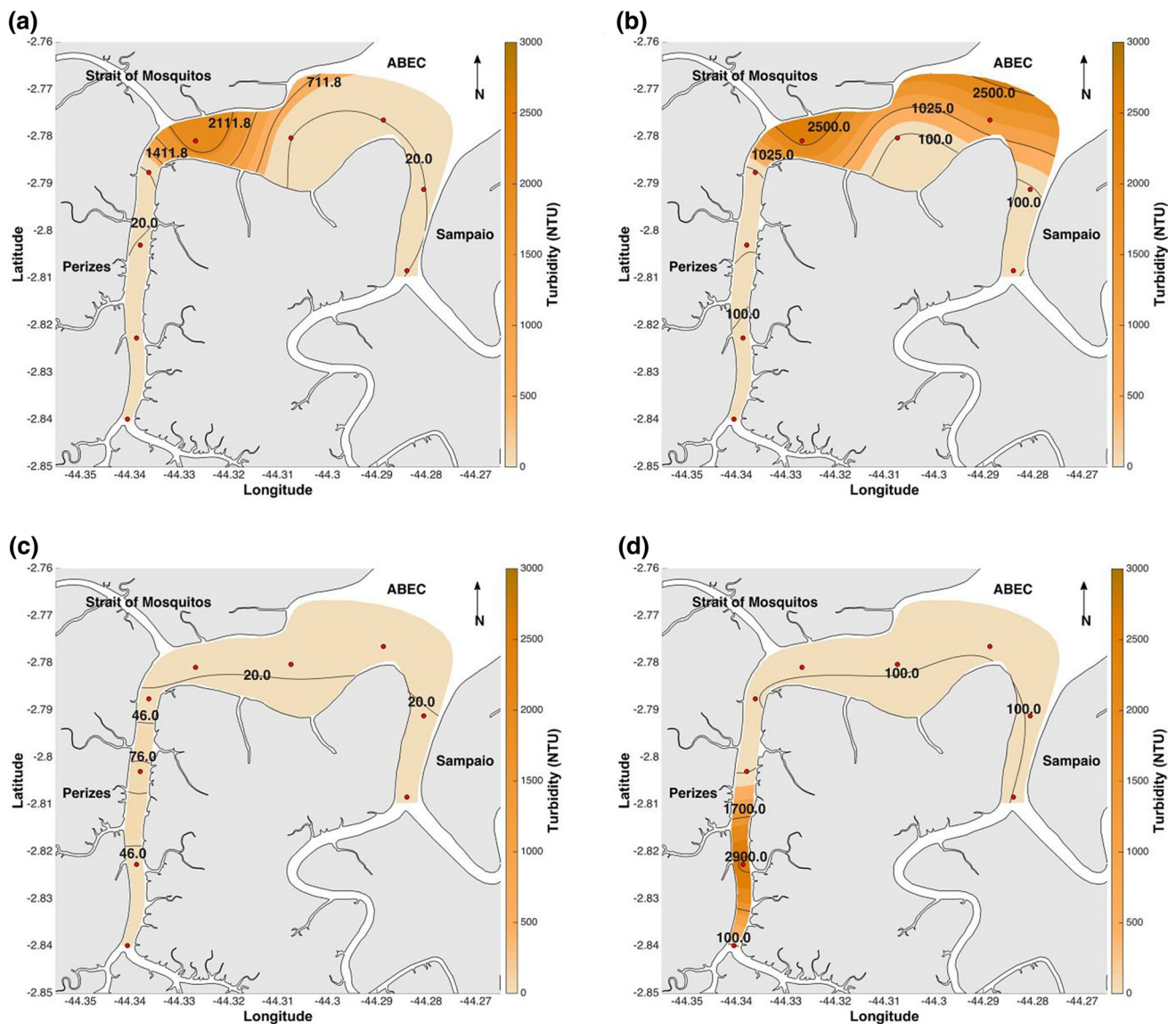


Fig. 5 Turbidity distribution in Arraial Bay Estuarine Complex (ABEC) in August. Spring tide: surface **a** and bottom **b**; and Neap tide: surface **c** and bottom **d**

positive correlation ($r=0.99$, $p<0.05$). The sampling was carried out in February, which despite being a month with a high historical average, in 2015 presented rainfall well below the historical average. In August, which is a transition month between the dry and the rainy seasons, the accumulated rainfall was higher in relation to February, which may have increased the freshwater discharge in ABEC.

Besides, the lowest flow rates in the two sampling campaigns for both tide conditions found in the stations located in Perizes River estuary (stations 1–4) can be explained by the width of the river and the fact that it is a more confined region in relation to the stations located in SRE. In addition, the depth at these stations is lower compared with those located in Sampaio River estuary. In a study in Conchas

estuary (Rio Grande do Norte, Brazil), Soares (2012) relates the low flow values to the narrowing and the low depths of the main channel. The values observed in the present study corroborate with the values found by other authors in studies in the north coast regions of Brazil (Böck et al. 2011; da Dias et al. 2013).

Small variations in temperature values are typical of tropical estuaries, which depend on meteorological conditions. The values observed in the present study corroborate with other studies carried out in the region. Azevedo et al. (2008), who also attributed these low amplitudes to the region geographic position (tropical region).

Higher salinity values registered in February indicate that the environment was under influence of marine waters,

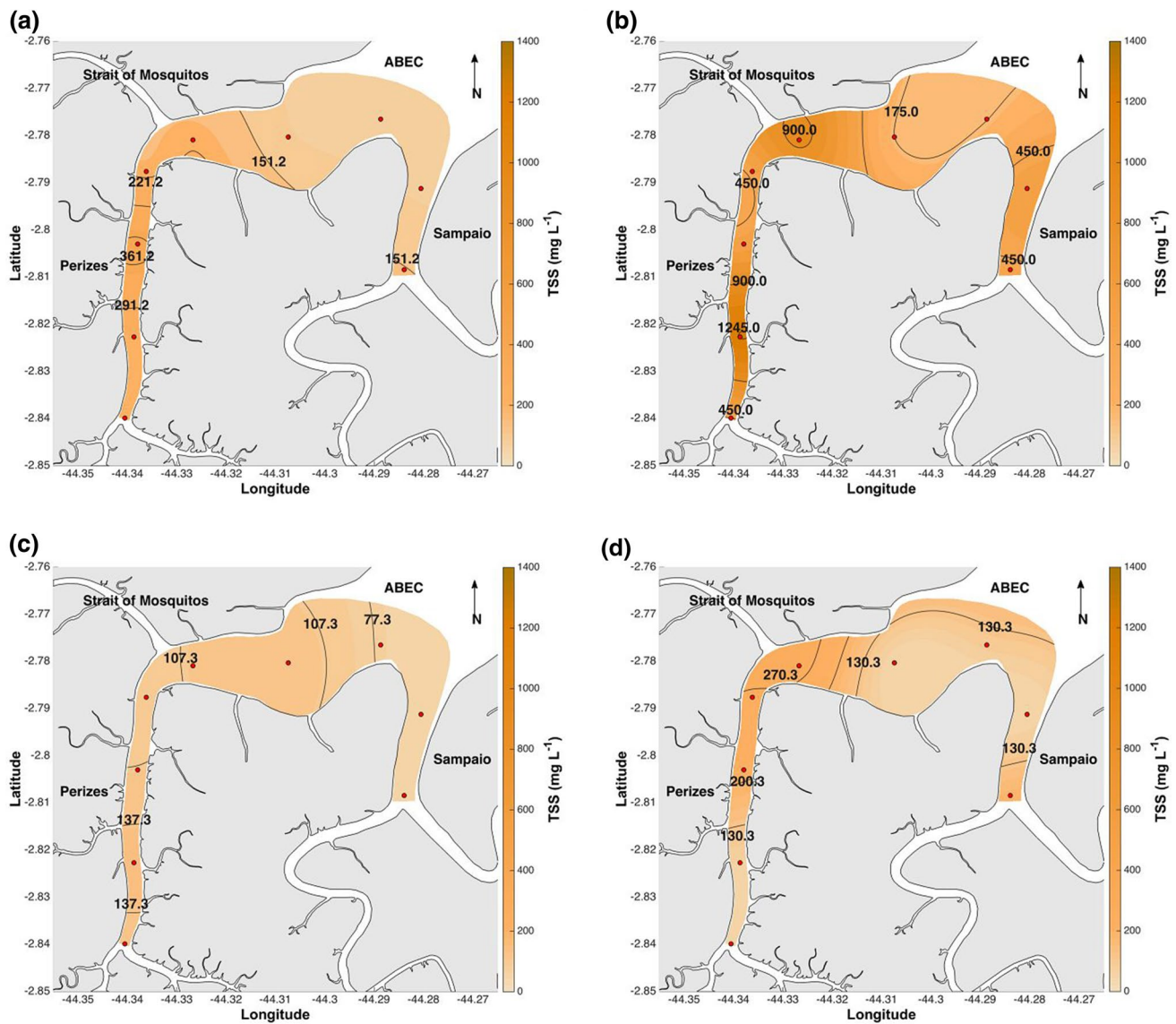


Fig. 6 TSS distribution in Arraial Bay Estuarine Complex (ABEC) in February. Spring tide: surface **a** and bottom **b**; and Neap tide: surface **a** and bottom **b**

which can be confirmed by the pH. The slight increase in the flow rates between the campaigns in the stations located at the mouths of the rivers Perizes and Sampaio, that flow into Arraial Bay, influenced the salinity. The correlation analysis showed a negative correlation between salinity and rainfall ($r = -0.99$, $p < 0.05$), and between salinity and volume transport ($r = -0.99$, $p < 0.05$), which means that these variables play an important role in the behavior of the salinity in the study area.

During neap tides, the salinity values are generally lower. This behavior is related to the greater or lesser volume of ocean water entering the estuary system as reported by Lima et al. (2014), who observed similar salinity behavior in a macrotidal estuary in north Brazil. The

estuaries show marked diurnal and seasonal variations in the salinity levels, being influenced by the tides, the fresh-water inflow from the rivers, and the terrestrial drainage caused by the rains (Bastos et al. 2005).

Regarding turbidity, the high registered values in August, when accumulated rainfall and flow rates were also higher, indicate that these factors control the turbidity values along the ABEC. The higher the rainfall and the flow, the greater the material input in the estuarine system. Bucci et al. (2012), in their study about the influence of turbidity on the temporal variability of chlorophyll *a*, found that in addition to being influenced by tidal cycles, turbidity was influenced by precipitation and flow, mainly in the shallower stations.

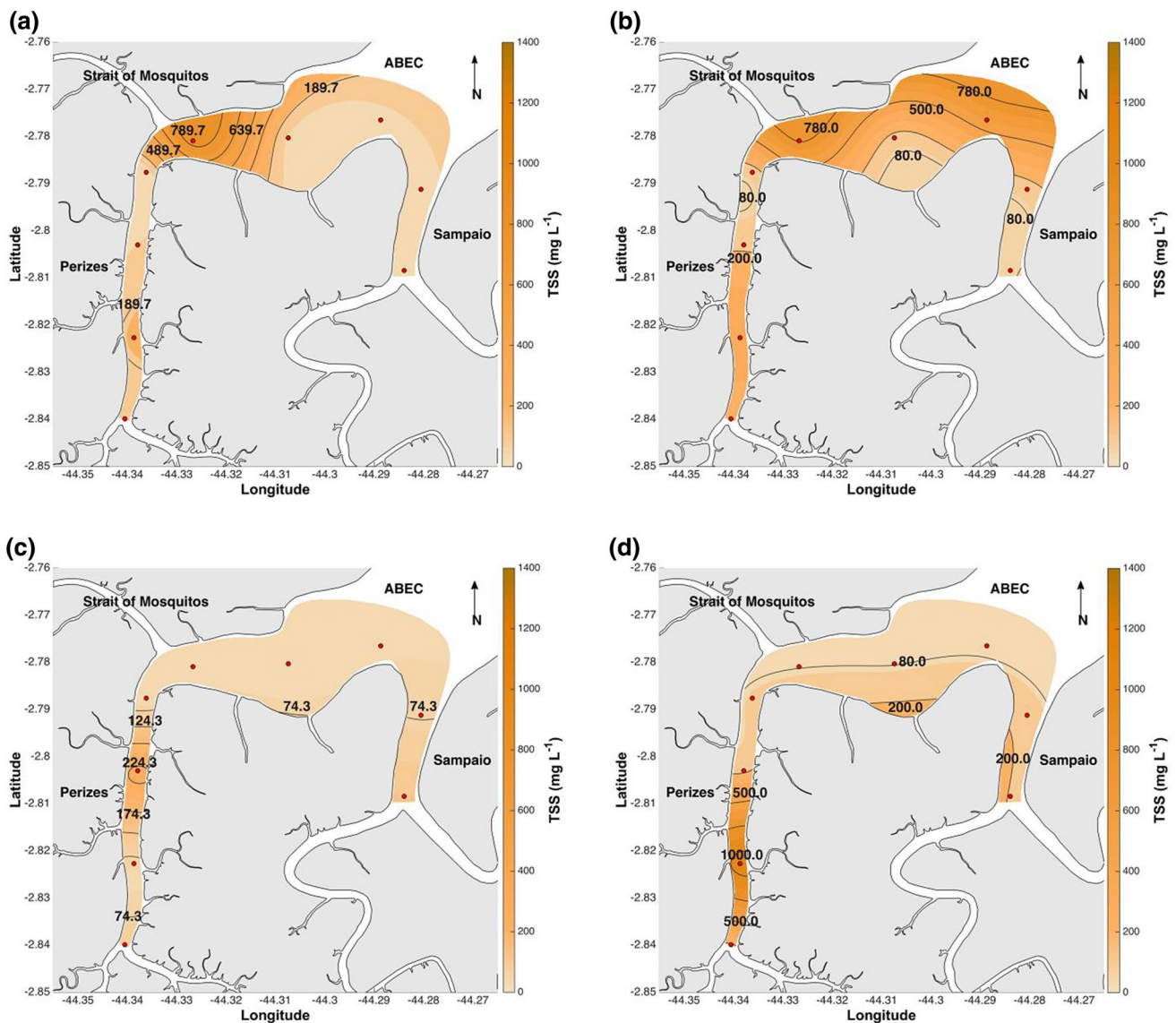


Fig. 7 TSS distribution in Arraial Bay Estuarine Complex (ABEC) in August. Spring tide: surface **a** and bottom **b**; and Neap tide: surface **a** and bottom **b**

The turbidity values were always higher near the bottom. These high values may have been influenced by local hydrodynamics and by the availability of fine sediments. Suzuki et al. (2010), in a study carried out in a macrotidal estuary (South Korea) observed that the local hydrodynamics plays an important role increasing the turbidity values in that region. Uncles et al. (2006) suggest that in tidal-dominated estuaries, high turbidity values may be influenced by the resuspension of sediments caused by waves, and by high input of sediment in the environment. In a study performed in the estuary of the Amazon River, Vilela (2011) observed similar behavior to those recorded in the present study. The highest values observed in some stations were probably influenced by the TSS. There was a positive correlation

between TSS and turbidity ($r=0.95$, $p<0.05$), indicating that the main factor controlling the turbidity in ABEC is the TSS. This feature is common in macrotidal estuaries, as observed by Suzuki et al. (2010).

Estuarine suspended sediment dynamics are complex, once it is usually controlled by a combination of different chemical and physical mechanisms (Van Maren et al. 2015). TSS values were higher in periods of higher rainfall and flow (during the study period), which suggests that these factors also control the TSS concentrations. Strong rainfall increases the rivers discharge. The increase in the flow rates, especially during spring tides, may have caused the availability of TSS sources to the study area and, consequently, to the ocean. This scenario is due to the increase of the erosion of

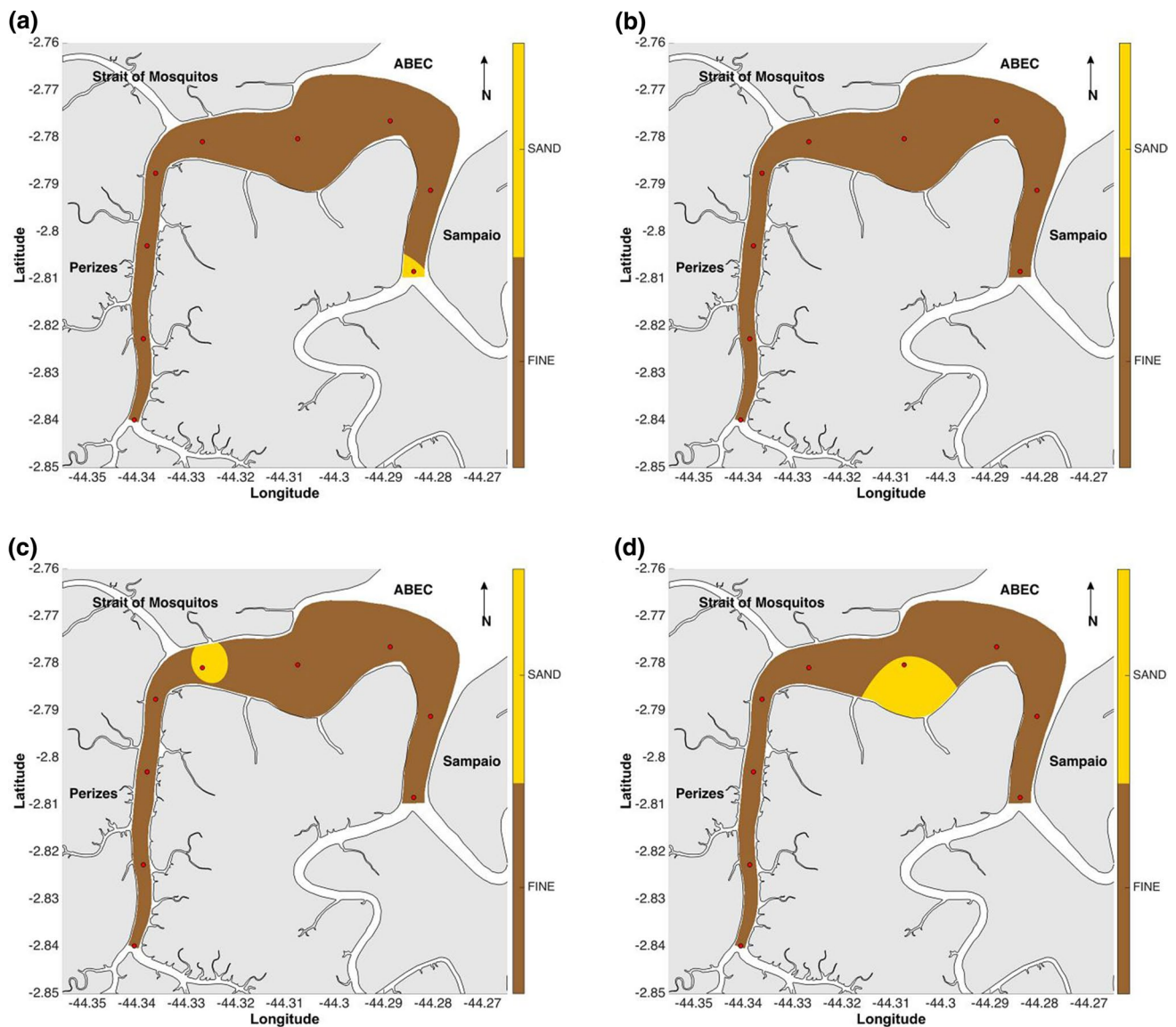


Fig. 8 Grain size distribution in Arraijal Bay Estuarine Complex (ABEC). February: Spring tide **a** and neap tide **b**. August: Spring tide **c** and Neap tide **d**

the margins, the inundations of floodplains and the resuspension of the sediment (Soares 2012). On the other hand, when high concentrations of TSS coincide with periods of low rainfall, TSS may be influenced factors such as resuspension (Purnachandra Rao et al. 2011) and winds. Strong winds can generate waves that resuspend the sediments in shallow areas (Le Hir et al. 2001).

In macrotidal estuaries, tidal cycles are significant for processes such as sedimentation. Comparing the samples taken during spring tide with those taken during neap tide, the samples of the latter showed lower TSS concentrations. In February, the mean TSS values for spring tide were 63.6% higher than the average for neap tide. In August, the average for spring tide was 39.7% higher than the average for

neap tide. According to Guézennec et al. (1999), during the spring tides, resuspensions are more significant than during the neap tides, increasing the concentrations of suspended solids in the water column. In spring tide conditions, current velocities are stronger (Guézennec et al. 1999) influencing variables such as salinity, turbidity and TSS. Similar behavior regarding neap–spring variations of TSS concentrations was reported by Gomes et al. (2013) in a macrotidal estuary located in the tide-dominated eastern sector of the Amazonian Coastal Zone.

Regarding the TSS bottom samples, in February, the means were 70.5 and 47.6% higher than at the surface for spring and neap tides, respectively. In August, the mean for the bottom samples was 67.5% higher during spring tide and

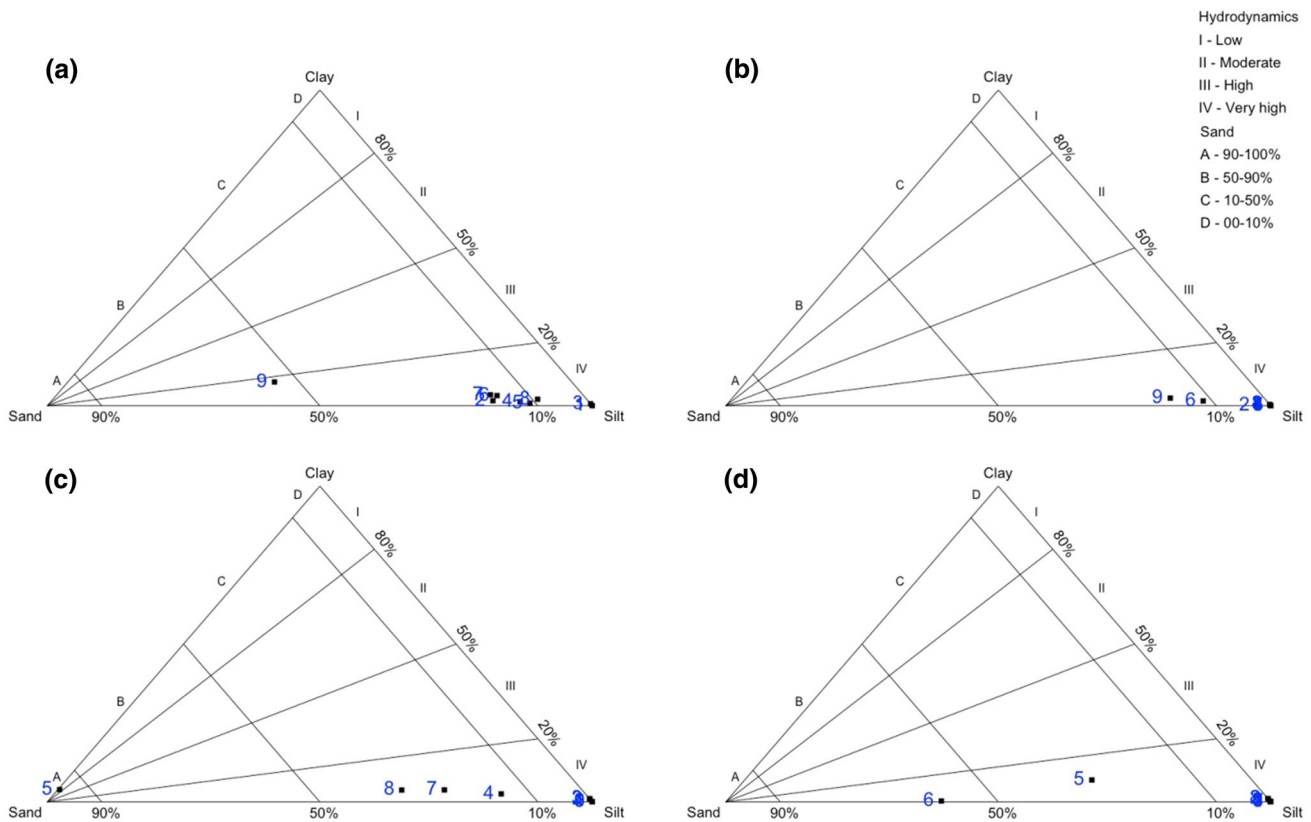


Fig. 9 Pejrup Diagram for samples collected in Arraial Bay Estuarine Complex (ABEC) showing the hydrodynamics conditions of the study area. February: Spring tide **a** and neap tide **b** August: Spring tide **c** and Neap tide **d**

65.4% for neap tide. Variations in the TSS concentrations, with regards to different depths, are often related to bottom morphology and to the effect of tides and salinity (Ruhl et al. 2001). In addition, Rollnic et al. (2018), in a study carried out also in the macrotidal estuary in the Amazonian Coastal Zone, stated that the low depth of the estuarine system favors the sediments resuspension processes in that estuary.

The highest values observed in stations 2 and 5 may be related to their location and depth. Station 2 is shallower compared to the other stations, which favors the resuspension of sediments caused by the waves (Shenliang et al. 2003). In addition, station 2 is located in an area where there are two small tributaries of the Perizes River, which contribute to the sediment supply to the area. Station 5 is located within Arraial Bay, near the Strait of Mosquitos. The strait connects Sao Marcos Bay and Arraial Bay, so that area receives sediments coming from the strait and the Perizes River.

The dynamics of spring and neap tides control the sedimentation and sediment transport. Grain size analyzes of the bottom sediments showed the predominance of silt in the study area, in both sampling periods. The study area features an extensive habitat of mangrove swamps and tidal flats, from where the fine material may be entering the

estuarine system. Although most of the sampling stations are located in sheltered areas, surrounded by mangroves, the percentage of clay in the samples was relatively small, which can be explained by the hydrodynamic conditions of the environment.

In a study carried out in a tropical macrotidal estuary located in the Amazonian Coastal Zone, Asp et al. (2018) reported that the sediments dynamics depend also on the season. Fine sediments reach the estuary through the Amazon River plume and its shelf deposits during periods of high rainfall. However, during the dry season, the fine sediments are transported from the shelf and reach the estuary through tidal processes. The authors also emphasized the role of the mangrove forests in the accumulation of these sediments and the role of the spring tides in the sediments resuspension. Therefore, mangrove forests are also of extreme relevance when understanding the sediment dynamics within tropical estuaries.

According to Pejrup diagram (Pejrup 1988), in both periods and for spring and neap tide conditions, the study area was classified as a very high hydrodynamic region. The local dynamics prevent the deposition of the finer particles, which are suspended, increasing the concentrations of TSS in the water column. The highest percentages of sand were

observed in August, mainly during neap tide. In addition, when comparing the environments, it was observed that the stations located in AB (Arraial bay) had higher percentages of sand. This is a result of the reworking of the margins, associated with the tidal dynamics. The stations within AB are located in a more open region and, therefore, they are more subject to the influence of the local hydrodynamics. As a result of the accumulation of sand, it is possible to observe the formation of sand banks along the AB, which may compromise the navigation in the area.

The fine sediments can be easily eroded by tidal currents, especially during spring tides. Comparing the tide conditions, spring tides showed higher percentages of sand. A negative correlation was observed between TSS and fine sediments ($r = -0.454$, $p < 0.01$), and turbidity and fine sediments ($r = -0.502$, $p < 0.01$) during the spring tides. As previously mentioned, sediment erosion and resuspension occur during spring tides due to the hydrodynamic conditions that are modified, such as the increase in velocity of the currents and the volume of marine water entering the estuary. This result corroborates with the results of TSS concentrations that were higher during spring tides, which confirms that the fine particles are resuspended during spring tides, increasing the concentration of TSS in the water column. The fine sediments are carrier of nutrients and pollutants; therefore, resuspension of the bottom sediments may make them available in the water column influencing the ecology and the environmental quality.

On the other hand, during neap tides, there was higher percentages of fine material (Silt and clay) and lower percentage of sand. During neap tides, the accumulation of fine sediments occurs due to the conditions that allow the rapid deposition of these sediments as observed by Guézennec et al. (1999) in Seine, a macrotidal estuary in France. Once the fine material is deposited, less sediment will be available in the water column, decreasing the concentrations of TSS during neap tides. For the neap tides, both TSS and turbidity showed a positive correlation with the fine sediments ($r = 0.550$, $p < 0.01$ and $r = 0.502$, $p < 0.01$), respectively. In the areas where fine sediments predominated, it is possible to observe the formation of mudflats which are exposed during low tide.

5 Conclusion

This study indicates that precipitation, fluvial discharge and tidal conditions are the main agents that govern the behavior of the parameters considered here. The parameters variations during spring tides are more accentuated, indicating the influence of the hydrodynamics caused by the tidal conditions in macrotidal estuaries. Precipitation increases the volume of freshwater in the environment, influencing the

salinity, fluvial discharge, and consequently the concentrations of TSS, which in turn, seems to be the main factor controlling turbidity in the region.

The tides play an important role in the dynamics between the surface bottom sediments and the TSS concentrations. The movements caused by the descent and rise of the waters resuspend the fine sediments, increasing the concentrations of TSS in the water column, besides controlling the distribution and reworking of the bottom sediments. The predominance of silt, the heterogeneity in the grain size classification, as well as the lack of a spatial and temporal pattern along the ABEC also reflect the influence of the tides. Although the Pejrup (1988) diagram classifies the study area as high hydrodynamic area, the predominance of fine material observed in the bottom shows the role of mangroves in the entrapment and supply of sediments to the region.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

- Asp, N. E., Gomes, V. J. C., Schettini, C. A. F., Souza-Filho, P. W. M., Siegle, E., & Ogston, A. S. (2018). Sediment dynamics of a tropical tide-dominated estuary: turbidity maximum, mangroves and the role of the amazon river sediment load. *Estuarine, Coastal and Shelf Science*, 214, 10–24.
- Association, American Public Health. (2005). Water Environment Federation (APHA). *Standard methods for examination of water and wastewater*, 21, 258–259.
- Azevedo, A. C. G., Feitosa, F. A. N., & Koenig, M. L. M. (2008). Distribuição Espacial e Temporal da Biomassa Fitoplanctônica e Variáveis Ambientais no Golfão Maranhense, Brasil. *Acta Botanica Brasílica*, 22, 870–877.
- Bastos, R. B., Feitosa, F. A., do, N., & Muniz, K. (2005). Variabilidade Espaço-Temporal Da Biomassa Fitoplanctônica E Hidrologia No Estuário Do Rio Una (Pernambuco-Brasil). *Tropical Oceanography*, 33, 1–18.
- Böck, C. S., Assad, L. P. F., & Landau, L. (2011). Influence of bottom morphology on the hydrodynamics of Guajará Bay (Amazon, Brazil). *Journal of Coastal Research*, 64, 981–985.
- Boletim de Informações Climáticas do CPTEC/INPE (INFOCLIMA). (2015). Ano 22, 577 n 02. Available: <http://infoclima.cptec.inpe.br/>. Accessed 20 December 2015.
- Bucci, A. F., Ciotti, A. M., Pollery, R. C. G., de Carvalho, R., de Albuquerque, H. C., & Simoes, L. T. S. (2012). Temporal variability of chlorophyll-a in the sao vicente estuary. *Brazilian Journal of Oceanography*, 60, 485–499.
- Costa, M. B. S. F., Mallmann, D. L. B., & Guerra, N. C. (2010). Caracterização Sedimentológica da Área de Fundeio de dois naufrágios

- na Plataforma Continental Pernambucana. *Management*, 10, 49–64.
- da Dias, F. J., da S., Marins, R. V., & Maia, L. P. (2013). Impact of drainage basin changes on suspended matter and particulate copper and zinc discharges to the ocean from the jaguaribe river in the semiarid NE Brazilian coast. *Journal of Coastal Research*, 29(0), 1137–1145.
- de Alcântara, E. H. (2004). Caracterização da Bacia Hidrográfica do Rio Itapecuru, Maranhão-Brasil. *Caminhos da Geografia*, 7, 97–113.
- de Menezes, M. P. M., Berger, U., & Mehlig, U. (2008). Mangrove vegetation in amazonia: A review of studies from the coast of Pará and maranhão states, North Brazil. *Acta Amazonica*, 38, 403–420.
- de Miranda, L. B., de Castro Filho, B. M., & Kjerfve, B. (2002). *Princípios de Oceanografia Física de estuários*. EdUSP: São Paulo.
- El-Robrini, M., Valter Marques J., Silva, M. M. A. da, El-Robrini, M. H. S., Feitosa, A. C., Tarouco, J. E. F., Santos, J. H. S. do S., & Viana, J. R. (2006). *Maranhão, Erosão e Progradação Do Litoral Brasileiro*, 1.
- Eschrique, S. A. (2011). Estudo do Balanço Biogeoquímico dos Nutrientes Dissolvidos Principais Como Indicador da Influência Antrópica em Sistemas Estuarinos do Nordeste e Sudeste do Brasil. [Ph. D. Thesis]: Universidade de São Paulo.
- Gilbert, E. R., de Camargo, M. G., & Sandrini-Neto, L. (2012). Rysgran: Grain size analysis, textural classifications and distribution of unconsolidated sediments. *R Package*. Version 2.
- Gomes, A. V. J. C., Freitas, P. T. A., Asp, N. E., Gomes, V. J. C., & Freitas, P. T. A. (2013). Dynamics and seasonality of the middle sector of a macrotidal estuary dynamics and seasonality of the middle sector of a macrotidal estuary. *Journal of Coastal Research*, 65, 1140–1145.
- González-Gorbeña, E., Rosman, P. C. C., & Qassim, R. Y. (2015). Assessment of the tidal current energy resource in São Marcos Bay, Brazil. *Journal of Ocean Engineering and Marine Energy*, 1, 421–433.
- Guézennec, L., Lafitte, R., Dupont, J. P., & Meyer, R. (1999). Hydrodynamics of suspended particulate matter in the tidal freshwater zone of a macrotidal estuary (The seine estuary, France). *Estuaries*, 22, 717–727.
- Nugeo/Labmet. Informativo Climático: Fevereiro de 2015. São Luís: UEMA, 2015. http://www.nugeo.uma.br/?page_id=209. Accessed 20 December 2015.
- Le Hir, P., Ficht, A., Jacinto, R. S., Lesueur, P., Dupont, J. P., Lafite, R., et al. (2001). Fine sediment transport and accumulations at the mouth of the seine estuary (France). *Estuaries*, 24, 950–963.
- Lima, M. W., Alves, M. A. M. S., Santos, M. L. S., Ribeiro, A. M., Santos, E. T., & Nunes, D. M. (2014). Influência do Ciclo de Maré na Variação dos Parâmetros Físico-Químicos no Estuário do Rio Curuçá, Nordeste Paraense. *Boletim Técnico Científico do CEPNOR*, 14, 9–15.
- Malheiro da Silva, R. S. (2011). Técnica de Interferometria SAR e Modelagem Hidrodinâmica Para Avaliação de Locais Adequados ao Aproveitamento da Energia das Correntes de Maré. [Ph. D. Thesis]: Universidade Federal do Rio de Janeiro.
- Park, G. S. (2007). The role and distribution of total suspended solids in the macrotidal coastal waters of Korea. *Environmental Monitoring Assessment*, 135, 153–162.
- Pejrup, M. (1988). *The triangular diagram used for classification of estuarine sediments: A new approach* (pp. 289–300). Dordrecht: Tide-Influenced Sedimentary Environments and Facies. Reidel.
- Purnachandra Rao, V., Shynu, R., Kessarkar, P. M., Sundar, D., Michael, G. S., Narvekar, T., et al. (2011). Suspended sediment dynamics on a seasonal scale in the mandovi and zuari estuaries, central west coast of India. *Estuarine, Coastal and Shelf Science*, 91, 78–86.
- Rezende, C. E., Pfeiffer, W. C., Martinelli, L. A., Tsamakidis, E., Hedges, J. I., & Keil, R. G. (2010). Lignin phenols used to infer organic matter sources to sepetiba Bay-RJ, Brasil. *Estuarine, Coastal and Shelf Science*, 87, 479–486.
- Rollnic, M., Costa, M. S., Medeiros, P. R. L., & Monteiro, S. M. (2018). tide influence on suspended matter transport in an amazonian estuary. *Journal of Coastal Research*, 85, 121–125.
- Rousseau, R., Egghe, L., & Guns, R. (2018). *Becoming metric-wise. A bibliometric guide for researchers*. Kidlington: Chandos-Elsevier.
- Ruhl, C. A., Schoellhamer, D. H., Stumpf, R. P., & Lindsay, C. L. (2001). Combined use of remote sensing and continuous monitoring to analyse the variability of suspended-sediment concentrations in San Francisco Bay, California. *Estuarine, Coastal and Shelf Science*, 53, 801–812.
- Samaritano, L., Chagas, F. M., Bernardino, J. C. M., Siegle, E., Tessler, M. G., & Uemura, S. (2013). Hydrodynamic modeling over a sand wave field at são marcos. *Marine and River Dune Dynamics*, 4, 241–247.
- Shenliang, C., Guoan, Z., & Shilun, Y. (2003). Temporal and spatial changes of suspended sediment concentration and resuspension in the yangtze river estuary. *Journal of Geographical Sciences*, 4, 498–506.
- Soares, H. C. (2012). Análise Hidrodinâmica e Morfodinâmica do Complexo Estuarino do Rio Piranhas-Açu/RN, Nordeste Do Brasil. [MS. Thesis], Universidade Federal do Rio Grande do Norte.
- Souza Filho, P. W. M. (2005). Costa de Manguezais de Macromaré da Amazônia: Cenários Morfológicos, Mapeamento e Quantificação de Áreas Usando Dados de Sensores Remotos. *Revista Brasileira de Geofísica*, 23, 427–435.
- Strickland, J. D. H., & Parsons, T. R. (1972). *A practical handbook of seawater analysis* (Vol. 167). Ottawa: Bulletin Fisheries Research Board of Canada.
- Suguio, K. (1973). *Introdução à Sedimentologia* (p. 1). São Paulo: Edgard Blücher.
- Suzuki, K. W., Gwak, W. S., Nakayama, K., & Tanaka, M. (2010). Instability of the turbidity maximum in the macrotidal geum river estuary. *Western Korea. Limnology*, 1(3), 197–205.
- UFMA/FSADU—Universidade Federal do Maranhão/Fundação Soudrade de Apoio e Desenvolvimento da Universidade Federal do Maranhão. (2009). Estudo de impacto ambiental da Refinaria Premium I, Bacabeira (MA).
- Uncles, R. J., Stephens, J. A., & Harris, C. (2006). Properties of suspended sediment in the estuarine turbidity maximum of the highly turbid humber estuary system, UK. *Ocean Dynamics*, 56, 235–247.
- Van Maren, D. S., Van Kessel, T., Cronin, K., & Sittioni, L. (2015). The impact of channel deepening and dredging on estuarine sediment concentration. *Continental Shelf Research*, 95, 1–14.
- Vilela, C. de P.X. (2011). Influência da Hidrodinâmica Sobre os Processos de Acumulação de Sedimentos Finos no Estuário do Rio Amazonas. [Ph. D. Thesis]. *Coastal oceanography engineering program, Federal University of Rio Janeiro*.

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