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TOTAL SUSPENDED SOLIDS AND DISSOLVED SILICATE IN COASTAL WATERS OF THE AMAZON-SEMI ARID INTERFACE: THE ARRAIAL BAY ESTUARINE COMPLEX

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Resumo

Estuários são ambientes complexos que precisam ser compreendidos, onde as questões ambientais (poluição, hipóxia e salinização), tornaram-se uma causa crescente de preocupação nas últimas décadas. Nesse contexto, este trabalho tem como objetivo investigar o silicato dissolvido e os sólidos suspensos totais em uma região de macro-maré (Nordeste do Brasil), considerando as variações sazonais, espaciais e de maré. As amostras de água foram coletadas em 9 locais, em maré de sizígia e quadratura e durante as estações chuvosa e seca. A salinidade variou de 9,81 a 31,28 g kg^{-1}, enquanto, o pH e a temperatura permaneceram quase constantes ao longo do estudo. O oxigênio dissolvido variou de 0,40 a 6,21 mg L^{-1}. Os sólidos suspensos totais variaram de 27,60 a 6.268,50 mg L^{-1} e o silicato dissolvido de 2,62 a 107,16 µmol L^{-1}. Os resultados da análise estatística mostraram evidências da sazonalidade e das condições das marés nos parâmetros observados. Os resultados obtidos nesse estudo aprimoram os conhecimentos nos estuários de macro-maré localizados na interface semiárido amazônico.

Palavras-chave: Macro-maré, Manguezal, Nutriente, Estuário e Hidroquímica.

Abstract

Estuaries are complex environments that need to be understood, where environmental issues, e.g. pollution, hypoxia, and salinization, have become an increasing cause of concern in recent decades. In this context, this work focuses on investigating the dissolved silicate (DSi) and total suspended solids in a macro-tidal region (northeastern Brazil), considering seasonal, spatial, and tidal variations. Water samples were collected in 9 sites, under spring and neap tides, during the rainy and dry seasons. The salinity ranged from 9.81 to 31.28 g kg^{-1}, and the pH and temperature remained almost constant throughout the study. The dissolved oxygen (DO) varied from 0.40 to 6.21 mg L^{-1}. The total suspended solids (TSS) ranged from 27.60 to 6,268.50 mg L^{-1} and the DSi from 2.62 to 107.16 µmol L^{-1}. Statistical analysis showed evidence of the seasonality and tidal conditions in observed parameters. These results improved the knowledge of macro-tidal estuaries located in the Amazon-semiarid interface.

Keywords: Macro-tidal, Mangrove forest, Nutrients, Estuary and Hydrochemistry.

Introduction

Estuarine systems are vulnerable to various human-induced activities, such as agriculture, urban development, and industrialization, due to the increasing urbanization of coastal regions and the substantial rise in population within their drainage basins (Kennish, 1986; Knox, 1986). These activities introduce large amounts of nutrients, sediments, toxic substances, sewage, waste, and pathogenic microorganisms into estuarine systems, affecting their quality and multiple uses (Miranda, 1990; van Leussen & Dronkers, 1988).

Experimental removal of vegetation cover has increased the land–ocean flux of many nutrients, especially nitrogen (N) (Likens et al., 1970). We have some knowledge about how processes affect the transport of N and phosphorus (P) (Howarth et al., 1996; Nixon et al., 1996), but we know much less about the transport of dissolved silicate (DSi), which makes it hard to assess how the silicon cycle responds to disturbance and land use changes. DSi is a macronutrient required by certain groups of plants, such as diatoms, which make up 40% of the world's marine primary production (Cao et al., 2020; Kranzler et al., 2019). The phytoplankton hardly affects the DSi concentration in the water column, since estuarine systems have high levels of this element. Inorganic silicate removal is not relevant in estuaries (Boyle et al., 1974; Fanning and Pilson, 1973) and is probably not significant in the open ocean either. Therefore, the Si levels can indicate river inputs, water dilution, and spreading in coastal areas (Falco et al., 2010; Riley and Chester, 1971).

The study of silicate in the Amazon-semi arid interface is important because it is an essential nutrient for primary production, and it can also show continental contribution. The DSi can provide information about the local hydrodynamics or the possible impacts of land use changes, caused by human activities in the drainage basin. In the last few decades, human activities have altered the amount of silicate in rivers worldwide, for example, dam construction will reduce DSi in aquatic systems (Conley et al., 2000; Humborg et al., 2000, 2008; Justić et al., 1995; Li et al., 2007; Neal et al., 2005; Paul, 2003; Roubeix et al., 2008; Vörösmarty et al., 2003).

The Arraial Bay Estuarine Complex (ABEC) is located in the state of Maranhão, in the northeast of Brazil (Fig. 1). Its main tributary is the Itapecuru River (IR), which covers 53,216.84 km² and 57 municipalities. The IR is the main source of public water supply for many cities in Maranhão (IBGE, 1998). However, the IR basin suffers from environmental stress due to land use, such as agriculture and shrimp farming, which can increase siltation rates. This can affect fish stocks, and consequently, local livelihoods and the economy (Silva and Conceição, 2011).

Research on DSi from land-based sources is lacking in the ABEC, unlike land-based sources of N and P. Moreover, compared to DSi studies in the São Marcos Estuarine Complex (SMEC) (Azevedo et al., 2008; Santos et al., 2020), we know little about how spatiotemporal variation, land-based input sources, and DSi behavior affect ABEC in Maranhão State. In addition, few studies have been done on ABEC, despite its importance for estuarine regions (Serejo et al., 2020; Dos Santos et al., 2023). To understand the role of biogeochemical silicon distribution and behavior in the estuarine system, especially under land-based sources, we conducted a land-ocean integrated field study on the spatiotemporal variation, land-based sources input, and DSi behavior in macro-tidal estuary.

Therefore, this study examines the seasonal and temporal variations of DSi and total suspended solids (TSS) in ABEC (Northeast Brazil), taking into account different periods (rainy and dry seasons) and tidal variations (spring-Sp and neap tides-Np).

Materials and Methods

Study area

The ABEC includes the Perizes (PR) and Sampaio (SR) rivers. It is bounded by Maranhão Island, and the mouth of the rivers Sampaio, Perizes, and Itapecuru. Additionally, it is connected to SMEC through the Strait of Mosquitos (Fig. 1 and Tab. 1). The estuarine complex comprises an area of about 23 km² (Serejo et al., 2020).

The ABEC is inserted in a region of climatic transition, between the Northeastern semiarid and the Amazonian super-humid (NUGEO, 2016). The local climate has two distinct periods: the rainy season (January to June) and the dry season (July to December), with total annual rainfall over 2,000 mm (Azevedo et al., 2008). The region has an extremely irregular geomorphology, with some estuaries and large mangrove systems (Silva et al., 2009; Souza Filho, 2005).

The hydrodynamic patterns are controlled by factors like a semidiurnal macro-tidal regime, with heights up to 7 m, with currents reaching values of 2 m s^{-1} (Pereira and Harari, 1995). Dos Santos et al. (2023) categorized Arraial-São José Estuarine Complex (ASJEC) as an estuary, type 1a, following the criteria for the dynamic classification of estuaries developed by Hansen and Rattray (1966); where there is no gravitational circulation and turbulent diffusion was responsible for salt transport towards the up-estuary.

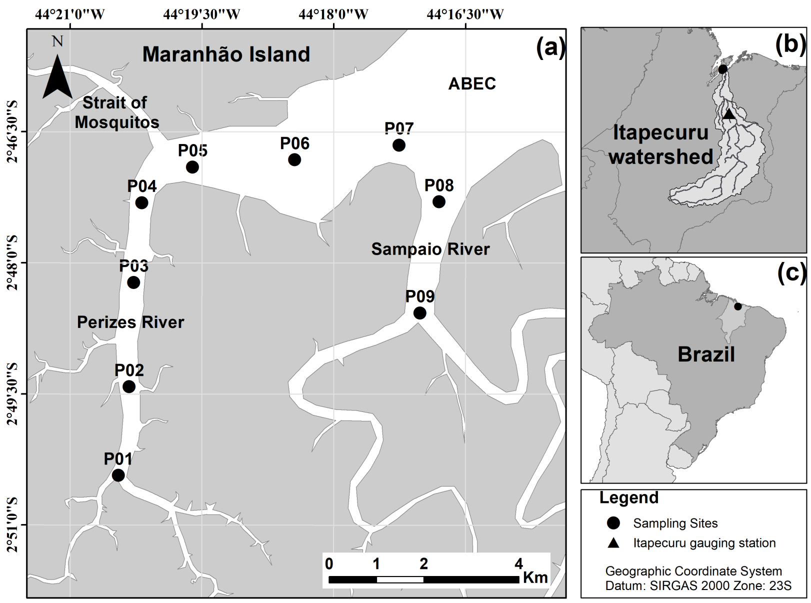

Figure 1. Location map of sampling sites in the Arraial Bay Estuarine Complex (a), Itapecuru watershed (b), Brazil (c).

Table 1. Stations, location and average depth of the selected stations in Arraial Bay Estuarine Complex (ABEC).

Station	Water body	Latitude (S)	Longitude (W)	Average depth
1	PR	2°50'25.80"	44°20'26.88"	2.9
2	PR	2°49'24.96"	44°20'19.68"	3.5
3	PR	2°48'13.32"	44°20'16.44"	4.3
4	PR	2°47 18.600	44°20'11.04"	5.1
5	ABEC	2°46 54.120	44°19'36.48"	9.5
6	ABEC	2°46 49.080	44°18'26.64"	3.9
7	ABEC	2°46 39.000	44°17'15.36"	5.5
8	SR	2°47 17.880	44°16'48.00""	9.0
9	SR	2°48 34.200	44°17'0.96"	16.0

Sampling and chemical Analysis

The samplings were carried out in 9 sites along the ABEC (Fig. 1), with a total of 4 sampling campaigns covering the different seasonal periods of the region, rainy (March 2014 and February 2015), and dry (July and October 2014) seasons. For each campaign, two samplings were performed, one under spring tide and the other under neap tide conditions, all of them carried out during ebb tide (Table 1).

Data regarding local rainfall was sourced from the National Institute of Meteorology (INMET), while freshwater discharge information was furnished by the Brazilian Water National Agency (ANA), utilizing the Itaperacu Gauge Station nearest to ABEC, located in Coroatá (#33630000; lat. -4.1258; lon. -44.1297).

The water samples were collected using a 5 L van Dorn bottle (surface and bottom) and immediately placed into 500 mL polyethylene bottles for each site. The samples were refrigerated at 2–5 °C until analysis at the laboratory. The water transparency (m) was determined according to Poole and Atkins (1929), which is based on the Secchi disk depth.

Water temperature (T), salinity (S) (Practical Salinity Scale), and pH were measured with a multiparameter Probe (Hanna HI-9828®, Hanna Instruments Portugal, Povoa de Varzim, POR), with an accuracy of ±2%. The state variables (T, S) obtained for this study were converted to the most recent international standard International Thermodynamic Equation of Seawater 2010 (http://www.teos-10.org/). The turbidity was measured with a turbidimeter (TB1000, MS Tecnopon, Piracicaba, BR). All equipment was previously calibrated using the standard solutions for the apparatus.

The determination of dissolved oxygen (DO) was performed by the method described by Strickland and Parsons (1972), with a precision of ±0.7 mg L^{-1}. Water samples were filtered by vacuum filtration with 47 μm diameter glass fiber filters and nominal 2.0 μm porosity. Total suspended solids (TSS) and suspended organic matter (MOS) were determined by the methodology described in APHA (2005). The DSi was determined by the method of Grasshoff et al. (1983), with the spectrophotometer (CARY 300 Conc UV-Visible Spectrophotometer, Agilent Technologies, California, USA). This method has a precision of ±0.01 μmol L^{-1} for DSi.

Statistical Analysis

The spatial representation of the ABEC for the hydrological and hydrochemical variables was delineated based on a spatialization of the action area of each variable, using Voronoi polygons (Aurenhammer, 1991). Descriptive statistics (maximum, minimum, average, and standard deviation) were determined for all of the physical and chemical variables.

Statistical tests were conducted to assess potential differences between the two collection depths (surface and bottom), various tidal conditions (spring and neap), and the two sampling campaigns (rainy and dry seasons) for each parameter. The Kolmogorov-Smirnov test was utilized to evaluate the normality of the data, while the Levene test was applied to analyze the homogeneity of variances. Student’s t-test (parametric) and Wilcoxon test (non-parametric) were employed to examine differences in parameters between the depths. It was observed that Turbidity, TSS, and MOS were variables that did not adhere to a normal distribution.

For the investigation of the effects of seasonal and tidal conditions on the hydrological variables, two-way ANOVA (parametric) and two-way PERMANOVA (non-parametric) were employed. Furthermore, Pearson’s Correlation Analysis was used to assess the relationship between the measured parameters. The significance threshold for all tests was set at 95% ($p<0.05$).

Results

Fig. 2a shows the monthly mean historical rainfall for Maranhão Island, based on the data from 1961 to 2015. The sampling periods of March 2014 and February 2015 had precipitation values much lower than the historical average for those months. They were 63.7% and 40.9% below the average, respectively. The campaigns in July and October 2014 also had lower values than the historical average, with rainfall being 63.1% and 62.6% below the average, respectively.

The hydrological station in Coroatá, managed by the ANA, recorded significant freshwater discharge ranging from 106.9 to 328.1 $m^3 s^{-1}$, with an average of 170.8 $m^3 s^{-1}$ during the rainy season (first campaign). However, in the dry season, a reduction was observed, with mean values of 44.3 $m^3 s^{-1}$ (second campaign) and 39.0 $m^3 s^{-1}$ (third campaign). In the fourth sampling campaign, freshwater discharge varied from 44.2 to 148.8 $m^3 s^{-1}$, with mean values of 80.5 $m^3 s^{-1}$ during the rainy season (Fig. 2b).

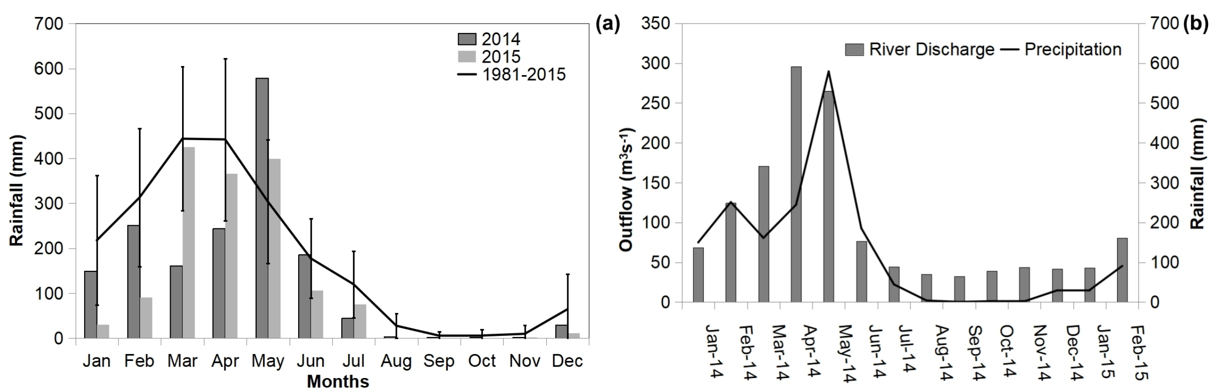

Figure 2. Rainfall in São Luís (meteorological station 82280 — INMET, 2020): line represents climatological mean and standard deviations (1981–2015); bars represent accumulated precipitation for 2014 and 2015 (a). (Bar) Monthly discharges obtained in the Itapecuru watershed and (line) monthly average rainfall in São Luís (b). Source: Hidroweb, ANA (2019).

The average sampling depth was 6.7 m, which is lower than the observed tidal range in this environment (Tab. 2). Transparency values of the water showed no statistically significant variations (Fig. 3a). The estuarine complex exhibited high turbidity, resulting in limited penetration of solar radiation into the water column during the study period. Statistical analysis (t-test) revealed no significant differences between the two collection depths (surface and bottom) for temperature, salinity, pH, DO, and dissolved silicate (p>0.05). However, notable distinctions were observed between the surface and bottom in terms of turbidity, TSS, and MOS.

Table 2. Summary of the physicochemical parameters measured in ABEC. Minimum – Min., maximum – Max. and average - Ave.

Parameters	Value	1st campaign (Rainy Season)		2nd campaign (Dry Season)		3rd campaign (Dry Season)		4th campaign (Rainy Season)	
		Spring	Neap	Spring	Neap	Spring	Neap	Spring	Neap
Depth (m)	Min.	1.0	4.0	3.0	2.5	2.1	2.5	3.0	2.5
	Max.	11.0	8.0	11.0	11.0	20.0	15.0	28.0	25.0
	Mean	7.6	3.4	6.7	5.7	7.9	5.3	8.9	7.7
	SD.	2.6	2.1	2.7	3.4	4.3	6.1	7.0	8.1
Water transparency (m)	Min.	0.4	0.2	0.1	0.5	0.6	0.6	0.4	0.1
	Max.	1.5	1.4	1.0	1.3	1.2	1.3	1.9	0.8
	Mean	1.0	0.9	0.6	0.8	0.8	0.9	1.0	0.2
	SD.	0.4	0.4	0.3	0.3	0.2	0.3	0.5	0.2
Water temperature (°C)	Min.	28.8	29.6	28.6	29.0	28.7	27.8	29.8	30.9
	Max.	29.7	31.1	29.7	30.3	31.6	30.2	31.0	31.7
	Mean	29.3	30.4	29.3	29.8	30.0	29.2	30.5	31.3
	SD.	0.3	0.4	0.3	0.4	0.9	0.6	0.3	0.2
Salinity (g kg^{-1})	Min.	14.2	11.0	16.4	20.6	29.6	30.9	31.0	31.1
	Max.	15.4	14.9	18.3	22.6	33.1	32.1	32.5	31.4
	Mean	14.5	13.3	17.4	21.6	31.4	31.3	31.8	31.2
	SD.	0.3	1.4	0.5	0.6	0.9	0.4	0.3	0.1
pH	Min.	7.7	7.8	7.4	7.6	7.7	7.8	7.2	7.2
	Max.	7.8	8.0	7.7	7.8	8.0	8.1	7.7	7.8
	Mean	7.7	7.9	7.6	7.8	7.9	8.0	7.6	7.5
	SD.	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
DO (mg L^{-1})	Min.	1.6	4.2	1.8	0.4	2.7	3.0	2.9	3.7
	Max.	3.9	5.1	3.8	4.6	4.5	5.1	4.5	6.2
	Mean	2.9	4.6	3.2	3.7	4.0	4.3	3.8	4.7
	SD.	0.7	0.3	0.7	1.1	0.6	0.5	0.6	0.6
DO (%)	Min.	33.4	85.8	37.8	8.1	61.9	66.9	66.3	84.3
	Max.	79.0	103.6	79.2	97.6	99.4	112.4	103.8	141.7
	Mean	58.1	94.2	66.1	79.6	89.2	96.7	86.8	108.1
	SD.	13.5	5.3	14.6	23.6	12.0	11.8	12.7	14.1
Turbidity (NTU)	Min.	11.0	18.1	29.0	20.0	28.0	28.0	16.5	14.7
	Max.	2589.0	1468.0	3012.0	2918.0	962.0	80.0	2803.5	80.0
	Mean	719.2	167.5	1428.9	254.9	230.5	56.4	484.4	33.5
	SD.	977.8	391.6	1276.4	737.0	342.3	20.5	820.1	21.1

TSS (mg L^{-1})	Min.	51.2	27.6	614.3	154.5	88.5	78.5	81.2	47.3
	Max.	2473.3	1739.0	6268.5	1441.0	548.3	344.0	1247.0	295.3
	Mean	784.3	266.4	3581.4	321.7	241.9	149.1	368.3	133.9
	SD.	647.5	427.9	1910.3	315.3	133.0	71.2	332.2	74.6
SOM (%)	Min.	13.5	9.3	65.9	11.9	16.6	17.7	13.0	19.5
	Max.	90.4	56.7	90.8	25.6	70.8	38.5	31.7	32.0
	Mean	62.2	22.7	81.3	20.5	31.3	25.3	19.9	25.5
	SD.	24.9	14.5	8.6	3.5	17.9	4.6	5.7	3.9
Silicate (µmol L^{-1})	Min.	5.9	3.3	6.0	2.6	63.9	58.4	20.6	22.2
	Max.	30.4	58.7	91.9	60.9	107.2	104.3	33.7	105.5
	Mean	18.9	24.2	47.0	20.4	82.0	75.3	24.6	54.6
	SD.	7.3	16.0	26.5	17.6	15.7	15.0	3.8	28.6

The water temperature exhibited significant variations associated with seasons ($p<0.001$) and tide periods ($p<0.05$) (Fig. 3b), featuring a thermal amplitude of 4.2 °C. The lowest temperature (28.0 °C) was recorded during the third campaign, while the highest (32.2 °C) occurred in the fourth campaign. Salinity values were statistically influenced by seasonality throughout the estuarine complex. Salinity ranged from 9.81 to 21.06 g kg^{-1} during campaigns 1 and 2, increasing to 26.26 and 31.28 g kg^{-1} during campaigns 3 and 4 (Fig. 4a-h). The pH levels were consistently high across all campaigns, averaging 7.72 (Fig. 3c). pH exhibited significant differences associated with seasons ($p<0.001$) and tide periods ($p<0.05$), with higher values observed during neap tide conditions.

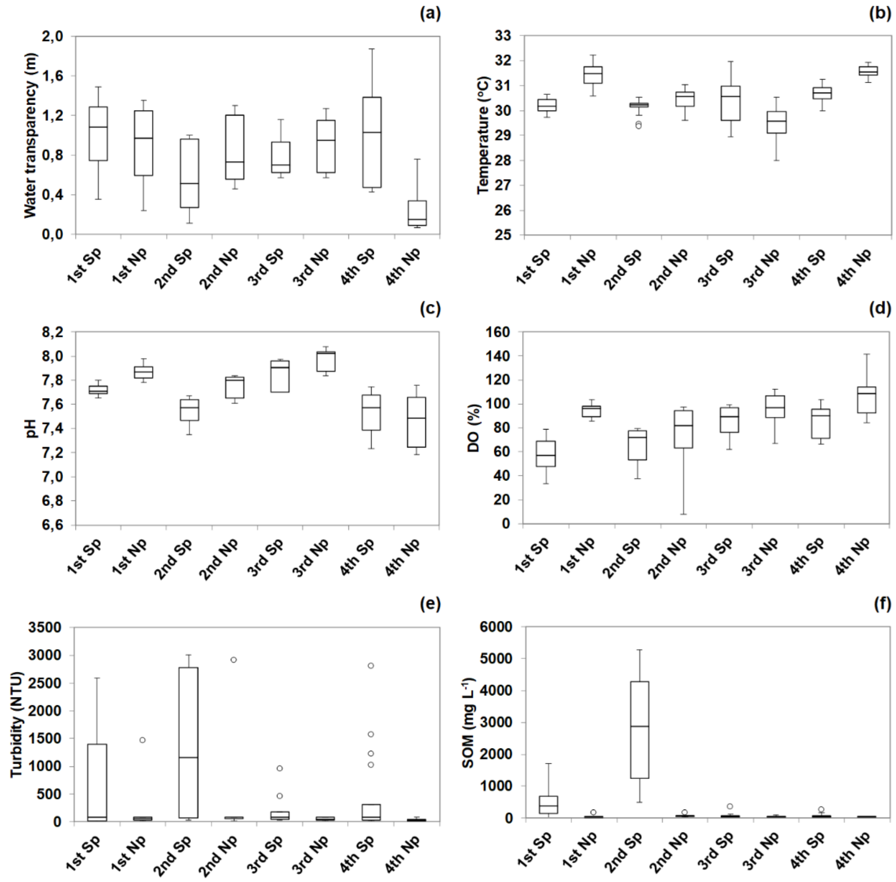

Figure 3. Physicochemical parameters of the water collected in Arraial Bay Estuarine Complex. Water transparency (a), temperature (b), pH (c), percentage of dissolved oxygen – DO% (d), turbidity (e) and suspended organic matter - SOM (f).

The average concentration of DO ranged from 3.47 to 4.27 mg L^{-1} during the study period (Fig. 4i-p). The slight variation in DO demonstrates significant differences related to tide periods ($p<0.05$) and tides ($p<0.001$), with the highest concentrations occurring during neap tides. The waters of ABEC were generally well-oxygenated, except for stations 1 and 2 during the first and second campaigns (DO < 2 mg L^{-1}). The percentage of dissolved oxygen saturation (% DO) in the waters had average values ranging from 73 to 97% (Fig. 3d). Notably, there was substantial variation between tides (Sp < Np) in the first and fourth campaigns, with the highest saturation values observed during neap tides.

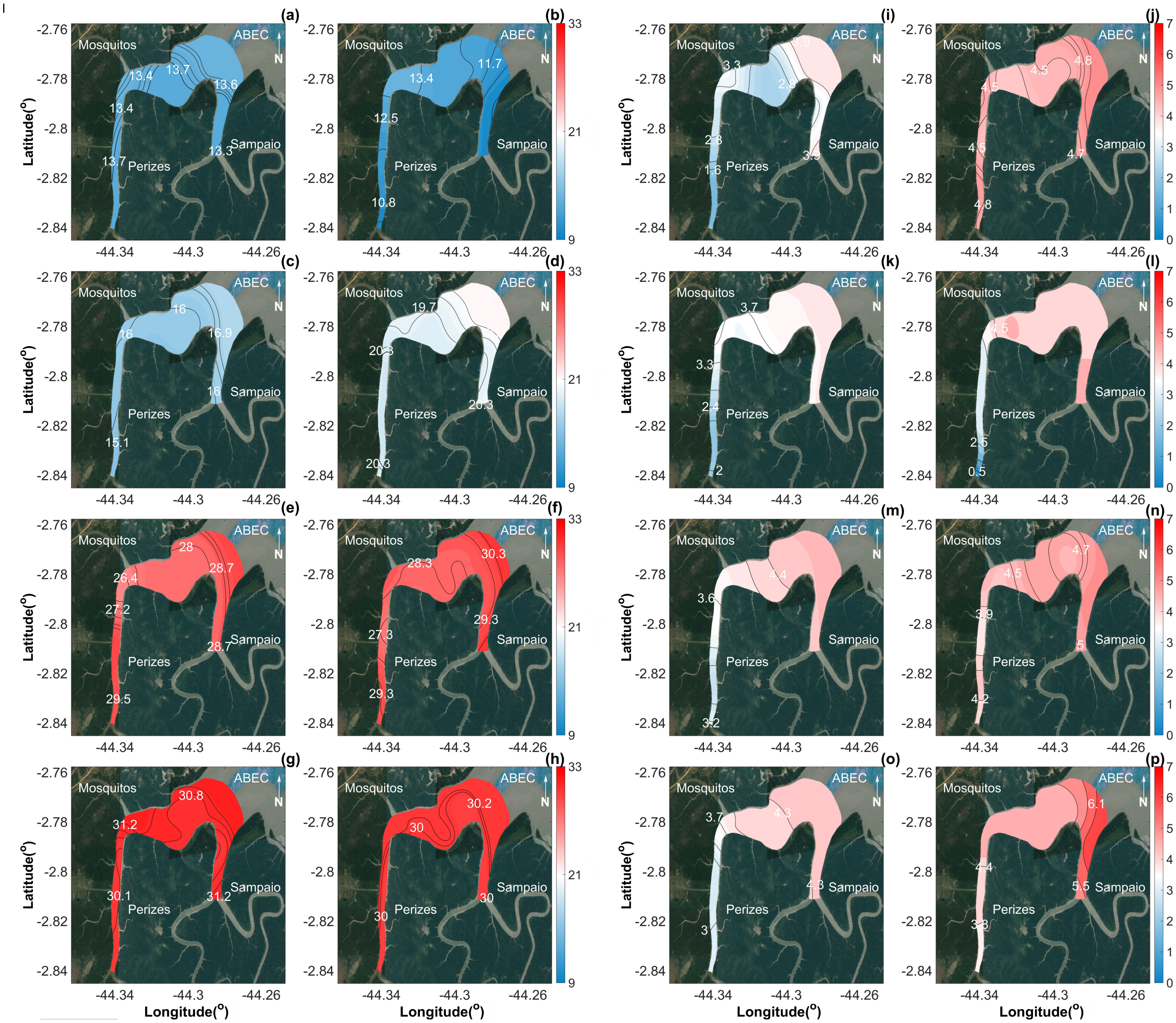

Figure 4. Spatial distribution of salinity (g kg^{-1}) and *DO* (mg L^{-1}) in the Arraial Bay Estuarine Complex. Spring tide: first campaign (a - i), second campaign (c - k), third campaign (e - m) and fourth campaign (g - o). Neap tide: first campaign (b - j), second campaign (d - l), third campaign (f - n) and fourth campaign (h - p).

The turbidity value varied along the estuarine complex (Fig. 3e), with average values of 487, 860, 134, and 258 NTU, for campaigns 1, 2, 3, and 4, respectively. Outliers were also noticed in all campaigns, with a maximum value of 3012 NTU in Arraial Bay (station 5). The average concentration values of TSS were 549, 2004, 191, and 251 mg L^{-1}, for campaigns 1, 2, 3, and 4, respectively (Fig. 5a-h). There was a tidal variation of TSS, with maximum concentrations found during the spring tides. Significant differences ($p<0.001$) were observed for the TSS between seasonal periods (rainy and dry seasons) and tide conditions (spring and neap tide).

When comparing the two depths, it was observed that the concentrations of the samples collected near the bottom were always higher compared to the ones collected at the surface.

The average concentrations of SOM were 288, 1502, 56, and 49 mg L^{-1} for campaigns 1, 2, 3, and 4, respectively. In percentage, the SOM accounted for 44, 52, 28, and 23% of the suspended matter (Fig. 3f). A significant difference ($p<0.001$) occurred between seasonal periods and tide conditions with the highest values occurring under spring tide during the first and second campaigns. The dissolved silicate showed significant differences ($p<0.001$) related to seasonal periods, with values varied from 2.62 to 107.16 µmol L^{-1} (Fig. 5i-p). The highest concentrations occurred in the third campaign (under neap and spring tides) and in the fourth campaign (under neap tide).

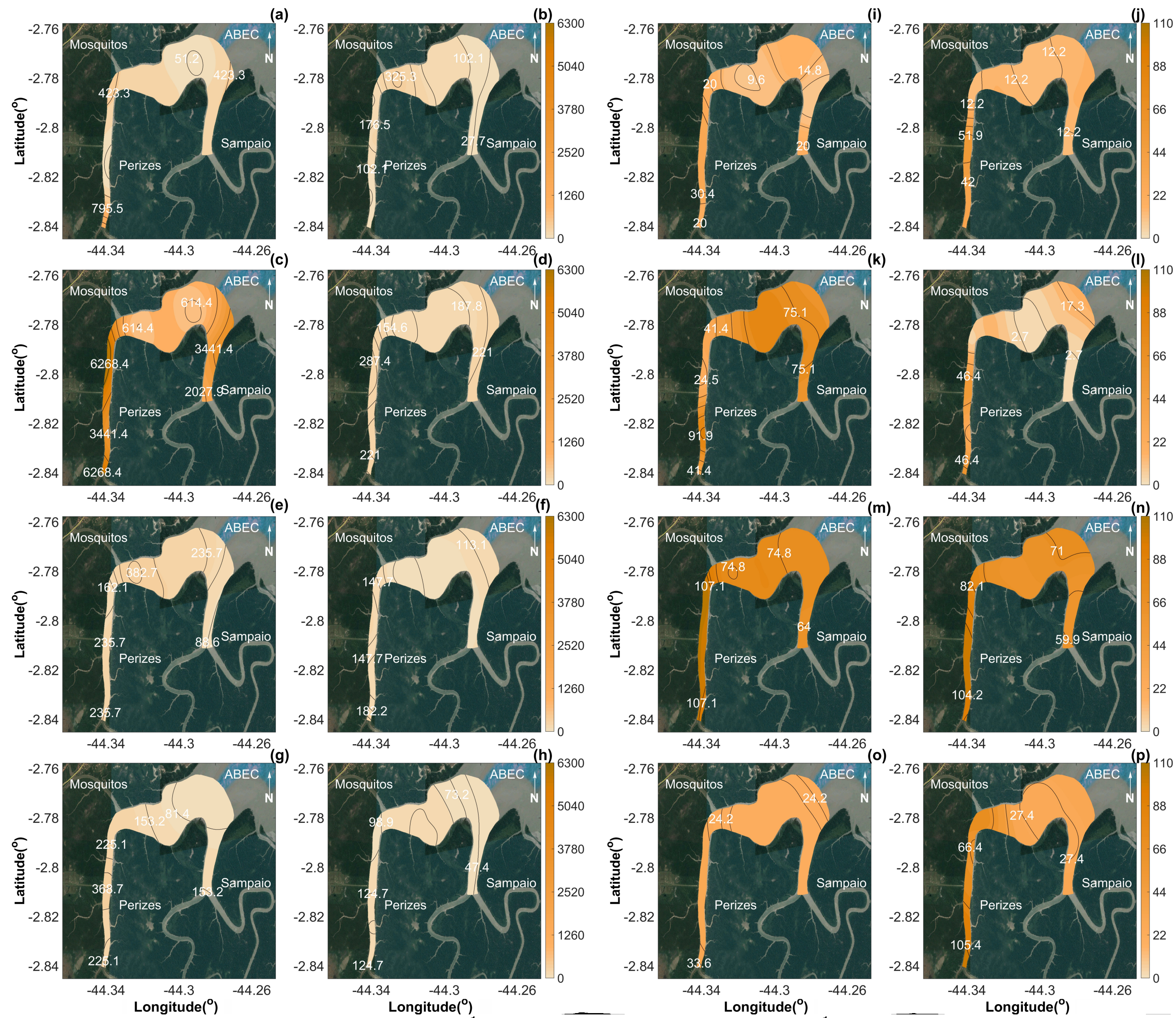

Figure 5. Spatial distribution of *TSS* (mg L^{-1}) and dissolved silicate (µmol L^{-1}) in the Arraial Bay Estuarine Complex. Spring tide: first campaign (a - i), second campaign (c - k), third campaign (e - m) and fourth

campaign (g - o). Neap tide: first campaign (b - j), second campaign (d - l), third campaign (f - n) and fourth campaign (h - p).

Discussion

The ABEC exhibited spatial and temporal variations in the variables considered in this study. During the ebb tide, the ABEC is primarily influenced by fluvial discharge, precipitation, and tidal effects, as documented by Azevedo et al. (2008), Serejo et al. (2020), and Corrêa et al. (2019).

The water temperature in the ABEC remained consistently high throughout the study period, a typical characteristic of tropical estuaries. According to Figueiredo et al. (2006), temperatures in tropical coastal areas exhibit high seasonal stability, dependent on meteorological conditions influencing insolation through cloud cover. Regarding salinity, the study area displayed estuarine water characteristics during the first and second campaigns; however, in the third and fourth campaigns, the environment resembled more of a sea-like condition. Salinity exhibited a negative correlation with discharge ($r=-0.54$, $p<0.001$), indicating that freshwater discharge plays a significant role in ABEC's salinity. This correlation is likely attributed to the substantial decrease in freshwater discharges during the dry period.

Another potential factor was the deficit in rainfall during the year of this study, leading to a reduction in river discharge (-35% in 2014) and an increase in salinity in ABEC. Salinity variation in estuaries in the northeastern region of Brazil is typically associated in the literature with tidal fluctuations and river discharge due to seasonal changes (Passavante and Feitosa, 2004). It is noteworthy that this study demonstrates a salinity pattern similar to that observed by Lima et al. (2021) in the SMEC, where a lag between precipitation volume and river flows into the environment was noted. The impact of freshwater discharge on the estuarine system was more pronounced in June (transition period) than in February (the month with the highest rainfall in São Luís). This delay is evident in the salinity values obtained during the second (dry period) and fourth (rainy period) campaigns. The temperature and salinity distributions were comparable to the values reported by Lima et al. (2021) and Lefèvre et al. (2017).

The water transparency indicated a photic zone of 0.8 m during the ebb tide. It exhibited a negative correlation with elevated turbidity, TSS, and SOM values ($p<0.05$). This leads to a reduction in the photic zone and a significant variation in its thickness. This result corroborated with Azevedo et al. (2008) and Hayami et al. (2019), which report an inverse correlation between TSS concentrations and the photic zone.

During the rainy season, the elevated pH values were likely associated with phytoplankton activities, heightened by an increased continental nutrient flux. According to Esteves (2011), the pH distribution can vary with photosynthesis through CO_2 assimilation, leading to a rise in water pH. The correlations between pH and water transparency ($r=0.53$, $p<0.001$), as well as DO ($r=0.40$, $p<0.001$), suggested that photosynthesis played a crucial role in pH and DO dynamics. However, during the dry season, high values were linked to marine intrusion in this environment. The pH distributions remained within the accepted limits for marine life, typically between 6.5 and 9.0 (Perkins, 1977).

Despite the limited photic zone, the dissolved oxygen (DO) levels in the ABEC exhibited an average value of 3.88 mg L^{-1}, sufficient for the biological processes within the estuarine complex, due to the tidal flux. However, substantial amounts of organic material led to low oxygen concentrations at the inner stations of PR during the rainy season, resulting in hypoxic zones (DO < 2.00 mg L^{-1}). During the ebb tide, the estuarine complex displayed a high DO production capacity, averaging 84% saturation in the waters. The study area can be characterized as a low-saturation environment (Noriega et al., 2022), except for certain inner stations of PR, specifically stations 1 and 2, classified as hypoxic with deficient DO, respectively. This was likely due to organic matter degradation, high total suspended solids (TSS) levels, and bottom sediment resuspension. In the third and fourth campaigns, some stations in the ABEC were classified as supersaturated, with oxygen saturation exceeding 100%. Similar instances of productive environments have been observed in other studies of tropical estuaries (Azevedo et al., 2008; Bastos et al., 2011).

This study in the ABEC, despite spatial sampling during the ebb tide, supports the TSS data observed by Dos Santos et al. (2023), who conducted sampling over a tidal cycle during both rainy and dry periods at a downstream station in the estuary. Similar data were also collected by Lima et al. (2021) in the SMEC. Both studies demonstrate elevated TSS values within this environment, with tidal influence playing a significant role in controlling this parameter. As noted by Serejo et al. (2020) in the ABEC, TSS concentrations were higher in samples collected during the spring tide. According to Allen et al. (1980), high current velocities play a crucial role in the resuspension and transport of sediments within estuarine systems, resulting in elevated concentrations during spring tides. The TSS concentrations in this study were significantly higher than those reported by Dos Santos et al. (2023), Lima et al. (2021), Serejo et al. (2020), Dias et al. (2016), Corrêa et al. (2019), Pamplona et al. (2013), and Monteiro et al. (2015). The maximum TSS concentrations obtained in the PR were compared to concentrations observed in another macro-tidal estuary located in Gironde, France (Sottolichio et al., 2011).

Similar to TSS, the SOM was higher during the first and second campaigns (spring tide). In some stations, suspended organic matter accounted for more than 91% of TSS. During the spring tide, the percentage of SOM (%SOM) exhibited a significant increase compared to neap tides, likely associated with organic matter from the mangrove forest and the resuspension of organic matter.

During the rainy season, river discharges dramatically increased terrestrial organic matter in the complex, leading to higher dissolved oxygen consumption. In the dry season, SOM concentrations decreased due to less terrestrial organic matter entering the estuarine system and the intrusion of oxygenated marine water.

High turbidity was observed during the second campaign (3012 NTU), with lower values in the first campaign (11 NTU). Strong positive correlations were found between turbidity and TSS ($r = 0.75$, $p<0.001$), and between turbidity and %SOM ($r = 0.65$, $p<0.001$), indicating that these variables were likely the primary factors controlling water turbidity in ABEC. The turbidity distribution obtained in this study aligned with findings from Serejo et al. (2020) and Pardal et al. (2011).

DSi exhibited the highest concentrations in the inner part of the ABEC, particularly in the PR region. According to Liu et al. (2009), DSi concentrations are typically linked to continental inputs. Therefore, the elevated DSi concentration may be associated with erosive processes along the environment's margins, as well as deforestation for agriculture or shrimp farming (Chen et al., 2014).

DSi showed a positive correlation with salinity ($r = 0.51$, $p<0.001$) and a negative correlation with discharge ($r = -0.54$, $p<0.001$), contrary to findings in other studies (Bradley and Philip, 1999; Pamplona et al., 2013). These inverted correlations are likely influenced by two factors: the observed delay in salinity values and the wind. Given that this environment is influenced by trade winds, particularly during the dry period, the winds contribute to a significant increase in wave height within ABEC. This intensifies erosive processes along the margins, banks, and channels in shallow areas (Le Hir et al., 2001).

Higher levels of DO can enhance the transformation of organic particulate matter into dissolved inorganic form. According to Tanaka and Takahashi (2013), Si in freshwater primarily exists as particles, colloids, and a small amount in the ionic form. In estuaries, particles and colloids precipitate after contact with NaCl. Consequently, Si is significantly released from particulate to dissolved form (DSi) and can serve as a nutrient available to diatoms. The DSi values obtained in this study are similar to values reported for other estuaries (Monteiro et al., 2015; Pamplona et al., 2013; Pardal et al., 2011).

Conclusion

The Arraial Bay Estuarine Complex (ABEC) showed some characteristics typical of other tropical estuaries: seasonality, fluvial contribution, and tidal and marine influence. The salinity was influenced by local seasonality, with the lowest values being observed in March and July 2014, while the highest values were observed during October 2014 and February 2015. About the obtained TSS values, despite the region exhibiting limited anthropogenic activity, markedly elevated concentrations were observed in the environment (TSS_{max} = 6,2 g L^{-1}). These values deviate from those obtained in other macro-tidal environments along the Brazilian coastline. In the context of this study, DSi delineated areas within the ABEC that exhibited evidence of continental input, notably the PR region which demonstrated the highest concentrations throughout the study period. Presumably, this influx of DSi emanates from the ecosystem's margins, a consequence of erosive processes induced by tides and wind-generated waves. Another important process in the Silicon (Si) cycle within estuaries may have contributed to the DSi levels, given that a substantial portion of Si arrives in the estuary in particulate form, subsequently undergoing recycling within these environments. This process renders Si readily available for assimilation by diatoms. Although this study was constrained by its exclusive focus on the ebb tide and its relatively short duration, which did not cover a complete semidiurnal tidal cycle in the ABEC, the sampling endeavor marks a substantial advancement in understanding the dynamics of this macro-tidal estuary located between the Brazilian semiarid region and the Amazon rainforest. Furthermore, the results hold the potential for broader applicability to similar areas in tropical zones worldwide.

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