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A Compartimentalização Sedimentar de um Estuário do Nordeste Amazônico

A Sedimentology Compartmentalization of a northeast Amazon Estuary

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Abstract

Sedimentological studies are the baseline to understand estuary contamination or pollution since the sedimentary characteristics are responsible for controlling and governing metals and nutrients distribution over the estuary. Hence, our main objective was to evaluate the sedimentary characteristics of the tide-dominated Mocajuba estuary located on the eastern Amazon coast, based on the sediment deposit dynamics (i.e., granulometry; hydrodynamics, and deposition of organic matter content and calcium carbonate). Granulometric, Cluster, and Principal Components Analysis was carried on classifying and identifying groups of sediments across the estuary. Three cluster groups and two environments (marine and estuary) were recognized. Cluster 1 represents the marine environment located at the mouth of the estuary, with a predominance of fine sandy sediments. This type of sediment is supplied by the continental shelf, which formed sandbanks and islands at the estuary mouth. Cluster 3 predominantly represents the estuarine environment and occupies the rest of the studied area, with fine sediments, a higher percentage of organic matter (OM), and calcium carbonate ($CaCO_3$). The estuarine environment had the highest percentage of fine sediments, due to the large muddy plains of the Amazon. The estuary showed low values of OM, mainly associated with fine grain size. The Mocajuba estuary has a small influence of contaminating effluents and human activities, thus the OM is mainly from natural sources. Calcium carbonate associated with fine particles, OM, and located at an upstream sector is an uncommon setting. Usually, $CaCO_3$ is found near the coast with sand sediments. This $CaCO_3$ association with fine sediment confirms that the tidal intrusion reaches long distances in the estuary, developed due to the local hydrodynamics - the action of the tides allied to the low river flow creating a favorable condition for this process. Based on this study, it was possible to advance our understanding of the Amazonian estuary environments and how the local tide-dominated dynamics of the region influence sedimentation processes. This will be very useful for future studies concerning the assessment and monitoring of the estuary, and for evaluating possible ecological changes.

Resumo
Os estudos sedimentológicos são a base para entender a contaminação ou a poluição de estuários, uma vez que as características sedimentares são responsáveis por controlar e governar a distribuição de metais e nutrientes no ambiente. Assim, nosso principal objetivo foi avaliar as características sedimentares do estuário do rio Mocajuba com base na dinâmica do depósito de sedimentos (ou seja, granulometria; hidrodinâmica e deposição de conteúdo de matéria orgânica e carbonato de cálcio). O estuário Mocajuba é dominado pela maré e está localizado na costa leste da Amazônia. A análise granulométrica, de cluster e de componentes principais foi realizada para classificar e identificar grupos sedimentares ao longo do estuário. Três grupos e dois ambientes (marinho e estuarinos) foram reconhecidos. O Cluster 1 representa o ambiente marinho localizado na foz do estuário, com predominância de sedimentos arenosos finos. Esse tipo de sedimento é fornecido pela plataforma continental, que forma bancos de areia e ilhas na foz do estuário. O cluster 3 representa predominantemente o ambiente estuarino e ocupa o estuário acima, com sedimentos finos, maior porcentagem de matéria orgânica (MO) e carbonato de cálcio (CaCO3). O ambiente estuarino apresentou o maior percentual de sedimentos finos devido às grandes planícies de inundação da Amazônia, que possuem alta predominância de sedimentos finos. O estuário apresentou baixos valores de MO, principalmente associados ao sedimento siltosos e argilosos. O estuário de Mocajuba tem pouca influência de efluentes contaminantes e atividades antrópicas, portanto a MO é principalmente de fontes naturais. O carbonato de cálcio associado a partículas finas, MO, e estar localizado em um setor a montante do estuário é um cenário incomum. Normalmente, o CaCO3 é encontrado próximo à costa com sedimentos arenosos. Esta associação de CaCO3 com sedimentos finos confirma que a intrusão de maré atinge grandes distâncias no estuário, desenvolvida devido à hidrodinâmica local - a ação das marés aliada a baixa descarga do rio criando uma condição favorável para este processo. Com base neste estudo, foi possível avançar em nossa compreensão dos ambientes estuarinos amazônicos e como a dinâmica local dominada pela maré da região influencia os processos de sedimentação. Isto será muito útil para futuros estudos de avaliação e monitorização do estuário, e para avaliar possíveis alterações ecológicas.

Palavras-Chave: Amazônia, Granulometria, Matéria Orgânica, estuário do rio Mocajuba, Sedimentos.

1. Introduction

In recent years, ecosystems in coastal wetlands have been reported as dynamic ecosystems, with high variation in their spatial-temporal parameters and extent (Ramsey III and Laine, 1997; Rodrigues & Souza-Filho, 2011; Adame *et al.,* 2013). In this scenario, the Amazon Coastal Zone (ACZ) includes several estuaries, tidal plains, beaches (oceanic and estuarine), and the greater continuous range of mangroves in the world, located in the east sector of the Amazon River (Souza-Filho, 2005).

The Amazonian aquatic ecosystem is a complex system formed by several distinct fractions of water bodies, such as rivers, lakes, and estuaries. All this dynamic is mainly caused by its geographic location, which is in a region that concentrates a high abundance of fresh water, with a complex connection with the ocean, since most of the river's discharge is in the Atlantic ocean. This complexity in Amazonian estuaries is highly linked to physical habitat changes caused by forcings such as precipitation and seasonality, diurnal tidal variations, and the input of continental waters, which act on different time scales (Prestes *et al.,* 2020), especially from the Amazonas river and Pará river. In turn, it results in a supply to the coastal zone, through intense transport of sediment toward the coast caused mainly by semidiurnal spring tides with amplitudes greater than 4m in this region (Souza Filho *et al.,*, 2003; Asp *et al.,* 2013). Several studies have focused their efforts on unraveling several facets of Amazonian estuaries (i.e., sedimentary deposition, water quality, and tidal dynamics) (Peixoto *et al.,* 2018; Machado *et al.,* 2022; Gomes *et al.,* 2020, 2021), however, this is the first sedimentological investigation for the Mocajuba river estuary. Sedimentological studies are the baseline to understand estuary contamination or pollution since the sedimentary characteristics are responsible for controlling and governing metals and nutrients distribution over the estuary.

Thus, understanding the hydrodynamics and sedimentation of the Amazonian environment is essential for its management, aiming at maintaining the ecosystem (Gruber *et al.,* 2003). According to Flocks *et al.,* 2009, we must determine the basin's natural state to measure environmental degradation. Also, among federal, state, and municipal Conservation Units, Pará accounts for 83 UCs, with about a third of its territory devoted to these areas (Vedoveto *et al.,* 2014). The Mocajuba estuary was used as a study case, located at ACZ, Brazil. The estuaries of the region present a landscape connectivity between each other, and the major forces (tides and currents) can facilitate the exchange between coastal ecosystems of estuarine components as organic and inorganic nutrients, chemical pollutants, pathogens, sediments, and organisms, (Nagelkerken, 2009).

The literature has reported over the last few decades that fine-grained fractions, such as clay, play an active role in the agglutination of metals (Fostner & Wittman 1981; Cruz *et al.,* 2013). Also, according to Chakraborty *et al.* (2015) and Gaonkar *et al.* (2021), OM can be another factor that controls the metal's association with sediments, showing a high correlation between these parameters. Related to nutrients, Gaspar *et al.* (2013) found a correlation between specific phosphorus fractions, $CaCO_3$ content in sediments, and grain size. Thus, the knowledge of the source and sink areas is important to mitigate the potential impacts of different origins. The sedimentological information can help to identify areas of high and low rates of sediment transportation, and consequently, accumulation, which will directly influence the accumulation of pollutants and biological communities, mainly benthic (Kanaya *et al.,* 2016; Yeager *et al.,* 2018; Muniz *et al.,* 2019).

The estuary geomorphology and the tidal regime influence the spatial and temporal variation of salinity in the system (Prandle, 2009). Thus, it is important to investigate the estuarine sediment characteristic and the major influence in the estuary (marine or terrestrial) to aid future resource management. The estuary has great potential for the development of sustainable activities and is used as such by the population. The environmental characteristics favor activities such as mariculture, artisanal fishing, crab fishing, and oyster cultivation, among others (ICMBio, 2014). Therefore, sedimentological knowledge and confirmation of the marine influence areas are important to increase this potential. Hence, our main objective was to evaluate the sedimentary characteristics of the tide-dominated Mocajuba estuary based on the sediment deposit dynamics (*i.e.,* granulometry; hydrodynamics, and deposition of organic matter content and calcium carbonate).

2. Methodology

Study Area

The Amazon Coastal Zone has its extension, stretching from Oiapoque river in Amapá (5°N, 51°W) to São Marcos Bay in Maranhão (2°S, 44°W) (Pereira *et al.,* 2009). The Mocajuba estuary is in Pará state and integrates the eastern sector of the Amazon coast. This region is a plain terrain, with sand and clay sediments (FAPESPA, 2018). The most recent stratigraphy of the region follows the deposits of the Pirábas Formation in the lower part, later the Barreiras and Pós-Barreiras Formation (Rossetti *et al.,* 2001). According to Aguilera *et al.* (2019), the Pirabas formation is characterized by a shallow-marine carbonate platform with high fossil diversity and abundant micro- and macrofossil remains. The Barreiras formation is composed of sedimentary siliciclastic rocks that extend along the Brazilian coastline, from the State of Rio de Janeiro to Amapá (Araújo *et al.*, 2006). The Pós-Barreiras formation defines the sediments deposited above de Barreiras formation, and its characteristic depends on the sedimentary deposition (Rossetti *et al.,* 2013; Souza *et al.,* 2020).

Rainfall is high from January to July, corresponding to the wet season, and the dry season corresponds to the months of August to December (Moraes *et al.,* 2005). The Mocajuba estuary is a coastal plain estuary, with a shared mouth and a channel that connects to the Mojuim estuary, in the west. It also has a connection to the Curuçá estuary through the Muriá channel, in the east (figure 1). The maximum depth of the Mocajuba estuary is 38m due to the presence of a tectonic fault (Asp *et al.,* 2013). According to the Observatório da Costa Amazônica (OCA, 2021), at the tide gauge station located at the mouth of the Mojuim-Mocajuba estuarine system, the tides reach amplitudes of up to 4.8 m in spring tide conditions and has a discharge of $8m^3.s^{-1}$ in the dry season and $68.5\ m^3.s^{-1}$ in the wet season (Asp *et al.,* 2013). Due to its characteristic of tidal dominance (Dalrymple, 1992), this estuary developed elongated sandy bars at its mouth (figure 2).

The residual volume transport (at equinoctial tide) is $24m^3.s^{-1}$ in the dry season, representing a small seaward exportation flow, and $-248m^3.s^{-1}$ in the rainy season, showing a landward importation flow (Gomes, 2018; Rollnic *et al.,* 2020a). In the rainy season, there is a reduction in flow due to the influence of the spring tide, which reduces the flow in Mojuim and generates imports in Mocajuba (accumulation of water and sediment). The Mocajuba estuary is well mixed through the water column (figure 3). According to Gomes (2018) and Rollnic *et al.* (2020a), the Mocajuba estuary has high salinity values throughout the estuary that decrease in salinity upstream, concentrating the highest values near the estuary mouth.

Sample collections and processing

Surface sediments were sampled with Van Veen's dredger in 71 points in the Mocajuba estuary in November 2015 (dry season), corresponding to ~18km of the river (figure 1). The Organic Matter (OM) content and Calcium Carbonate ($CaCO_3$) were analyzed using the calcination method (modified from Dean, 1974).

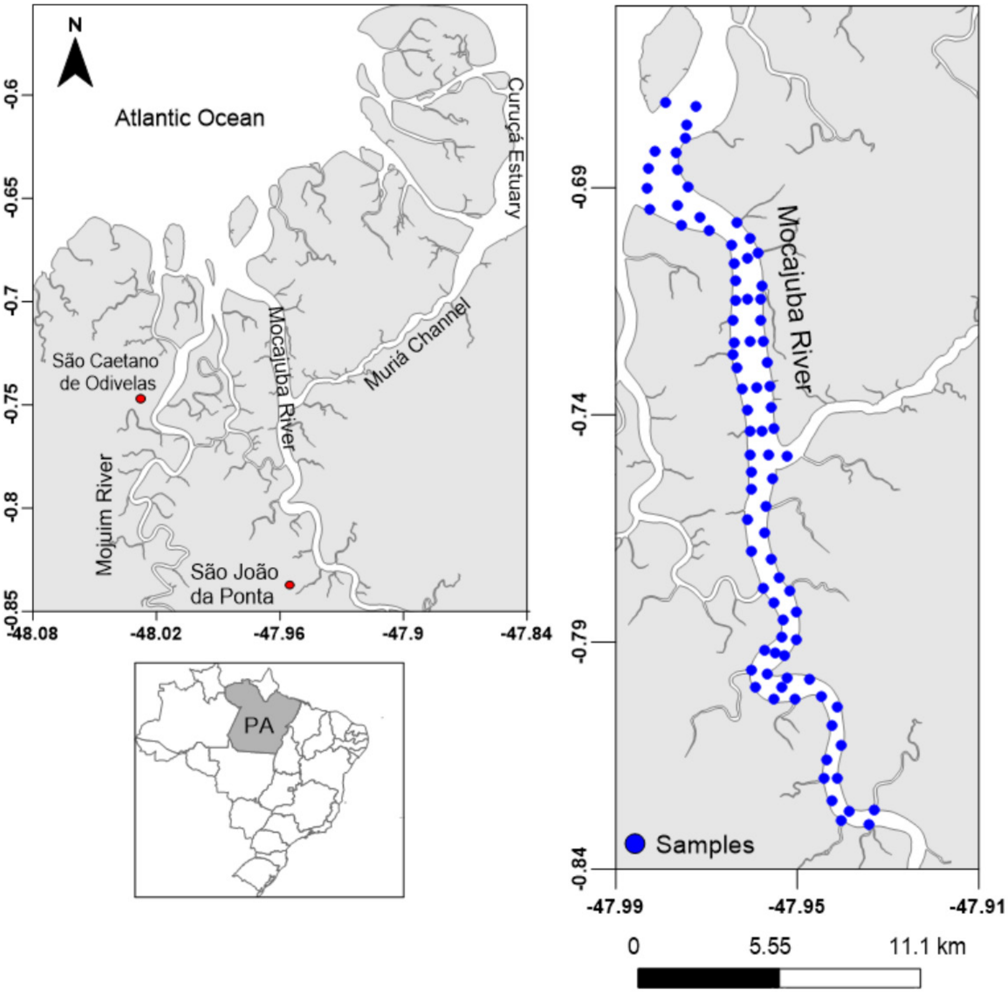

Figura 1. Mapa da região do estuário de Mocajuba. Os círculos azuis representam os pontos de amostragem.
Figure 1. Map of the region of the Mocajuba estuary. Blue circles represent the sampling points.

For the granulometry analysis, the sediment's OM content was removed by the immersion of the sediment with Hydrogen Peroxide 30% (H_2O_2) (Robinson, 1922; Mikutta *et al.,* 2005). The sieving methods followed the IS: 2720 (Part 4) – 1985 method, using 50g of sediment. Thirty samples from the lower estuary presented a higher percentage of sand, thus, dry sieving was performed. In the remaining 41 samples, a wet sieving methodology was used. To separate the silt and clay fractions, Sodium Pyrophosphate (Bates *et al.,* 1978) at 10% was used. The samples were centrifuged at 1000 rpm for 2 minutes, the supernatant (water and clay) was removed, and the decanted material (silt) was dried and weighed.

For spatial analysis, the Sysgran 3.0 program was used to generate the diagrams of Pejrup (1988) to define the hydrodynamics, and the classification table of Folk and Ward (1957) to define the sedimen-

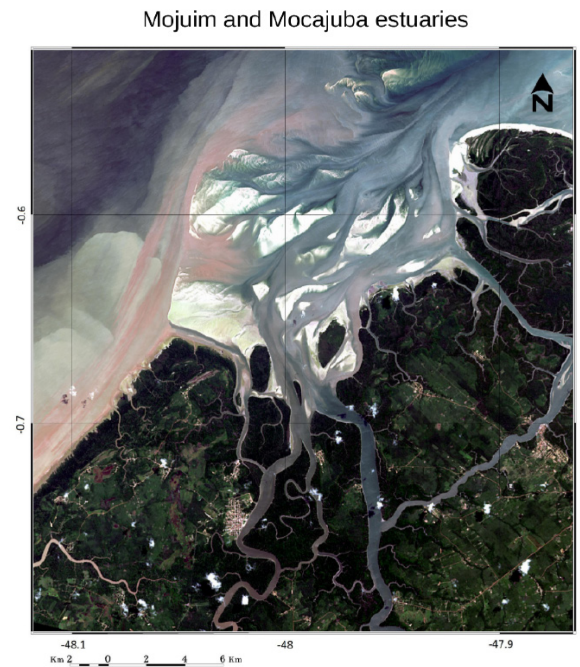

Figura 2. Bancos de areia na foz do estuário de Mocajuba em 2018 obtidos com uma imagem Landsat.
Figure 2. Sandbanks at the Mocajuba estuary mouth in 2018 obtained with a Landsat image.

tary characteristics (*i.e.,* selection, sand percentage, mud percentage, grain size). After this procedure, we obtained the classes: VCS - very coarse sand; CS - coarse sand; MS - medium sand; FS - fine sand; and VFS - very fine sand, silt, and clay. Thus, the sedimentary distribution and characterization maps were generated using the Kriging interpolation method.

Statistical analysis

For statistical analysis, the variables standard deviation, mean, sedimentary characteristics, OM percentage, and $CaCO_3$ content were tested in a Simpson correlation analysis, to remove the correlation effect between the variables. Autocorrelated variables (>70%) were removed from the analysis. Only the variables granulometry, OM percentage, and $CaCO_3$ content were adopted. As these variables have different measurement scales, a standardization was performed (Eq. 1):

$$Z=(X-\mu)/\sigma \qquad \text{Eq. 1}$$

Where X is the value to normalize; μ represents the arithmetic mean of the distribution and σ represents the standard deviation of the distribution. The Cluster Analysis was performed on the sediment data to evaluate the similarities between the samples and to investigate if there is a group formation between them. The Principal Component Analysis (PCA) was used to summarize the information contained in the OM, $CaCO_3$, and sedimentological variables for the representation of data in linear combinations.

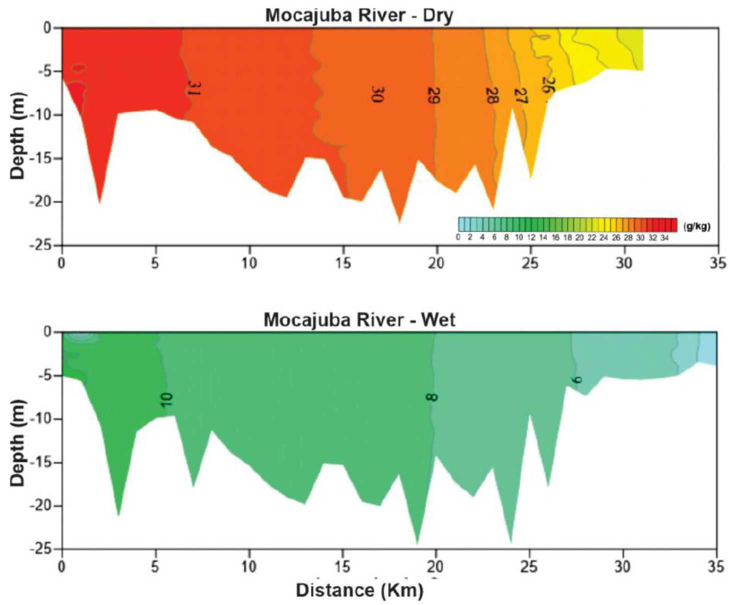

Figura 3. Perfis verticais de salinidade foram medidos ao longo de uma seção longitudinal do rio Mocajuba, períodos secos (acima) e chuvosos (abaixo). Fonte: Gomes (2018) e Rollnic *et al.* (2020a).
Figure 3. Vertical salinity profiles were measured along a longitudinal section of the Mocajuba River, dry (above) and rainy (below) periods. Source: Gomes (2018) and Rollnic *et al.* (2020a).

3. Results

Distribution and sedimentary parameters

According to Folk and Ward (1957) classification, the mean particle composition of the Mocajuba estuary was 44.2% muddy fraction and 55.8% sandy fraction (Figure 4A). In this regard, we could see that there is a dominance of sandy sediments, especially coarse sand to very fine sand granulometry. It is possible to define two major environments, from north to south (Figure 4A). The first environment can be considered a marine-dominated environment since it shows a greater percentage of sand (90.59 %), located at the estuary mouth. Then we could observe a mixed area (central basin), with a smaller fraction of sediments, as very fine sand, and silt. Adjacent to the Muriá channel there is a higher concentration of sandy sediments. According to Reis (2016, non-published), this channel is mainly composed of sand sediments, thus it may be exporting its sediments into the estuary.

The estuarine sediment in these two environments was classified as: poorly selected (60.6%) and moderately selected (23.9%), which could represent moderate to high hydrodynamics (*i.e.,* tidal and wave movement as a driver for greater or lesser sediment deposition activity). Figure 4B shows that the estuary presents just a few areas with low or very low hydrodynamics, which may indicate intense tidal activity in most of the estuary. However, in these areas, with low hydrodynamics, we could notice deposits of very fine particles (*i.e.*, silt). Surprisingly, OM concentration

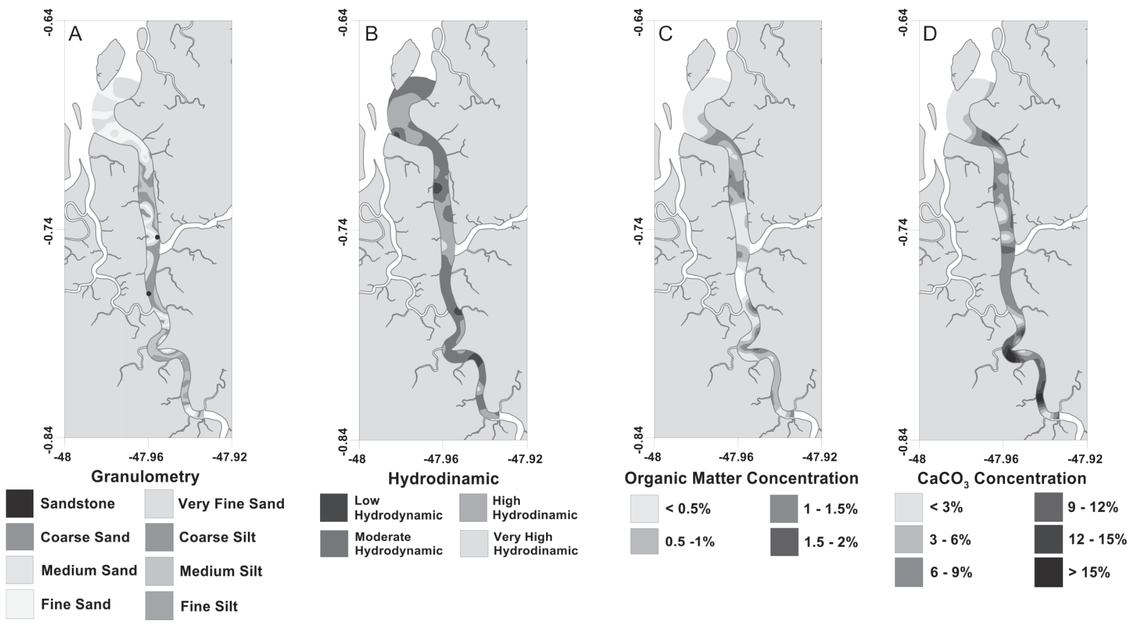

Figura 4. Mapas de distribuição baseados nos diagramas de Perjup e Folk & Ward e análise de calcinação, resultando em a) Granulometria; b) Hidrodinâmica; c) Porcentagem de Matéria Orgânica do estuário de Mocajuba; e d) Porcentagem de Carbonato de Cálcio.

Figure 4. Distribution maps based on Perjup and Folk & Ward diagrams, and Calcination analysis, resulting in a) Granulometry; b) Hydrodynamics; c) Percentage of Organic Matter of the Mocajuba estuary; and d) Percentage of Calcium Carbonate.

did not exceed a maximum of 2% along the estuary and oscillates from very low concentrations in sandy sediments (less than 0.5%) up to 2% in the finer sediments (figure 4C). In contrast, $CaCO_3$ concentration had a remarkable variation along the estuary, ranging from 20.98% maximum to 0.24% of minimum in the upper sector, and was associated with silt sediments (figure 4D). At the estuary mouth, we see a lower concentration of $CaCO_3$ (<3%).

Statistical analysis

A Cluster analysis (CA) and a Principal component analysis (PCA) revealed the formation of three distinct sedimental groups. The cluster distribution is presented in table 1. The first cluster group was located near the mouth, composed of a high percentage of fine sand. This group is, also, located in an open area with a moderate to higher hydrodynamic, which explains the lower percentage of OM and $CaCO_3$, since the influence of the tide and wave energy is high. On the other hand, cluster group number two surprisingly does not exhibit any distribution pattern based on sedimentation along the Mocajuba estuary, which may reflect your “between zones/groups and blending zone” characteristics, represented mainly with medium sand.

Clusters 1 and 2 both show a very similar lower percentage of mud and OM. Additionally, we could observe a slight increase (~0.10%) in the OM content in cluster group 3. Thus, cluster 3 showed the highest percentage of mud sediment (<80%) as well as $CaCO_3$ (<9%). In the estuary groups distribution, there is a clear division between groups 1 and 3, while group 2 is well mixed with the other groups throughout the study area (figure 5).

Tabla 1. Características sedimentares médias dos grupos de setorização.
Table 1. Mean sedimentary characteristics of the sectorization groups.

Cluster	N samples	Classification	% Gravel	% Sand	% Mud	%OM	%$CaCO_3$	Hydrodynamic	Selection
1	14	Very fine sand to Fine sand	0.01	90.59	9.40	0.67	6.25	Moderate to High	Poor
2	22	Medium sand	3.35	90.85	5.80	0.68	5.99	High	Moderate
3	35	Medium silt to Coarse silt	0.39	15.90	83.71	0.75	9.38	Moderate to High	Poor

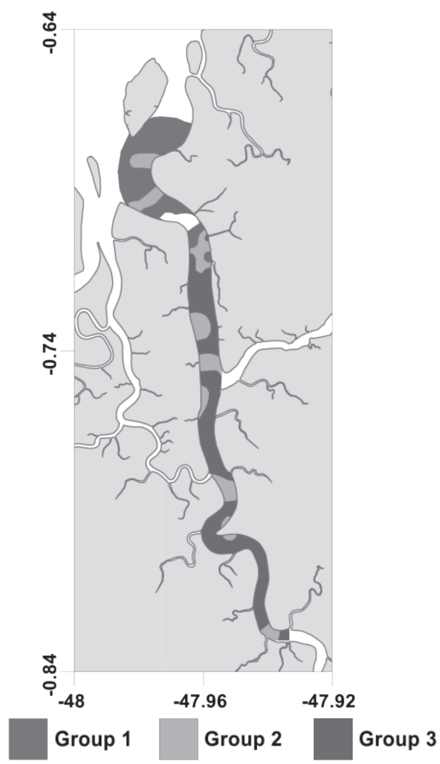

Figura 5. Distribuição de grupos de aglomerados no estuário de Mocajuba.
Figure 5. Cluster group distribution in Mocajuba estuary.

The PCA allows us to identify distinct clouds of points, which can be interpreted as groups with similar sedimentary characteristics (*i.e.,* also a group formation approach). The first two axes of PCA explained 67.2% of the total data variation (figure 6, table 2). For axis 1 the variables that contributed most positively were Gravel, VCS, CS, MS, and FS, and negatively VFS, Silt, Clay, OM, and CaCO3. For axis 2, Gravel, VCS, CS, Silt, Clay, OM, and $CaCO_3$ contributed positively, just MS, FS, and VFS contributed negatively. We observed that the cutoff value was 0.7. After sorting it is visual the formation of 3 different groups in relation to the sedimentological characteristics (figure 7), similar to the Cluster analysis. Factorial plans (figure 7) indicate the clear influence of fine sand sediments on the isolation of cluster 1; coarse sand percentage on the isolation of cluster 2; and the influence of fine sediment percentage in cluster 3.

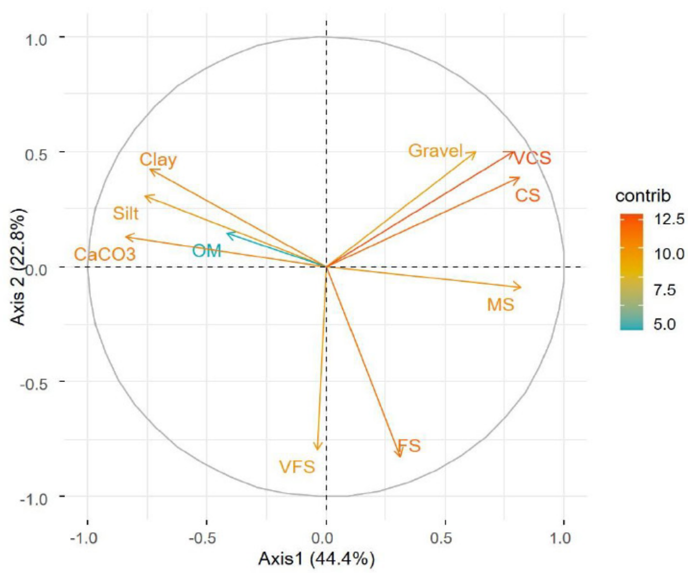

Figura 6. Representação gráfica das coordenadas das variáveis sedimentológicas e suas correlações com os eixos 1 e 2.
Figure 6. Graphical representation of the coordinates of the sedimentological variables and their correlations with axes 1 and 2.

Tabla 2. Carregamentos de cada variável, autovalores, um critério de parada (Broken-Stick), e contribuição de cada eixo da Análise de Componentes Principais.
Table 2. Loadings of each variable, eigenvalues, a criterion of stop (Broken-Stick), and contribution of each axis of the Principal Components Analysis.

Variables	Axis 1	Axis 2
Gravel	0.298	0.332
Very Coarse Sand	0.373	0.331
Coarse Sand	0.385	0.255
Medium Sand	0.389	-0.059
Fine Sand	0.150	-0.545
Very Fine Sand	-0.016	-0.527
Silt	-0.359	0.202
Clay	-0.349	0.282
OM	-0.198	0.095
$CaCO_3$	-0.399	0.087
Eigenvalue	4.439	2.280
Broken stick	2.928	1.928
Contribution of the axes	44.4%	22.8%

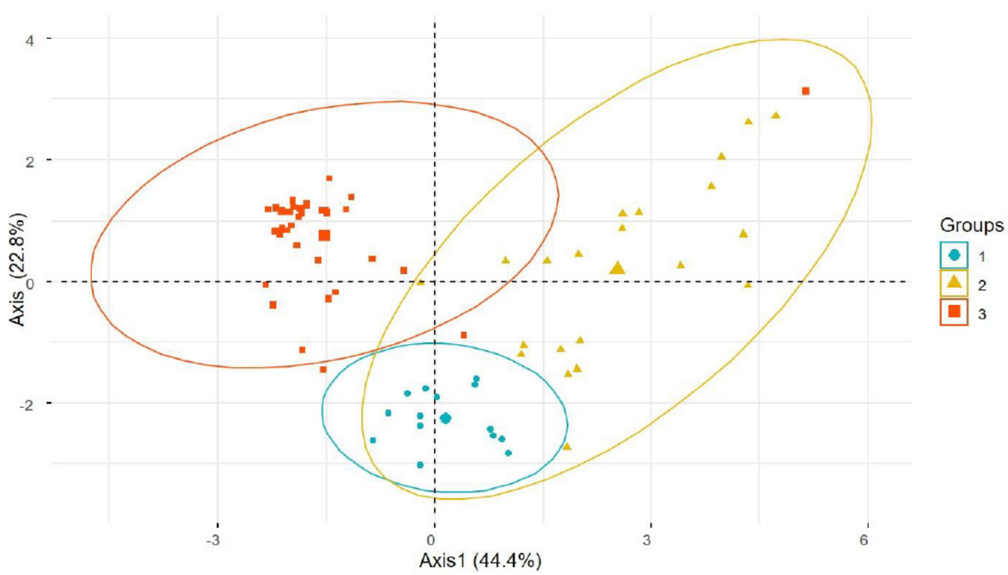

Figura 7. As variáveis sedimentológicas e suas correlações com os eixos 1 e 2 com a formação dos grupos.
Figure 7. The sedimentological variables and their correlations with axes 1 and 2 with the formation of groups.

4. Discussion

Cluster 1 presents fine and very fine sands, and we can identify that it is predominantly distributed at the lower section of the Mocajuba estuary. The Landsat satellite image from 2018 (figure 2) shows the formation of sandbars located at the mouth of the Mocajuba and Mojuim estuary, corroborating the findings. Peixoto *et al.* (2018) also found similar granulometry (fine and very fine sand) at the confluence between Mojuim and Mocajuba estuaries, while studying the Mojuim estuary. Thus, Cluster 1 shows evidence of greater marine influence since this type of sediment is generally supplied by the continental shelf (Coutinho, 2005; Souza-Filho *et al.*, 2009; Flemming, 2011).

The middle estuary sector has a specific channel geometry, "straight"-meandering-"straight" (Dalrymple & Choi, 2007), visible in the Mocajuba estuary. This sector is represented mainly by the third cluster, and showed a greater estuarine influence, supported by the high salinity values, minimum river flow, and the residual volume transport found in the Mocajuba estuary (Rollnic *et al.,* 2020a). The third cluster had the highest muddy fraction occurrence in comparison to the other clusters. The fine sediments may be provided by the muddy plains around the estuary (França *et al.,* 2016), as a result of the well-developed muddy plains and floodplains of the Amazon region (Gregório & Mendes, 2009).

The development of the muddy plains can be influenced by the Amazon river and Pará river plumes in the rainy season, when the plume is widespread over the continental shelf and can expand towards the southeast, supplying fine sediments to the region (Asp *et al.,* 2018; Rollnic *et al.,* 2020b). The muddy fraction also goes through the processes of the interaction of tidal and fluvial processes, which can cause physical-chemical changes, i.e., flocculation in the water column (Son & Hsu, 2011), resulting in the deposition of flocculated sediments at the bed of the estuary. The grain sizes found in the Mocajuba estuary are in accordance with Dalrymple and Choi (2007) since the grain size downstream has larger proportions than the middle estuary (central basin).

The second cluster group represents a transition between the estuarine and fluvial environments, mainly composed of sand, from medium to gravel sediments. Mechanical processes in sediment transport are the main factors in decreasing sediment particles along river pathways (from coarse material - from gravel to clay) (Flemming, 2011). However, tides' influence can cause a mix in the surface sedimentary layer, bringing coarse sediments into the estuary (crossed sedimentary lens), through bidirectional transport. Tides modify the river outflow (discharge) promoting a rapid mix and momentum exchange between the river and the ocean, redirecting the sediment-transporting flows and remodeling pre-existent deposits (Wright, 1977). The source of the Mocajuba estuary coarse sediments may comprise not only the riverbed but also gravel plains, tabular plateaus, and rocky outcrops located at the margin and inside the river reworked through erosion (França *et al.,* 2016).

The high energy found in the Mocajuba estuary, and the bimodal transport also affect the sediment selection. Throughout the estuary, the selection range was classified as poor to moderate selection. According to Ponçano (1986), the selection is related to previous conditions, before the sedimentation occurs, and it reflects the flux energy variation of the environment. The literature has reported that sediments in rivers follow gradual sedimentation according to the grain size (coarse to fine) due to the unidirectional flow energy (Flemming, 2011), generating a good or moderate sediment selection (Nichols, 2009). However, tidal agitation is responsible for mixing sediment deposits, causing a poor selection.

The mean level of OM had a maximum of 2% in the Mocajuba estuary. Group 3 showed a higher percentage of OM, which is expected since OM has a higher correlation with clay and silt sediments (e.g., through adsorption) (Sarkar *et al.,* 2018). Comparatively, for the Mojuim estuary, Peixoto et al. (2018) found higher values of OM, up to 10% in mud sediments. The author attributed this value to natural sources (mangroves, freshwater discharge, and tidal channels) and from municipalities in the surrounding area of the estuary. Both samplings in the Mojuim-Mocajuba estuaries occurred during the Amazon dry season and in the El Niño period, which means that Mojuim effectively shows higher content in organic matter compared to the Mocajuba estuary. According to Vilhena *et al.* (2018), the Mocajuba estuary has a small influence of contaminating effluents and human activities, thus the OM is mainly from natural sources.

Also, OM contents can be considered a useful tool of evidence to the anthropic interference in the estuaries. Concentrations higher than 5% of OM are generally associated with anthropic inputs or anthropic activities (Cunha & Calijuri, 2008; Zhang *et al.,* 2009; Oliveira *et al.,* 2014). The OM content found in this research is low in comparison to eutrophic estuaries from Brazil. Noronha *et al.* (2011) found values of ~7% to 25% in Timbó river; and Oliveira et al. (2014) found values of 1% to 15% of OM content in the estuarine complex of the Capibaribe rivers, Beberibe and Pina Basin. Also, according to Vilhena *et al.* (2018), the sedimentary organic matter in the Mocajuba river estuary is mainly composed of marine organic matter (60%), which shows a greater marine influence over the sedimentary characteristics.

Calcium carbonate associated with fine particles, OM, and located at an upstream sector is an uncommon setting. Usually, $CaCO_3$ is found near the coast with sand sediments (Oliveira *et al.,* 2014). The $CaCO_3$ association with fine sediment confirms that the tidal intrusion reaches a greater distance in the estuary, which provides a favorable environment for the establishment of $CaCO_3$ carapace organisms since many organisms required a salinity range of 15 to 25 g/kg for their best development (Funo *et al.,* 2015). Thus, the association of cohesive sediments and $CaCO_3$ verified upstream of the system indicates the relationship with the local hydrodynamics - the action of the tides allied to the low river flow creates a favorable condition for this process. The Mocajuba estuary is macrotidal and has landward importation flow (Rollnic *et al.,* 2020a), mainly in the rainy season. This favors the trapping of carbonate sediments in the upper estuary. Thus, the calcium carbonate associated with sediment is a vestige of benthic organisms forming $CaCO_3$ carapaces, which are responsible for this deposition in comparison to the planktonic ones, the diatoms with siliceous shells found abundantly in the Mocajuba estuary (Vilhena *et al.,* 2014).

The benthic organisms, mainly oysters, settle in natural and artificial banks of oysters throughout the estuary until they reach ~28 km of distance from the mouth (Sampaio *et al.,* 2017; Teles & Pimentel, 2018). Thus, the Mocajuba estuary has great conditions for $CaCO_3$ organisms to settle and develop. Also, the system has outcrops and oyster banks (natural and artificial) along its course, being an important place for these organisms to settle. In addition, the region of the Mocajuba estuary was developed over the Pirabas Formation, which is characterized by the variety of carbonate and siliciclastic facies (Vasquez *et al.,* 2008), being this formation exposed upstream of the estuary, also contributing with high concentrations of $CaCO_3$ upstream, as can be seen in figure 8 and 9.

Figura 8. Os depósitos de conchas estão localizados a montante do estuário do rio Mocajuba (Nazaré do Mocajuba, coordenadas geográficas -47,926400 e -0,881500).
Figure 8. Shell deposits are located in upstream of the Mocajuba estuary (Nazaré do Mocajuba, geographical coordinates -47.926400 and -0.881500).

Figura 9. Imagem mais aproximada dos depósitos de conchas (Nazaré do Mocajuba, coordenadas geográficas -47,926400 e -0,881500).
Figure 9. A closer image of the shell deposits (Nazaré do Mocajuba, geographical coordinates -47.926400 and -0.881500).

4. Conclusions

In the Mocajuba estuary, it was possible to recognize two principal environments: a marine, with predominantly sandy sediments, an estuarine environment, with fine sediments, a higher percentage of OM and $CaCO_3$; and a vestige of the fluvial environment, contributing coarser sediments to the estuarine and marine areas.

The high percentage of mud in the middle sector reflected the interaction between the coastal and river water, and the catchment from the mud plains of the Amazon coast. The distribution of calcium carbonate throughout the estuary and its direct relationship with cohesive sediments shows that seawater influences the sedimentation and the biological parameters in the system since it has a greater capacity to enter the estuary over long distances. Also, the calcium carbonate distribution is explained by the Pirabas Formation and the oyster banks along its course, being an important place for these organisms to settle.

Based on this study, it was possible to advance our understanding of the Amazonian estuary environments and how the local tide-dominated dynamics of the region influence sedimentation processes. This will be very useful for future studies concerning the assessment and monitoring of the estuary, and for evaluating possible ecological changes.

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