Seasonal and macrotidal influence on the morphodynamics of estuarine beaches (Marajó island - Eastern amazon - Brazil)

Influência sazonal e macrotidal na morfodinâmica de praias estuarinas (ilha de Marajó/amazônia Leste - Brasil)

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Abstract

The Marajó island, situated at the mouth of the Amazon estuary, is recognized as the largest estuarine island in the world. It is surrounded by the Amazon estuary to the west, Pará estuary to the east, the Tocantins river to the south, and the Atlantic Ocean to the north. The Pará estuary border of the Island is divided by the Paracauari channel, creating a division between two distinct coastlines: the coast with active cliffs and narrow beaches like Grande beach (35 m) and Joanes beach (58.4 m), located in Salvaterra. On the other side, extensive beaches such as Barra Velha beach (285 m) and Pesqueiro beach (240/300 m) with low topography and paleo mangrove terraces, located in Soure. The unique hydrodynamic conditions include tides reaching up to 5.7 m, currents of 1.7 m/s, and waves up to 1.5 m high originating from the northeast, along with average wind speeds of 7 m/s. The sedimentary equilibrium is more pronounced in the low sector. The low sector (Pesqueiro beach = 525 m^3/m) exhibits a higher sedimentary balance compared to the high sector (Joanes beach = 250 m^3/m and Grande beach = 89 m^3/m). The beaches displayed an intermediate morphodynamic character, except for Grande beach (reflective/rainy season) and Joanes beach (reflective/dry). According to the RTR model, these beaches had an intermediate nature characterized by runnels and bars, except for Joanes beach (reflective/dry).

Keywords: Coastal island; morphology; sedimentology; mesotidal beaches; coastal transport.

Resumo

A ilha do Marajó, situada na foz do estuário do Amazonas, é reconhecida como a maior ilha estuarina do mundo. É cercada pelo estuário do Amazonas a oeste, estuário do Pará a leste, rio Tocantins ao sul e oceano Atlântico ao norte. O canal de Paracauari divide dois litorais distintos: o litoral com falésias ativas e praias estreitas como as praias Grande (35 m) e Joanes (58,4 m) em Salvaterra; do outro lado, extensas praias como as da Barra Velha (285 m) e do Pesqueiro (240/300 m), com topografia baixa e terraços de paleo mangue, em Soure. As condições hidrodinâmicas únicas incluem marés que atingem até 5,7 m, correntes de 1,7 m/s, ondas de até 1,5 m de altura originadas do Nordeste, e ventos com velocidade média de 7 m/s. O equilíbrio sedimentar é mais pronunciado no setor baixo (praia do Pesqueiro = 525 m^3/m), que apresenta um balanço sedimentar superior ao sector alto (praia de Joanes = 250 m^3/m e praia Grande = 89 m^3/m). As praias apresentaram caráter morfodinâmico intermediário, com exceção da praia Grande (reflectiva/época chuvosa) e da praia de Joanes (reflectiva/seca). De acordo com o modelo RTR, estas praias têm um carácter intermediário, caracterizado por *runnels* e barras, com excepção da praia de Joanes (refletiva/seca).

Palavras-chave: Ilha costeira; morfologia; sedimentologia; praias mesotidais; transporte costeiro.

1. Introduction

The coastal zone is extremely dynamic, experiencing changes at various temporal and spatial scales. Changes in coastline position (erosion or accretion) are inevitable along any sandy coastal stretch, responding to sea level fluctuations, sediment budget, and hydrodynamic conditions (Lira et al. 2016).

According to Scott et al. (2011), beach morphology varies in time with changing hydrodynamic forcing while the modal beach morphology changes spatially in response to the geographical variability in environmental conditions (such as ocean movements, sediment budget, and geology).

Understanding these processes holds significant value for planning the sustainable utilization of the

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coastal zone, which is considered a natural and economic asset.

This zone accommodates 60% of the global population (Hauer et al. 2021) and serves as a hub for socioeconomic activities, carrying a substantial potential for influencing sedimentary dynamics.

As highlighted by Lira et al. (2016), human activities and settlements are expanding in coastal regions, leading to a rise in management issues and challenges. These challenges arise from the need to balance coastal evolution and human occupation.

According to Krönckle et al. (2018), the sandy beach can be divided into different zones: nearshore, outer nearshore and offshore, based on environmental factors, hydrodynamic conditions, sediment composition, and macro fauna communities.

However, Prodger et al. (2016) suggested that grain size and sorting are crucial parameters for characterizing sediments and modeling beach morphology and sediment transport. These authors emphasized the significance of grain size and composition in influencing the behavior and variability of sandy beach gradients.

Fine grains tend to create a profile with a smooth gradient, while coarse grains lead to profiles with steeper slopes. The beach face slope can change depending on the level of wave energy. An inverse correlation between wave height and grain size was established by Wright & Short (1984) and Short (1999). Masselink & Short (1993) explain that tidal influences on hydrodynamics, and beach morphology are a result of changes in water level, where tide affects sediment transport and morphological changes. An increase in tidal amplitude leads to a decrease in the overall beach slope, inhibits the formation of offshore sandbars, and enhances circulation nearshore under certain tide conditions. According to Wright & Short (1984) & Short (1999), fine sand results in a low gradient (1 to 3º) in the swash zone and higher sand transport in the surf zone. Meanwhile, the beaches with medium to fine sand have a greater gradient and less sand being transported to the surf zone. During the dry period, the swash zone has less turbulent energy, and the sand removed behind the back beach zone tends to migrate again, now towards the swash zone (Masselink & Short 1993). An increase in tidal amplitude leads to a decrease in the overall beach slope, inhibits the formation of offshore sandbars, and enhances circulation nearshore under certain tide conditions. The study of coastal morphodynamics involves investigating the changes to the physical processes and bedforms in the coastal environment over a broad range of scales in space and time, from the microscale to the macroscale (Magar 2020). Sandy beaches can vary significantly from their initial state, depending on seasonality, vegetation, changing wave conditions, tides, changing width, extent (Erickson et al. 2017), being susceptible to erosion, transport and, finally, granulometric distribution.

Grain size distribution analysis has been widely used by sedimentologists to classify sedimentary environments and elucidate transport dynamics (Ayodele & Madukwe 2019). The distribution of grain size and textural parameters can indicate the method of transport and the past depositional events of a particular region. Several researchers have sought to deduce a depositional and hydrodynamic setting from grain size information. The fluid dynamics influences the sediment transport, leading to changes in the coastal morphodynamic features over time (Cowell & Thom 1997). Alterations in grain size can potentially cause modifications to the beach state (Anfuso & Garcia 2005, Benavente et al. 2006). The state characterized as dissipative-reflective can be elucidated through two relative indices, namely the similarity parameters of surf (Σ) and the scale of surf (ξ) (Carter 1988).

The Eastern edge of Marajó island (Fig.1) is composed of distinct features: (1) towards the south, there are high terrains where the Coastal Plateau extends over the Pará estuary, intersected by narrow and shallow estuarine channels formed within the Barreiras sediments; and (2) towards the north, the landscape is lower and covered by vast coastal plains, intersected by a few tidal channels. These regions are divided by the Paracauari channel. The tidal channel extending from Paracauari channel to the southwest exhibits a highly meandering pattern, with moderate deviations east-west along its course, while further upstream, it experiences significant inflection (e.g., 90° angle), flowing north-south and southeast, attributed to a strong tectonic influence (Souza & Rossetti 2011).

This deep channel (reaching depths of up to 50 m, facing Soure/Salvaterra) segregates these two sections, characterized by two blocks: elevated to the south, where the coastal plains are eroded, giving rise to Joanes and Grande beaches (Salvaterra) along the Coastal Plateau, and lower to the north, where Pesqueiro and Barra Velha (Soure) extensive beaches (Fig. 1).

The study area experiences a significant amount of precipitation (mean of 2.800 mm/year) and is characterized by semidiurnal mesotidal (average range of 3.85 to 4.40 m) (NIM 2023). Situated within estuarine waters (mixing zone), this island is bordered by these beaches positioned at the entrance of the Pará estuary, leading to the generation of robust tidal currents that impact the transportation of sediment towards the coastline.

Few studies are conducted on estuarine beaches in the Marajó island (França et al. 2007, El-Robrini et al. 2018). However, additional investigations are notable, including studies on neotectonics in the Marajó island (Souza et al. 2013), the influence of climatic variations and/or relative sea-level adjustments on the mangroves of the Marajó island (França et al. 2012), palynology

(Rodrigues et al. 2011), and the geological evolution of the lower Amazon (Rossetti & De Toledo 2006). This paper aims to analyze the impact of seasonal variations in the Amazon region (wet and dry seasons), tidal patterns, and their repercussions on the morphodynamics of the estuarine coastlines of Joanes and Grande (located in Salvaterra facing the coastal plateau) as well as Pesqueiro, Barra Velha (in Soure on the sandy plain) within the Marajó island.

2. Study area

2.1 Geomorphology

The Paracauari channel, located to the southwest, exhibits meandering characteristics with moderate deviations in an east-west direction, and significant inflection (at a 90° angle) upstream due to pronounced neotectonic influences (Souza & Rossetti 2011). This deep channel, reaching depths of up to 50 m near Soure/Salvaterra, separates two distinct areas, representing different geological blocks: (1) Southern side, Salvaterra, features the Coastal Plateau encroaching over the Pará estuary, intersected by narrow and shallow estuarine channels eroded from Barreiras sediments. The main Joanes and Grande beaches, situated in front of the Coastal Plateau, contribute to the erosion at the base of cliffs and the formation of abrasion platforms; (2) moving towards the north, Soure presents a lower relief characterized by extensive coastal plains where Pesqueiro and Barra Velha beaches, the main ones, gradually shift over the surrounding mangroves (Fig. 1). This region exposes muddy terraces, remnants of paleo mangroves, and fallen trees. The sandy prisms found at these beaches extend from the high spring tide level at the base of dunes or cliffs to the low spring tide level, occasionally intersected by tidal channels. These channels, including Jubim/Salvaterra and Andiroba/Pesqueiro beach-Soure, serve as pathways for sediment drainage, influenced by the tidal patterns throughout the seasons (Fig. 1). As outlined by Nascimento (2013), the Andiroba channel displays a depth of 5.32 m upstream, decreasing to 0.29 m at the mouth, featuring ebb tide deltas with multiple shallow arms divided by exposed sandbanks during low tide (França et al. 2007), a common characteristic among tidal channels. The presence of sandbanks near the Andiroba channel is also notable within the Pará estuary (Fig. 1). The beaches studied here are located at the mouth of the Pará estuary, which induces the formation of strong tidal currents, influencing sediment transport to the coast.

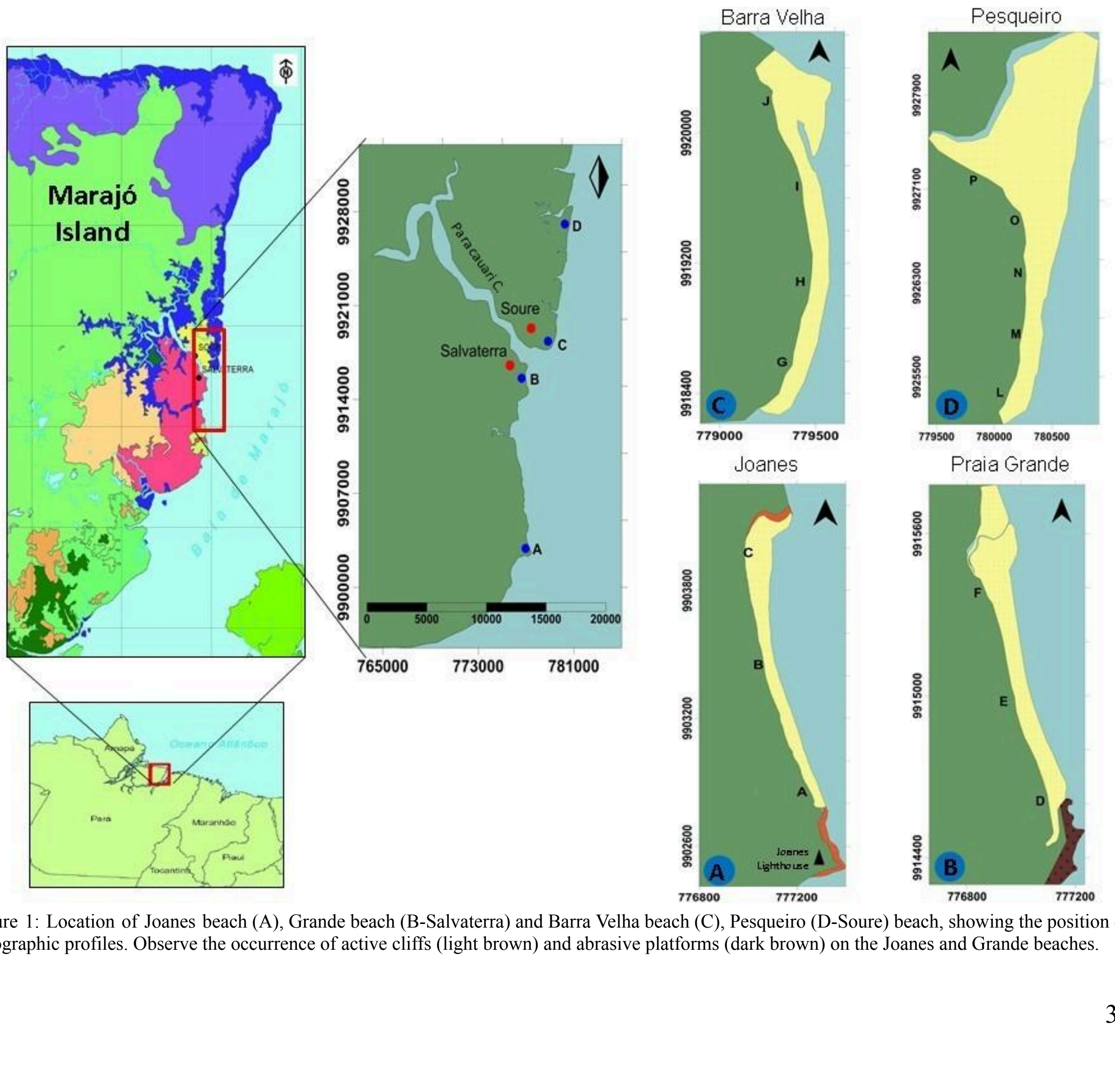

Figure 1: Location of Joanes beach (A), Grande beach (B-Salvaterra) and Barra Velha beach (C), Pesqueiro (D-Soure) beach, showing the position of topographic profiles. Observe the occurrence of active cliffs (light brown) and abrasive platforms (dark brown) on the Joanes and Grande beaches.

2.2 Climate and meteorological parameters

The research region exhibits a torrid climate zone, featuring a humid Equatorial Domain (Eq"oam) and an Amazonian Coastal climate type (Novais & Machado 2023), characterized by an average annual temperature of 27.3°C (NIM 2023). A substantial amount of rainfall, averaging 2.800 mm/year, is received in the study area (NIM 2023). The precipitation pattern is influenced by the latitudinal movement of the Inter Tropical Convergence Zone (ITCZ), described as the maximum precipitation in tropical or as a tropical band of convective clouds, with its seasonal positioning fluctuating between 9 to 2°N in the Equatorial Atlantic Ocean (Utida et al. 2019). The area experiences two distinct periods, the rainy season (December - May) and the dry season (June - November). Wind patterns predominantly follow a NE direction, with an average velocity of 7 m/s, exhibiting seasonal variability due to the migration of the ITCZ.

2.3 Hydrodynamics: tide, currents and waves

Tidal, current, and wave dynamics govern the movement of estuarine waters near the coastline, with the extent of the tide dictating the breadth of the coastal area impacted by wave action (Gupta 2011). Marajó island's Eastern boundary experiences three instances of spring tide and two occurrences of ebb tide within a monthly cycle. During the spring tide phase, the tidal range peaks at 5.7 m (highest range observed during the rainy season) and drops to a minimum of -0.4 m, characterized by mesotidal and semidiurnal macro tide patterns (averaging between 3.85 to 4.40 m). Conversely, the ebb tide showcases a maximum range of 5.6 m and a minimum of -0.1 m in February, aligning with heightened water discharge at the mouth of the Amazon River (206 × 10^3 m^3/s, Callede et al. 2010). The mean tidal range recorded stands at 2.68 m (HND 2023). As per findings by Baltazar et al. (2011) and Rosário et al. (2016), the Pará Estuary is characterized by asymmetry and exhibits type 1 attributes (well mixed), lacking vertical stratification. Salinity levels in the Pará estuary can vary between 1.7 (maximum) and 5.6 (Rosário et al. 2016). Flow rates during flood and ebb periods reach 78 m^3/s and 176 m^3/s, respectively. Tidal current velocities peak at 1.7 m/s (maximum during ebb) and 0.3 m/s (minimum during flood) at the surface, while at the bottom, velocities reach 1.07 m/s (maximum during ebb) and 0.3 m/s (minimum during flood). Throughout the water column, velocities range between 1.15 m/s (maximum) and 0.04 m/s (minimum).

On the Eastern margin of Marajó island, the tidal channels exhibit a SW-NE orientation, consequently leading to tidal currents that flow in the direction of the 45° (ebb) and 225° (flood) quadrants. Within the Andiroba channel, the tidal currents attain velocities of 0.62 m/s during ebb and 0.57 m/s during flood, as indicated by the Shepard diagram, which highlights a significant to extremely significant level of hydrodynamics (Nascimento 2013).

3. Material and methods

3.1 Data acquisition

Two field campaigns were conducted: (A) during the wet season (30/03 to 02/04/2014), characterized by significant atmospheric conditions, and (B) in the dry season (25 to 29/11/2014). The research involved:

3.2 Beach topography

To assess the beach morphology and erosive or accretional patterns, measurements were taken on cross-sectional profiles of the coastline during spring low tide, starting from the Spring High Tide Line (SHTL) to the Spring Low Tide Line (SLTL) (Fig. 1). Topographic profiles were generated using total station and reflector prism, applying the Stadia method proposed by Birkemeier (1985), with elevations recorded at 5 m intervals (Grande and Joanes beaches) and 20 m intervals (Barra Velha and Pesqueiro beaches).

3.3 Beach sediments

Surface sediment collection on the beach face was carried out concurrently with the topographic profiles (Fig. 1), during the Spring Low Tide, located using GPS. Sediment samples were collected between SHTL and SLTL using a 5 cm PVC pipe to capture the surface sediment layer representing the most recent semi-diurnal deposition. This process was repeated every 20 m or at any morphological feature (bar or runnel).

3.4 Beach hydrodynamics

Wave height, period, and direction of wave incidence were measured between the surf zone and the beach face at ebb and flood tide for each beach studied (Muehe 2002). Tidal current measurements were conducted using drifters (Fig. 1).

3.5 Winds

Local wind direction and velocity measurements were conducted using anemometers at each beach studied (Fig. 1).

3.6 Beach sediment analysis

Sediment samples were separated into granulometric fractions using a set of sieves with specific intervals (mm) of (0.71 - 0.50 - 0.35 - 0.25 - 0.18 - 0.125 - 0.09 - 0.063 - <0.063). The granulometric data were inserted into the SysGran 3.0 Program to calculate textural characteristics of the sediments using statistical parameters. This approach involves creating graphs based on the weight percentage of each granulometric fraction, utilizing statistical parameters for grain size distribution such as mean, median, standard deviation, asymmetry, and kurtosis (Muehe 2002). Surfer 8 and Excel software were utilized to generate graphs and digitize sand grain size data for determining sediment texture characteristics.

3.7 Morphodynamic classification

The superposition of the topographic profiles enables the computation of morphometric parameters:

- Sediment volume variation in m^3/m (Vv) - utilizing Golden software Surfer 8 to assess volume changes for common distances to two surfaces;

- Beach face gradient (β) - calculated using the Tanβ formula where Tanβ = opposite/adjacent (Oliveira et al. 2004). The opposite side represents the height difference between the maximum and minimum of the momentary scan acquired in the field, while the adjacent side corresponds to the distance between the maximum and minimum of the momentary scan.

- Beach width (Yb) is the horizontal dimension of the beach in meters, covering the distance from the spring low tide line to the spring high tide line, is required to calculate the area of the surveyed transect. This measurement was done using the calculation of the coordinates of the total station internal GPS.

- Settling velocity of sediment particles (Ws) in m^3/m (Short & Hesp 1982), derived from the mean particle size expressed in phi, following Dean (1973), Muehe (2002), and Masselink & Short (1993).

The morphodynamic classification was based on the sequential model of morphological evolution by Wright and Short (1984), and Masselink & Short (1993). Through the dimensionless fall parameter omega (Ω, Equation 1) from Wright & Short (1984), the beach morphodynamic states were linked to the variables affecting the energy level of the beach:

$$\Omega = Hb/Ws*T \quad (1)$$

Hb represents the wave height at the break, Ws denotes the settling velocity, T stands for the average wave period. Considering the tidal effects on beach morphology, the RTR parameter introduced by Davis & Hayes (1984) and recommended by Masselink & Short (1993) was utilized: RTR = MSR/ Hb, where RTR signifies the Relative Tidal Range, MSR indicates the tide variation, and Hb represents the wave height at the break.

4. Results

4.1 Hydro-oceanographic parameters

The hydrodynamic parameters (wave height, period, and tidal current intensity) exhibit higher intensity during the rainy season (Table 1). In this season, the highest wave heights are observed on Joanes beach (up to 0.79 m) and Grande beach (up to 0.82 m) south of the Paracauari channel, where the beaches have a steeper gradient leading to higher waves. Conversely, in the Northern sector of the channel, the beaches display dissipative characteristics with a gentle slope, extensive beach face, and smaller spilling waves. Pesqueiro beach experiences the highest wave height reaching a maximum of 0.72 m during the rainy season.

During the rainy season, currents exhibit a predominant SE direction during ebb tide and NE during flood tide across all studied beaches (Table 1). The currents are most vigorous in the Southern sector during ebb tide (Joanes and Grande beaches) reaching a maximum of 0.38 m/s, and in the Northern sector during ebb tide (Pesqueiro and Barra Velha beaches) with a peak of 0.31 m/s at Pesqueiro beach.

Table 1. Hydro-oceanographic parameters of the Eastern margin of the Marajó island, during the rainy (first value) and dry (second value) season.

Beach	Tide	Wave			Wind		Tidal current	
		Height (m)	Period (s)	Direction	Vel. (m/s)	Direction	Vel.(m/s)	Direction
Joanes	Ebb	0.48/0.37	8.2/6.7	E	2.7/3.2	E/NE	0.14/0.12	SE/SE
	Flood	0.79/0.71	6.8/6.2	NE	4.6/5.1	NE/NE	0.18/0.16	NE/NE
Grande	Ebb	0.51/0.44	7.3/6.1	E/E	2.2/3.8	E/NE	0.16/0.13	SE/SE
	Flood	0.82/0.73	6.1/5.8	NE/NE	1.6/3.2	NE/NE	0.38/0.29	NE/NE
Barra Velha	Ebb	0.39	7.4	NE	1.6	NE	0.22	SE
	Flood	0.64	6.1	SE	3.2	SE	0.16	NE
Pesqueiro	Ebb	0.41/0.34	7.1/6.5	NE/NE	2.2/4.1	NE/NE	0.31/0.26	SE/SE
	Flood	0.72/0.66	6.5/5.1	NE/NE	3.9/4.9	NE/NE	0.16/0.21	NE/NE

In the dry season, a decrease in wave parameters was observed, despite an increase in wind intensity (Table 1). Nonetheless, these parameters exhibited a similar trend to that of the rainy season, showing larger waves in the Southern sector of the Paracauari channel. During this period, the Southern sector displayed reflective attributes, with wave average height fluctuating between 0.37 and 0.73 m, peaking during the flood (Table 1). Conversely, in the Northern sector of Paracauari (Pesqueiro beach), wave heights were minimal, averaging 0.34 m (ebb) and 0.66 m (flood) (Table 1).

Throughout this season, waves predominantly moved in a NE direction during both flood and ebb, except at Grande beach, where waves from the East were dominant during ebbing tides (Table 1). NE winds were more prevalent in the rainy season. Wind speed averages were higher in the Southern sector, reaching a maximum of 5.1 m/s at Joanes beach. Winds at

Pesqueiro beach (Northern sector) peaked at 4.1 m/s during ebb and 4.9 m/s during flood (Table 1). Tidal currents in the dry season were weaker than in the rainy season, due to the decrease in the wave energy, which are one of the main sources of these currents.

In the Southern sector, the most intense currents were observed during flooding at both beaches, reaching a peak of 0.16 m/s at Joanes beach and 0.29 m/s at Grande beach, flowing SE during ebb and NE during flood. Pesqueiro beach experienced higher currents during ebb, averaging 0.26 m/s (Table 1).

4.2 Morphology and granulometry of the beach face

4.2.1 Joanes beach

Joanes beach extends in a North-South orientation, covering 1.42 km. A distinct shoulder is noticeable in the Southern sector, particularly prominent during the dry season, reaching a height of 0.5 m (Fig. 2). Reflective morphodynamic features characterize the beach in both periods, especially in the South and Central sectors, where the beach face gradient (β) is steeper, and the width (Yb) is narrower. Conversely, the Northern sector displays dissipative beach characteristics, hosting two runnels and bar systems at the boundaries of the intertidal and subtidal zones (Fig. 2) during the rainy season.

In the rainy season, the mean width of the beach measures 58.4 m, with the widest section found in the Northern sector (90 m) and a gradient ranging from 2.36 to 4.97°. Erosive processes alter the beach morphology, resulting in a steeper beach face and sediment extraction primarily from the supratidal and upper intertidal zones. Sediments removed from the beach face during this season are deposited in the submerged area, forming longitudinal bars and runnels parallel to the coastline in the Northern sector.

During the dry period, the average width of the beach face increases to 65 m throughout Joanes Beach, with a greater width observed in the Northern sector (85 m), and the gradient ranges from 2.55 to 4.28°. This period experiences an increase in sediment balance, particularly in the supratidal zone, due to reduced erosive energy attributed to lower wave heights. Strong winds facilitate the deposition of transported sediments (wind transport), resulting in the formation of a distinct beach berm in the supratidal line (Fig. 2).

Joanes beach predominantly consists of medium sand (1.16 to 1.88 phi) during both the dry and rainy seasons (Fig. 2). In the rainy season, surface sediments in the subtidal zone of the Central and Northern sectors exhibit fine sand granulometry (2.05 to 2.52 phi). However, coarse sand (0.14 to 0.99 phi) is present in the Southern sector, contributing to its erosive characteristics during this period. Conversely, in the dry season, beach sediments range from average sand (1.17 to 1.88 phi) to coarse sand (0.55 to 0.92 phi) (as depicted in Fig. 2). The most significant changes in average grain size occur in the intertidal and subtidal zones during the dry season, characterized by a reduction in grain size resulting from decreased wave energy.

4.2.2 Grande beach

Grande beach, stretching 1.57 km in a north-south direction, exhibits cliffs retreat and abrasion platforms in this specific area (Fig. 3). During the wet season, the beach displays a steep profile (Fig. 3) due to erosion caused by increased wave energy, resulting in a smooth beach surface in both the Northern and Southern sectors (Fig. 3).

The beach face gradient varies from 5.70 to 8.26° in the Southern and Northern sectors, respectively, with an average width of 35 m, reaching a maximum of 40 m in the Northern sector. During this time, the beach demonstrates dissipative characteristics (Short 1999), characterized by a high gradient, narrow beach width, and plunging waves (Fig. 3).

In contrast, the beach appears flatter and more expansive in the dry season, with a beach face gradient (β) ranging from 3.52 to 6.20° and an average width of 55 m. The Northern sector exhibits the steepest gradient (6.20°) and the most significant increase in beach width, expanding by 20 m between the wet and dry seasons (Fig. 3). Comprised mainly of medium sand, the beach experiences a reduction in grain size from the wet to dry season (Fig. 3). This decrease is observed across all beach zones (supratidal, intertidal, and subtidal), except for the intertidal zone in the Southern sector, where sediment size increases, leading to erosive features during the dry season. The reduction in grain size is attributed to the diminished wave energy and height during this period.

During the rainy season, the surface sediments range from medium to coarse sand, predominantly coarse sand (0.12 to 0.91 phi) (Fig. 3), particularly in the intertidal and subtidal zones along the entire beach length, while medium sand (1.14 to 1.47 phi) is found in the supratidal zone. In the dry season, the average grain size decreases, with sediments primarily consisting of medium sand (1.02 to 1.63 phi), and coarse sand present only in the supratidal and intertidal zones of the northern sector (Fig. 3).

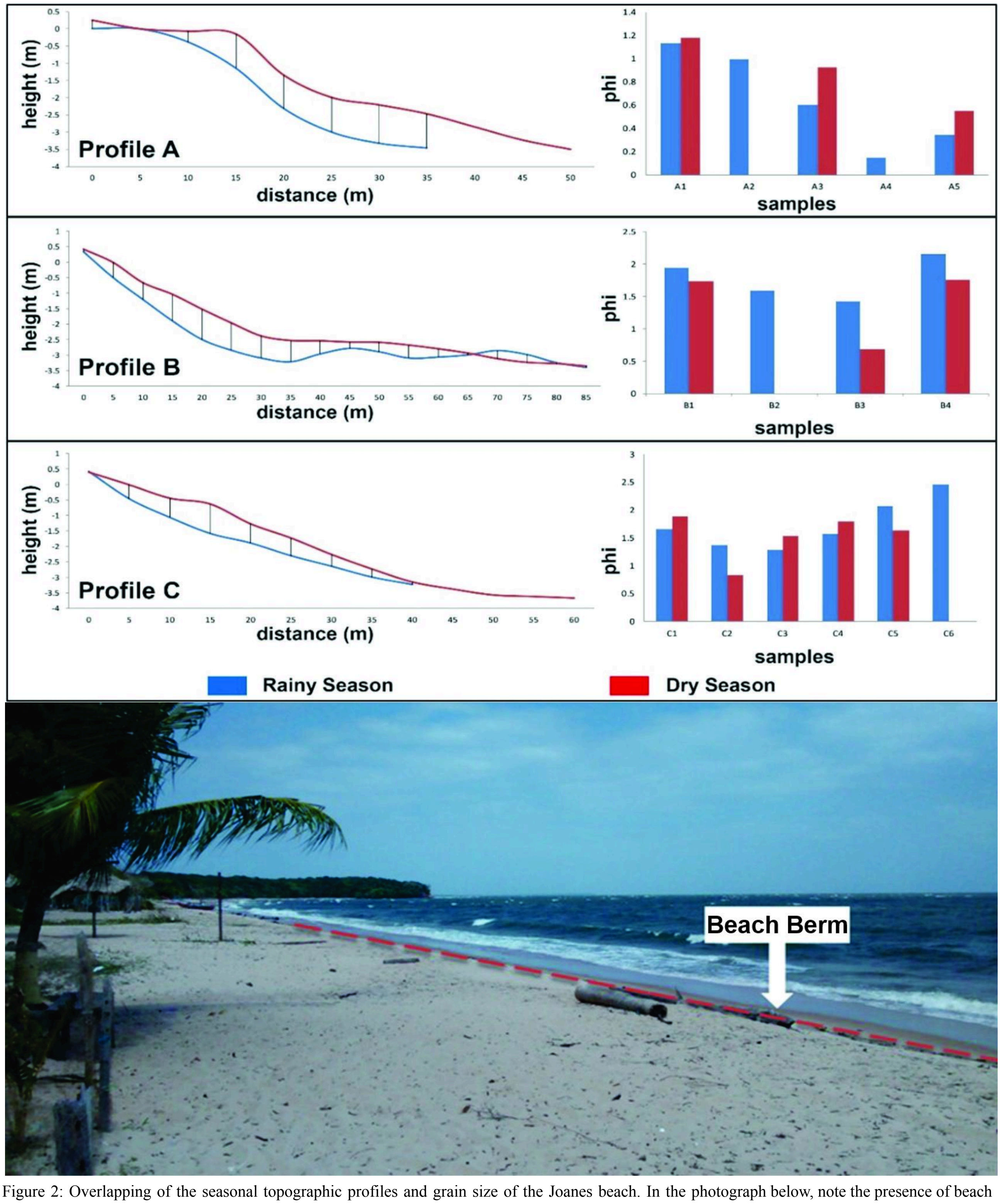

Figure 2: Overlapping of the seasonal topographic profiles and grain size of the Joanes beach. In the photograph below, note the presence of beach berm, in the dry season (Source: GEMC collection).

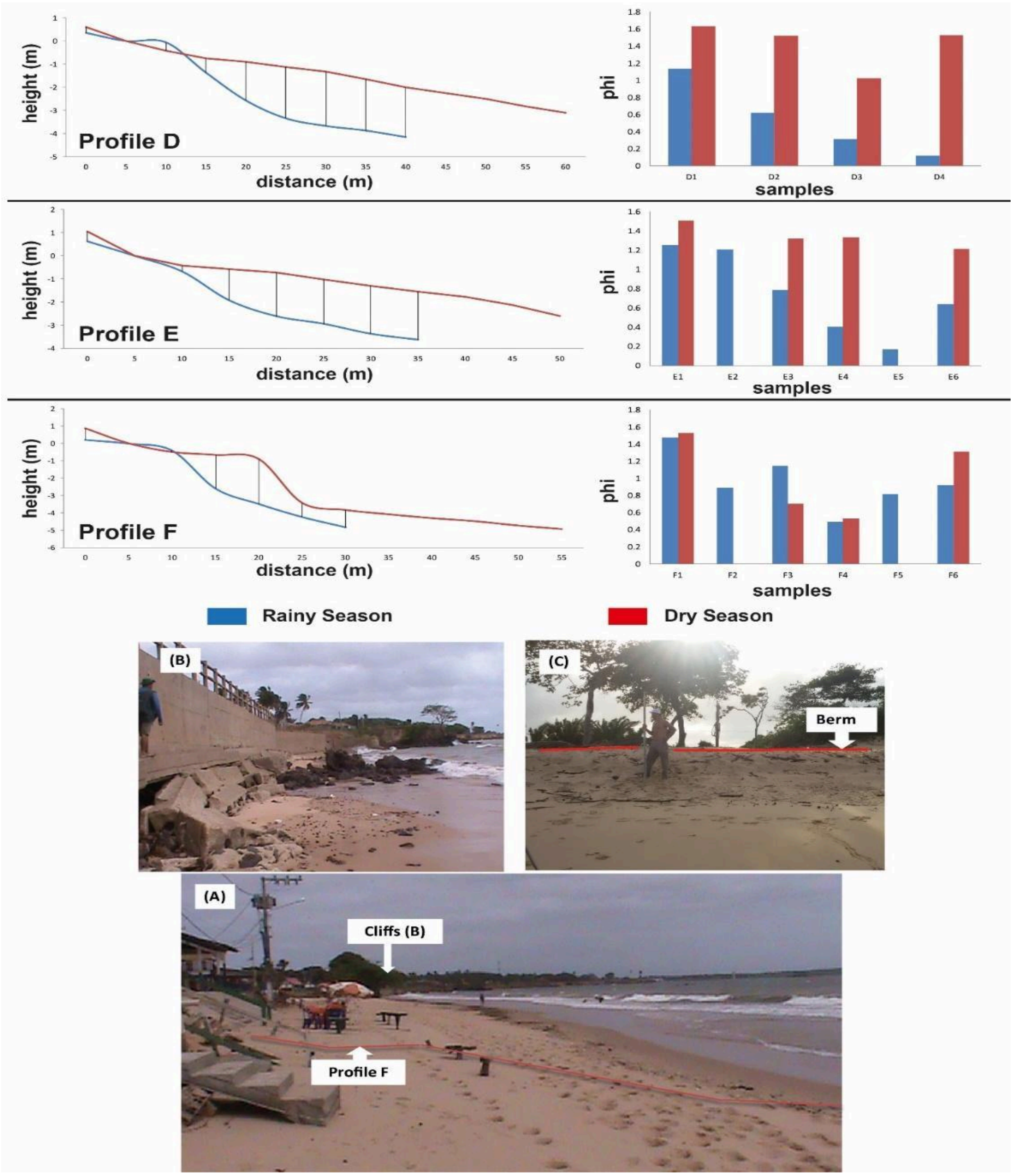

Figure 3: Overlapping of seasonal topographic profiles and granulometry of the beach face on Grande beach; (A) profile F (Northern sector) on the Grande beach (Salvaterra), (B) cliffs in the Northern sector of the beach and (C) berm (Central sector of the beach) (Source: GEMC collection).

4.2.3 Barra Velha beach

Barra Velha beach, spanning 2.1 km in a north-south orientation, is situated near the Paracauari channel, which divides Salvaterra and Soure. Research was conducted solely during the rainy season, as access to the beach was closed during the dry season. The beach morphology exhibited a very gradual gradient in all sectors, with inclinations ranging from 0.99 to 1.34°, with the gradient increasing from north to south. During the rainy season, the beach width (Yb) averaged 185 m, with the minimum width observed in the Central sector (140 m) and the maximum in the Southern sector (260 m) (Fig. 4).

In the rainy season, a well-developed runnel and bar system emerged in the intertidal zone of the Northern and Upper sectors of the Central sector (as depicted in Fig. 4), characteristic of dissipative beaches according to Short (1999), indicating migration towards the shoreline termination point (SLTM) due to the high energy present during this period. Sediments on this beach predominantly consist of fine and very fine sand. The latter class was exclusively found in the intertidal zone, specifically in the Southern (3.13 phi) and Northern (3.75 phi) sectors (Fig. 4).

Across all sections of the beach, a muddy terrace (paleo mangrove) is visible in the middle and upper parts of the intertidal zone (as illustrated in Fig. 4), resulting from the disappearance of the sandy prism. This paleo mangrove is primarily exposed during the rainy season, where high hydrodynamic energy erodes the beach face, revealing the paleo mangrove and increasing the presence of silt in the initial meters of the intertidal zone (Fig. 4).

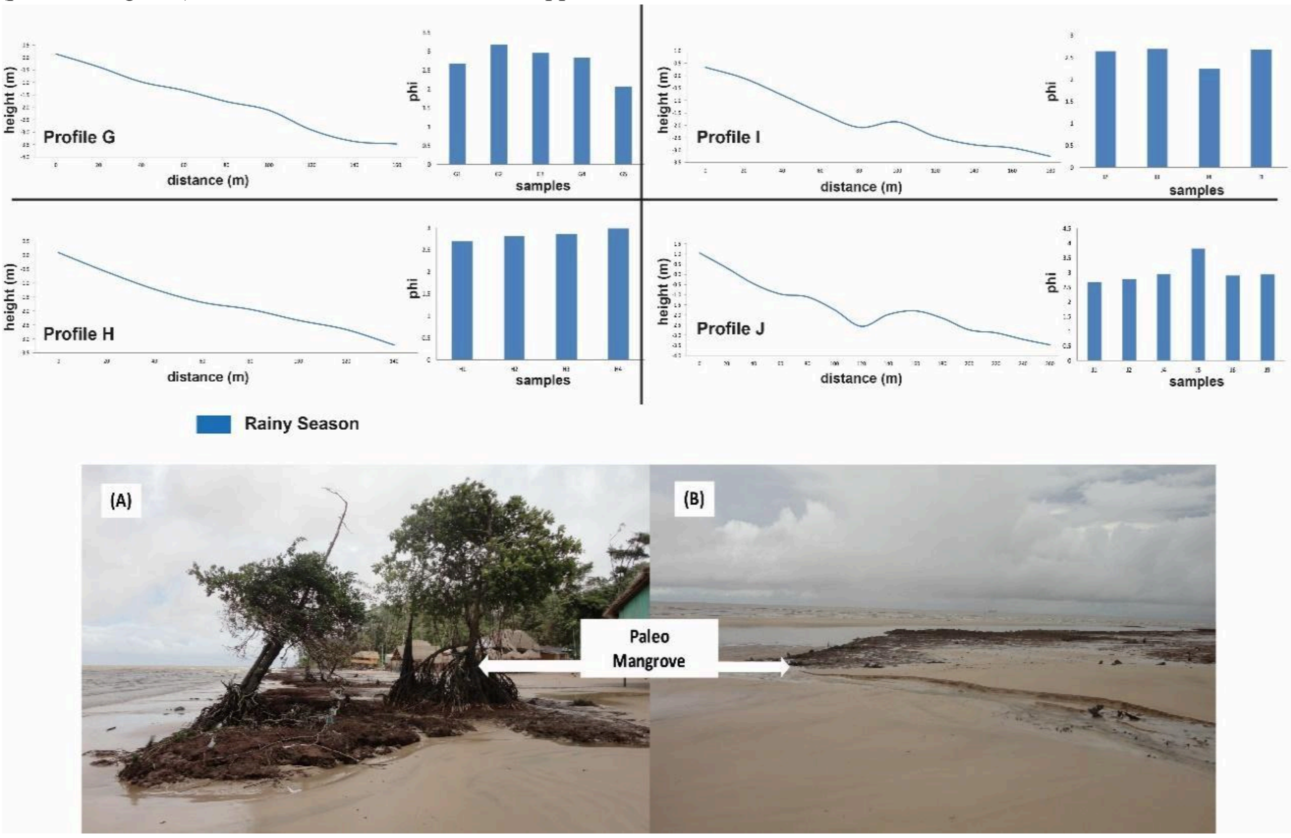

Figure 4: Topographic profiles and granulometry in Barra Velha beach (Soure). Observe the palaeo mangrove muddy terrace, (A) Northern sector and (B) Central sector (Source: GEMC collection).

4.2.4 Pesqueiro beach

The Pesqueiro beach is oriented north-south, with an extension of 2.75 km. Along the beach there is an extensive muddy terrace (paleo mangrove), which becomes more exposed in the lower part of the Central sector and in the Southern sector of this beach (Fig. 5). This muddy terrace occurs in both seasons, however, during the rainy season, this becomes more evident, exposing about 50 cm of the terrace (Fig. 5). During the dry season, the terrace is partially exposed and vegetated (Fig. 5). The morphodynamic conditions of this beach have been changing seasonally, where it noticed that the profile was much steeper (β) and smaller (Yb) than in the dry season.

In the rainy season, the beach topography was steeper, ranging from 1.05 to 2.95° and smaller average width of 148 m. The beach presents one to two runnel and bar systems in the intertidal zone (60 to 120 m) along the entire length (Fig. 5), which according to Short (1999), is characteristic of dissipative beaches. This feature migrates towards the Low Tide Mark (LTM), resulting from the high-energy processes during this period. During this season, a system of runnel and bars characteristic of dissipative beaches, as well as in the rainy one, was present.

The beach is primarily composed of fine sand in both seasons, with coarser particle sizes observed during the dry season (Fig. 5) and grains ranging from fine sand (2.62 to 2.89 phi) to very fine sand (3.05 to 3.42 phi) during the rainy season, with the latter type limited to the Southern sector subtidal zone in the Central and Northern sectors. The sediments exhibit a decrease in size from the supratidal zone to the subtidal zone (Fig. 5). During this season, there is a higher presence of fine sediments and silt (silt/clay), attributed to the increased contribution of continental sediments to the coastal area due to higher rainfall.

The dry season was marked by an increase in the average grain size of surface sediments on the beach, ranging from average sand (1.56 phi) to very fine sand (3.09 to 3.13 phi), predominantly consisting of fine sand, like the previous season. Sediments containing medium sand were only found in the Southern sector, specifically in a channel within the lower intertidal zone.

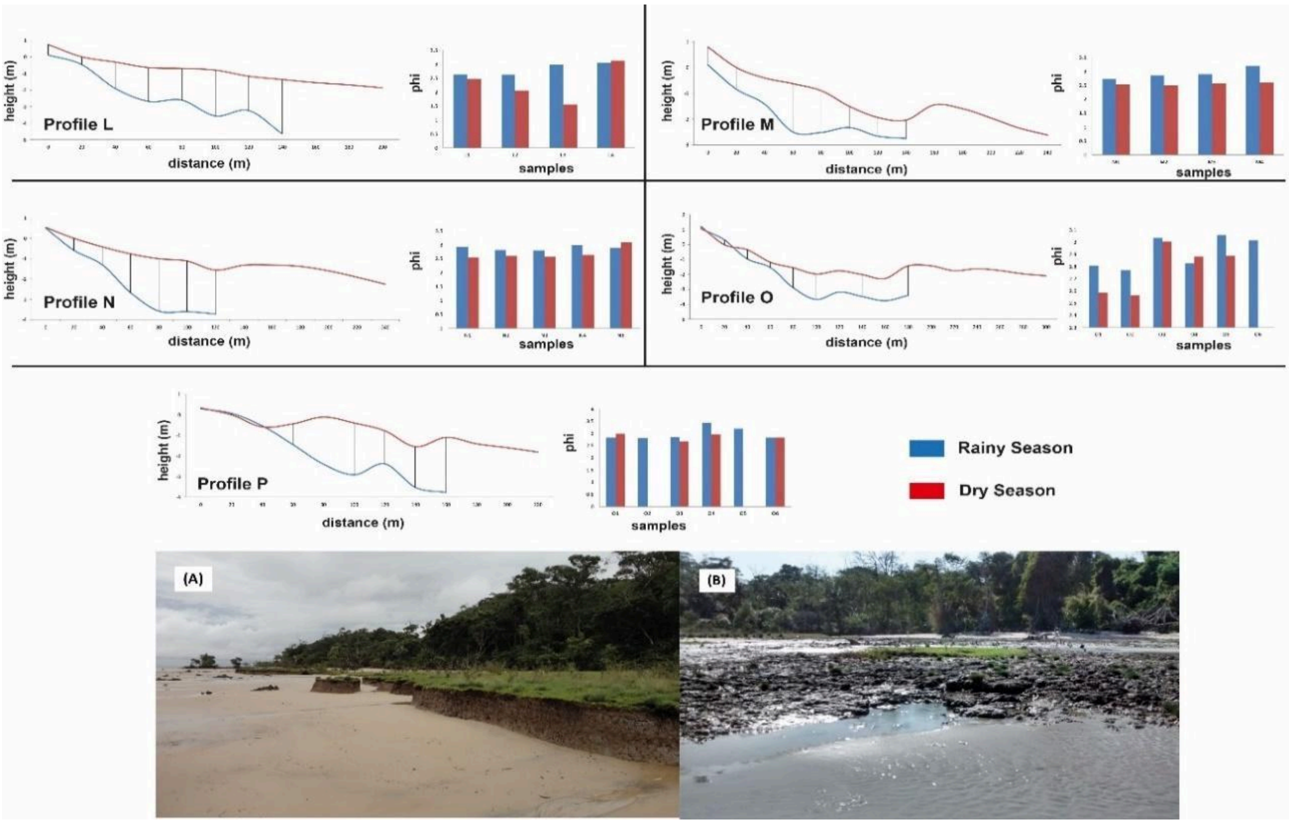

Figure 5: Overlapping of the seasonal topographic profiles and granulometry of the Pesqueiro beach, to observe the muddy plain: (A) rainy and (B) dry seasons (Source: GEMC collection).

4.3 Morphodynamic state

Despite being classified as intermediate by Ω, Joanes beach's morphometric parameters (slope, beach width variation) suggested a reflective beach, with a steep slope (2.36 to 4.97°) and narrow width (average of 58.4 m). In the dry season, the beaches showed a variety of morphodynamic states, with Ω values categorizing Grande and Pesqueiro beaches as intermediates, with values of 2.02 and 2.75, respectively (Table 2).

Joanes beach is characterized as reflective (Table 2). According to Short (2003), dissipative beaches are predominantly composed of fine sands and experience short-spilling waves. These characteristics were observed in both rainy and dry seasons at Barra Velha and Pesqueiro beaches (rainy season) and Pesqueiro beach (dry season).

Considering the Relative Tide Range (RTR) used for beaches with large tidal ranges, such as the study area (mesotidal), the average RTR values on the studied beaches ranged from 4.5 to 6.9 (wet season) and from 4.71 to 6.36 (dry season) (Table 2), indicating that the beaches are mainly influenced by the interaction between waves and tides.

Table 2: Morphodynamics states of estuarine beaches on the Marajó island.

Beach	Rainy period		Dry period	
	Ω	RTR	Ω	RTR
Joanes	2,06	4,7	1,23	5,89
Grande	1,62	4,5	2,02	4,71
Barra Velha	2,43	6,8	N/A	N/A
Pesqueiro	2,76	6,9	2,75	6,36

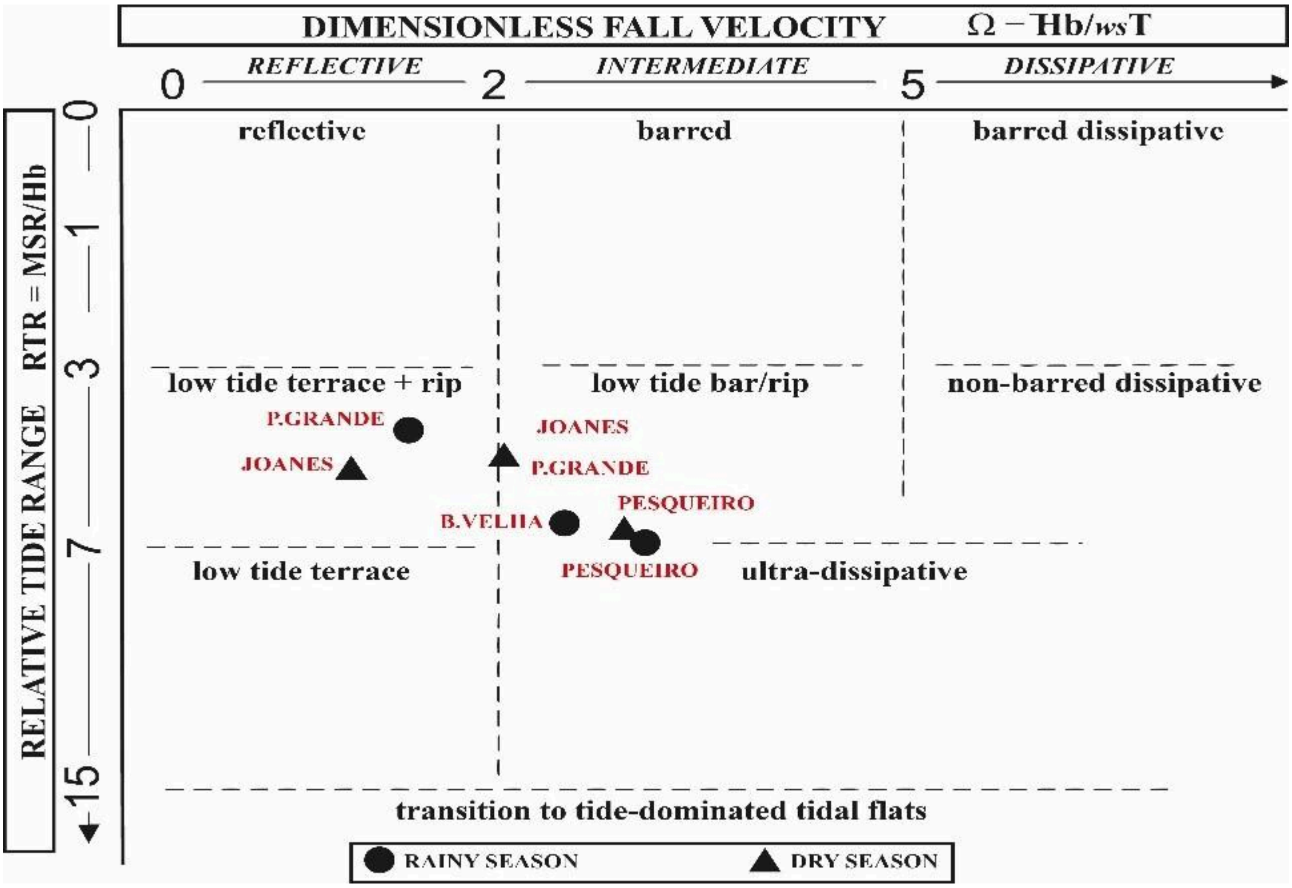

Figure 6: Morphodynamic states of beaches in the rainy and dry seasons, according to the beach model, using the parameter Ω and RTR.

4.4 Sediment balance

On the Eastern margin of Marajó island, the beaches showed a positive sedimentary balance between the rainy and dry seasons (Fig. 7). This behavior is typical of the region where the rain and waves are more intense and the beach starts to have an erosive character, with the removal of sediments from the beach face, and in the dry season, the waves decrease in intensity, favoring the deposition of sediment on the beach face. Joanes beach (Fig. 7) had a sediment gain of 250 m^3/m in this season; however, the Northern sector received the largest volume (192 m^3/m).

At Grande beach (Fig. 7), the sedimentary balance was quite subtle in relation to the other beaches, with 89 m^3/m, and a maximum of 50 m^3/m in the Southern sector of the beach, near Salvaterra.

Pesqueiro beach (Fig. 7) had the largest sediment stock, and mainly in the underwater (subtidal) part among the studied beaches, this confers its dissipative character. This beach had a total sedimentary balance of 525 m^3/m between periods, the Southern sector obtained the greatest gain (325 m^3/m); and the Northern sector is close to the Pesqueiro channel, where there is a large ebb delta, which can represent a sandy stock.

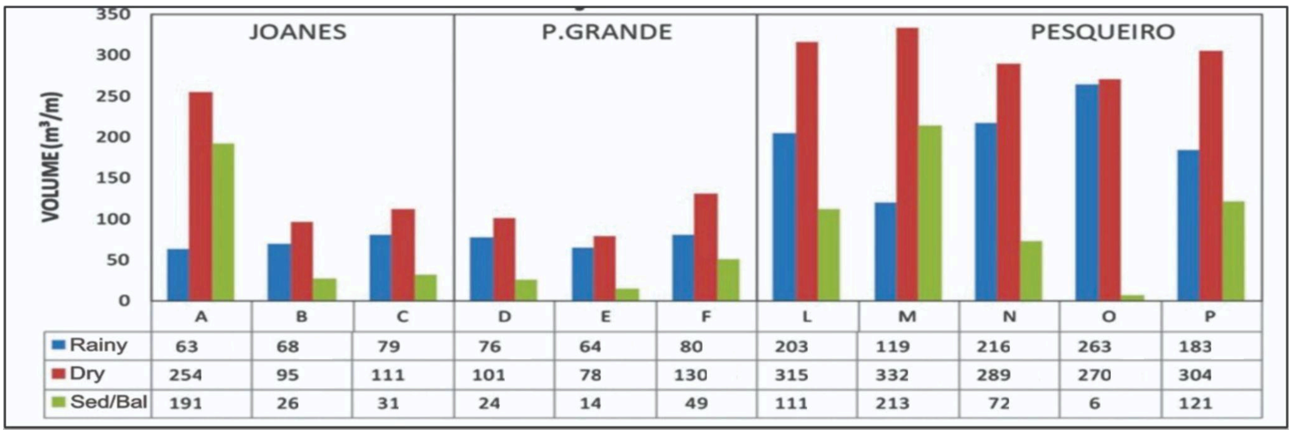

Figure 7: Sedimentary balance (m^3/m) of the Joanes, Grande (Salvaterra) and Pesqueiro (Soure) beaches.

5. Discussions

In general, the rainy period is characterized by being more erosive, due to high-energy events, associated with the waves in the beach face (Braga et al. 2007). Nevertheless, when the rainy season passes, the sediments are brought back towards the emerging beach (Ranieri & El-Robrini 2012).

During the dry season, wave energy is low (El-Robrini et al. 2018) and reflects a decrease in the erosive character of the waves and an increase in sediment deposition on the beach face, influencing the increase in beach width and the consequent decrease in beach gradient.

According to Braga et al. (2007), the morphological changes are associated with high-energy events (tides and waves in the beach face) during the rainy season.

According to Biausque et al. (2020), ridge and runnel beach morphologies remain relatively understudied environments, where sandy bars form around a convergence point, defined as a breaking point, where sediment transported towards the sea meets sediment transported towards the coast. Consequently, sediment from both directions converges at this rupture point, leading to a decrease in net sediment transport and accumulation/deposition of sediment, resulting in ridge formation.

Robin et al. (2009) associated the limited migration rates of intertidal bars in Regnéville (Normandy/France) to the influence of macrotides. They suggested that local wind-induced waves tend to migrate bars toward the emerged areas in micro and mesotidal regimes, while macrotidal beaches expose bars for shorter durations due to hydrodynamic processes, thus limiting their reworking and resulting in slower migration rates compared to micro-mesotidal environments.

During the rainy season, sediments removed from the beach face are deposited in the submerged area, forming longitudinal bars and channels parallel to the coastline. As the dry season progresses, sediments are transported back to emerged parts of the beach. This seasonal variation aligns with the principle established by Masselink et al. (2020), where in a relative rise in sea level reduces the supply of nearshore sediments from offshore and longshore sources.

Masselink & Short (1993) further note that sands removed toward the sea during the rainy season tend to migrate back toward the dry spreading zone. The morphology of bars and runnels persists in both rainy and dry seasons, constructed primarily by high-energy events, as observed by Braga et al. (2007) in their study of Ajuruteua beach (NE of Pará).

Hence, in the dry season, sedimentary accretion and elevated wave energy prevail on the eastern beaches of Marajó Island, diminishing the influence of tidal currents. It is hypothesized that initially, the runnels and bars migrate toward the island's interior. Subsequently, with the progression of the dry season, these features undergo total or partial filling, adapting to the island's topography.

On Pesqueiro beach, the high sediment load from coastal transport and local winds may have facilitated the anticipation of channel migration to the island's interior, even during the middle of the rainy season. Sediment collection points with a bar system exhibited decreased particle size across all sectors and seasons. Additionally, the retreat of cliffs contributes to sediment on Joanes and Grande beaches (Salvaterra) during the rainy season, reflecting high coastal sediment transport and erosive characteristics during this period.

Changes in sediment transport and distribution on the studied beaches exhibit seasonal variability. The beaches are characterized by dissipative morphodynamic states, with high wave energy and large surf zones, providing temporal stability due to their low gradient. The construction of seawalls, however, as noted by Balaji et al. (2017), may exacerbate erosion problems, alter hydrodynamic conditions, and disrupt sediment transport, ultimately affecting beach profiles and local sediment supply, as observed on Grande beach after seawall construction.

Barra Velha and Pesqueiro beaches in Soure exhibit predominantly well-selected fine sand (> 2 to 3 phi), with a majority falling within the range of 0.35 to <0.50 phi and very well-selected sand (<0.35 phi) across all periods. This behavior is similar to findings observed on the microtidal beach of the Pacas river (Santa Catarina island) (Güttler et al., 2007) and the macrotidal beach of Ajuruteua (Braga et al., 2007), suggesting that granulometric variability is independent of tidal height, beach extent, and morphodynamic state. However, there are variations in sediment transport and distribution based on seasonality. During both rainy and dry seasons, the average grain size tends to increase from south to north, indicating an increase in asymmetry, with higher degrees of classification observed in the Northern sector.

No significant variations in wave incidence angles on the coast are observed during tidal flooding, with waves primarily facing the northeast on the beach. During high tide in the rainy season, wave heights peak due to intensified climate conditions, while during high tide, values are lower than during ebb tide, likely because of the high tide superimposed on the waves. Generally, wave heights on the beaches are higher in the dry season, attributed to stronger winds.

During ebb tide in both seasons, there is a decrease in wave period in the Western sector due to the angle of wave incidence with the coastline's elevation, leading to increased wave crest acceleration after the surf zone, as waves progressively align parallel to the coast (Schmiegelow 2004).

The beaches exhibit a dissipative morphodynamic state characterized by a low slope, high wave energy, and a large surf zone. This state provides greater temporal stability due to the low gradient, making them less susceptible to coastal processes. Observations by Braga et al. (2007) at Ajuruteua beach corroborate this finding. Levoy et al. (2000) emphasize the significant influence of waves on cross-shore transport and tides on beach morphology, particularly on macrotidal beaches.

During the rainy season, the beaches experience increased dissipative due to the erosive impact of equinoctial tides. Conversely, in the dry season, characterized by sedimentary accretion, there is a rise in the topographic gradient, leading to a reduction in the dimensionless parameter (Ω).

Analysis of sedimentary balance indicates maximum values at Pesqueiro beach (525 m^3/m) and minimum values at Grande beach (89 m^3/m), suggesting that the latter is more vulnerable compared to the others.

Lastly, according to Balaji et al. (2017), the effect of seawalls on beaches remains poorly documented, with many instances showing that seawalls exacerbate problems by inducing active or passive erosion. Seawalls often fail to effectively protect affected coasts and alter hydrodynamic conditions, affecting beach sediment transport and causing changes in beach profiles (Griggs and Tait 1988). On Grande beach, the construction of a retaining wall (700 m long) led to a reduction in width from 59-85 m to 40 m and an increase in gradient from 1.23° to 8.26° after construction.

6. Conclusions

The beaches of Marajó island exhibit dissipative characteristics, primarily influenced by waves during the dry season and both waves and tides during the rainy season. They feature gentle slopes with beach faces typically not exceeding 2°. Throughout both seasons, a runnel and channel parallel to the coast are observed in the intertidal zone across all beaches. Despite being a characteristic of sedimentary accretion during the dry season, the filling of this channel with continental sediments has not been observed thus far.

Beaches south of the Paracauari channel (Salvaterra) display more erosive traits, whereas those north of the channel (Soure) demonstrate depositional characteristics, exhibiting a positive sedimentary balance. The latter beaches exhibit stable sediment distribution patterns, with subtle variations in sediment transport observed from the rainy to the dry season.

Average granulometry and asymmetry values increase from Joanes beach (south) to Pesqueiro beach (north), while sorting and kurtosis values increase from the west to the east sector, indicating the direction of sediment transport from east to west. This circulation pattern is attributed to local winds and incident waves originating from the northeast, generating longitudinal currents flowing westward.

Among all studied beaches, Grande beach stands out as the most vulnerable, with a minimal sediment balance of 89 m^3/m. Recognizing the vulnerability of Grande beach, a recent seawall construction was undertaken to safeguard the coastal avenue and nearby residences. However, reports from residents suggest that three streets in front of this avenue have already succumbed to the strong hydrodynamics of the Pará estuary, resulting in the beach shrinking to a narrow sandy strip. These observations underscore the significant impact of the seawall, prompting ongoing investigations into its effects.

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P.V.M.S.: Validation, Writing, editing;

J.S.G.: review, editing, English Review;

L.A.R.: review, editing.

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