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Artigo de Pesquisa

Short to medium-term morphodynamic behavior of the beaches of the municipality of Goiana, Pernambuco, Brazil

Comportamento morfodinâmico de curto a médio prazo das praias do município de Goiana, Pernambuco, Brasil

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Abstract: Sandy beaches undergo rapid morphological variations in response to changes in coastal processes and climate conditions. It is known that many of them exhibit dynamics related to geological control exerted by nearby geological outcrops or on the very coastline. The coastline of the municipality of Goiana, Pernambuco, Brazil, is characterized by a sandy beach strip along the *Ponta de Pedras* mega salient, which forms in the shadow zone of a large adjacent offshore reef line. The morphosedimentary dynamics of the region are still poorly understood, and the studied area has been undergoing a rapid urbanization process, as well as showing erosive conditions in certain areas. To understand the short to medium-term morphological responses of the beach ridge, this study aimed to survey the topographic and sedimentological conditions of the beaches in the area, with the objective of identifying their dynamics between July 2017 and May 2019. It was observed that the central beach profiles of the study area have greater stability in all subsectors of the beach profiles, from the backshore to the upper foreshore, favored by the protection of the reefs. At the same time, the coastal circulation generated, influenced by these obstacles, favors the formation of multiple sandbars parallel and transverse to the beach, with poorly selected sediments due to the presence of carbonate gravels. The profiles farther from the center of the mega salient are subject to greater mobility within the sediment package due to complex interactions with openings between the reefs, tide variations, and locally generated circulation cells. The observed erosive conditions are associated with the influence of the Itapessoca River mouth to the south, and the impermeabilization and fixation of the backshore sector by urbanization over the beach stretch.

Keywords: beach profile; morphology; coastal erosion.

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Resumo: As praias arenosas sofrem variações morfológicas rápidas em resposta a mudanças nas condições dos processos costeiros e do clima. Sabe-se que muitas delas apresentam uma dinâmica em relação ao controle geológico exercido por afloramentos próximos ou pela própria linha de costa. O litoral do município de Goiana, Pernambuco, Brasil, é caracterizado por uma faixa de praia arenosa na linha de costa da mega saliência de Ponta de Pedras, que se forma na zona de sombra de uma grande linha recifal offshore adjacente. A dinâmica morfossedimentar da região ainda é pouco compreendida, e o trecho estudado vem passando por um processo de urbanização acelerado, além de apresentar condições erosivas em determinadas áreas. Para compreender as respostas morfológicas de curto a médio prazo do cordão praial, este trabalho teve por objetivo realizar um levantamento das condições topográficas e sedimentológicas das praias da referida área, com o intuito de identificar sua dinâmica entre julho de 2017 e maio de 2019. Observou-se que os perfis praiais centrais da área de estudo possuem uma maior estabilidade em todos os subsetores dos perfis praiais, desde a pós-praia à antepraia superior, favorecida pela proteção dos recifes, ao mesmo tempo que a circulação costeira gerada influenciada por estes obstáculos favorecendo a formação de múltiplas barras arenosas paralelas e transversais à praia, com sedimentos pobremente selecionados pela presença de cascalhos carbonáticos. Os perfis mais afastados do centro da mega saliência estão sujeitos a maior mobilidade no pacote sedimentar devido à complexa relação com as aberturas entre os recifes, variação da maré e as células de circulação geradas localmente. As condições erosivas observadas encontram-se associadas à influência da desembocadura do Rio Itapessoca, a sul, e à impermeabilização e à fixação do setor de pós-praia pela urbanização sobre a faixa de praia.

Palavras-chave: perfil de praia; morfologia; erosão costeira.

1. Introduction

Beaches are transitional environments bordering continents and seas, where coastal processes converge, responsible for their short-term morphological variability. Such rapid topographic modifications result, in part, from the interaction of wave climate conditions on the internal and external beach compartments (beach face and foreshore) that favor bidirectional sediment movement through the surf zone (Calliari *et al.*, 2003). According to Manso (2003), the high speed of beach morphology variation is the result of continuous adaptation to the varying energy of factors controlling sediment transport (waves, tides, and longshore currents). These coastal agents act on grains, selecting them by size, density, and shape. The intensity of these factors can change over short time intervals due to the morphological characteristics of the coastline. These variations directly influence the morphology of the shoreline. Moreover, there is a direct relationship between the morphology of beach profiles and the class of sediments that compose them, reflecting the wave energy conditions geologically controlled by the local physiography (Silva *et al.*, 2009; Calliari *et al.*, 2003). The influence of geological controls, such as offshore rock outcrops and coral reefs, on beach morphodynamics and sediment transport has been a growing area of study. According to Gallop *et al.* (2020), substrate geology influences beach formation by providing accommodation, and the morphology of rocky platforms, including elevation and gradient, is crucial. Geologically controlled beaches can exhibit significant variations in sediment cover with seasons and storms, and geological controls have fundamental influences on their contemporary morphodynamics. This includes wave sheltering by headlands and rocky/coral formations, inducing strong alongshore gradients in wave energy, resulting in corresponding variations in beach morphodynamic state and storm response. Geologically induced rip currents, such as shadow rips, deflection rips, and mega-rips that can develop on embayed beaches during storms, are an integral feature of the nearshore circulation and morphodynamics of geologically controlled beaches.

The coastal environments with the most dynamic responses, i.e., short-term morphological responses, are sandy coastal zones dominated by waves (Short & Hesp, 1982; Del Río *et al.*, 2013). Significant variations between the forcing factors (wave height, period, tide amplitude, among others) that converge on the beach system cause significant morphological changes, generating different morphodynamic responses (Wright & Short, 1984; Masselink & Short, 1993). It is important to note that classic models consider the responses of wave-dominated beaches and/or those influenced by tide amplitude based on wave condition parameters – breaking wave height (Hb) and wave period (T) – that interact with sediments and tide influence. However, it is important to note that sandy beaches are rarely subject to these parameters alone, often having some form of structural control caused by geological structures outcropping on or near the coastline.

Sandy beaches under the influence of rocky and coral outcrops are known as 'geologically controlled' because such structures directly influence wave transformation, coastal circulation patterns, current production, and sediment accommodation (Gallop *et al.*, 2020). Geologically controlled beaches exhibit gradients of longshore currents modulated seasonally by offshore obstacles, where sediment transport flows vary in direction and volume, reflecting in the morphological variability of the beach prism (Gallop *et al.*, 2013). Sandstone and coral reefs produce geological control similar to submerged breakwaters by attenuating wave energy and, consequently, influencing the evolution of beach profiles (Muños-Perez & Medina, 2010).

Coastal reefs and submerged structures not only modify wave propagation and sediment dynamics in the coastal zone but also play a crucial role in shoreline stabilization, especially in wave-dominated environments, by directly influencing the incident energy regime and circulation patterns (Castelle & Masselink, 2023; Ma *et al.*, 2020). These structures act as natural or artificial barriers that can attenuate wave height and alter their angles of incidence, which, in turn, affects sediment transport and beach resilience to extreme events.

The coastline of the state of Pernambuco features a rich shoreline with various forms in plan, including coves, spits, barriers, and beaches nestled in promontories, with approximately 83% of the coastal strip consisting of sandy beaches (Pereira *et al.*, 2016). Noteworthy are the multiple lines of sandstone and coral reefs arranged parallel to the coast, attenuating the energy of incident waves and directly influencing the morphological response of sandy beaches (Costa *et al.*, 2016; Martins *et al.*, 2019). The morphodynamic response of beaches influenced by reef systems has been extensively studied in diverse coastal settings, as demonstrated by the assessment of a beach-barrier system's response to an artificial reef in New England (Grilli *et al.*, 2023; Masselink *et al.*, 2021). These studies highlight the variability of sediment transport patterns and their implications for coastal management, showing how the presence of reefs can promote sediment accumulation in certain areas, stabilize the shoreline, or, conversely, induce complex patterns of erosion and deposition that require adaptive management strategies

Coastal reefs provide natural protection to the shoreline, favoring progradation on adjacent sheltered beaches and influencing sediment transport. The stability of sandy beaches protected by reefs depends on the geometric factors of these structures (e.g., distance, depth, and extent) relative to the coast, producing transformations in the incident waves and, consequently, coastal circulation patterns that reflect in the morphological dynamics of the beach prism.

The beach stretch in the municipality of Goiana, in the northern coast of the state of Pernambuco, lies within the *Ponta de Pedras* mega salient. Despite being sheltered by an extensive reef line, this region has shown signs of erosive processes along its beach strip. Some studies conducted in the region have characterized the geoenvironmental aspects, considering the preservation of the beach system, morphology and sedimentology of beach profiles, degree of urbanization, among others, of this section of the Pernambuco coastline (Xavier, 2007; Oliveira, 2013; Madruga *et al.*, 2017). Significant advances in local sediment dynamics were achieved by Oliveira (2017), who conducted a survey of morphodynamics through sedimentological studies, morphology of transverse profiles, and coastal modeling based on wave climate data. It is important to emphasize that despite the advances, there is a need to shed light on the integration of these findings and beach morphological responses, given the current conditions of continuous urban growth in this coastal stretch and the imminent sea-level rise, which will exacerbate coastal erosive processes.

To understand the short to medium-term morphosedimentary condition, this research aimed to investigate the seasonal dynamics of the beaches in the municipality of Goiana from July 2017 to May 2019 and characterize the effects of reefs on sediment transport in this section of the state's coastline. Thus, it intends to infer the implications of geological control on beach dynamics and its behavior in the study area, contributing new advancements to regional coastal management.

2. Study Area

The studied beaches are located between UTM coordinates 9164000 - 9150000 N and 2926000 - 301000 E (datum SAD 1969), covering approximately 15 km of coastal strand, specifically along the seafront of the municipality of Goiana, Pernambuco, between the namesake river, Goiana, to the north, and the Itapessoca River to the south (Figure 1). The studied area represents about 8% of the 187 km of coastline that the state of Pernambuco possesses and is situated in the outer portion of the coastal plain of the northern region of the state.

The study area is located on the *Ponta de Pedras* mega salient, resulting from the influence of the shadow zone of partially submerged reefs near the coast (Macêdo *et al.*, 2022). These obstructions, together with the tidal amplitude, are responsible for modulating the transmission of wave energy, being higher during low tide due to the partial exposure of the reefs and lower at high tide due to submersion, partially dissipating the incident waves (Costa *et al.*, 2016).

The regional ocean circulation is characterized by the Brazil Current, which flows southward at speeds ranging from 0.2 to 0.5 m/s (Madruga Filho, 2004). The tidal regime is semidiurnal with 12-hour and 42-minute cycles, controlled by astronomical components (99.7%) and minor influence from meteorological events, with a typical mesotidal environment amplitude (0.97 to 2.07 m) (Pereira *et al.*, 2016; MCT/UFPE, 2010).

The wave climate is seasonally influenced by the rainy and dry seasons. Consequently, the predominant winds in the rainy season from SE generate incident waves in the same direction, ranging from 1.5 to 2.5 m in significant wave height (Hs) and peak period (Tp) between 8 and 10 seconds, while in the dry season, they result from E winds, with Hs between 1.5 and 2 m and Tp between 6 and 12 seconds (Macêdo *et al.*, 2022).

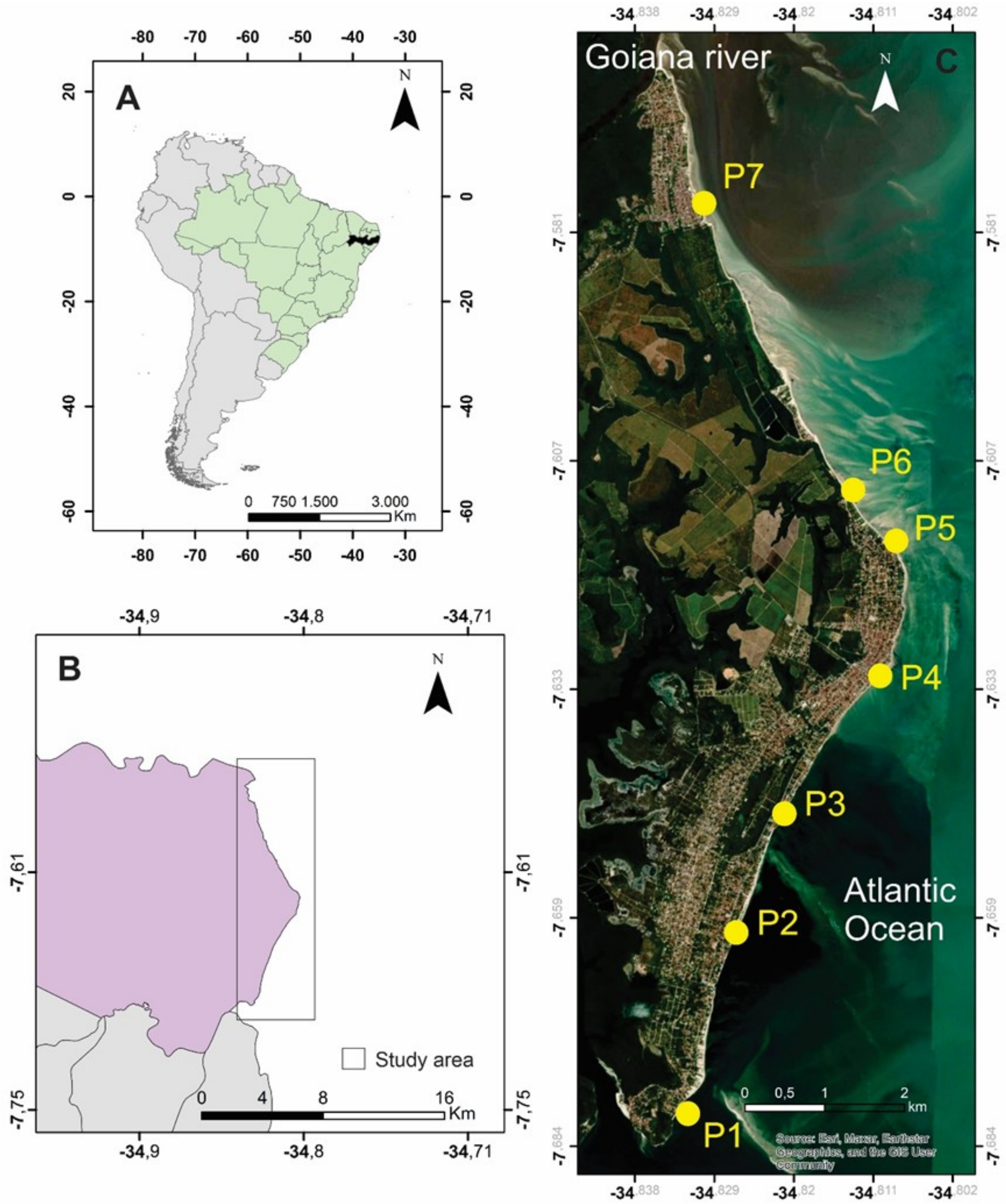

Figure 1. Location of the studied area: (A) State of Pernambuco; (B) municipality of Goiana; (C) Location of the seven studied beach profiles.

Figura 1. Localização da área estudada: (A) Estado de Pernambuco; (B) município de Goiana; (C) Localização dos sete perfis praiais estudados.

3. Materials and Methods

To carry out the morphological and sedimentological analyses of the coastal line of the municipality of Goiana, bimonthly surveys of the transverse topographic profiles to the coast were conducted at seven points located at the southern end, central section, and northern end of the area (see Figure 1 again). This analysis was performed between July 2017 and May 2019, totaling twelve topographic profiles for each of the seven defined points.

For the survey of the profiles, fixed Reference Levels (RLs) were established (Table 1). To ensure vertical stability over time, the RLs were defined on permanent and stable structures such as building corners and foundations of structures located in the backshore. Th RLs were determined by GPS, Garmin 12® model, which has an accuracy of approximately 3 m, while for the topographic measurements, the following were used: a Pentax level, a tripod, and a topographic rod assisted by vertical rods positioned at the points of topographic inflection, a tape measure, and seven metal stakes for marking elevation levels. This fieldwork took place during low tides, before each spring tide, aiming to capture as much morphological variation as possible across the entire aerial and subaerial profile. The level differences between each point in the profiles were measured through readings obtained by horizontal sightings, and the distances between the points were measured using a tape measure (Garcia & Piedade, 1987).

Table 2. Coordinates of the reference points for the topographic profiles along the shoreline of Goiana, datum SAD 1969.

Tabela 1. Coordenadas dos referenciais de nível dos perfis topográficos ao longo da faixa de praia de Goiana, datum SAD 1969.

PROFILES	COORDINATES	OBSERVATIONS
P1	9150636N, 297806E	Near the mouth of the Itapessoca River
P2	9152605N, 298435E	Located 2 km north of P1
P3	9154276N, 299058E	Located 1.2 km from P2, in front of Marina de Catuama
P4	9156188N, 300420E	Located 2.4 km from P3, on a small salient of the coastline
P5	9157476N, 300564E	Near Ponta da Felicidade, located 1.3 km from P4
P6	9158187N, 299870E	Northern portion of the *Ponta de Pedras* mega salient, located 1 km from P5
P7	9161958N, 297944E	Near the mouth of the Goiana River, located 4.2 km from P6

After the data collection, the calculations of the absolute levels were made based on the tide height recorded on the day of the survey. Thus, the profile graphs were generated for all seven points, and then the subaerial profile volume was calculated to establish comparisons and determine the seasonal morphological dynamics. For this purpose, the aerial and subaerial profile was considered in its entirety, from the RN in the backshore to the zero elevation (mean sea level) on the beach face, multiplying the result by one to obtain the total volume per linear cubic meter.

The beach sediment samples were collected along the segments of the topographic profiles, covering the compartments of the swash zone, foreshore, and backshore. Only profiles P1 and P3 did not have collections in the backshore, as this compartment is filled. The samples were subjected to granulometric analysis at the Laboratory of Marine Geology and Geophysics (LGGM) of the Geology Department at UFPE and went through the following stages: (a) pre-drying at room temperature; (b) drying in an oven at 60ºC; (c) manual quartering and weighing of 100 g on a semi-analytical balance, with an approximate error of 0.050 g; (d) after the first weighing, wet sieving was performed under running water to separate the gravel (> 2 mm) and mud (< 0.063 mm) fractions. The muddy sediments (silt and/or clay) were discarded, as the percentage was not statistically significant; (e) after washing, the selected samples were dried in the oven in beakers at 60ºC; (f) after drying, the samples were weighed again and sieved in a sieve shaker for 10 minutes to separate the fractions: very coarse sand (≥ 1.00 mm), coarse sand (between 1.00 and 0.500 mm), medium sand (between 0.500 and 0.250 mm), fine sand (between 0.250 and 0.125 mm), and very fine sand (between 0.125 and 0.063 mm).

The fractions were weighed, and the resulting data were processed in the SYSGRAN software (Camargo, 2006), generating a table with statistical parameters for granulometric classification and determination of the degree of selection according to Folk & Ward (1957).

4. Results and Discussion

4.1. Beach Profiles

After 12 months of alternating topographic surveys for each of the seven reference points along the Goiana coastline, a total of 84 cross profiles were compiled (Figure 2). The volumes calculated for the profiles are available in Table 2, thus allowing the establishment of the temporal dynamics of the sediment balance at the respective points.

The first profile (P1) is in the southern section of *Barra de Catuama* beach and has the smallest beach strip and, consequently, the smallest volume among the analyzed profiles. Its length varied from 14.5 to 31.7 m during the studied months. It is characterized by the absence of a backshore and an average swash zone length of 13.2 m, with a gradient that ranged from 7º to 9º. The absence of a backshore results from urbanization encroaching on this physiographic unit. Despite the RN of P1 being fixed in a concrete structure, an erosive process was observed after January 2018 (Figure 6), with a lowering of about 80 cm in the RN height. In a previous study conducted between November 2014 and September 2015 at this same point, Madruga (2017) had already recorded the ongoing erosive process, with a final sediment balance deficit of 19.8%. The former RN (9150616S and 297826E) established by the mentioned author is currently submerged due to the ongoing erosional trend since then, with the difference between the current and previous RN positions indicating a 55 m retreat of the coastline.

Temporal analysis indicated that from July 2017 to July 2018, this point on the coastline showed an erosive trend with a deficit of -22 m^3/m, recovering in September 2018, which recorded the highest volume with sediment gain in the lower swash zone and foreshore (Figure 2 - P1). From September to October 2018, the profile experienced a significant loss of sediment material (-20 m^3/m), but remained relatively stable from November to May of the same year, with an average volume of 28 m^3/m. Despite the stability, its final sediment balance was -15 m^3/m.

Urbanization of the beach backshore has been widely recognized as a key driver of erosion on sandy beaches. Hard structures built along the shore can block alongshore sediment transport, leading to shoreline changes and affecting the sediment deposition balance (Luijendijk *et al.*, 2018). Additionally, the location of P1 is near the mouth of the Itapessoca River, a naturally dynamic area influenced by river discharge and tidal cycles. Despite the presence of reefs that partially shelter this region from wave energy, in such low-energy environments, the morphology may be restricted to a steep foreshore (Jackson *et al.*, 2002).

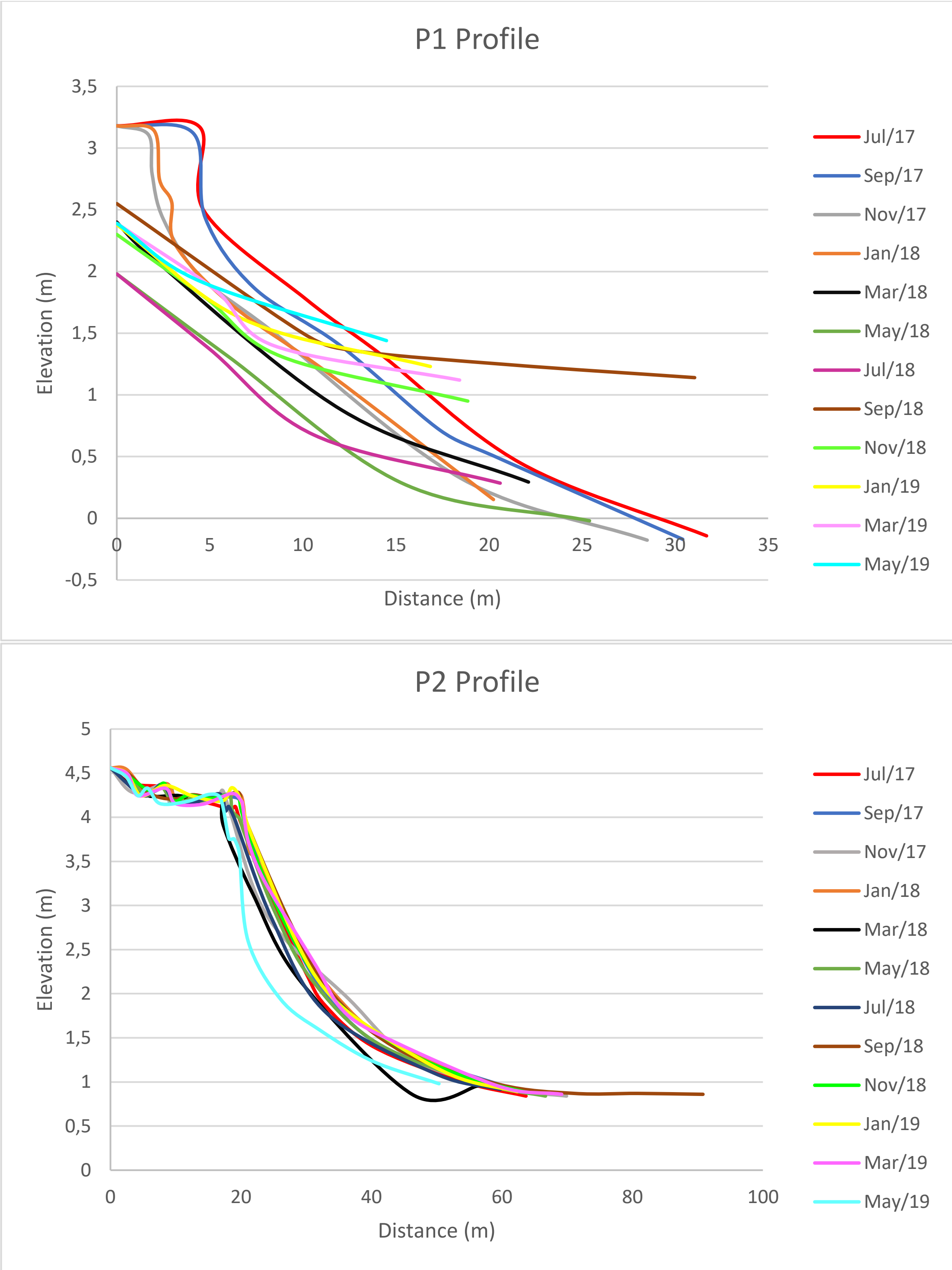

Figure 2. P1 and P2 Beach profiles of the Goiana shoreline surveyed from July 2017 to May 2019.

Figura 2. Perfis de praia P1 e P2 do litoral de Goiana, levantados de julho de 2017 a maio de 2019.

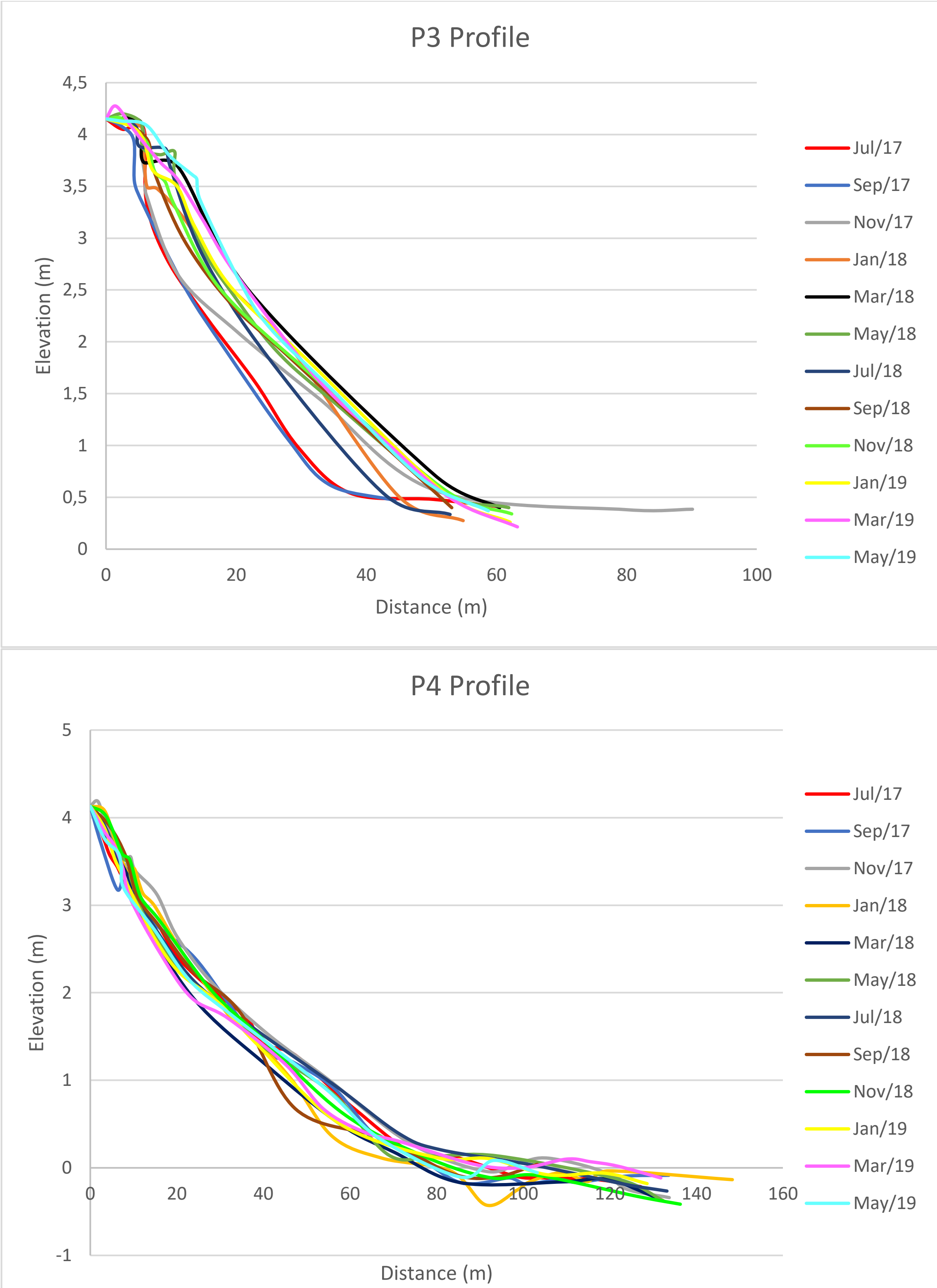

Figure 3. P3 and P4 Beach profiles of the Goiana shoreline surveyed from July 2017 to May 2019.

Figura 3. Perfis de praia P3 e P4 do litoral de Goiana, levantados de julho de 2017 a maio de 2019.

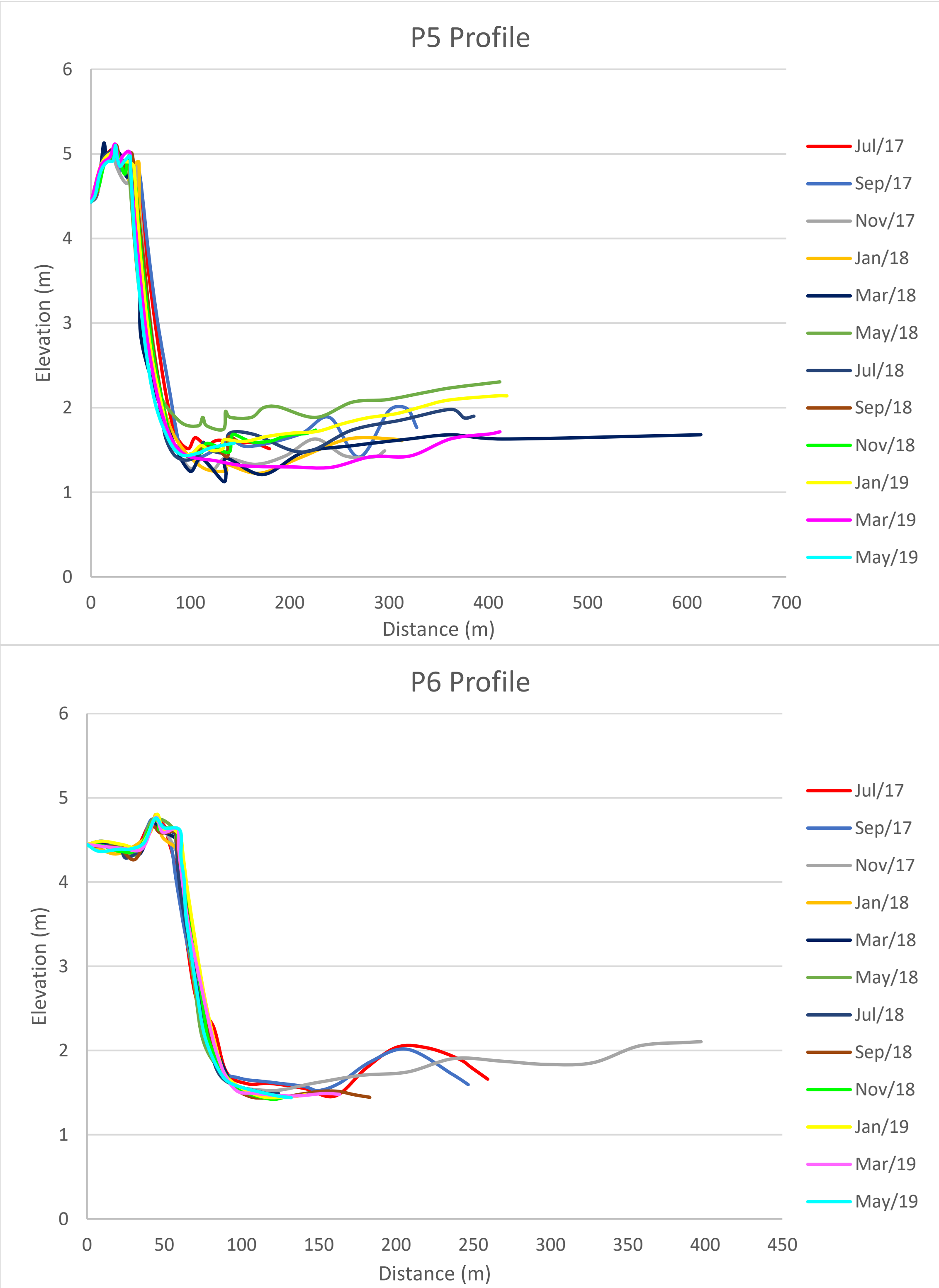

Figure 4. P5 and P6 Beach profiles of the Goiana shoreline surveyed from July 2017 to May 2019.

Figura 4. Perfis de praia P5 e P6 do litoral de Goiana, levantados de julho de 2017 a maio de 2019.

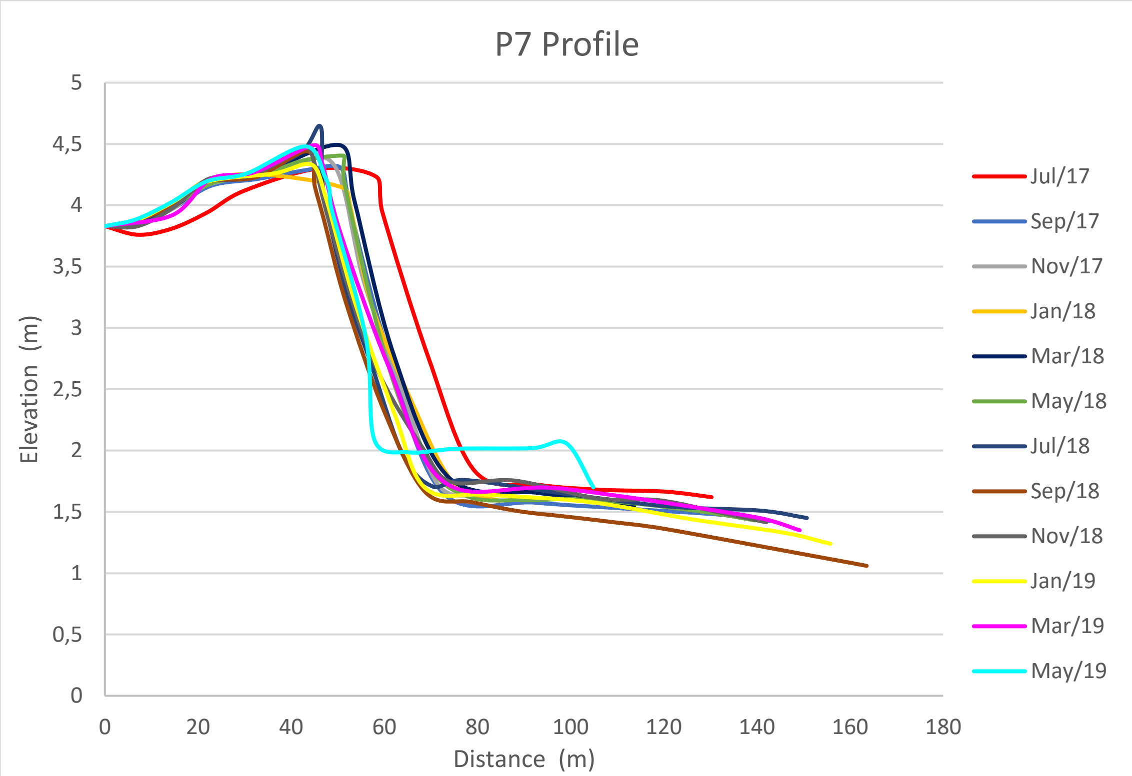

Figure 5. P7 Beach profile of the Goiana shoreline surveyed from July 2017 to May 2019.

Figura 5. Perfil de praia P7 do litoral de Goiana, levantado entre julho de 2017 e maio de 2019.

Table 2. Volume variation in m/m³ of the profiles from July 2017 to May 2019. The orange color represents sediment deficit in relation to the initial month. The blue color indicates a surplus of sediments in relation to the initial month. The final negative sediment balance is represented by the red color and the positive one by the green color.

Tabela 2. Variação do volume em m³/m dos perfis de julho de 2017 a maio de 2019. A cor laranja representa déficit de sedimentos em relação ao mês inicial. A cor azul indica um excedente de sedimentos em relação ao mês inicial. O balanço sedimentar final, negativo, é representado pela cor vermelha e o positivo, pela cor verde.

MONTH/PROFILE	P1	P2	P3	P4	P5	P6	P7
jul/17	41	159	90	134	493	642	384
sep/17	37	160	80	130	751	615	378
nov/17	29	167	119	145	629	904	285
jan/18	29	170	110	123	658	353	292
mar/18	25	124	128	116	816	370	345
may/18	19	164	119	130	980	381	376
jul/18	19	154	105	138	825	397	386
sep/18	47	190	111	125	424	489	380
nov/18	27	165	118	133	548	410	376
jan/19	28	164	121	124	928	436	386
mar/19	29	170	123	124	783	462	391
may/19	26	132	124	128	395	411	327
Balance	**-15**	**-27**	**34**	**-6**	**-98**	**-231**	**-57**

Figure 6. P7 Records of erosive processes in the region of profile P1. (A) Location of the reference level (RN) in July 2017; (B) Condition of the reference level in March 2018; (C) Foundation of the former residence on the backshore beginning to lose support in May 2018; and (D) Debris of the residence following continuous erosion.

Figura 6. Registros de processos erosivos na região do perfil P1. (A) Localização do nível de referência (RN) em julho de 2017; (B) situação do nível de referência em março de 2018; (C) fundação da antiga residência sobre a pós-praia inicia perda de sustentação em maio de 2018; e (D) escombros da residência pós-contínuo processo erosivo.

The profile P2 is the third shortest in length among those studied, with its width varying from 50.3 to 90.8 m. The backshore region averaged 20 m in length and was marked by the presence of Ipomea pes-caprae vegetation (known as *salsa de praia* in Brazilian portuguese), which reduces sediment reworking by wind action. The berm at this point is well-defined and steep, with an average slope of 19º, reaching 40º in March 2018. The swash zone has a gentle to medium slope of 10º.

Throughout the topographic survey period, this profile showed a predominantly surplus sediment balance compared to the initial month, except for March and July 2018 and May 2019. Between July 2017 and January 2018, there was a positive volume variation of about 11 m^3/m, possibly resulting from the deposition of part of the eroded material from the upper swash zone (between 17 and 34 m) to the lower swash zone, between 35 and 46 m (Figure 2 - P2). From the beginning of the historical series in July 2017, the final sediment balance was negative (-27 m^3/m) due to significant retreat across the swash zone and a backshore retreat of approximately 4 m. Despite the observed erosive trend indicated by the volume data, this might likely be a false negative, and its overall trend should be stable, given that the total average length of profile P2 was not considered, with a maximum length of 50 m mapped in the historical series. This is because, at the end of May 2019, the low tide of 0.3 m made it difficult to acquire the elevation levels in the foreshore region.

The profile P3 is located in the central portion of the southern bay of the coastline, situated in front of Marina de Catuama in *Ponta de Pedras*. It has the second shortest length among the others, with a minimum extension of 44 m and a maximum of 90 m. Its gradient varied from gentle to medium, with a slope between 5º and 12º throughout the historical series. The berm at this point was quite steep, reaching 54º in March 2018.

The backshore region has a short length, averaging 5.5 m, and the swash zone is quite mobile – observed in the profile P3 section corresponding to distances between 4 and 50 m – with a width varying from 30 to 80 m. The cross profiles measured in July and September 2017 had the lowest sediment volumes, indicating a transition from an erosive condition to significant progradational recovery. In March 2018, the profile reached its highest volume (128 m³/m), a result of deposition throughout the swash zone. In the historical series, from November 2017 to May 2019, this portion of the beach strip maintained a positive balance with an average volume of 118 m³/m, with significant variability of about ±7 m³/m.

Nearshore reefs diffract most incident waves, causing their reorientation, which in turn leads to refraction by inner subparallel-shore sandbanks. This process may favor the stable to progradational condition of profiles P2 and P3 (Macêdo, 2015). A previous planform analysis using the Parabolic Bay Shape Equation for this area (Macêdo, 2015) indicated that the southern bay of the *Ponta de Pedras* megasalient is in a dynamic condition. In this case, the shoreline is in an accretional condition. A shoreline movement analysis from 2007 to 2017, conducted by Jesus (2023), showed that the same beach stretch was characterized as stable.

The beach profile P4 is located in the southern area of the *Ponta de Pedras* mega salient, on a secondary salient of smaller extension resulting from wave sheltering formed by the outcrop of limestones from the Maria Farinha Formation, beach rocks, and corals in the foreshore (Macêdo, 2015). Point P4 is in one of the most urbanized sections of the Goiana beach strip, comprising one of the most visited regions of the northern coast of Pernambuco. Many urban facilities, such as vacation homes and bars, are installed in the backshore strip.

The average measured slope of the swash zone for this profile is quite gentle, about 6º, reaching a minimum of 2º in January 2019.

In its historical series, this profile mostly exhibited erosive conditions, with only two months (November 2017 and July 2018) showing progradational conditions. However, it is worth noting that the negative variations were minimal, with March 2018 showing the greatest retreat of the beach face (between 9 and 30 m in distance) with a volume of 116 m³/m. Conversely, November 2017 showed the greatest sediment gain, around 145 m³/m. The overall erosive trend for the period was relatively low (-6.2 m³/m), indicating low morphological mobility. This stability is related to the presence of rocky outcrops (Figure 7) that form abrasion platforms in the intertidal region, near the beach face. The presence of these obstacles attenuates wave action, creating a shadow zone that favors the formation of a salient. In this region, sandbanks exchange sediment with the beach profile as a result of incoming material from the deceleration of longshore transport from the southern profiles in an erosional condition (Jesus, 2023), thus providing a depositional condition.

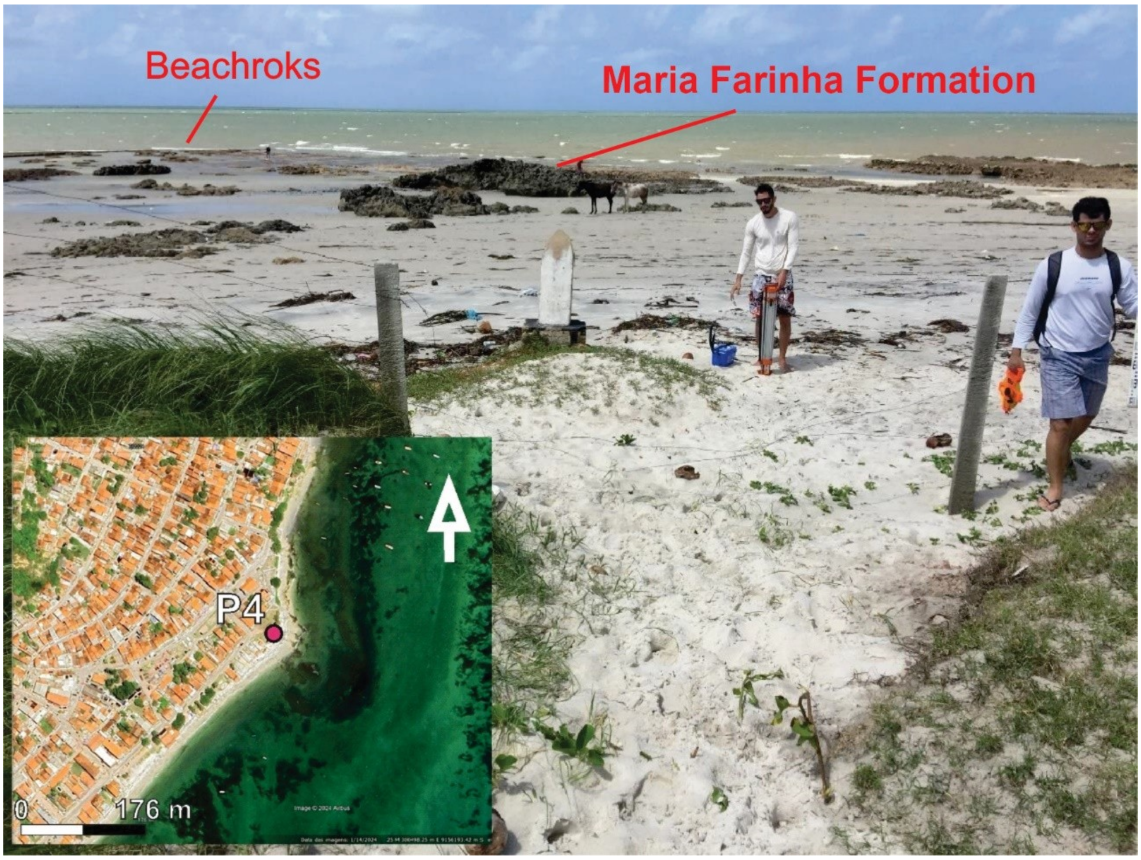

Figure 7. Location of profile P4 at the district landmark on *Ponta de Pedras* beach. In the photograph from July 2017, the Marinha Farinha Formation and partially submerged beachrocks, as well as coral banks, can be observed. In the smaller image at the bottom left, the location of point P4 is shown on the salient formed behind the obstacles present on the beach face and foreshore.

Figura 7. Localização do perfil P4 no marco do distrito na praia de Ponta de Pedras. Na fotografia de julho de 2017, observam-se aflorando a Formação Marinha Farinha e beachrocks parcialmente submersos, assim como bancos de corais. Na imagem menor, no canto inferior esquerdo, localização do ponto P4 na saliência formada atrás dos obstáculos presentes na face de praia e na antepraia.

Profile P5 is located at Ponta da Simplicidade, the apex region of the *Ponta de Pedras* mega salient, in the northern area of the Goiana coastline. This profile has the longest recorded extension at approximately 309.8 meters, where a wide tidal flat occurs. The swash zone slope, averaging 8°, varied between 7° and 11° during the studied period. Due to its gentle profile and location in one of the most sheltered zones of the coastline, a wide tidal flat emerges during low tides (Figure 8).

As in profile P2, profile P5 still preserves part of the beach vegetation composed of the species Ipomea pes-caprae in the backshore, reflecting in the low morphological variation in the mentioned physiographic unit, as well as relative stability in the swash zone (Figure 2 - P5). However, in the foreshore zone, there is high morphological mobility with the presence of multiple sandbanks starting at 100 m in the profile. The mobility of these subaerial features may be related to their carbonate composition, predominantly formed by algae of the genera Halimeda and Lithothamnium, which have low density and are therefore easily remobilized. According to Jesus (2023), this region acts as a transitional area between the southern and the northern bays. The transverse sandbars tend to migrate onshore, and occasionally, some banks may attach to the coast.

Figure 8. Photographs of the tidal flat during low tide in July 2018 (A) and March 2019 (B) at profile P5, showing sandy banks subparallel to the coastline.

Figura 8. Fotografias da planície de maré durante baixamar em julho de 2018 (A) e março de 2019 (B) no perfil P5 expondo bancos subparalelos à linha de costa.

The study period identified a progradational trend for this profile most of the time recorded, with the highest volume in May 2018 (980 m³/m) due to the greater sediment gain in the foreshore sandbanks, and the lowest in May 2019 (395 m³/m), reversing the trend to an erosive condition. Despite the deficit in the final sediment balance, in the order of -98 m³/m, point P5 shows its subaerial zone to be relatively stable, highlighting the influence and high dynamics of the banks in the tidal flat. This provides a cross-shore sediment exchange indicating a progradational condition of that region (Manso *et al.*, 2006; Jesus, 2023).

Profile P6 is in the northernmost portion of the *Ponta de Pedras* beach mega salient, approximately 1 km from point P5. This profile exhibits similar morphodynamic behavior to P5, with a stable backshore and swash zone throughout the monitoring period, where the latter has a gentle to medium slope (between 7° and 11°).

The main variations were recorded in the cross-section after the distance of 100 m, due to the presence of sandbars (Figure 2 - P6). The overall sediment balance indicated an erosive trend, ending the historical series with a volume deficit in the order of -231 m³/m, representing the greatest loss among the beach profiles analyzed in the study area. However, as observed in the beach section of profile P5, the sediment dynamics are restricted to the foreshore zone where large sandbars form on the extensive tidal terrace. The highest recorded volume occurred in November 2017 (904 m³/m), and this is associated not only with the greater mapped length but also with the accretion of the tidal terrace by three sandbars. These findings are consistent with Jesus (2023), who mapped and monitored sandbars and the shoreline profile. Notably, the multiple bars develop transversely to the coastline (Figure 6), unlike the parallel bars in the sections of profiles P4 and P5. The quasi-stable aerial morphological behavior of this sector, particularly at P5 and P6, was previously confirmed by Martins *et al.* (2016), whose work classified this beach stretch as being in a state of null erosion condition.

Figure 9. Google Earth Pro satellite image of the apex region of the mega salient of *Ponta de Pedras*. It is possible to observe that in the section between points P4 and P5, the sandbars are aligned parallel to the coast, while from point P5 to P6, the sandbars are transverse.

Figura 9. Imagem orbital do Google Earth Pro da região do ápice da mega saliência de Ponta de Pedras. É possível observar no trecho entre os pontos P4 e P5 que as barras arenosas se dispõem paralelas à costa, enquanto do ponto P5 a P6, as barras encontram-se transversais.

The last beach profile, P7, is in the northern area of the study region, on Carne de Vaca beach, south of the Goiana River. Its average analyzed length was 120 m, with a relatively extensive backshore (~45 m), despite the existing urbanization in this stretch, and a gently to moderately sloping swash zone that varied from 6º to 11º.

This point showed a general erosive trend, with a final sediment balance of -57 m³/m. There was significant morphological variation across the entire cross-section, with the most substantial changes occurring between July 2017 and March 2018. In most of the other monitored months, the profile volumes remained relatively stable, with quantities close to the initial value (~387 m³/m). The beach strip in this region shows some morphological mobility, with the highest volume observed in July 2017 in the section from 60 to 80 m, corresponding to the beach face. November 2017 recorded the most deficit volume (285 m³/m). May 2019 was the second most deficit month, interrupting the progradational trend of the previous two months, with significant erosive retreat in the backshore and swash zone and accumulation of part of this material in the subaerial portion of the lower swash zone and subaerial portion of the foreshore, comprising distances from 65 to 104 m of the cross profile.

The erosional condition observed at the northernmost location (P7) in the northern bay of the *Ponta de Pedras* megasalient likely results from multiple factors. The proximity of the Goiana River mouth and the Tracunhaém River influences alongshore sediment transport, while the estuary complex formed by these rivers generates mobile submerged ebb-tide deltas, as evidenced by historical satellite imagery (Google Earth). Additionally, this region is directly exposed to higher-energy waves due to a gap in the reef system (Macêdo, 2015). The inner-shelf reefs, modulated by tidal cycles, control wave direction, causing waves to approach this shoreline stretch nearly perpendicularly (Oliveira, 2017). Furthermore, the absence of transverse submerged sandbars (Jesus, 2023) may exacerbate sediment deficit along the coast.

4.2. Granulometric Parameters: Mean Diameter and Sorting

The overall distribution of mean diameter and the sorting degree of the sediment samples from the beach profiles in the study area are shown in Figure 10. Throughout the study area, approximately 55% of the sediments are in the fine sand fraction, followed by medium sand (24%), very fine sand (12%), coarse sand (5%), and very coarse sand (4%).

The backshore and swash zones are responsible for the largest stock of fine to medium sands (Figure 7 - A). It is observed that in the foreshore sectors, coarser sediments are in the central areas of the mega salient, particularly in profiles P4, P5, and P6, while finer to medium sediments predominate in the more distal areas (P1, P2, P3, and P7).

The beach sediments analyzed are generally moderately sorted, especially in the backshore and swash zones, due to the predominant presence of medium diameter sands (Figure 7 - B). Profiles P4, P5, and P6 again stand out for their poor degree of sorting in the foreshore zone, reflecting the granulometric variation of the coarse sediments present. The high algal productivity in this central sector is influenced by the substantial amount of gravelly carbonate material deposited on the tidal terrace. The low density of the carbonate material indicates that the hydrodynamic conditions in the central region of the study area favor its deposition, suggesting low energy of the incident waves, which have insufficient competence to mobilize the bioclasts.

In the southern bay profiles, from P1 to P5 (except P3), a small proportion of well-sorted sediments is observed in at least one of the three beach sectors of each profile. This is possibly due to the continuous supply of a specific grain class or the predominance of a geological agent in the transport and deposition processes, or a combination of these elements in this area. The geographic location of the large southern bay near the mouth of the Itapessoca River may experience greater influence from the fluvial processes of this river compared to the northern bay, adjacent to the mouth of the Goiana River. The differentiating factor for these two cases would possibly be the direction and influence of the south-to-north longshore currents, which favor greater deposition of fluvial sediments from the Itapessoca River, while the central area and northern bay receive less sediment input from the rivers bordering the Goiana beach stretch. This fluvial influence is particularly evident in profile P1, situated directly adjacent to the river's mouth.

Computer simulations of waves conducted using the Coastal Modeling System (SMC-Brasil, 2024) by Oliveira (2017) for this same region show three large shadow zones generated by the reef lines on the shallow platform. Using historical wave climate data in intermediate waters for the coast of Pernambuco (Hs50% = ~1.4 m; Tp50% = ~7.5 s; Dir = ESE), the author simulated three sea level scenarios (low tide, mean sea level, and high tide) to verify the effects of obstacles on incident waves. The arrangement of the reefs relative to the coastline and the direction of wave origin favor greater protection from wave energy, especially during low tides, creating a first shadow zone to the south in the beach strip of profiles P1 and P2, with profile P3 exposed. The second shadow zone shelters the central profiles P4, P5, and P6, where profile P6 is at the threshold of this protection, receiving more energy than the others. Finally, the third shadow zone is located just after profile P6, encompassing P7. In this area, the waves arrive obliquely relative to the coast, which is also evidenced by the south-to-north longshore drift in this area, where erosive processes have led residents to stabilize part of the coastline by planting coconut trunks perpendicular to form groynes that block and stabilize the beach strip.

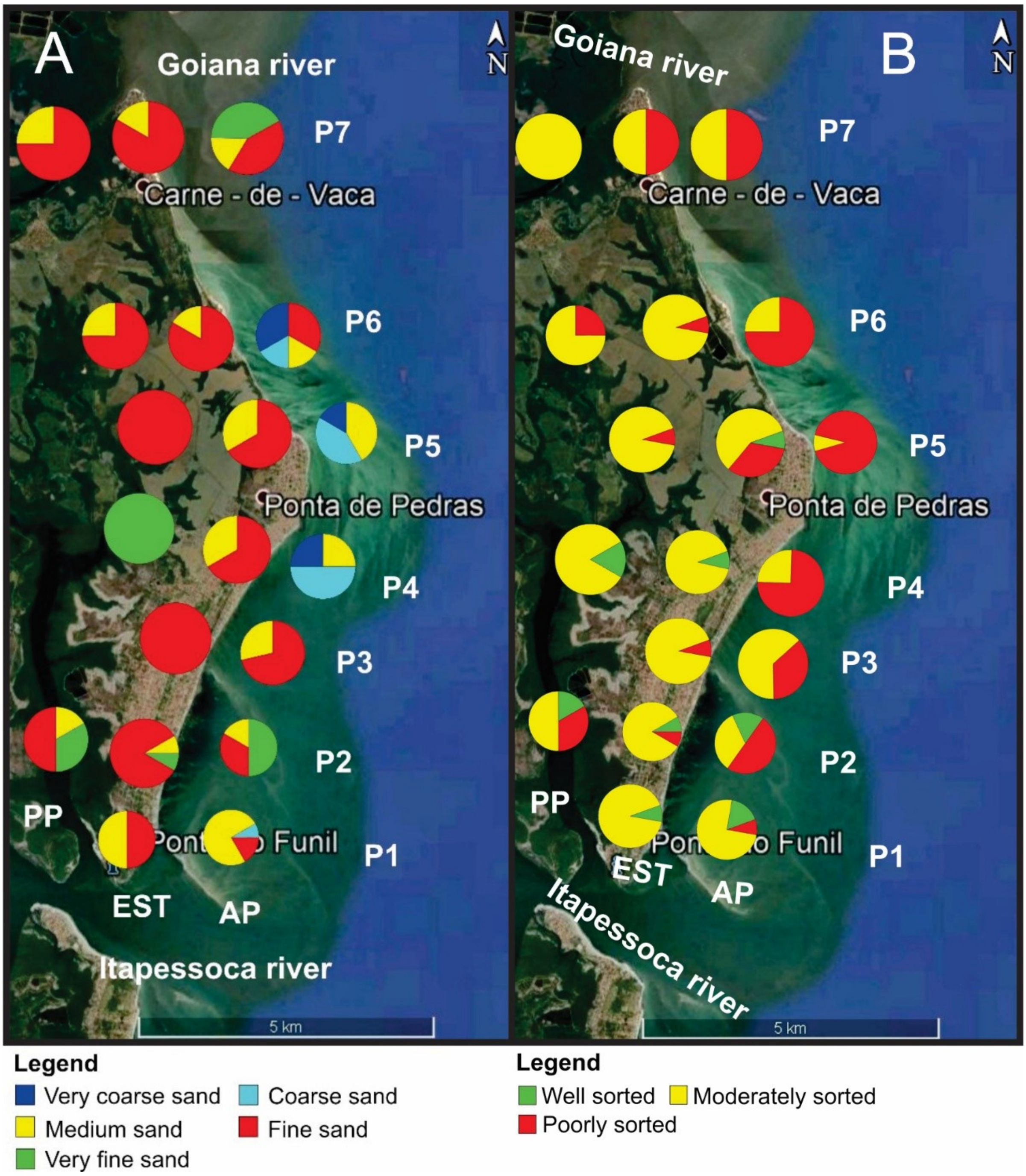

Figure 10. *Classification (A) and degree of selection (B) of sediments in the beach profiles of the Goiana coastline in the backshore (PP), swash zone (EST), and foreshore (AP) sectors*.

Figura 10. Classificação (A) e grau de seleção (B) dos sedimentos nos perfis praiais do litoral de Goiana nos setores pós-praia (PP), estirâncio (EST) e antepraia (AP).

4.3. Sediment Transport and Morphological Stability of the Goiana Coastline

An analysis using descriptive statistics can be useful in characterizing the mobility of the sediment stock in the profiles. The mean values of the historical series for each profile, combined with dispersion measures (standard deviation and coefficient of variation), can help shed light on beach dynamics. The Pearson coefficient of variation was adapted by Short & Hesp (1984) as the mean variation of the coastline. According to the authors, low CV values indicate low mobility of the backshore and/or beach, whereas high values characterize high mobility and thus greater susceptibility to episodes of erosion or accretion of the beach prism.

Profiles P2, P3, P4, and P7 exhibited the lowest mobility in terms of volumes, with P3 having the highest CV value (12%) and P4 the lowest (6%). The other profiles, P1, P5, and P6, showed CV values ≥ 27 (see Table 3).

Table 3. Descriptive statistics from monthly volume data where $\bar{u}$ is the mean, σ is the standard deviation, and CV is the coefficient of variation, where CV = $(\sigma/ \bar{u})*100$.

Tabela 3. Estatística descritiva dos dados de volumes mensais onde $\bar{u}$ é a média do volume, σ é o desvio padrão e CV é o coeficiente de variação o qual CV = $(\sigma/ \bar{u})*100$.

PROFILES	P1	P2	P3	P4	P5	P6	P7
$\bar{u}$	30	160	112	129	686	489	359
σ	8	17	14	7	185	153	36
CV (%)	27	10	12	6	27	31	10

Profile P4 is the most stable, with its low morphological variation observed across all its morphological sectors (backshore, swash zone, and foreshore). Besides its position in the most sheltered region at the apex of the *Ponta de Pedras* mega salient, rocky outcrops on the beach face stabilize the coastline so that its physiographic sectors behave similarly the same over time. This low cross-shore mobility can also be observed to some extent in profiles P2, P3, and P7, which is likely related to their positions along the Goiana beach strip in relation to the large partially submerged reef line on the shallow marine platform. For these latter three profiles, the swash zone and foreshore experience higher mobility.

Profile P1 is among the most mobile, showing high mobility from the swash zone to the foreshore. The southern sector of the study area is close to the river mouth, which naturally exhibits high dynamics in its coastline due to the mobility influenced by the Itapessoca River discharge. Adding to this is the intense urbanization of the beach strip, impermeabilizing and fixing the backshore zone, preventing natural seasonal exchanges in the cross-section of the beach profile.

Besides the interference of rocky outcrops on the continental shelf that create structural control on the Goiana coastline, forming the *Ponta de Pedras* mega salient (Macêdo *et al.*, 2022), a complex circulation pattern is generated by ebb and flood tidal currents due to these flows over the reefs. Oliveira (2017) highlighted that the highest magnitudes of currents occur at high tide, characterized by patterns of multiple circulation cells intensified during flood tides. It is noteworthy that the simulations produced by the author identified that the longshore currents for this section of the coastline are bimodal (Figure 11), with a divergent bifurcation occurring in the region of the mega salient apex.

Figure 11. *Sediment transport model by longshore drift of the beaches of Goiana. The blue arrows indicate drift in the north-south direction, and the yellow arrows indicate drift in the south-north direction. Adapted from Oliveira (2017)*.

Figura 11. Modelo de transporte sedimentar por deriva litorânea das praias de Goiana. As setas azuis indicam deriva com sentido norte-sul, as amarelas indicam deriva com sentido sul-norte. Adaptado de Oliveira (2017).

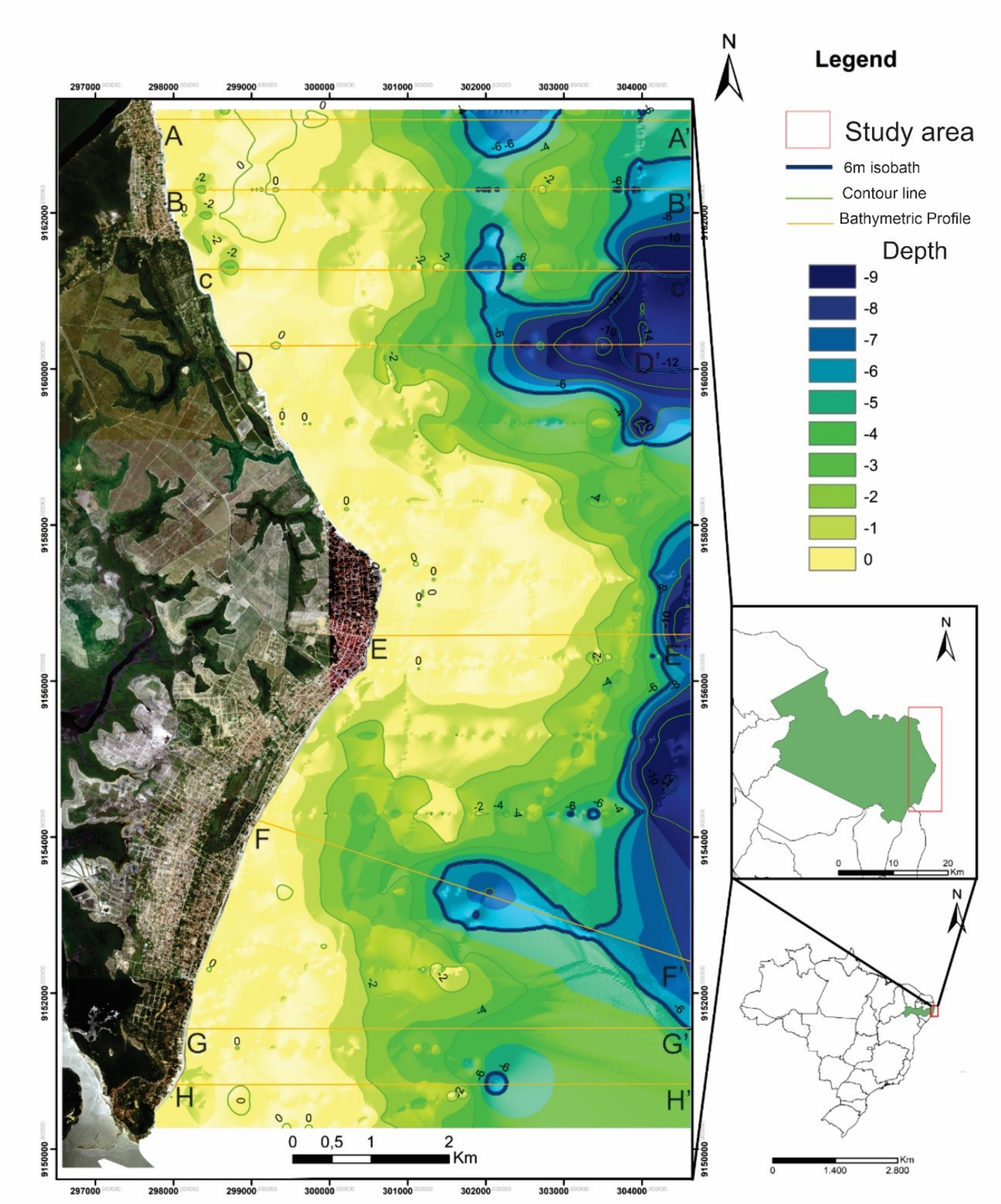

Figure 12. *Bathymetric map of the municipality of Goiana, Pernambuco*.

Figura 12. Mapa batimétrico do município de Goiana, Pernambuco.

In the northern bay, the net sediment transport follows the regional trend from south to north, while in the southern bay the direction is reversed, from north to south, from the beach strip of profile P4 to P3, resuming the south to north direction in the remainder of the southern bay. The oblique incidence relative to the coast corresponds to the observations made by Ranasinghe & Turner (2006), who identified that the structural control of submerged obstacles, such as reefs, induces the predominant inversion of drift which is weakened by the nearshore circulation, favoring the deposition and maintenance of sediment volume along the coastline behind these structures.

5. Conclusions

A survey of the morphological variations and sedimentological characterization of the beach profiles in Goiana, on the northern coast of Pernambuco, was conducted in this research. The analysis of these variables allowed for the identification of short-term seasonal morphological behavior, as well as the establishment of some relationships in beach dynamics that are geologically controlled by the obstacles present on the shallow platform near the coast.

Different sections of the study area exhibited distinct behaviors of the beach prism influenced by local factors. The reefs produce significant effects on waves and tides, generating patterns of refraction and tidal currents, creating divergent longshore currents from the apex of the mega salient and coastal circulation cells, which are reflected in the sediment classes and their degree of sorting.

The short-term morphological behavior indicated that the beach strip in the central region presents stable subaerial profiles with greater variation in the foreshore zone, caused by the presence of mobile sandy bars with a high proportion of gravelly carbonate material on the low tide terrace. The geometric configuration and the arrangement of the beach rocks promote the formation of bars parallel to the coast in the region of profiles P4 and P5 (south-central apex of the mega salient), while in the north-central portion, where P6 occurs, the bars are arranged transversely. Although the volumetric variation in the profiles of this section showed a general trend of a negative balance, this erosive condition does not represent the long-term stability condition of the subaerial beach strip, being restricted to the dynamics of the foreshore.

Profile P1, located at the southern end of the Goiana coastline, showed the highest erosional tendency of the entire studied stretch, possibly influenced by the fluvial dynamics of the Itapessoca River mouth and the intense urbanization process over the backshore. At the other end, where profile P7 is located, there is a dynamic profile with homogeneous morphological behavior in its beach sectors. Despite being located on a coastline altered by the presence of low amplitude groynes, this profile is in an area of relative morphological stability given its low variability over the studied interval.

Overall, the Goiana beach strip shows relative stability in the short to medium term, except for its southernmost region. However, a long-term analysis considering other natural variables (bathymetry, reef geometry, backshore vegetation cover) and anthropogenic variables (urbanization, artificial structures) may verify if this condition is lasting.

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