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The coastline and the line of occupancy: risks of urbanization in the coastal area of Macaé

A linha de costa e a linha de ocupação: riscos da urbanização na zona costeira de Macaé

La línea de costa y la línea de ocupación: riesgos de la urbanización en la zona costera de Macaé

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Abstract: Coastal zones perform essential ecological functions and concentrate a significant portion of the world's population, although they are increasingly affected by urban pressure and coastal erosion. This study analyzed the relationship between unplanned urban occupation and coastal erosion in the Special Zone of Social Interest (ZEIS) Fronteira, located in Macaé (RJ), Brazil. The research employed CBERS-4A satellite imagery, the Normalized Difference Water Index (NDWI), and five perpendicular transects to monitor shoreline changes between 2020 and 2024. Spatial analyses were conducted in QGIS, while statistical treatments were performed in R using the Linear Regression Rate (LRR) method. The results indicated a cumulative reduction of 11.23% in the beach strip and average distances of up to 1.59 meters between urban occupation and the shoreline. Linear regression demonstrated a continuous trend of shoreline retreat and marine advance over urbanized areas. Approximately 160 dwellings are already affected, with up to 1,300 housing units potentially vulnerable within the ZEIS. Erosion patterns were heterogeneous, with accretion near the mouth of the Macaé River and severe erosion in other sectors. The findings demonstrate that the interaction between natural processes and anthropogenic factors intensifies socio-environmental vulnerability in ZEIS Fronteira,

highlighting the need for integrated public policies focused on erosion control, safe resettlement, resilient infrastructure, and sustainable environmental management.

Keywords: Coastal erosion. Unplanned urban occupation. Socio-environmental Vulnerability.

Resumo: As zonas costeiras concentram elevada densidade populacional e desempenham importantes funções ecológicas, porém sofrem intensa pressão antrópica, favorecendo processos de erosão costeira. Este estudo analisou a relação entre ocupação desordenada e erosão costeira na Zona Especial de Interesse Social (ZEIS) Fronteira, em Macaé (RJ). A pesquisa utilizou imagens do satélite CBERS-4A, o Índice de Diferença Normalizada da Água (NDWI) e cinco transectos perpendiculares para monitoramento da linha de costa entre 2020 e 2024. As análises espaciais foram realizadas no QGIS e os tratamentos estatísticos no software R, utilizando o método Linear Regression Rate (LRR). Os resultados indicaram retração acumulada de 11,23% da faixa de areia, com distâncias médias de até 1,59 metros entre a ocupação urbana e a linha de costa. Observou-se tendência contínua de avanço do mar sobre áreas urbanizadas, afetando aproximadamente 160 imóveis, com potencial de atingir até 1.300 unidades habitacionais vulneráveis. A erosão apresentou comportamento heterogêneo, com ocorrência de acreção próxima à foz do rio Macaé e erosão severa em outros trechos. Conclui-se que a interação entre processos naturais e ações antrópicas intensifica a vulnerabilidade socioambiental da ZEIS Fronteira, evidenciando a necessidade de políticas públicas integradas voltadas à contenção da erosão, reassentamento seguro, infraestrutura resiliente e gestão ambiental sustentável. título deve ser breve e representar fielmente o estudo.

Palavras-chave: Erosão costeira. Ocupação urbana desordenada. Vulnerabilidade socioambiental.

Resumen: Las zonas costeras cumplen funciones ecológicas esenciales y concentran una parte significativa de la población mundial, aunque están cada vez más sometidas a presión urbana y procesos de erosión costera. Este estudio analizó la relación entre la ocupación urbana desordenada y la erosión costera en la Zona Especial de Interés Social (ZEIS) Fronteira, ubicada en Macaé (RJ), Brasil. La investigación utilizó imágenes satelitales CBERS-4A, el Índice de Diferencia Normalizada del Agua (NDWI) y cinco transectos perpendiculares para monitorear la línea de costa entre 2020 y 2024. Los análisis espaciales se realizaron en QGIS y los tratamientos estadísticos en R, mediante el método Linear Regression Rate (LRR). Los resultados indicaron una reducción acumulada del 11,23% de la franja arenosa y distancias medias de hasta 1,59 metros entre la ocupación urbana y la línea de costa. La regresión lineal evidenció una tendencia continua de retroceso costero y avance del mar sobre áreas urbanizadas. Aproximadamente 160 viviendas ya presentan impactos directos, mientras que hasta 1.300 unidades habitacionales podrían encontrarse en situación de vulnerabilidad. La erosión presentó un comportamiento heterogéneo, con acreción cerca de la desembocadura del río Macaé y erosión severa en otros sectores. Se concluye que la interacción entre procesos naturales y factores antrópicos intensifica la vulnerabilidad socioambiental de la ZEIS Fronteira, destacando la necesidad de políticas públicas integradas orientadas al control de la erosión, reasentamiento seguro, infraestructura resiliente y gestión ambiental sostenible.

Palabras clave: Erosión costera. Ocupación urbana desordenada. Vulnerabilidad socioambiental.

1 Introduction

Coastal zones concentrate a significant portion of the world's population, with approximately 44% of the global population living near the coast. It is estimated that there are more than 2,000 coastal cities with populations exceeding 100,000 inhabitants, highlighting the intense urbanization process occurring within these territories (NEUMANN et al., 2015). Urban expansion in these urban-coastal environments has considerably increased pressures on local ecosystems, affecting their ecological structure, compromising the provision of environmental services, and intensifying risks associated with natural phenomena such as erosion and sea encroachment (NEUMANN et al., 2015; NIAMIR; PACHAURI, 2023). Brazil, whose coastline extends for approximately 9,200 km, hosts around 111.28 million inhabitants within its coastal zone, corresponding to 54.8% of the Brazilian population, which underscores the intense human occupation along the coastline and the pressures exerted on coastal ecosystems (IBGE, 2023).

At the interface between aquatic and terrestrial environments lies the coastline, one of the most dynamic geographic features on the planet, shaped by the continuous interaction among continental,

atmospheric, and marine processes. Its configuration is naturally unstable, alternating between phases of advance and retreat across different temporal scales, ranging from extreme events to gradual and persistent transformations (Da SILVA; BULHÕES, 2023). This instability may critically materialize through shoreline retreat, that is, the encroachment of the sea onto the continent, representing a direct threat to coastal urban areas. According to Boak and Turner (2005), the coastline constitutes the interface between the ocean and the continent, whose spatial position is highly variable and influenced by both natural processes and human activities, making it an unstable boundary and, in many situations, difficult to detect and map (ROCHA; FERNANDEZ, 2020; CASTELLE; MASSELINK, 2023). Therefore, the careful selection of an appropriate indicator for coastline analysis becomes essential both for its identification and for understanding its dynamics. Boak and Turner (2005) classify coastline indicators into two main groups: (a) those defined from vertical references, such as tidal datum or mean sea level; and (b) those based on visually identifiable coastal features. In the second group, references may include the vegetation line, the base of the frontal dune scarp, the top or base of cliffs, as well as the contact line between wet and dry surfaces.

The intensification of erosive processes along the Brazilian coastline currently constitutes one of the main challenges for coastal management. This phenomenon is aggravated by anthropogenic factors associated with disorderly urbanization along the coastal strip, such as the suppression of native vegetation and frontal dunes, as well as the implementation of coastal engineering structures that alter longitudinal and transverse sediment transport, favoring the morphodynamic imbalance of the coastline (NEGRÃO et al., 2022). Added to these factors are the effects of sea-level rise driven by global climate change, which tends to intensify erosive processes and increase the vulnerability of coastal communities, especially those historically marginalized (GRIMM, 2019). In urbanized areas, the impacts are even more severe, affecting infrastructure, compromising territorial planning, and generating significant economic and social losses (BULHÕES, 2020).

The impacts caused by coastal erosion are diverse and affect both the physical environment and socioeconomic dynamics. Among the main effects are shoreline retreat, the reduction or disappearance of beaches, the loss of seaside properties and assets, damage to urban structures and sewage systems, as well as the degradation of water bathing quality. Also noteworthy are the reduction in landscape and real estate value in coastal areas, losses to fishing and tourism activities, and the increasing artificialization of the coastline through containment structures (MARENGO; SCARANO, 2016). These processes entail high costs related to environmental restoration and urban restructuring (SOUZA et al., 2005; SOUZA, 2009).

In this context, the municipality of Macaé, located on the northern coast of the state of Rio de Janeiro, exemplifies the challenges faced by coastal cities undergoing accelerated urbanization. Known as the “national capital of oil,” Macaé experienced profound transformations in its urban dynamics beginning in the 1970s, with the consolidation of the offshore oil industry in the Campos Basin. The local economy became centered around the oil and gas sector, attracting investments and migrants from various regions of the country, which led to significant population and territorial growth (Da COSTA; MANHÃES, 2024). Although this economic

appreciation stimulated urban development, it also intensified processes of real estate speculation and sociospatial segregation, pushing low-income populations toward peripheral or environmentally vulnerable areas, such as wetlands, lagoon margins, and coastal zones susceptible to erosion (GUIMARÃES; FERREIRA, 2018).

The occupation of these areas often occurs in a precarious and disorderly manner, lacking basic infrastructure and adequate urban planning, thereby exacerbating environmental and social risks (MARENGO; SCARANO, 2016). The Fronteira neighborhood, located in the northern zone of the municipality of Macaé, represents an emblematic case of the challenges faced by urbanized coastal communities under conditions of socioenvironmental vulnerability. The territory is classified as a Special Zone of Social Interest (ZEIS) within the framework of the Local Social Housing Plan (MACAÉ, 2010), reinforcing its priority status for housing policies and land tenure regularization. The area demonstrates the impacts of disorderly urban expansion on environmentally sensitive territories. Historically occupied by artisanal fishers, the region has, in recent decades, received an increasing number of low-income families seeking affordable housing, becoming one of the most densely occupied settlements in the municipality. Occupation, initiated irregularly during the 1980s, occurred on federally owned coastal lands and was marked by verticalization processes and the absence of adequate infrastructure (MACAÉ, 2010). The lack of effective public policies regarding housing, inspection, and territorial planning intensified uncontrolled densification, exposing residents to the impacts of coastal erosion, flooding, and sea encroachment—phenomena already materialized through recurrent episodes involving the destruction of streets, residences, and even the sandy beach strip itself (GUIMARÃES; FERREIRA, 2018).

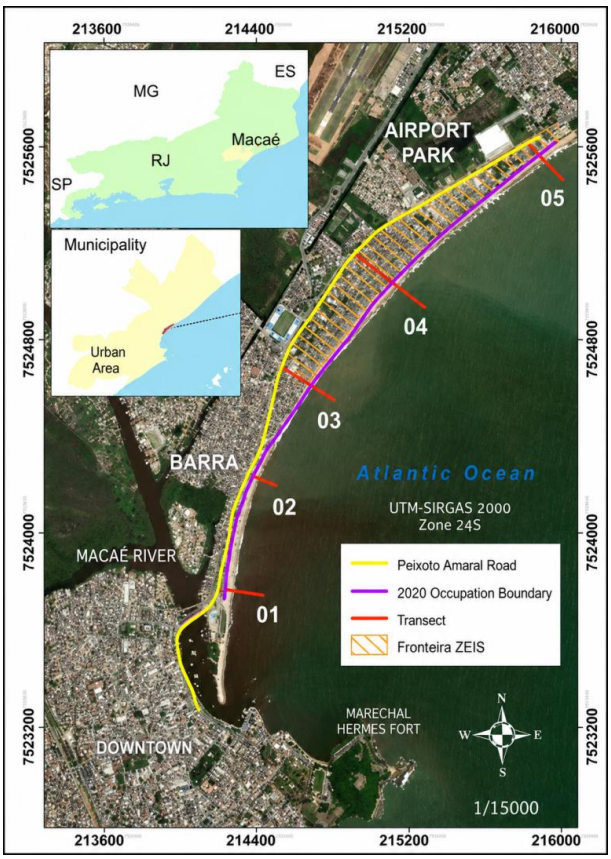
Given this scenario, the present study aims to test the hypothesis that the analyzed area presents typical characteristics of a region subject to coastal erosion and that disorderly urban occupation in vulnerable zones significantly contributes to the intensification of the socioenvironmental risks associated with this process.

1.1 Study Area

The present study focuses on the Fronteira Special Zone of Social Interest (ZEIS), located in the Barra de Macaé neighborhood, along the northern coastline of the municipality. The area consists of an irregular settlement established during the 1980s on federally owned land composed of unconsolidated deposits and subject to the fluvio-marine influence of the Macaé River and the Atlantic Ocean (SAYD, 2015). In order to monitor shoreline dynamics within the Fronteira ZEIS, five transects perpendicular to the coastline were defined and numbered from 01 to 05, distributed along the coastal strip. Each transect represents a cross-sectional profile of the beach, enabling the assessment of variations in beach width and the identification of areas with a greater occurrence of erosive processes. The transects were positioned between the slope of the Amaral Peixoto Highway and the shoreline, defined as the interface between the sea and the beach, encompassing sectors with distinct morphological characteristics and different levels of urbanization.

The ZEIS is home to more than four thousand residents distributed across approximately 1,280 households — the most recent available data according to the Local Social Housing Plan (MACAÉ, 2010). The local population is continuously exposed to risks associated with storm surges, flooding, and coastal erosion. The area presents internal variations regarding infrastructure and construction patterns, with older sectors being partially urbanized and other portions undergoing irregular expansion. Despite the presence of essential public facilities — such as schools, daycare centers, health units, and social assistance programs — land tenure conflicts and socioenvironmental risks persist, requiring continuous attention from public authorities (MACAÉ, 2010).

Figure 1. Study area containing the Fronteira ZEIS, the transects, the Amaral Peixoto Highway, and the urban block front at the occupation boundary with the beach.



According to the Köppen climate classification, the region presents a humid tropical climate (Am), with mean annual temperatures ranging from 18 °C to 27 °C and average annual rainfall around 1,300 mm. The coastline is predominantly composed of medium and coarse sands, interspersed with muddy sectors associated with fluvio-marine influence and sediment supply from the Macaé River (OLIVEIRA; MUEHE, 2008). Inserted within the Campos Basin Macrocompartment, the northern portion of this coastal sector is directly exposed to storm waves originating from the Southeast and South-Southeast quadrants, which explains the occurrence of recurrent erosion episodes at Cavaleiros Beach, in Macaé, causing significant impacts on both the beach strip and the urbanized waterfront (MUEHE et al., 2018).

A predominance of wave climate conditions associated with fair weather is observed, characterized by low-energy waves mainly originating from the northeast (NE) quadrant, with heights ranging from 1 to 2 meters and periods between 2 and 6 seconds. This condition prevails mainly during the summer months under the influence of the South Atlantic Subtropical Anticyclone. However, the region is also seasonally exposed to higher-energy events associated with the activity of extratropical cyclones, cold fronts, and migratory high-pressure systems, particularly between April and September. During these periods, waves originating from the south, southeast, and southwest quadrants reach the coastline with significant average heights around 3.2 meters and maximum heights close to 4 meters, with an average duration of 36 hours (SOUZA et al., 2015). The occurrence of these storm events reveals a bimodal pattern: on one hand, south-southwest to southeast waves linked to migratory cyclones impact the coastline between Macaé and the southern portion of São João da Barra; on the other hand, east-southeast waves associated with persistent winds more intensely affect the coastal strip between São João da Barra and São Francisco do Itabapoana. This bimodality reinforces the dynamic and heterogeneous nature of the Northern Fluminense coast's exposure to storm waves (SOUZA et al., 2016; LINS-DE-BARROS et al., 2018).

2 Materials and Methods

To monitor shoreline dynamics, the five transects positioned in sectors with the highest historical recurrence of erosive processes were used (LIMA et al., 2024) (Fig. 1). The highway geometry was extracted from the cartographic database of the RJ25 Project (GEOINEA, 2021). As a temporal reference, the year 2020 was adopted due to the availability of satellite imagery for the delimitation of the irregular occupation line (urban block frontage) over the beach strip, from which the distances to the highway were measured along each transect.

Images from the CBERS-4A satellite were used, developed through a partnership between Brazil (INPE) and China and launched on December 20, 2019, with the objective of generating high-resolution optical imagery for environmental and territorial monitoring. Among the onboard sensors, the WPM sensor stands out, featuring a spatial resolution of 8.00 meters in the multispectral band. The images underwent radiometric corrections, a stage in which top-of-atmosphere (TOA) reflectance is calculated through an equation that converts the digital numbers (DN) of each pixel into physical reflectance values. This process is essential to enable comparisons among different images and to minimize the effects of solar illumination variability at the time of image acquisition. Considering that the shoreline can be defined as the interface between dry and wet regions (Kraus and Rosati, 1997), the Normalized Difference Water Index (NDWI) was applied. Shoreline delimitation was performed based on the average monthly distances obtained along each transect. These distances were derived from the application of the NDWI to CBERS satellite images available according to Table 1, covering the period from January 2020 to December 2024, with a spatial resolution of 8.00 meters.

Table 1. Number of monthly CBERS-4A images available and used for NDWI determination, organized by year.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020						02		01		01		01
2021	01	01	01	01	01	01	01	02			01	
2022		01	01				01	01		01		
2023		01		01			01	01				
2024	01			01	01	01	01		01			01

The NDWI was calculated using the green (Bg) and near-infrared (Bnir) bands, as expressed in Equation 01:

$$\mathrm{NDWI} = \frac{(\mathrm{Bv} - \mathrm{Biv})}{(\mathrm{Bv} + \mathrm{Biv})} \quad (01)$$

Proposed by McFeeters (1996), the NDWI primarily aims to discriminate between water surfaces and dry areas. Positive index values (NDWI > 0) indicate wet regions, whereas negative values (NDWI < 0) correspond to dry areas. NDWI values were generated using the map algebra tool available in the QGIS software.

All distance and area measurements were carried out within a Geographic Information System (GIS) environment using QGIS software. Statistical analyses were implemented in the R environment (R Core Team, 2019).

2.2 Classification of Shoreline Variation

To analyze shoreline behavior, the Linear Regression Rate (LRR) method was adopted, which is widely used in coastal dynamics studies (RADER et al., 2018; BARIK et al., 2019; LEISNER et al., 2023). The LRR method consists of fitting a linear trend line to shoreline positions recorded on different dates in order to estimate the average rate of variation expressed in meters per year, considering the entire analyzed time interval.

In order to standardize and interpret the obtained results, these rates were classified into shoreline behavior categories according to criteria established in the literature (MACHADO et al., 2024), as presented in Table 2.

Table 2. Erosion classes and rates for shoreline classification.

Classes	Rate
Accretion	> 0,50 m/year
Stability	- 0,50 m/year to 0,50 m/ year
Erosion	- 0,50 m/year to -1,00 m/ year

Severe Erosion	- 1,00 m/year to -3,00 m/ year
Extreme Erosion	< -3,00 m/year

Modified from Machado et al. (2024).

2.3 Quantification and Estimation of Vulnerable Properties

The quantification of properties impacted by shoreline retreat was carried out through field surveys conducted between 2024 and 2025, encompassing both buildings directly affected and those with structures compromised by marine action. Each property was individually identified and measured, with measurements performed using a laser distance meter, ensuring greater precision in obtaining building dimensions and constructed areas.

Simultaneously, a detailed photographic survey of each property was conducted in order to document the physical conditions of the structures, the observed damages, and the context of the affected areas. Subsequently, based on the field data obtained, individualized floor plans for each building were produced, enabling the technical representation of the properties and supporting analyses related to built-up areas, construction typology, and the characterization of existing improvements.

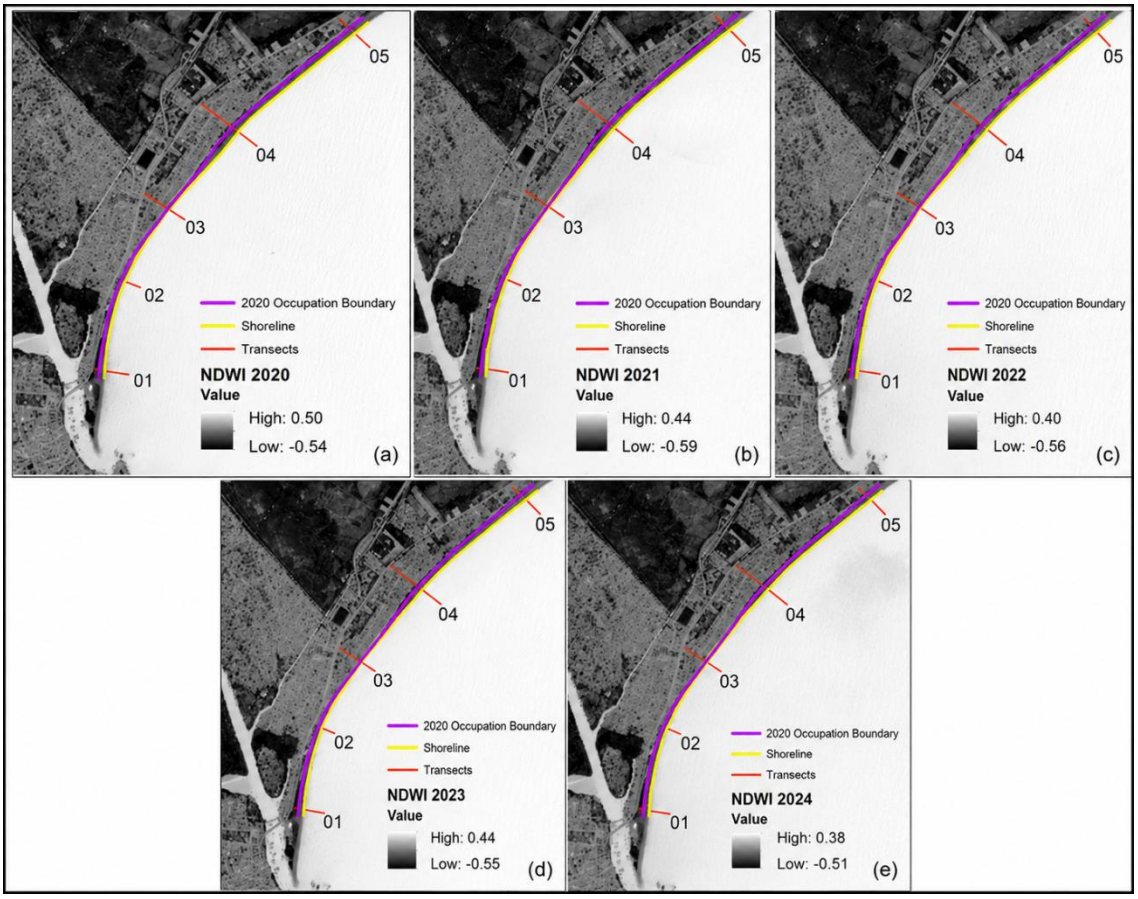
3. Results

3.1 Shoreline Variation

Each image presents the five transects defined perpendicular to the coastline, the boundary of the irregular occupation in 2020, and the distribution of the mean NDWI values for each analyzed year.

NDWI index values ranged, respectively, from -0.54 to 0.50 (2020), -0.59 to 0.44 (2021), -0.56 to 0.40 (2022), -0.55 to 0.44 (2023), and -0.51 to 0.38 (2024). The images show the spatial delimitation of areas with positive NDWI values (indicative of wet surfaces or water presence) and negative values (associated with dry surfaces).

Figure 2. Mean NDWI images for each year of the time series between 2020 and 2024.



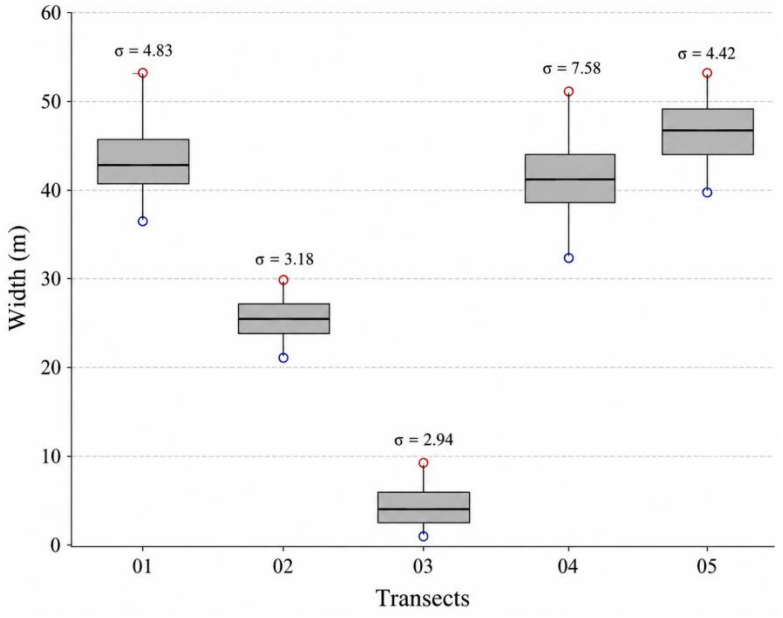
The overlap of graphical elements facilitates the analysis of coastal dynamics in sectors with a history of erosive processes, highlighting possible variations in the beach strip and wet areas throughout the five-year observation period. The images also reveal the relative position of the shoreline in relation to the transects and the urban occupation recorded in 2020, allowing comparisons of the changes that occurred over time. Table 3 presents the shoreline retreat in relation to the occupied areas.

Table 3. Mean distance (m) between irregular occupations and the shoreline along each transect.

DATE	TRANSECT				
	01	02	03	04	05
2020	49,10	21,36	1,59	50,33	47,18
2021	47,69	27,46	8,53	45,49	50,29
2022	37,32	24,09	3,14	39,87	52,97
2023	48,42	26,81	1,92	33,22	46,84
2024	45,55	29,54	1,76	33,10	41,18

The distance values between the boundary of consolidated occupation and the sea, that is, the width of the beach strip along each transect, can be observed in Fig. 3. The mean values along transects 01 to 05 were 45.62, 25.85, 3.39, 40.40, and 47.69 meters, respectively.

Figure 3. Mean values of beach strip width variation between 2020 and 2024 and their respective standard deviation values.



The central line of each box represents the median beach strip width recorded for each transect between 2020 and 2024. Higher median values may be interpreted as situations of relative shoreline advance, associated with greater beach width availability, whereas lower median values reflect relative shoreline retreat due to beach narrowing.

Figure 4. Area located between transects 02 and 03, where the street has already been partially destroyed (a); most critical section located at transect 03, where the street and part of the buildings were completely destroyed by erosion, highlighting the exposed foundations (b).



Thus, transect 03, with a median value around 3 m, indicates a critical retreat condition, whereas transects 01 and 05, with median values exceeding 40 m, demonstrate greater relative advance and spatial stability.

As presented in Table 4, the beach strip area showed significant variations throughout the period from 2020 to 2024. In the initial year of the series, the area was estimated at 121,017.00 m². In 2021, an increase of 4.00% was observed, totaling 125,864.00 m², which may be interpreted as a temporary fluctuation. However,

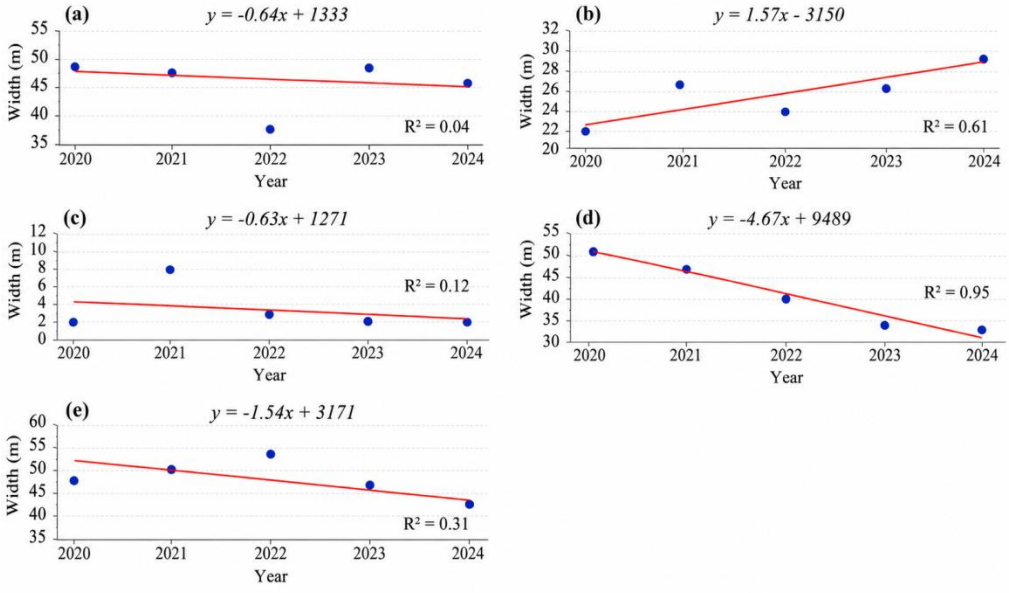
this behavior did not persist in the following years. Beginning in 2022, the area started a continuous retreat process: a reduction of 9.25% relative to 2021 was recorded, followed by additional decreases of 3.91% in 2023 and 2.11% in 2024. By the end of the analyzed period, the total beach strip area had been reduced to 107,423 m², representing a cumulative decrease of 11.23% compared to the year 2020.

Table 4. Beach strip area and its respective variation throughout the analyzed period.

YEAR	AREA (M²)	VARIATION (%)
2020	121,017.00	-
2021	125,864.00	4.00
2022	114,217.00	-9.25
2023	109,747.00	-3.91
2024	107,423.00	-2.11

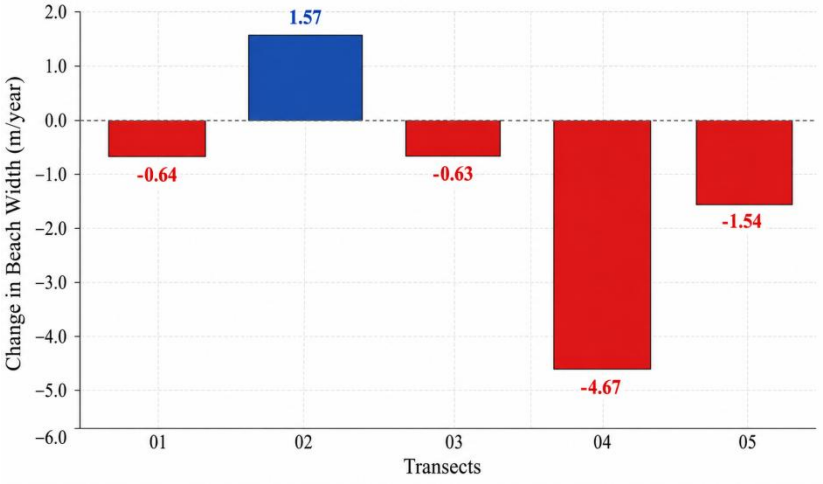
In order to examine the temporal trend of this variation, a simple linear regression analysis was applied between the observed years and the respective measured areas. The following graph (Fig. 5) presents this regression, whose trend line reveals a negative correlation between the variables. This relationship indicates that, over time, the beach strip area has progressively decreased, although with intermediate oscillations. Linear regression makes it possible to identify and quantify this trend, demonstrating that the reduction of the sandy strip did not occur randomly, but rather within a pattern of continuous decline. This result is relevant for supporting future analyses of the coastal dynamics of the region and may provide a basis for environmental planning and monitoring strategies. Although the factors causing this reduction are not the direct focus of this section, the obtained results suggest the existence of environmental pressures that deserve detailed investigation in subsequent sections of the study.

Figure 5. Linear regression applied to beach strip width values considering the period between 2020 and 2024. Beach strip width at transect 01 (a), transect 02 (b), transect 03 (c), transect 04 (d), and transect 05 (e).



The modeled equations make it possible to project the expected rates of shoreline variation over the coming years, as represented in the graph shown in Figure 6.

Figure 6. Mean shoreline variation rates along each transect.

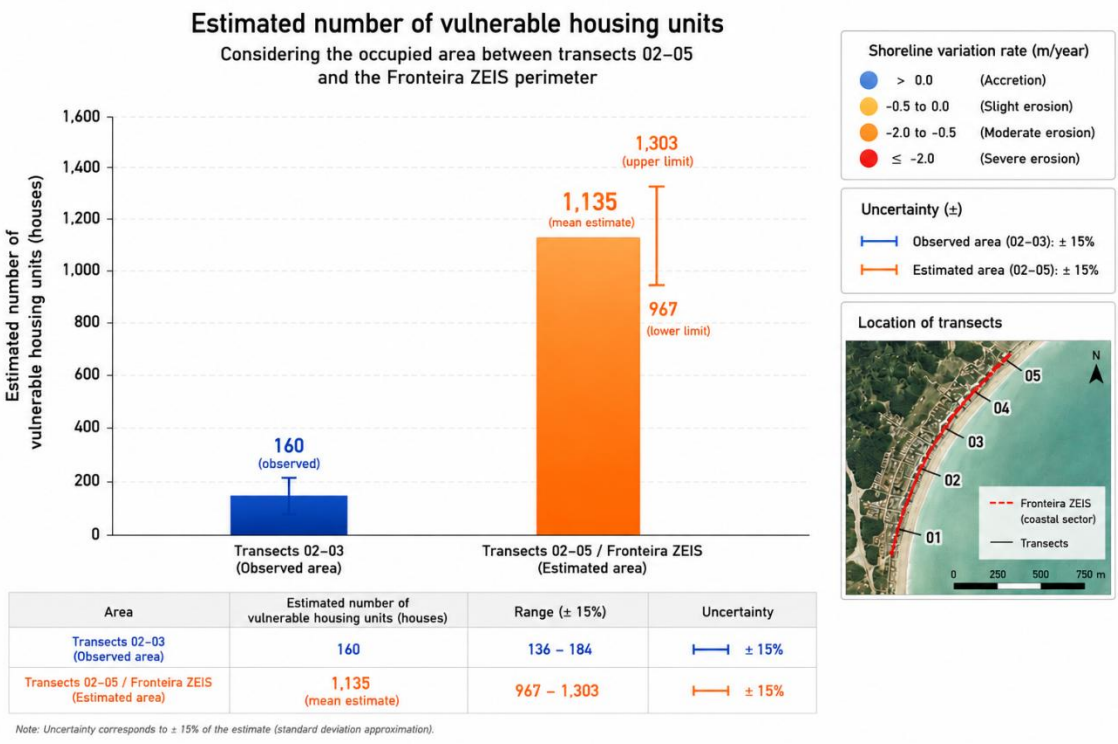


The analysis of shoreline variation rates obtained through linear regression revealed distinct behaviors among the five evaluated transects. Transect 01 presented a rate of −0.64 m/year and was classified as erosion. Transect 02 showed a positive rate of +1.57 m/year, classified as accretion, indicating advancement of the sandy strip. Transect 03 exhibited a value similar to the first (−0.63 m/year), also characterized as erosion. The most critical scenario was observed at Transect 04, whose rate of −4.67 m/year corresponds to the extreme erosion category, revealing pronounced coastal retreat. Transect 05 presented a rate of −1.57 m/year, which classifies it as severe erosion.

3.2 Quantification and Estimation of Vulnerable Properties

The most affected area, currently undergoing interventions by public authorities, is located between transects 02 and 03 and corresponds to a strip measuring 340 meters parallel to the occupation line and 30 meters perpendicular to it, totaling approximately 10,200 m². Within this area, approximately 160 properties are distributed, with an average area of 52 m². Considering an estimated variation of ±15% in the dimensions of the housing units, a standard deviation of approximately 7.80 m² was obtained, indicating that the individual property area may vary between 44.20 m² and 59.80 m². These properties are distributed along the extension parallel to the coastline, resulting in a linear occupation density of approximately 0.47 properties/m (±0.07 properties/m).

Figure 7. Estimated number of properties and their respective standard deviation considering the effectively occupied area and the perimeter comprising the Fronteira ZEIS, considering the perpendicular distance to the occupation line.



Area	Estimated number of vulnerable housing units (houses)	Range (± 15%)	Uncertainty
Transects 02–03 (Observed area)	160	136 – 184	± 15%
Transects 02–05 / Fronteira ZEIS (Estimated area)	1,135 (mean estimate)	967 – 1,303	± 15%

Note: Uncertainty corresponds to ± 15% of the estimate (standard deviation approximation).

Based on this occupation pattern, it was possible to estimate the number of housing units within transects 02–05 and throughout the Fronteira ZEIS, considering the possible variations. In transects 02 to 05, the number of vulnerable properties may range from approximately 967 to 1,303 units. The graph in Figure 7 presents the results of this estimation, highlighting the approximate number of properties in each area.

4. Discussion

Despite the relatively short interval, the obtained results proved to be consistent and suitable for the proposed objectives, especially within the context of an interannual assessment. It is noteworthy that this type of approach is supported by the literature, in which short time series are commonly applied, for example, in the analysis of storm impacts. However, the results presented here should not be interpreted as a long-term trend, but rather as a specific temporal snapshot that contributes to understanding the recent dynamics of the study area. Garcia et al. (2021), for example, analyzed the evolution of the São Paulo coastline based on satellite imagery over a nine-year period (2009–2018). Marino and Freire (2013) investigated coastal changes between Futuro Beach and Porto das Dunas, in Ceará, within a five-year interval (2003–2008). In another case, Lamle and Bulhões (2017) evaluated shoreline changes in Atafona (RJ) using two similarly short temporal intervals: 2003–2010 and 2010–2016.

Another limiting factor concerns the spatial resolution of orbital sensors in shoreline mapping. In this study, instantaneous CBERS-4A satellite images with 8-meter resolution were used, enabling a more detailed representation of coastal dynamics compared to LANDSAT imagery (30 m). Nevertheless, the results remain susceptible to tidal variations at the moment of orbital acquisition, as observed by Chen and Chang (2009) regarding the estimation of shoreline position and change from satellite imagery considering tidal fluctuations, which constitutes a limitation of the present mapping. The higher spatial resolution and elevated temporal frequency of the images contributed to reducing uncertainties and enabled a more accurate capture of spatial variations over time, supporting a robust analysis of dynamic coastal zone processes.

Between 2020 and 2024, the temporal analysis of the shoreline revealed a retreat of the beach strip, indicating the predominance of coastal erosion during the period. This trend became evident through the reduction in mean beach strip width values, reflected in the decrease of its total area, as presented in Table 4, reinforcing concerns regarding the advancement of erosive processes, especially in urbanized coastal areas. In Macaé, the predominant shoreline retreat reflects localized erosive processes whose non-uniform dynamics resemble patterns observed in barrier-lagoon systems of the Paraíba do Sul River Deltaic Complex, where retrogradation and geomorphological rollover are modulated by morphological and sedimentological factors (NOVAK et al., 2024). Furthermore, similarly to what was observed by Machado (2010) along the coastal strip of the Jurubatiba Restinga National Park, the intensity and distribution of erosion may be influenced by variations in wave height and direction, sediment granulometry, and the geological history of the region, factors that contribute to the heterogeneity of retrogradation and reinforce the importance of continuous shoreline monitoring in urbanized areas.

In 2020, it was already evident that urban occupation within the ZEIS was consolidated in areas of high environmental vulnerability, with buildings located at very short distances from the shoreline, reaching only 1.59 meters at transect 03. The analysis of the five transects revealed that this irregular proximity reflects the absence of urban planning aligned with the natural dynamics of the coastline. Although urban expansion toward the sea may intensify erosion impacts, it is not the primary cause of shoreline retreat. Most of the observed retreat, especially at Transect 03, is related to the natural coastal configuration, slightly embayed, which concentrates greater wave energy. These natural factors, combined with the morphological and sedimentological context, are the main drivers of retreat, as discussed by Novak et al. (2024) and Machado (2010). Disorderly occupation of the waterfront, marked by the presence of fixed structures on the beach strip, compromises natural sediment transport and intensifies erosive processes, especially retrogradation, which is the predominant process along urbanized sectors of the Brazilian coastline (CONCOLATO, 2022).

The temporal analysis of the total beach strip area (Table 4) demonstrates a clear retreat trend between 2020 and 2024. After a slight expansion in 2021, possibly related to natural oscillations or short-term meteorological events, the subsequent years showed continuous narrowing of the sandy strip, resulting in a cumulative loss exceeding 11% relative to 2020.

The applied linear regression (Fig. 5) did not show statistical significance (p-value > 0.05), possibly due to the limited number of observations. Nevertheless, the results indicated a negative correlation between the years and the beach strip width, suggesting a pattern of continuous decline rather than isolated fluctuations. Previous studies have also identified similar erosive trends through statistical models, demonstrating that, despite interannual variations, sea encroachment has intensified over recent decades (MUEHE et al., 2018).

The spatial distribution of erosion along the transects shows that transects 02 and 03 present the smallest mean beach strip widths (25.85 m and 3.39 m), evidencing that erosion does not occur uniformly. Novak et al. (2024) attribute this heterogeneity to the geological and geomorphological context of the region, formed by a retrograding barrier since the Holocene Sea-Level Highstand approximately 6,000 years ago. Thus, shoreline retrogradation occurs unevenly, resembling patterns observed in barrier-lagoon systems of the Paraíba do Sul River Deltaic Complex, modulated by morphological factors, wave propagation, and sediment availability. This heterogeneity may be related to factors such as wave regime, the presence of artificial structures, seabed topography, and land use and occupation — variables also highlighted by Castro et al. (2021) in the Cabo Frio region (RJ) and by Da Silveira and Bonetti (2018) along the coast of Florianópolis (SC).

Linear regression analysis revealed distinct erosive dynamics along the evaluated transects. Transect 02, classified as an accretion area, was the only one to record an increase in beach strip width, with an average rate of +1.57 m/year. This behavior may be attributed to the natural protection provided by the Marechal Hermes headland, which reduces wave energy in the region and favors sediment deposition. In contrast, Transect 03 — historically the most affected by sea encroachment — maintained its retreat pattern, with an average rate of −0.63 m/year, characterizing a continuous erosion process. This trend is corroborated by data presented by Lima et al. (2024), who reported an erosion rate of −0.90 m/year in the Fronteira neighborhood. An intensification of the erosive process in the south-to-north direction of the study area was also observed, especially at Transect 04, which presented the highest annual beach strip retreat rate (−4.67 m/year), being classified as extreme erosion. This elevated value may be related to the limited number of observations, highlighting the need for continuous monitoring in the coming years. Subsequently, transects 05 (−1.54 m/year), classified as severe erosion, and 01 (−0.64 m/year), classified as erosion, also stand out. This spatial pattern may be associated with the progressive reduction of fluvial sediment influence with increasing distance from the mouth of the Macaé River, in addition to possible variations in wave regime exposure and shoreline morphological characteristics. These results reinforce the hypothesis that erosive processes act asymmetrically along the studied coastline, being strongly conditioned by both natural and anthropogenic factors. The observed asymmetry highlights the importance of coastal management strategies that consider local specificities and adopt integrated mitigation approaches.

The proximity of urban occupation to the shoreline constitutes a critical factor of socioenvironmental vulnerability, especially considering the high estimated housing density (Fig. 7), which demonstrates intense

linear occupation in erosion-prone areas. The significant concentration of vulnerable properties within the Fronteira ZEIS, distributed over approximately 10,200 m², reinforces the need for public policies aimed at urban reorganization and environmental risk mitigation (GONDIM, 2025).

Machado et al. (2024) identified that, in the district of Atafona, located in the municipality of São João da Barra, northern Rio de Janeiro State, coastal erosion presents an average retreat rate of approximately −5.00 m/year. Between 1976 and 2019, this process resulted in the loss of buildings across an area equivalent to 12 urban blocks — corresponding, on average, to one block every 3.5 years — highlighting the severity and persistence of the urban-environmental problem in the region. Lins-de-Barros et al. (2018), when analyzing storm surge occurrences between 1979 and 2013 along the Rio de Janeiro coastline, identified Fronteira Beach, in Macaé, as an especially vulnerable area marked by disorderly occupation and recurrent sea encroachment. Beginning in 2006, the municipal government implemented rock revetment works, reinforced in 2008 and 2013, as an attempt to contain coastal erosion. In 2011, 274 households were classified as being within a risk area and, in 2017, a risk polygon was delineated to support resident relocation actions. Following a new sea encroachment event in 2024, which displaced 180 people, the Municipal Housing Department intensified mapping activities, the measurement of high-risk properties in the area, and the resettlement of families to other locations through the Assisted Purchase Program.

Therefore, the central issue discussed in this study is the need for more sustainable and inclusive urban planning that considers the specificities and risks of coastal areas. Public policies should be adopted based on robust scientific data, such as those presented in this research, which identify the most critical areas and the factors contributing to environmental degradation. According to Gondin (2023), who conducted studies along the Ceará coastline, integrated coastal zone management should go beyond the simple recovery of degraded areas, prioritizing the construction of more resilient and safer territories for local populations. The author proposes a set of articulated strategies, such as land tenure regularization, the implementation of green infrastructure, and the promotion of environmental education, highlighting these actions as essential for addressing the socioenvironmental challenges of coastal regions. Gondin also emphasizes the role of nature-based solutions — such as ecosystem restoration and the creation of natural barriers — in mitigating erosion and reducing the impacts of extreme climate events. Furthermore, the author advocates for the importance of monitoring and early warning systems capable of strengthening local communities' response capacity and ensuring greater safety in the face of environmental risks.

5. Conclusion

Shoreline retreat behavior was identified in the Fronteira ZEIS, in Macaé (RJ), associated with coastal erosion processes intensified by disorderly urban occupation in environmentally vulnerable areas. The analysis of beach strip dynamics between 2020 and 2024, based on the application of the NDWI and systematic transect

measurements, revealed a cumulative loss of more than 11% of the beach area during the studied period, with predominantly erosive spatial patterns along the coastline. It is noteworthy that, at the most critical analyzed point, the distance between urban occupation and the sea is less than 2 meters, evidencing a situation of high risk.

The combination of the absence of adequate urban planning, precarious housing conditions, and anthropogenic pressure on the coastal strip resulted in high levels of socioenvironmental vulnerability, directly affecting hundreds of properties and exposing the local population to increasingly severe risks. Field surveys identified approximately 160 properties currently impacted, while projections for the entire analyzed area indicate that the maximum number of vulnerable units may reach approximately 1,303 housing units.

The results reinforce the urgent need for integrated public policies that encompass not only shoreline containment and recovery measures, but also territorial planning actions, safe resettlement, and the strengthening of resilient urban infrastructure. Furthermore, the experience of the Fronteira ZEIS highlights the importance of strategies grounded in scientific data to support coastal management and promote socioenvironmental justice. The implementation of policies that combine land tenure regularization, environmental restoration, and the strengthening of community participation is essential to address the challenges imposed by coastal erosion in precarious urban contexts. Progress toward more sustainable and inclusive coastal territories depends on the capacity to integrate technical knowledge, environmentally sensitive urban planning, and political commitment to social equity.

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