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Research paper

Shoreline Change and Coastal Erosion: An Analysis of Long and Short-Term Alterations and Mitigation Strategies on the Coast of Icapuí, Northeast Brazil

Mudança na Linha de Costa e Erosão Costeira: Uma Análise das Alterações a Longo e Curto Prazo e Estratégias de Mitigação no Litoral de Icapuí, Nordeste do Brasil

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Abstract: Sandy beaches play a crucial role as natural barriers against climate change and hold significant socioeconomic value. In the municipality of Icapuí, on the eastern coast of Ceará, erosion has affected some of its beaches since the 2000s, impacting structures near the Shoreline (SL), such as schools, inns, and residences. This article analyzed the SL dynamics on the beaches of Barreiras de Baixo, Barreiras de Cima, and Barrinha, located in the mentioned municipality, using two scales of analysis: in the short term, with *in situ* surveys using geodetic receivers between 2015 and 2023, and in the long term, with orbital images from 2002 to 2024. For statistical analysis, the End Point Rate (EPR) and Linear Regression Rate (LRR) methods were applied in ArcGIS software using the Digital Shoreline Analysis System (DSAS) version 5.1 extension. The short-term analysis revealed an average EPR of 0.0 m/year, with a maximum progradation of 7.1 m/year and maximum erosion of 6.4 m/year. The LRR showed an average of -0.2 m/year, with a maximum progradation of 7 m/year and maximum erosion of 6.7 m/year. The long-term analysis showed an average EPR of -1.1 m/year, with a maximum progradation of 0.5 m/year and a minimum erosion of 3.9 m/year, while the LRR indicated an average of -0.7 m/year, with maximum erosion of 3.6 m/year and maximum progradation of 1.6 m/year. These results indicate a more pronounced retreat of the SL over time. The analysis also revealed that containment structures, such as Rip-rap, have replaced wooden stakes and sandbags previously used by local communities, stabilizing 63.2% of the SL. The forecasts obtained through this study for the years 2034 and 2044 indicate shoreline retreat in areas still without protection, highlighting the urgent need for effective participatory planning. It is essential to align this planning with the Municipal Climate Change Adaptation Plan and the Integrated Coastal Management Plan (ICMP). Maintaining protection structures and conducting continuous monitoring is crucial to adapting coastal management strategies, protecting vulnerable communities and ecosystems.

Keywords: Coastal Dynamics; Coastal Monitoring; Climate Change; Urban Planning.

Resumo: As praias arenosas desempenham um papel crucial como barreiras naturais contra as mudanças climáticas e possuem um valor socioeconômico significativo. No município de Icapuí, Litoral Leste do Ceará, a erosão tem afetado parte de suas praias desde os anos 2000, impactando construções próximas à Linha de Costa (LC), como escolas, pousadas e residências. Este artigo analisou a dinâmica da LC nas praias de Barreiras de Baixo, Barreiras de Cima e Barrinha, localizadas no município em questão, utilizando duas escalas de análise: em curto prazo, com levantamento in situ usando receptores geodésicos entre 2015 e 2023, e em longo prazo, com imagens orbitais de 2002 a 2024. Para a análise estatística, foram aplicados os métodos End Point Rate (EPR) e Linear Regression Rate (LRR) no software ArcGIS utilizando a extensão Digital Shoreline Analysis System (DSAS) versão 5.1. A análise de curto prazo revelou uma média de EPR de 0,0 m/ano, com progradação máxima de 7,1 m/ano e erosão máxima de 6,4 m/ano. O LRR apresentou uma média de -0,2 m/ano, com progradação máxima de 7 m/ano e erosão máxima de 6,7 m/ano. A análise de longo prazo mostrou uma média de EPR de -1,1 m/ano, com progradação máxima de 0,5 m/ano e erosão mínima de 3,9 m/ano, enquanto o LRR indicou uma média de -0,7 m/ano, com erosão máxima de 3,6 m/ano e progradação máxima de 1,6 m/ano. Esses resultados indicam um recuo mais acentuado da LC ao longo do tempo. A análise também revelou que estruturas de contenção, como enrocamentos, substituíram estacas de madeira e sacos de areia anteriormente utilizados pelas comunidades locais, estabilizando 63,2% da LC. Os prognósticos obtidos por meio deste estudo para os anos de 2034 e 2044 indicam recuo da LC em áreas ainda sem contenção, ressaltando a necessidade urgente de um planejamento participativo eficaz. É essencial alinhar esse planejamento com o Plano Municipal de Adaptação à Mudança do Clima e o Plano de Gerenciamento Costeiro Integrado (PGI). Manter as estruturas de proteção e realizar monitoramento contínuo é fundamental para adaptar as estratégias de gestão costeira, protegendo comunidades e ecossistemas vulneráveis.

Palavras-chave: Dinâmica do Litoral; Monitoramento Costeiro; Mudanças Climáticas; Planejamento Urbano.

1. Introduction

Sandy beaches occupy more than a third of the global coastline and have great socio-economic value associated with leisure, tourism and various ecosystem services. They also play a crucial role as natural barriers against the advance of the sea. However, they are subject to constant change due to natural and/or human factors, and many are already in advanced stages of coastal erosion (Vousdoukas *et al.*, 2020).

Coastal erosion is present in many coastal regions around the world, and is not restricted to Brazil alone, and more specifically to the state of Ceará, in northeastern Brazil. This coastal erosion has been increasingly intensified by rising sea levels, which are a major effect of global climate change. In addition, there is a growing population along the coasts, exposing more people and their properties to marine flooding and coastal erosion (Muehe, 2006; Luijendijk *et al.*, 2018; Brasil, 2018; Vousdoukas *et al.*, 2020; Paula *et al.*, 2022; Pang *et al.*, 2023; Vasconcelos *et al.*, 2024).

The literature shows that coastal erosion is inherent to coastal dynamics and is directly linked to the balance of the beach system, with global and/or local natural factors as the main driving mechanisms. Changes, driven by natural and/or anthropogenic factors that can cause a decrease and/or break in the cycle of sediment supply to coastal areas, lead to a so-called negative sediment balance, theng to the retreat of the shoreline (SL) (Bird, 2008; Roebeling *et al.*, 2011).

The interruption of this cycle can occur due to various factors acting on different scales. Natural factors that aggravate the erosion process include rising sea levels, which cause flooding of coastal areas and the loss of sediments, and climate and ocean changes, which increase the intensity and frequency of storms, aggravating the erosion of frontal dunes (Dillenburg *et al.*, 2004; Muehe, 2005; Morais *et al.*, 2006; Nichols *et al.*, 2007). Anthropogenic factors include disorderly occupation and the establishment of buildings in dune areas, as well as the construction of rigid coastal containment and recovery works, which alter the natural sedimentary balance (Souza and Suguio, 2003; Souza *et al.*, 2005; Morais and Pinheiro, 2011; Paula, 2015; Kuriyama and Banno, 2016). These human interventions often exacerbate the erosion process and hinder the natural regeneration of the dunes and SL.

Le Cozannet *et al.* (2014) point out that sea level rise has not been the main factor in SL retreat in recent decades, stressing that local variability limits generalized conclusions about this relationship. The authors recommend expanding the database to include observations of coastal processes and stress the need to clearly define the assumptions and limitations of the methods used. Although current methodological approaches have limitations, they offer an initial framework for detecting the impact of sea level rise, and it is essential to expand the data and improve observations for a deeper understanding.

In the same vein, Cooper *et al.* (2020) states that sandy beaches vary in shape and context, and do not show a single response to sea level rise. They can migrate towards the continent without losing width, they can recede due to sediment transport towards the ocean, or they can remain stagnant on the seabed, depending on specific conditions. In addition, they can progress when there is a favorable sediment supply. The supply of sediment from dune erosion can help mitigate coastal retreat, since this sediment is essential for the morphodynamic balance of beaches. Shoreline responses, however, are influenced by local factors such as terrain morphology and local coastal dynamics.

The same authors stress the need to improve data collection methods and approaches to predicting the impacts of sea level rise. In addition, they emphasize that the greatest threat to the survival of beaches is represented by coastal protection structures, especially rigid ones (e.g. groynes, rip-raps and bagwalls), which limit the natural migration capacity of beaches, compromising their adaptation to environmental changes and exacerbating the erosion process in the long term.

Paula (2012; 2015) and Lacerda Barros (2018; 2021) point out that coastal erosion becomes a problem when it starts to directly influence the daily lives of the population living near the coast, causing damage to the structures built in these areas and generating economic losses for the municipality and its local inhabitants. This scenario is frequently covered in the local, regional and national news.

Luijendijk *et al.* (2018), using satellite imagery between the years 1984 and 2016 and supervised pixel classification, found that 31% of the world's ice-free SLs are sandy. Furthermore, analysis of this data indicated that 24% of the world's sandy beaches are eroding at rates above 0.5 m/year, while 28% are accumulating sediment and 48% remain stable. Erosion is prevalent on many sandy SLs in marine protected areas, raising significant concerns.

Boak and Turner (2005) identified three main types of SL indicators. The first type is based on the alignment of man-made structures, such as the edge of a revetment structure. The second type is based on a morphological feature, such as an erosion scarp. The third type involves visibly discernible features, including those based on the position of a selected water line, such as the high-water level of the previous high tide.

The shoreline is a dynamic system that responds quickly to natural and/or anthropogenic changes, making it essential for analyzing the situation of beaches, especially those affected by coastal erosion (Lima, 2021). Its spatial variation should be monitored by mapping at different times, using field data collection or satellite imaging (Liu *et al.*, 2013; Diniz *et al.*, 2020).

The shoreline varies according to the delimitation criteria, such as geomorphological, oceanographic and anthropogenic features. Muehe and Klumb-Oliveira (2014) define the coastline as the intersection between sea level and dry land, considering spring tides. Mazzer and Dillenburg (2009) characterize it as a highly dynamic geomorphological element, influenced by coastal processes of different frequencies and magnitudes, ranging from tidal variation to major meteorological and climatic events.

Among the types of indicators, the most widely used are those based on the position of the high tide water level or the Maximum High-Water Line (HWL), which fall into the third type as mentioned above. This indicator is widely used to characterize the position of the SL in sandy coastal areas. It consists of observing the “line” that marks the limit reached during the high tide, characterized by a clear change in tone of the beach sands (Crowell;

Leatherman; Buckley, 1991). Therefore, due to the great dynamism of the SL, temporal and spatial perspectives must be considered in its definition. The action of different forces (anthropogenic and natural) makes its delimitation complex, as its position changes constantly due to these factors (Boak; Turner, 2005).

The littoral zone of the state of Ceará is collapsing due to various impacts, both natural and man-made (Morais *et al.*, 2006; Paula, 2012, 2015; Morais *et al.*, 2018). The most significant impact and the one that requires the most attention is coastal erosion, the processes of which are already affecting the 20 municipalities located along the Ceará SL. According to Morais *et al.* (2018), of the 573 km of SL, 30% is already in a state of erosion, while another 17% has erosive tendencies, which reinforces the need for urgent management and mitigation measures. Adding these together, this 47% indicates a worrying scenario in relation to the dynamics of our SL. With climate change expected to worsen over the next decade, the situation is even more alarming, threatening not only ecosystems, but also human health and crucial economic activities such as tourism, urbanization, aquaculture and fishing. It is essential to recognize the seriousness of this ongoing problem and act proactively to mitigate its impact.

This erosion became a cause for concern in the municipality of Icapuí (Ceará) around the beginning of the 2000s, when the first reports of erosion in the municipality began to appear more frequently in the state media. During this period, a series of incidents were reported of damage to buildings built very close to the SL due to the direct tidal action (Lacerda Barros, 2018; Chacanza *et al.*, 2022; Leite; Almeida, 2023). In addition, this situation often requires the implementation of coastal protection and/or recovery structures, which can be the subject of controversy due to their objectives, the techniques employed and potential failures in planning, management or monitoring of these structures (Williams *et al.*, 2018; Lacerda Barros *et al.*, 2021).

The history of accelerated shoreline retreat on stretches of the Icapuí coastline, coupled with the implementation of often ineffective containment alternatives, highlights the need for an in-depth analysis of local coastal dynamics. In this context, this study aims to understand the variation of the shoreline on the beaches of Barreiras de Baixo, Barreiras de Cima and Barrinha, in the municipality of Icapuí, located in Northeast Brazil (NEB). The research aims to provide input for the development of more effective coastal erosion mitigation strategies. To this end, we used geodetic and orbital data covering the period from 2002 to 2024, as well as analyzing projections of the coastline for the years 2034 and 2044.

1.1. Study Area

The area in question is in the municipality of Icapuí, on the northern coast of Northeast Brazil, in Sector 1 - East Coast, according to the Coastal Management of the State of Ceará (GERCO-CE). It borders the state of Rio Grande do Norte to the east and the municipality of Aracati to the west and south. It has approximately 46 km of coastline and 14 beaches distributed between three districts: Icapuí (Sede), Ibicuitaba and Manibu (Meireles *et al.*, 2016) (Figure 1).

The study area is in the onshore portion of the Potiguar Basin, where there are several geological formations associated with the drift phase of the basin's evolution. The main geological formations in the region include the Jandaíra Formation, from the Cretaceous period, composed predominantly of limestone; the Barreiras Formation, from the Miocene, made up of conglomerates and sandstones; and the Potengi Formation, from the Quaternary, characterized by eolian sandstones (Ximenes Neto *et al.* 2024a). These formations play a fundamental role in supporting the cliffs and paleo-cliffs that extend along the coast, providing important geomorphological features.

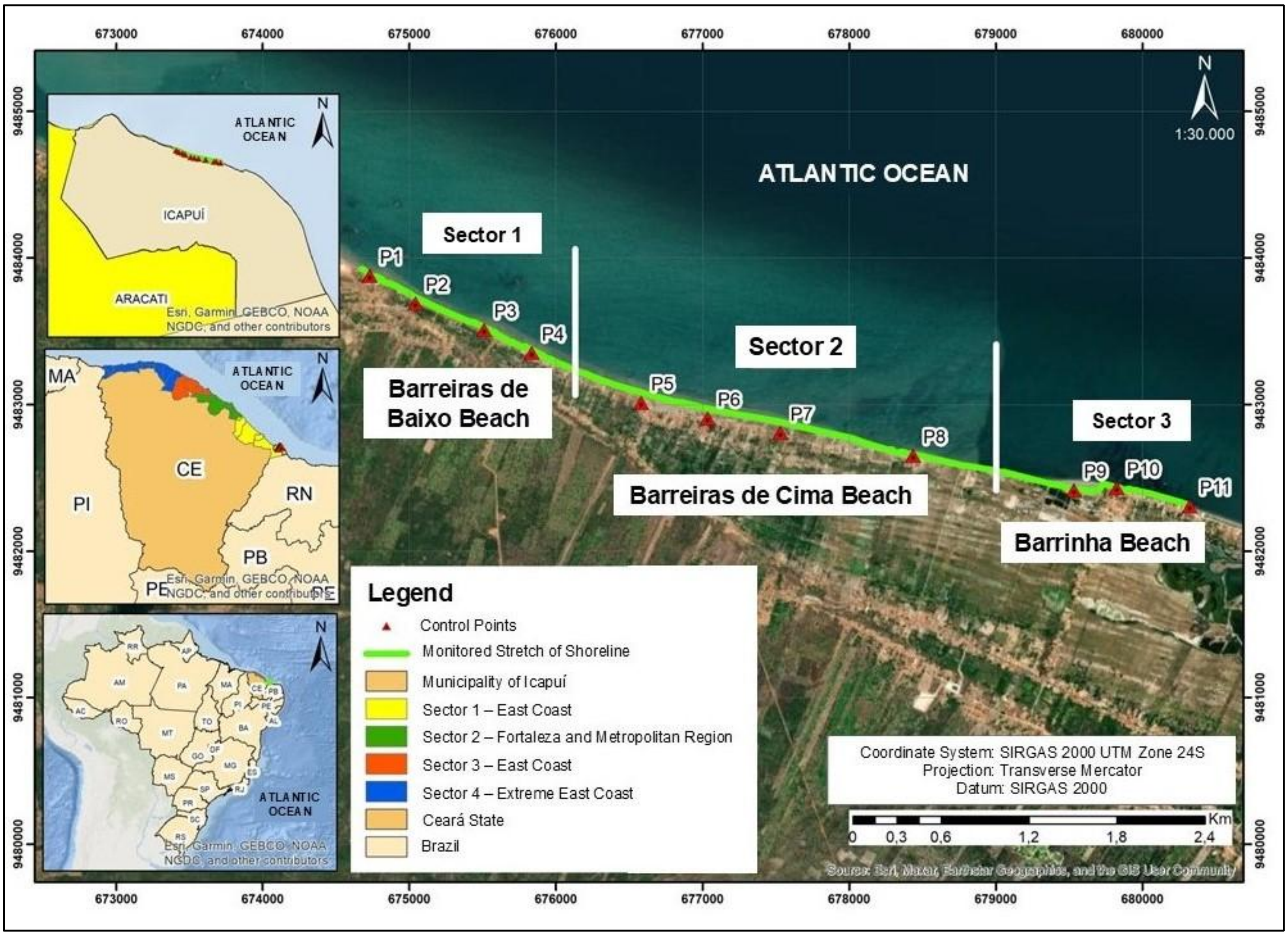

Figure 1. Location of the municipality of Icapuí and the stretch analyzed.

In addition to these older units, the study area also includes environments of more recent origin, formed during the Holocene. These Holocene environments play a crucial role in the current configuration of the landscape and are the result of sedimentary and geomorphological processes that took place during this period.

Specifically, the study area is associated with a marine terrace formed during the Late Holocene, in the last 1,200 years BP (Ximenes Neto *et al.*, 2024b). This marine terrace is located between the paleo-cliffs and the modern coastline and plays a significant role in the current dynamics of the coastal zone. The presence of this terrace contributes to understanding the erosion and sedimentation processes that shape the region, providing important insights for coastal management and conservation.

The Icapuí Coastal Plain is characterized by geomorphological features resulting from variations in sea level during the Quaternary. The Holocene marine terraces, dunes, cliffs and paleo-cliffs, beaches, lagoons and coastal lagoons originated and evolved through global events related to the processes of marine regression and transgression at the end of the Quaternary (Meireles *et al.*, 1991; Meireles, 2011; Ceará, 2016; Ximenes Neto *et al.*, 2024b). Some stretches receive sediment directly from coastal dunes and mass movements, making the cliffs and dunes crucial sources of sediment for coastal dynamics (Morais *et al.*, 2006; Pinheiro *et al.*, 2016; Lacerda Barros *et al.*, 2024).

The climate in northeastern Brazil is strongly influenced by the Intertropical Convergence Zone (ITCZ), where the northeast and southeast trade winds meet. Rainfall is seasonal, occurring mainly from February to May, followed by a dry period for the rest of the year, with variations possible due to the El Niño Southern Oscillation (ENSO) (Marengo *et al.*, 2017). Intermittent surface drainage, combined with the semi-arid climate, contributes to the low quantity of sediment being deposited on the beach system and continental shelf of Ceará (Morais; Pinheiro, 2011). The Icapuí climate station recorded a historical average rainfall for the period between 1988 and 2023 of 714 mm, according to the Ceará Foundation for Meteorology and Water Resources (FUNCEME).

The tides on the Ceará coast are semi-diurnal, characterized as mesotidal environments, with amplitudes of 3.2 m (Morais, 1981; Maia, 1998; Pinheiro *et al.*, 2016). In Icapuí, according to the Areia Branca Port Tide Table, a port located in the state of Rio Grande do Norte and the closest to the area analyzed here, the amplitudes can reach 3.8 m.

Wave heights in the area, according to the Wavewatch III model, peak between December and March, reaching up to 2.2 m (Lacerda Barros, 2018), with the peak recorded in February 2016 (Lacerda Barros, 2018). In other months, they range from 0.8 m to 1.5 m, with periods between 4.1 s and 9.9 s. Swell waves have periods between 10 s and 11.5 s. Sea type waves predominate in Ceará, with 72% of occurrences, while Swell type waves account for 28% (Carvalho *et al.*, 2007). Coastal drift is preferably east-west, i.e. the sediment is transported in the direction of the neighboring municipality of Aracati.

2.Materials and Methods

The methodology for identifying and analyzing the shoreline in the monitored stretch in Icapuí took place in four stages: i) Evaluation and sectorization of the study area *in situ*; ii) Obtaining the SL using orbital images; iii) Obtaining the SL using a geodetic survey; and iv) Analysis of variations in SL positioning (Figure 2).

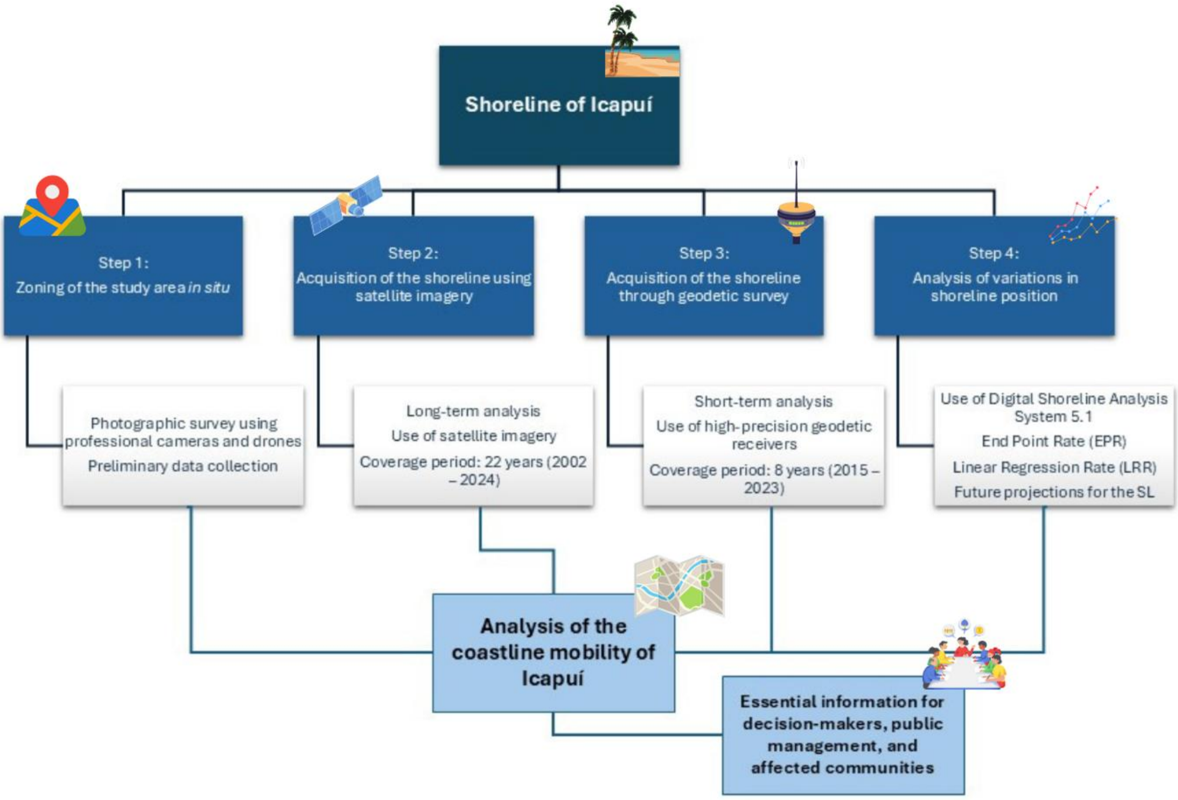

Figure 2. Methodological flowchart used in the research.

The first stage consisted of an on-site analysis of the area to be monitored. Direct observations were made on site to assess the current conditions of the SL, identify relevant geographical features and collect preliminary data to support subsequent analyses. At this stage, the three beaches analyzed (Barreiras de Baixo, Barreiras de Cima and Barrinha), with a length of 6 km, were divided into 3 sectors: Sector 1: Barreiras de Baixo beach, with intense coastal erosion, damage to accommodations and erosion containment measures, such as sandbags, wood and rockfill. Sector 2: Praia de Barreiras de Cima, characterized by the presence of frontal dunes, occupation further from the SL and rockfill. Sector 3: Barrinha Beach, like Sector 1, with part of the erosion and retreat of the SL induced by structures installed at the site.

The second stage involved the use of orbital images from Quickbird satellites, supplied by the Superintendência Estadual do Meio Ambiente (SEMACE) (State Superintendence of the Environment - SEMACE); the RapidEye satellite, made available by the GeoCatálogo of the Ministério do Meio Ambiente (MMA) (Ministry of the Environment - MMA); and the Sentinel-2 satellite, accessed through the Copernicus tool, developed by the

European Space Agency (ESA). For the long-term analysis, 10 satellite images were used, covering a period of 22 years (2002 to 2024). In this process, the availability of images, cloud cover and periods of rain and drought in the region were considered to provide a more accurate analysis of local seasonality. By covering a significant period, it is possible to capture events and processes that may not be evident in short-term analyses, allowing for a more complete and accurate understanding of the environmental dynamics of the coastal stretch under analysis (Table 1). The images were georeferenced to the SIRGAS 2000 Zone 24S reference system, selected based on the criterion of obtaining the best possible resolution and minimal cloud cover, using geodetic receivers and physical points along the study area.

The shoreline analysis was carried out using the images available for each year, rather than annual mosaics, which ensured greater temporal consistency in the comparisons between the periods observed. This approach was made possible by the scale of analysis adopted, which allowed the monitored area to be completely included in each selected image. However, the variation in the spatial resolution of the different sensors used can influence the results, especially in the accuracy of the SL delimitations. To mitigate possible distortions, we standardized the analysis process, and the indicators used, seeking to ensure consistency in the comparisons. Thus, the variation in spatial resolution was considered a limitation of the study.

Table 1. Details of the images used in the study.

Sensors	Spatial resolution	Month/Year of image	Image source
Quickbird	0.6 m	Dec/2002	State Superintendence of the Environment - SEMACE
Quickbird	0.6 m	Apr/2009	State Superintendence of the Environment - SEMACE
RapidEye	5.0 m	Apr/2012	Image Catalog / Ministry of the Environment - MMA.
RapidEye	5.0 m	Jul/2013	Image Catalog / Ministry of the Environment - MMA.
RapidEye	5.0 m	Mar/2014	Image Catalog / Ministry of the Environment - MMA.
RapidEye	5.0 m	Jun/2015	Image Catalog / Ministry of the Environment - MMA.
Sentinel 2	10.0 m	May/2018	European Space Agency - ESA
Sentinel 2	10.0 m	Oct/2019	European Space Agency - ESA
Sentinel 2	10.0 m	Apr/2020	European Space Agency - ESA
Sentinel 2	10.0 m	May/2024	European Space Agency - ESA

The third stage, referring to the short-term analysis, consisted of obtaining the SL using geodetic receivers configured for high-precision data collection on seven occasions, distributed between the rainy season (first semester) and the dry season (second semester) in the region, allowing for a seasonal analysis; it should also be noted that all field activities were carried out at low tide (Figure 3). The first six surveys took place between October 2015 and November 2016, using a TechGEO GTR-G2 L1/L2 DGPS (Differential Global Positioning System) receiver. Subsequently, an information update campaign was carried out in October 2023, using a South Kolida K20S RTK (Real Time Kinematic) receiver. The UTM coordinate system, Sirgas 2000 Zone 24S Datum (EPSG 31984), was used for both pieces of equipment.

The data obtained by the DGPS receiver was processed using Novatel CDU software and TechGEO's GTR Processor. In the program, the base files (fixed-file.pdc) and the rover files (mobile-file.gps) were imported to convert the ellipsoidal height into orthometric height and correct the 15º inclination, according to the software's specifications. The coordinates obtained by the RTK receiver were sent to the platform of the Instituto Brasileiro de Geografia e Estatística (IBGE) (Brazilian Institute of Geography and Statistics - IBGE) for GNSS data post-processing, using the Precise Point Positioning (PPP) technique.

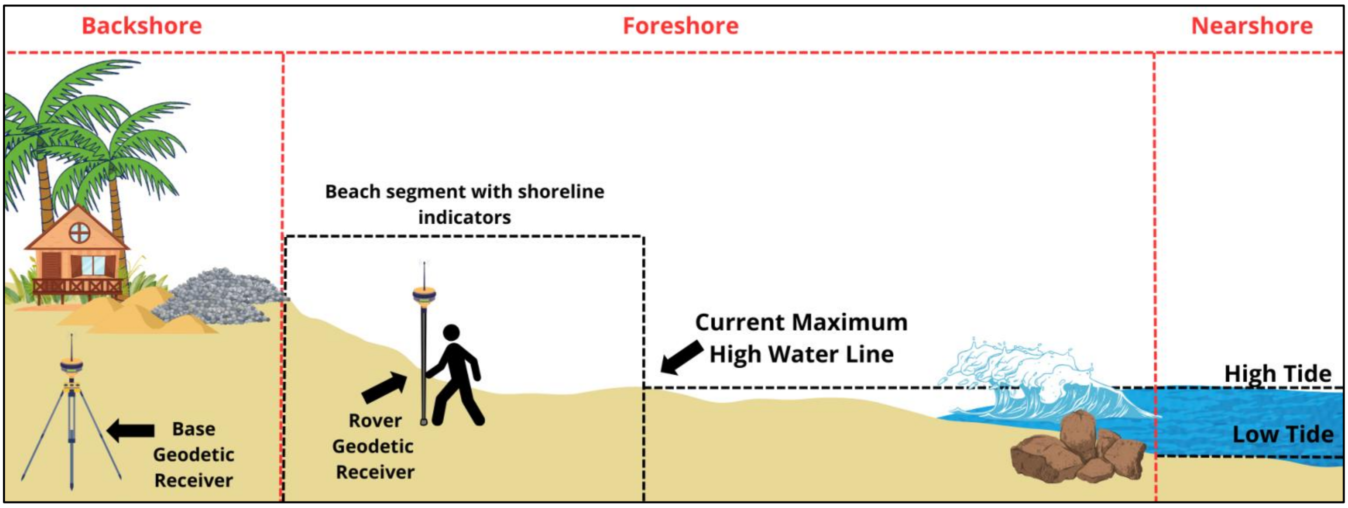

Figure 3. Field stage, monitoring the shoreline in Icapuí using a geodetic receiver.

Table 2 details the area monitored and the geo-indicators used in both field measurements and image analysis. The field stage is fundamental for the analysis of the SL as it provides precise location data that serves as a reference in subsequent Geographic Information System (GIS) analyses. The methodology used to detect the SL was based on the proposals by Leatherman (2003), Boak and Turner (2005), Baptista *et al.* (2011), Mendonça *et al.* (2014) and Muehe and Klumb-Oliveira (2014). The maximum reach of the spring tide was the SL, complemented by other geo-indicators identified during the field stage.

Table 2. Situational picture of the monitored area.

Beaches analyzed	**Municipality**	**Coastal sector (GERCO-CE)**	**Shoreline extension and analyzed Shoreline**	**Direction of the shoreline**	**Type of shoreline exposure**	**Geoindicators**	
						(Short Term / 2015 - 2023) *In situ* Activities	**(Long Term / 2002 - 2024) Orbital images**
Barreiras de Baixo	Icapuí	Sector 1 - East Coast	46 km 6,039 km (13,1 %)	East-West	Exposed	Base of frontal dune, maximum reach of the streambed and limit of floodplain, occupation and erosion containment works	Maximum reach of the wave flow and urbanized seafront
Barreiras de Cima							
Barrinha							

The fourth and final stage consisted of analyzing variations in SL positioning, both in the short term (field data) and in the long term (orbital data), allowing erosion and/or progradation rates to be obtained for the stretch under analysis (Figure 4). Seventeen SLs were used, manually delimited both in the field with geodetic receivers and in the GIS environment, where the lines were manually vectorized following the SL indicators in the literature. The maximum time interval considered was 22 years (Figure 4). The rates were calculated using ArcGIS software, using its Digital Shoreline Analysis System (DSAS) extension, version 5.1. This version also allows predictions to be made about the behavior of the SL for the next 10 years (2034) and 20 years (2044), using the statistical base incorporated into the software.

The methodology applied is widely used in the literature, as cited by Morton *et al.* (2005), Albuquerque *et al.* (2013), in microtidal environments, Rangel-Buitrago *et al.* (2015), Lima *et al.* (2019), Moreira *et al.* (2020), Quang *et al.* (2021), Baía *et al.* (2021), in macrotidal environments, Vasconcelos *et al.* (2021), Khakhim *et al.* (2024), Nascimento; Andrade (2024), and in mesotidal environments, and Machado *et al.* (2024).These prognoses are guided by the trends observed according to the statistical methods applied. It is important to note that the software does not consider the presence of containment structures; it only uses the information available in the database used. It was therefore crucial to carry out a more detailed analysis of the behavior and predictions of future SLs in the areas in question.

For the short-term analysis, 10 meters were adopted. This shorter spacing allows for a more detailed resolution of the data, which is essential for capturing rapid variations and small changes that can occur over shorter time intervals. Thus, the program established a total of 586 transects. For the long-term analysis, we opted for a spacing of 20 meters, giving a total of 293 transects along the 6 kilometers of SL analyzed. This greater spacing is justified by the need for a more comprehensive and less detailed view, suitable for identifying trends and patterns of change that occur over longer periods. The smaller number of transects is sufficient to capture significant, larger-scale variations, providing an efficient analysis without compromising the representativeness of the data.

The statistics used to quantify the rates were based on the End Point Rate (EPR), which considers the ends of the analyzed interval, and the Linear Regression Rate (LRR), which uses all the SLs inserted into the GIS environment. The methodology employed has a limitation related to the difference in sampling frequency, which can impact the consistency of short-term analysis. Although the End Point Rate (EPR) method is suitable for short intervals, the use of Linear Regression (LRR) may be less reliable in scenarios with irregular temporal data. Thus, in such conditions, LRR may not accurately reflect long-term temporal trends.

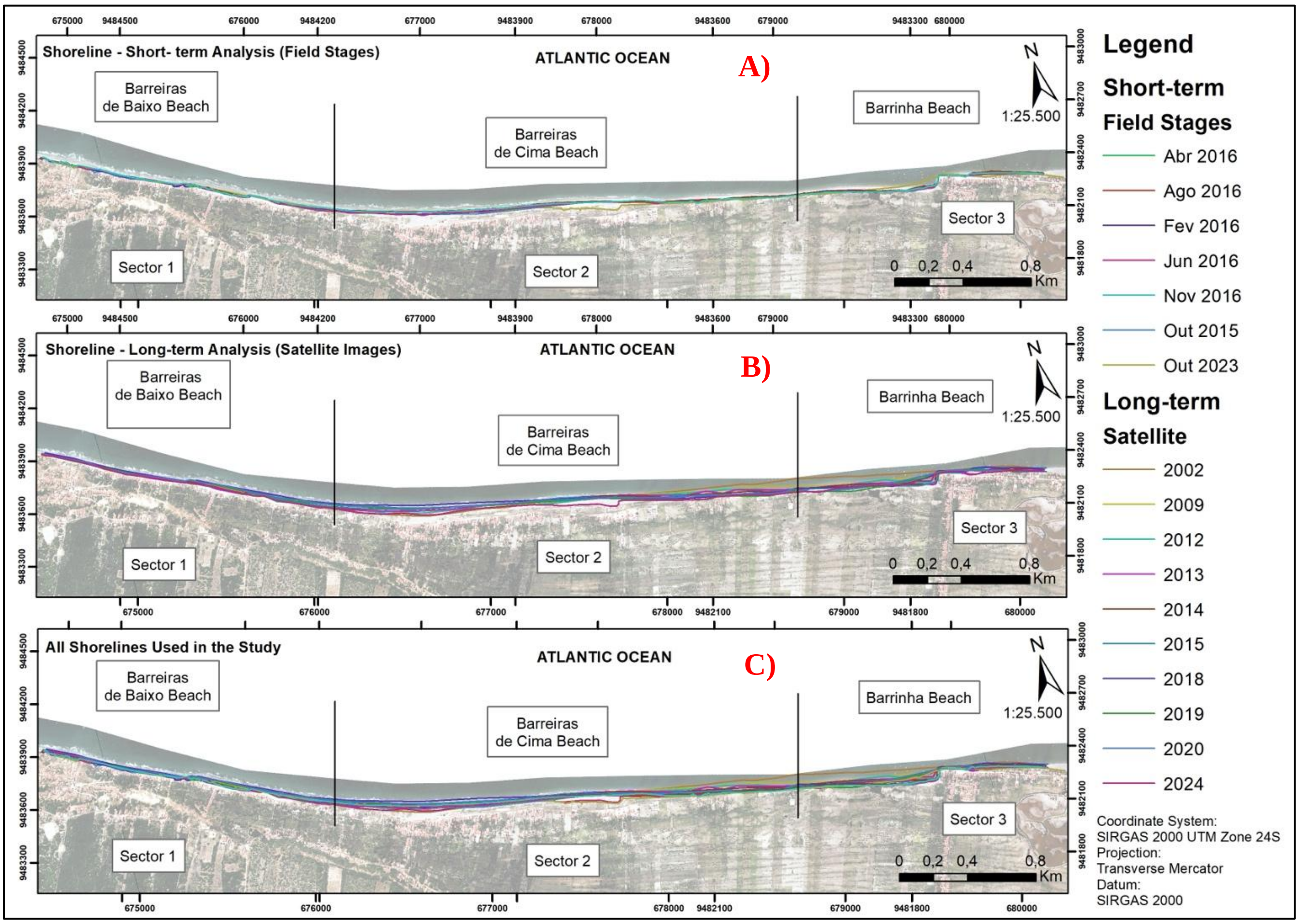

Figure 4. Shoreline of monitored sectors. A) Short-term analysis using field work; B) Long-term analysis using satellite images; C) All the shorelines used in the study.

3. Results

The short-term erosion and progradation rates showed an average EPR of 0.0 m/year. However, when analyzing the extreme values, we found that during the analyzed period, there was a maximum progradation of 7.1 m/year (totaling 56.8 m) and a maximum erosion of 6.4 m/year (totaling 51.2 m) (Figure 5A). For the same situation, using the LRR, an average of -0.2 m/year was observed. Sections with a maximum progradation of 7 m/year (totaling 56 m) and others with a maximum erosion of 6.7 m/year (totaling 53.6 m) were identified (Figure 5B).

For the long-term analysis (satellite images) using the EPR, the rates showed an average value of -1.1 m/year, with sections of maximum progradation of 0.5 m/year (totaling 11 m) and minimum erosion rates of 3.9 m/year (totaling 85.8 m) (Figure 6A). The LRR, for the same analysis, again shows a negative average, with a value of -0.7 m/year. Sections with maximum erosion of 3.6 m/year (totaling 79.2 m) and sections with maximum progradation of 1.6 m/year (totaling 35.2 m) were identified (Figure 6B).

The highest maximum rates of erosion and progradation, both in the short-term and long-term analyses, were identified in sector 2, at Barreiras de Cima beach (maximum erosion), and in sector 3, at Barrinha beach (maximum progradation).

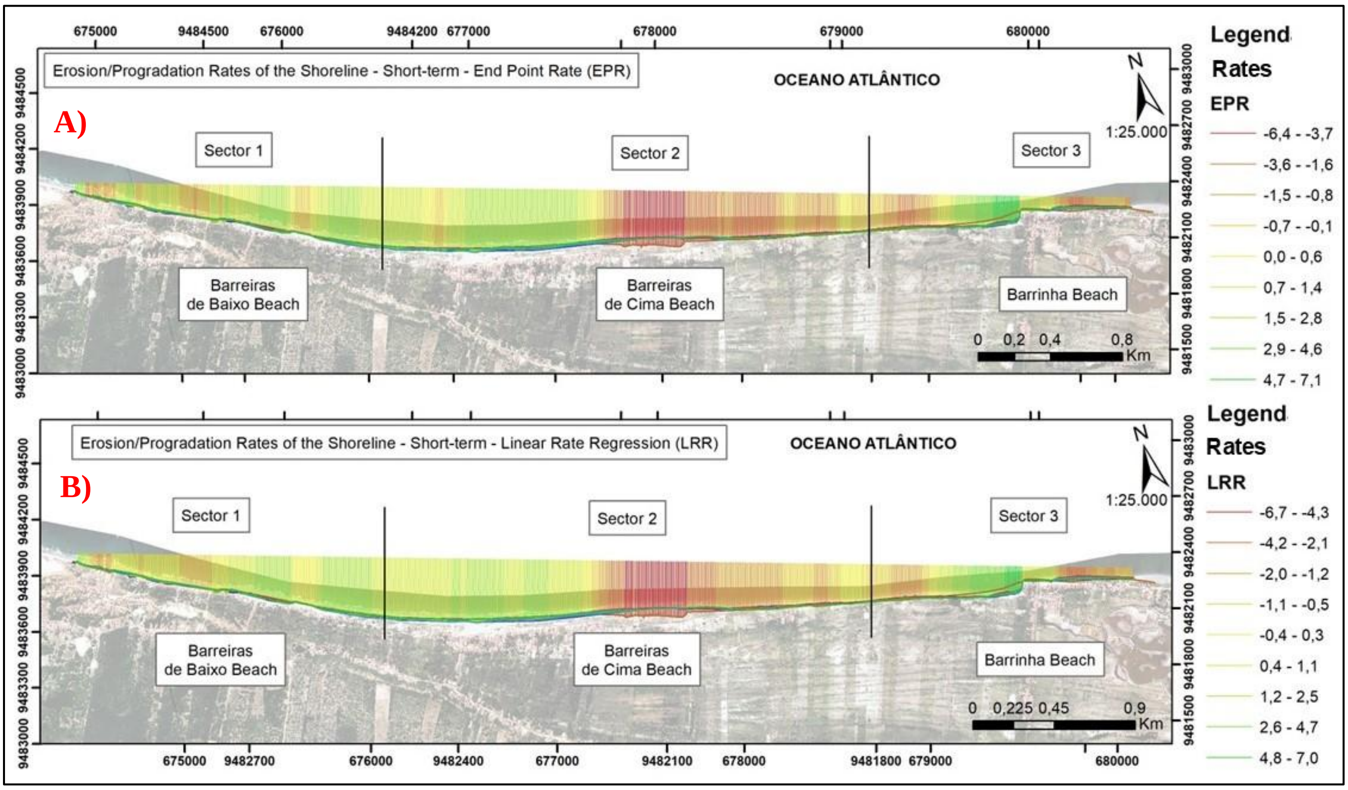

Figure 5. Erosion/Progradation Rates of the Shoreline during the Short-Term Analysis. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

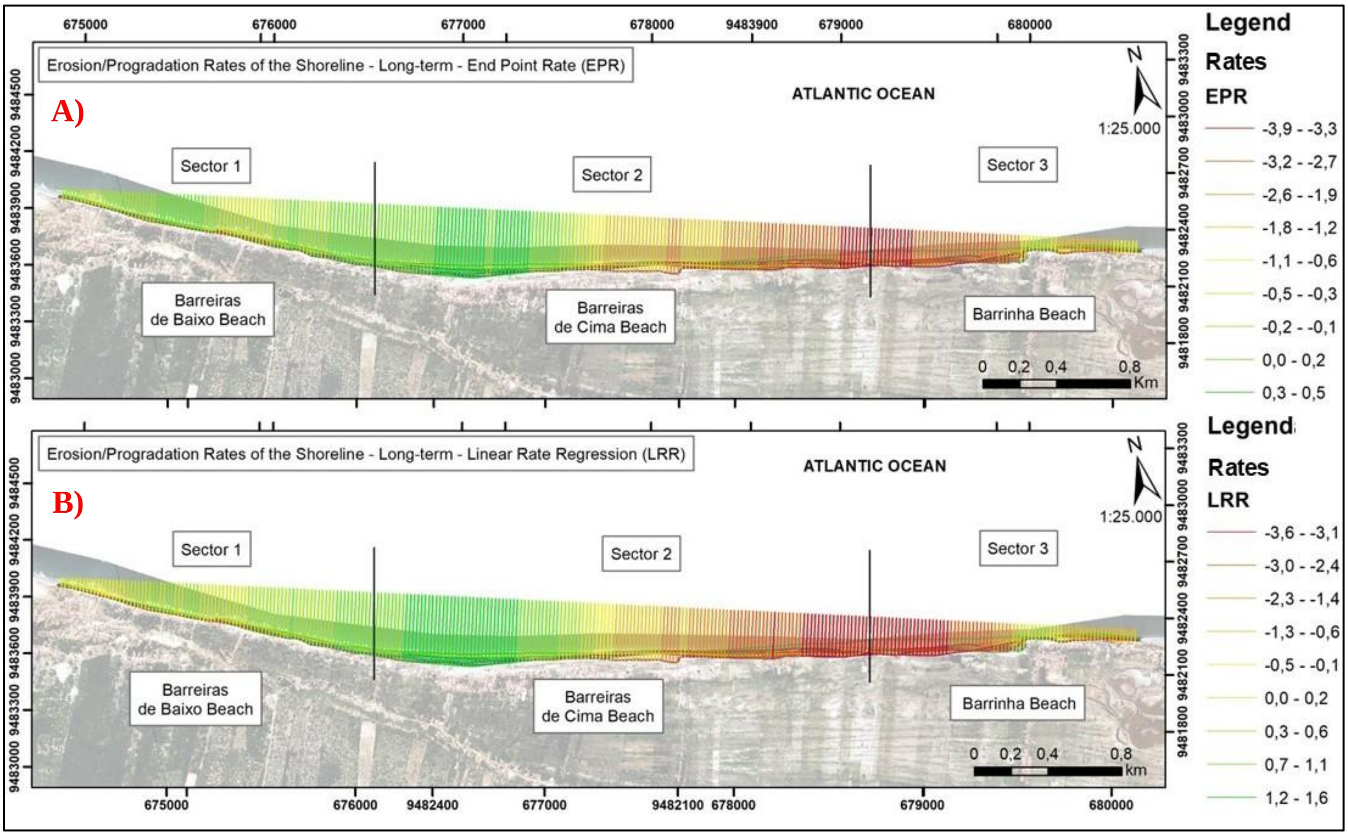

Figure 6. Erosion/Progradation Rates of the Shoreline during the Long-Term Analysis. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

3.1. Sector 1 – Barreiras de Baixo Beach

The analysis of short-term erosion and progradation rates for sector 1 shows an average of 0.6 m/year for the EPR and 0.3 m/year for the LRR. The maximum progradation was 4.1 m/year (32.8 m) and the maximum erosion was 2.8 m/year (22.4 m) using the EPR as the statistical method (Figure 7A). When using the LRR, a maximum progradation of 3.6 m/year (28.8 m) and a maximum erosion of 1.5 m/year (12 m) were identified (Figure 7B).

The long-term analysis shows an average rate of -0.2 m/year according to the EPR and 0.3 m/year for the LRR. The maximum progradation rate during the EPR analysis was 0.2 m/year (4.4 m), and the maximum erosion rate was 0.5 m/year (11 m) (Figure 8A). For the LRR, a maximum progradation rate of 0.9 m/year (19.8 m) was identified, and the maximum erosion rate was 0.3 m/year (6.6 m) (Figure 8B). Overall, both in the short-term and long-term analyses, this sector shows a greater tendency for SL stability and a relatively low progradation rate.

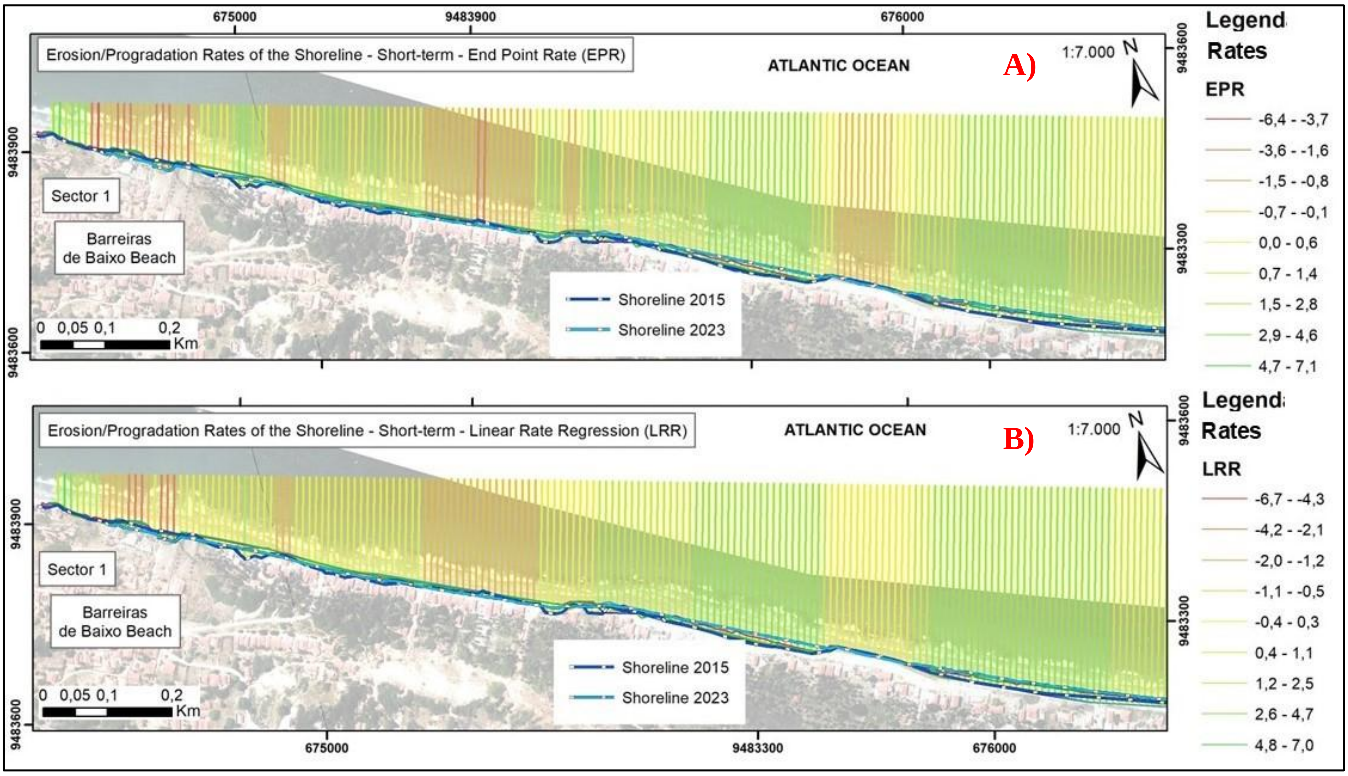

Figure 7. Erosion/Progradation Rates of the Shoreline during the Short-Term Analysis for Sector 1. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

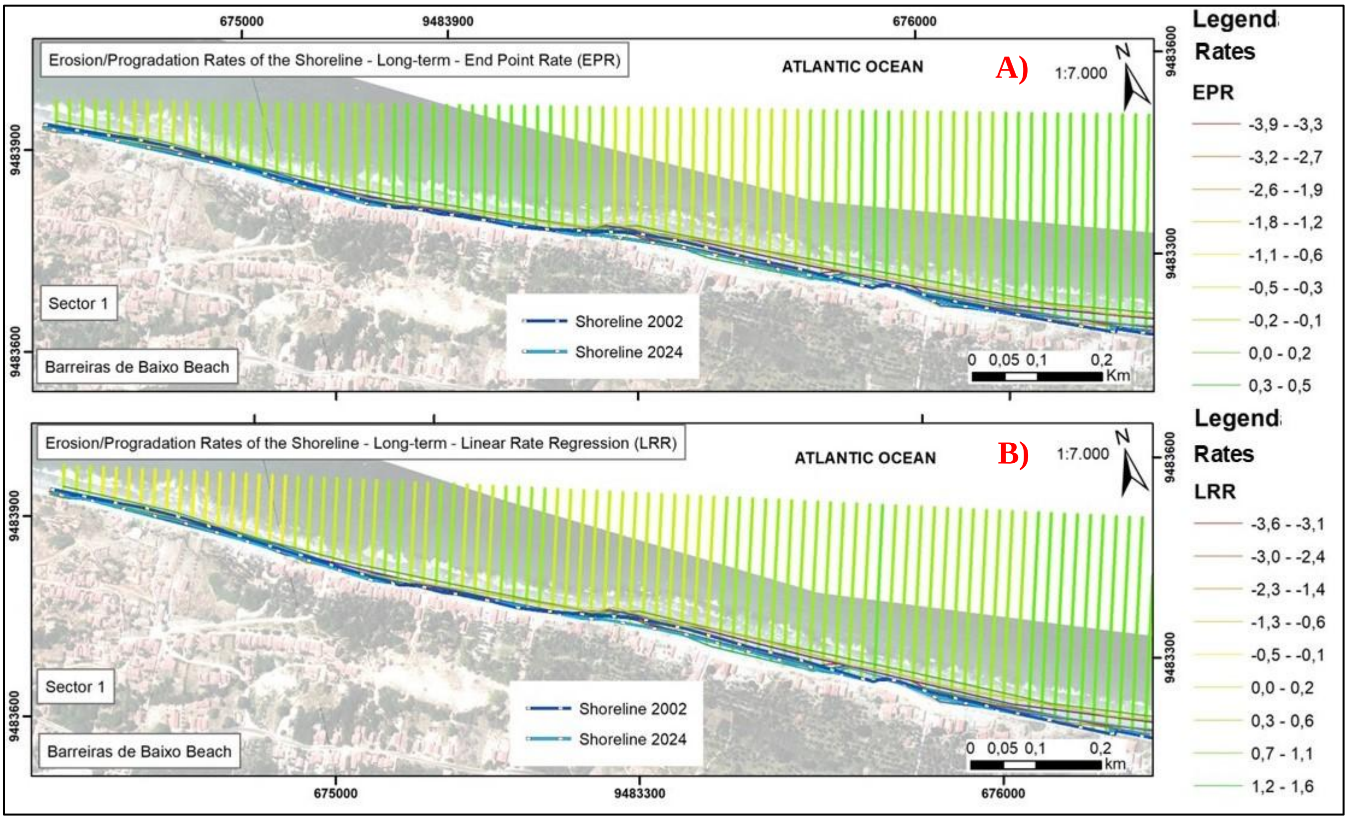

Figure 8. Erosion/Progradation Rates of the Shoreline during the Long-Term Analysis for Sector 1. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

3.2. Sector 2 – Barreiras de Cima Beach

The detailed analysis for sector 2 shows that, in terms of short-term rates, the average erosion and progradation rates were -0.7 m/year (EPR) and -0.9 m/year (LRR), respectively. The EPR analysis showed a maximum progradation of 2.5 m/year (20 m) and a maximum erosion of 6.4 m/year (51.2 m) (Figure 9A). On the other hand, the LRR analysis indicates a maximum progradation of 1.7 m/year (13.6 m) and a maximum erosion of 6.7 m/year (53.6 m) (Figure 9B).

When analyzing the long-term rates, average values of -1.2 m/year (EPR) and -0.8 m/year (LRR) were identified. The EPR analysis showed a maximum progradation of 0.5 m/year (11 m) and a maximum erosion of -3.7 m/year (81.4 m) (Figure 10A). The LRR presented maximum progradation rates of 1.6 m/year (35.2 m) and maximum erosion rates of 3.6 m/year (79.2 m) (Figure 10B).

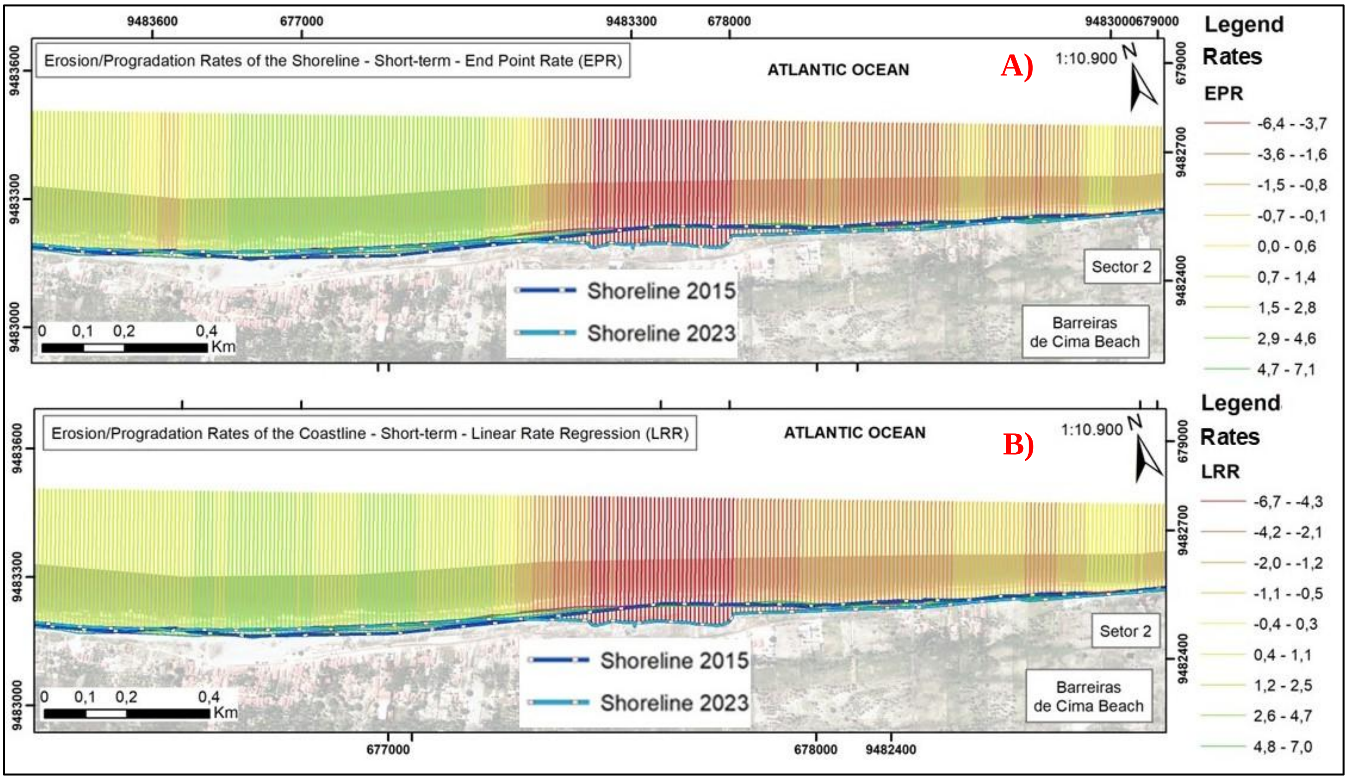

Figure 9. Erosion/Progradation Rates of the Shoreline during the Short-Term Analysis for Sector 2. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

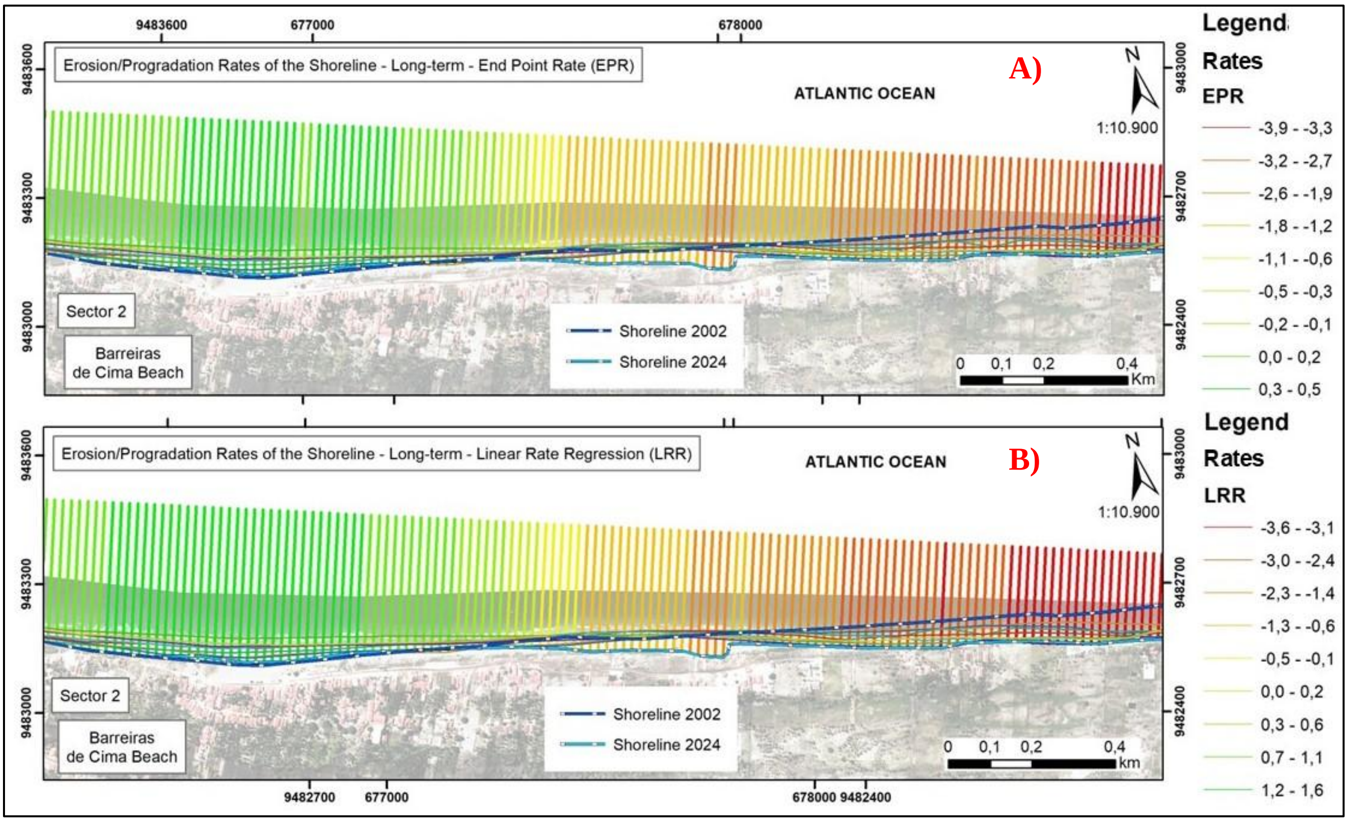

Figure 10. Erosion/Progradation Rates of the Shoreline during the Long-Term Analysis for Sector 2. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

3.3. Sector 3 – Barrinha Beach

The third and final sector showed average rates of 0.5 m/year (EPR) and 0.4 m/year (LRR) during the short-term analysis. According to the EPR, the maximum progradation rate was 7.1 m/year (56.8 m), and the maximum erosion rate was 2.3 m/year (18.4 m) (Figure 11A). For the LRR, a maximum progradation of 7 m/year (56 m) and a maximum erosion of 2.6 m/year (20.8 m) were observed (Figure 11B).

The average rates obtained from the long-term analysis show -2.1 m/year for the EPR and -1.9 m/year for the LRR. Unlike the rates presented during the analysis of the other sectors, the long-term analysis for the EPR shows only negative values, with a minimum erosion rate of 0.4 m/year (8.8 m) and a maximum of 3.9 m/year (85.8 m) (Figure 12A). The LRR showed a maximum progradation of 0.2 m/year (4.4 m) and a maximum erosion rate of 3.5 m/year (77 m) (Figure 12B).

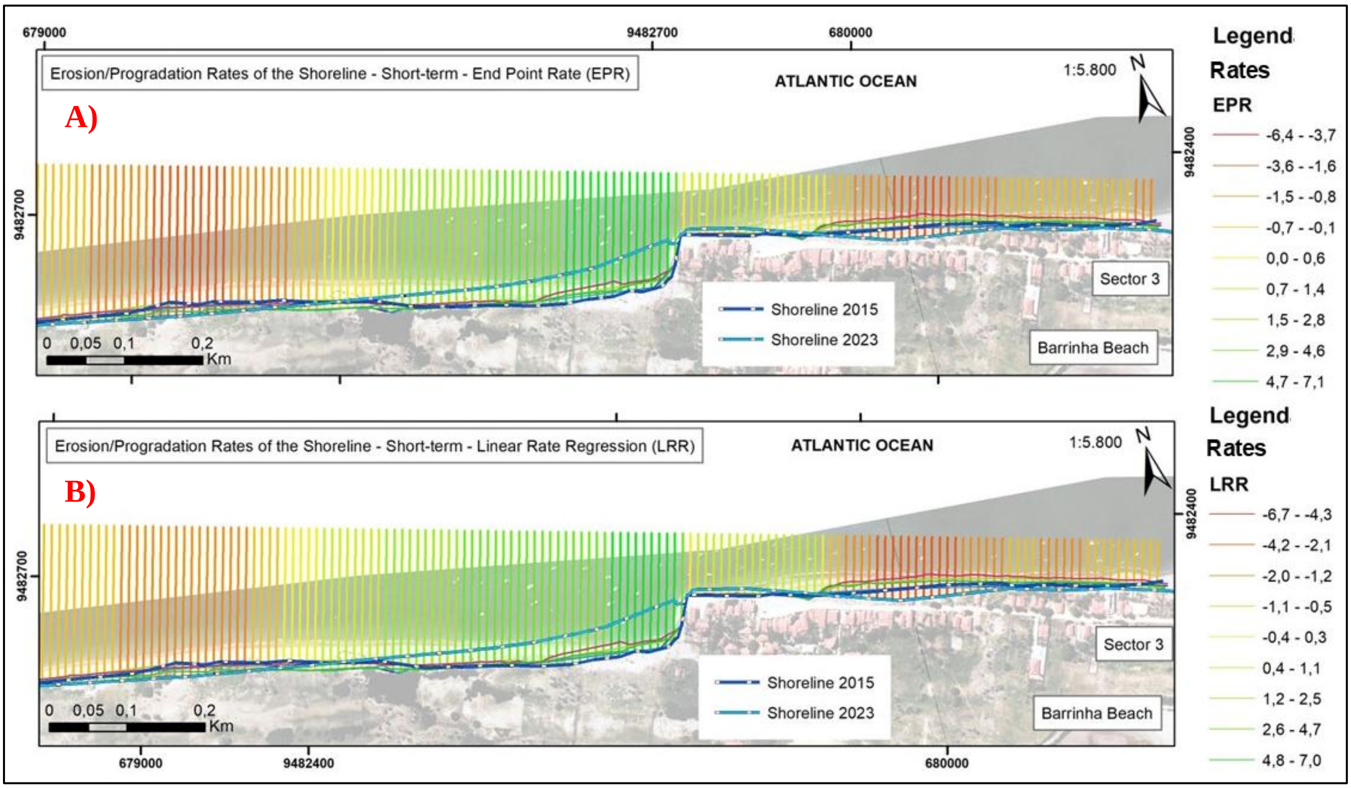

Figure 11. Erosion/Progradation Rates of the Shoreline during the Short-Term Analysis for Sector 3. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

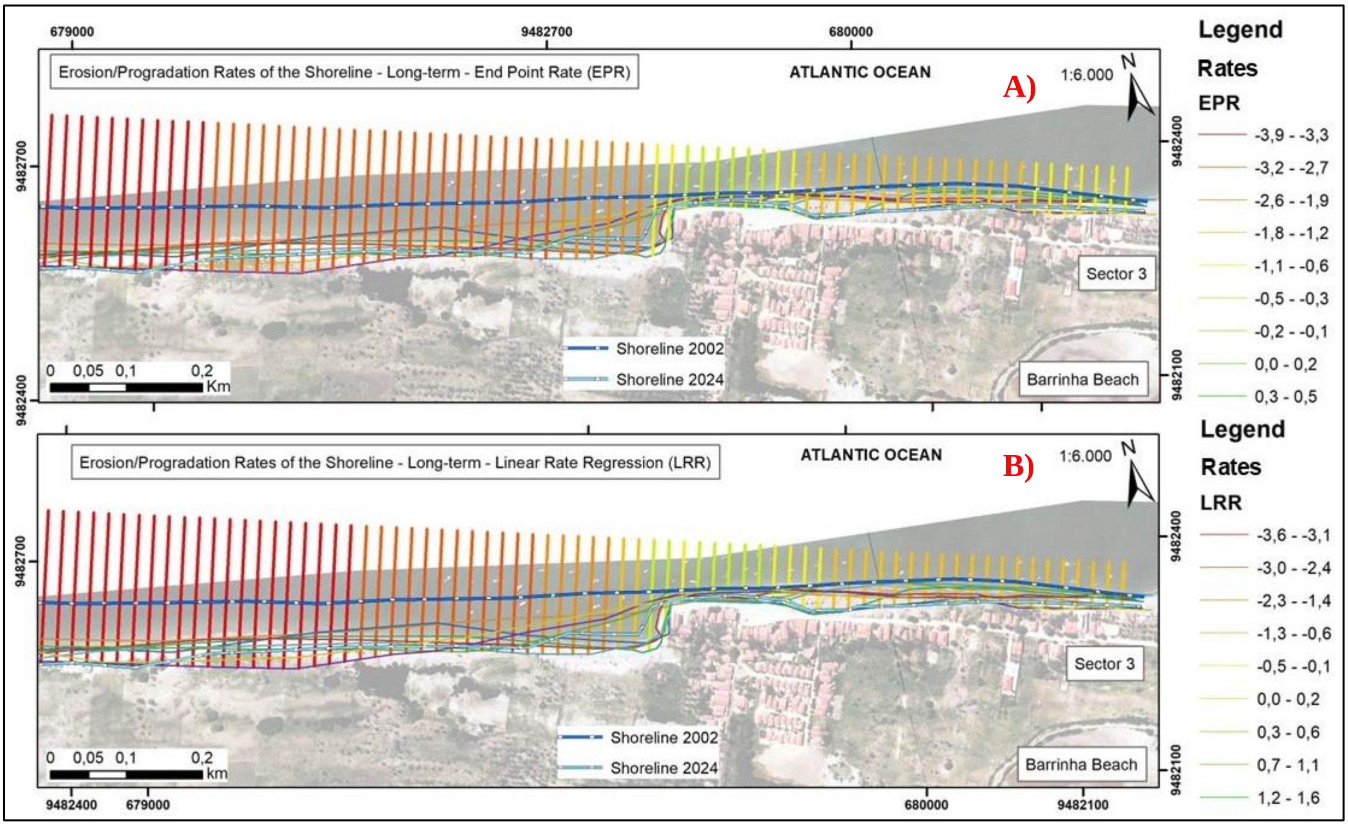

Figure 12. Erosion/Progradation Rates of the Shoreline during the Long-Term Analysis for Sector 3. A) End Point Rate (EPR); B) Linear Rate Regression (LRR).

3.4. Future Perspectives for the Monitored Shoreline Section in Icapuí

Protection structures against erosion processes and SL retreat have been implemented in Icapuí through private initiatives, such as sandbags and wooden stakes, as well as government measures like Rip-rap. This information is crucial for coastal urban planning, helping to identify areas suitable for long-term occupation and those that need to be preserved due to the risks of coastal erosion and SL retreat.

Figure 13 illustrates the timeline of Rip-rap construction along the analyzed section of the SL in the municipality. Notably, the first structure was installed in 2009 in sector 1, and the "L"-shaped structure was installed in sector 3 in 2011. The latter exacerbated the SL retreat between 2011 and 2019; however, the area began to prograde again during this period.

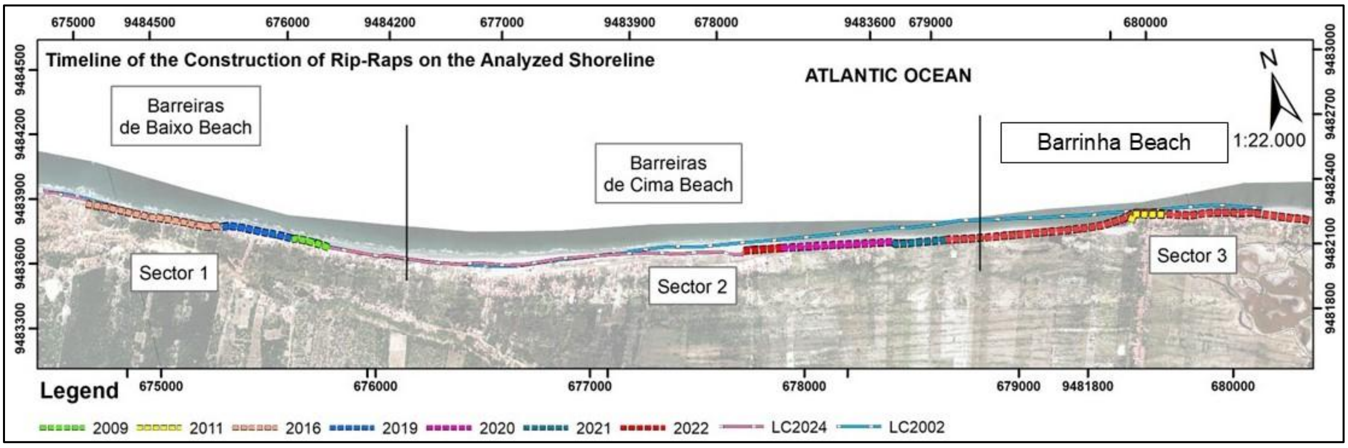

Figure 13. Timeline of Rip-rap contruction along the analysed section of shoreline.

This study reveals that approximately 63.2% or 3.814 km of the analyzed SL is stabilized due to the presence of Rip-rap, mainly in sectors 1 and 3. Regarding the future of these specific sections, the SL is expected to remain stable if monitoring and maintenance measures for the structures are implemented, considering the erosive trends observed in the presented results.

In general terms, on a short-term analysis scale, higher peaks were identified for both erosion and progradation of the SL. Progradational trends were observed in sector 1, possibly due to the installation of erosion containment structures. During field activities for SL detection, the SL reference constantly changed, alternating between areas with and without protection. These structures can act as sediment traps, promoting the accumulation of material and driving the progradation of the SL, provided there is sediment availability in the affected area (Figure 14 A and B).

In the central region of sector 2, an increase in SL retreat was observed due to the end of the Rip-rap installed there. The analysis for the year 2034 indicates that the area may retreat by up to 89 m from its current SL position. The projected scenario for the year 2044 suggests that the SL could retreat by up to 144 m in this section. Additionally, a slight trend of progradation and stabilization of the SL is noticeable in this sector, especially in the westernmost stretch, due to the Rip-rap. Conversely, there is a slight retreat of the SL in the eastern area, up to 47 meters, when considering the maximum forecast period, resulting from anthropogenic changes in sector 3.

Therefore, this is a sector that requires attention from public authorities due to the potential for a more pronounced worsening of SL retreat, which is already evident in this stretch. The final sector demonstrates significant progradational trends, as indicated by the projected SL for the year 2034, with an anticipated advance of up to 89 meters toward the ocean. By the year 2044, the area may be prograde by approximately 157 m from its current SL position.

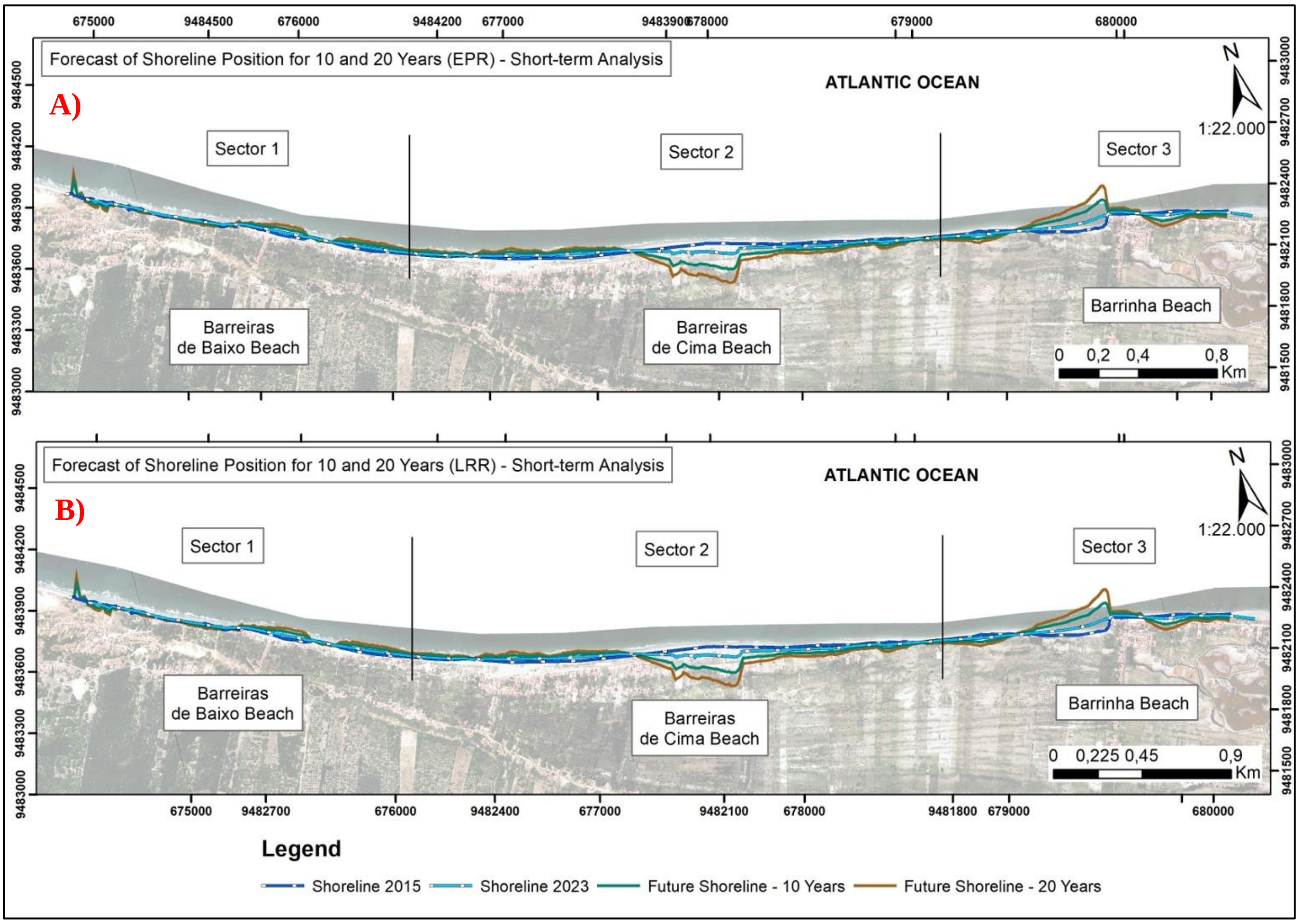

Figure 14. Short-term Forecast of the Shoreline Position for 10 and 20 Years for the Analyzed Section. A) According to the rates obtained through the End Point Rate (EPR); B) According to the rates obtained through the Linear Rate Regression (LRR).

Figure 15 A and B display the future projections of the SL for the years 2034 and 2044, based on the long-term analysis data. At this scale of analysis, we observe an adjustment of the future lines, without the presence of more pronounced peaks in terms of SL erosion and progradation. This is likely due to the broader temporal range of data incorporated into the software.

Sector 1 is not expected to undergo significant changes according to the projections for SL behavior, both for 2034 and 2044. This stability is attributed to the stabilization provided by the Rip-rap constructed in recent years in the area, which ensures the protection of the existing urban infrastructure. However, it is crucial that these coastal protection structures receive ongoing maintenance and monitoring to sustain these stability trends.

Sector 2 exhibits a trend of progradation, particularly in the western portion, where an approximate advance of 90 m is anticipated by the maximum projection period (2044). This area is significant for urban planning in the region, as it is a strategic stretch for the municipality due to the presence of frontal dunes and a receded occupation. Maintaining these characteristics is essential to avoid future issues with SL retreat caused by local erosion. However, a generalized trend of SL retreat was observed in the eastern section, toward Sector 3, where a retreat of approximately 94 m is expected by the year 2044.

The area between Sector 2 and Sector 3 emerged as the most critical stretch concerning SL erosion along the 6 km of monitoring, across different time scales, including longer-term periods such as 10 and 20 years into the future. Even with the stabilization provided by Rip-rap, this concern remains, highlighting the need for more rigorous monitoring by public authorities regarding the integrity of the structures in the future.

Recently, a process of beach nourishment has been observed in the area adjacent to the Rip-rap constructed at Praia da Barrinha. However, continuous and long-term studies are necessary to determine whether this progradational trend will persist or if the stretch will behave as predicted by the DSAS for the location. From an urban planning perspective, this area is critical and requires an occupation plan based on studies like this one to avoid damage to existing infrastructure or, at the very least, to minimize such damage.

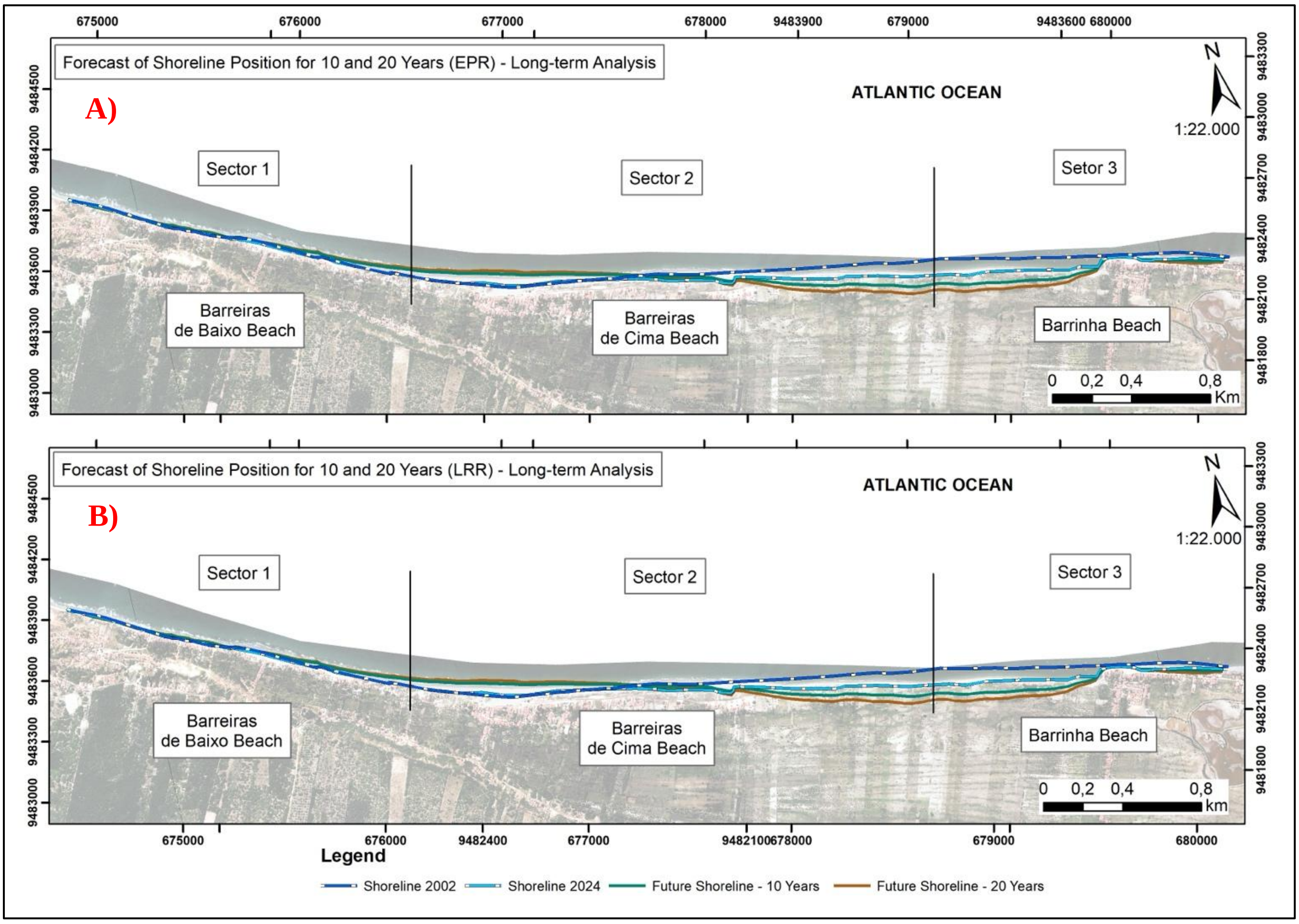

Figure 15. Long-term forecast of the position of the shoreline for 10 and 20 years for the analyzed stretch. A) According to the rates obtained through the End Point Rate (EPR); B) According to the rates obtained through Linear Rate Regression (LRR).

The coefficient of determination R^2 for the statistical methodologies in the short-term analysis was 0.9461. Therefore, the two statistical methodologies used explain approximately 94.61% of the variability observed in the data. In terms of long-term analysis, the value was around 0.9431, or 94.31%. In both situations, there is a strong relationship between the analyzed variables. The results thus demonstrate a good capacity for methodologies to model or explain the behavior of the studied variables (Figure 16 A and B).

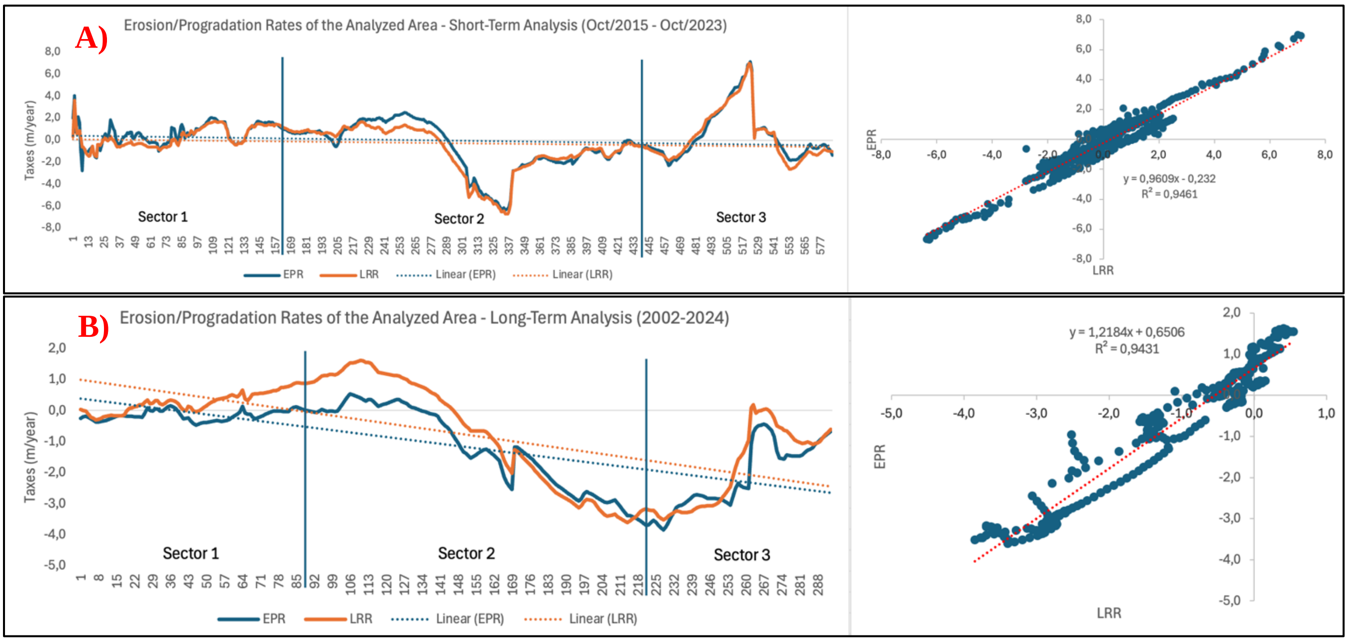

Figure 16. Coefficient of determination R^2 for the statistical methodologies used. A) Short-Term Analysis; B) Long-Term Analysis.

4. Discussion

When analyzing the average erosion and progradation rates of the SL (EPR and LRR) for both short and long-term periods, a slight trend of coastal retreat is observed. However, this trend is more pronounced over long-term analysis. This is likely due to two factors: the use of a longer time frame and the absence of erosion control structures in certain areas during the 22-year period analyzed. The latter explains the lower rates obtained for the short-term period of 8 years, as there is a general trend towards coastline stabilization due to the presence of these structures.

Pinheiro *et al.* (2016) states that the morphological characteristics of the SL are influenced by coastal hydrodynamic processes along the inner shelf and the SL, including the attenuation, refraction, and diffraction of waves over outcrops, sand spits, sandbanks, and within bays. According to these authors, the area analyzed in this study, features tide-dominated beaches, which are predominantly classified in the morphodynamic stages as Reflective with Low Tide Terrace (R+LTT) and Ultradissipative (UD).

Morais (2000) and Lacerda Barros (2018) also associate the fact that the analyzed section features flat beaches in both its emerged and submerged portions, a characteristic that extends to the inner and outer continental shelf, which along this part of the Ceará SL has a low elevation gradient and shallow depth. Thus, the coastline in question has tides as the main driving force of the local hydrodynamics and is subject to higher retreat rates during phenomena such as spring tides, Supermoon tides, and the conjunction of these tides with storm events, the latter causing short coastal flooding events.

Sector 1 of the analyzed SL has the highest population density, with the presence of fishermen's houses, local businesses, and inns. According to Lacerda Barros (2018), these small to medium-sized developments occur closer to the SL and sometimes even on top of it. This situation has exacerbated the effects of erosion processes in the area, something that has been observed since the early 2000s. To prevent further retreat of the SL due to erosion, stabilization measures were implemented, including Rip-rap built between 2015 and 2016 (see Figure 17). The area had already been using makeshift containment structures, such as wooden stakes and sandbags, but these alternatives proved ineffective over time and may have even intensified the erosion process in the region.

Figure 17. Containment measures are used to prevent the retreat of the coastline and mitigate the action of the tides. A and B) Alignment of wooden stakes, limestone blocks, and sandbags – 2015; C and D) Use of rigid structure in the form of Rip-rap in the same location to prevent the retreat of the coastline – 2024.

Figure 18 presents a timeline in image form of the structural intervention process carried out in the westernmost stretch of Barreiras de Baixo Beach through a rock revetment. According to Alfredini (2005) and Klein *et al.* (2005), structural measures, such as the construction of coastal defense works, combat coastal erosion by influencing wave action and sediment transport to stabilize or advance the SL. These interventions reflect waves and retain or add sediments for this purpose. Therefore, coastal protection and restoration works are used to preserve natural systems and human elements along the coast (USACE, 2002). However, their characteristics can impact the evolution of natural processes, landscapes, and habitats (Nordstrom, 2014).

Construction work began in 2015, with part of it completed in 2016, and its extension was expanded into part of sector 2, further to the east, in the following years. This sector is where the first erosion control structure in the analyzed stretch was installed in 2009, in the form of a rock revetment (Lacerda Barros, 2018).

This structure virtually halted any significant variation in the SL of this part of the municipality, protecting the constructions that were still present at the time. Lacerda Barros (2018) highlights that, over the years, the area became more valued, with new buildings emerging and improvements made to the urban infrastructure. This was noted by the local community, although there were initial complaints about the difficulty in accessing the beach (due to the elevated altimetric level caused by the construction and the lowering of the beach profile). As a result, staircases—16 in total so far along the stretch analyzed in this study—and access ramps were installed to facilitate the transport of materials used in local fishing, albeit implemented later than needed.

Figure 18. Evolution of the process of installing a rock revetment at Barreiras de Baixo Beach between 2015 and 2023. A) Section of Barreiras de Baixo Beach with the accommodations destroyed due to erosive processes and the retreat of the shoreline. The presence of temporary structures for tidal and erosion control is highlighted; B) Beginning of the installation process of the rock revetment to prevent shoreline retreat; C) Completed installation of the rock revetment; and D) General overview of the rigid structures built in the analyzed sector between 2009 and 2019.

According to USACE (2002), Nordstrom (2014), Brasil (2018), and Lacerda Barros *et al.* (2021), Rip-rap, the containment alternative used in Icapuí, are structures composed of rock blocks positioned and aligned directly and parallel to the SL, aimed at protecting roads, houses, walkways, etc., against wave action through the reflection or dissipation of wave energy. Negative impacts resulting from wave turbulence and interaction with the base of the structure are highlighted, including the excavation of the base of the structures and the lowering of the beach profile. Additionally, there is a loss of landscape and recreational value of the beach due to decreased accessibility in the area.

It was observed for Sector 2 that both in the short-term analysis and the long-term analysis, this sector exhibits erosive trends, unlike what was pointed out by Lacerda Barros (2018) when analyzing the period from 2002 to 2016, during which the same sector was predominantly progradational along much of its extent.

Currently, the highest concentration of more intense rates of SL retreat is found in this sector, especially in the central and eastern regions, where the SL migrates toward the mainland. Part of this retreat is still a result of the direct influence of a containment structure built in Sector 3 around 2010 and 2011. However, it was also observed that elevated rates of progradation are present in the western portion of this sector.

Part of the intensification of the SL retreat process in this sector between 2020 and 2023 is also directly linked to anthropogenic interference in this stretch and in Sector 3. The tip of a rock revetment built during this period has been causing an intensification of erosion in the central portion of the sector due to changes in oceanographic forcing patterns, which can be easily observed through the analysis of satellite images and photographs taken at the site (Figure 19).

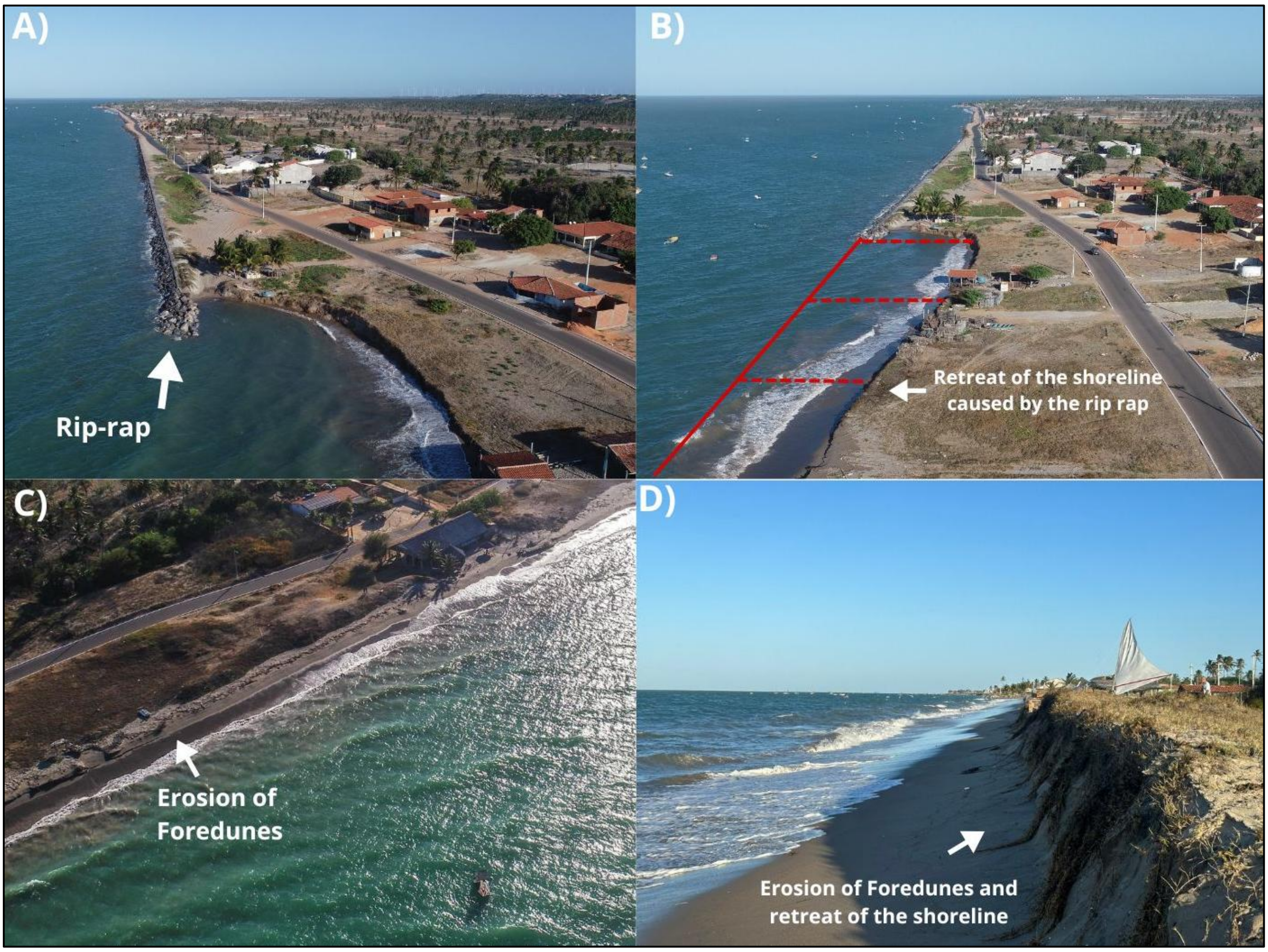

Figure 19. Changes in the shoreline were caused by the installation of a rock revetment in Sector 2. A) Tip of the rock revetment installed in the sector; B) Retreat of the shoreline caused by the tip of the revetment; C and D) Erosion of frontal dunes and retreat of the shoreline.

In sector 2, the damage caused to the infrastructure installed near the SL is reduced compared to sectors 1 and 3. This is due to three factors: the urbanization in this section of the municipality's SL being farther from the coastline; the presence of an extensive post-beach area with frontal dunes that act as a protective barrier for the coast and a source of sediments, which are currently steep due to the erosive action of local tides and waves; and finally, the material deposited in this sector originating from the erosion of part of the stretch in sector 3 (which years ago was experiencing significant retrogradation of the SL) to the leeward side, due to the predominant direction of longshore sediment transport in the area, east to west as it is in the majority of Ceará state.

Sector 3 is characterized by the presence of sections with no occupation or with occupation further away from the SL, featuring frontal dunes and sections with a similar type of occupation found at Barreiras de Baixo Beach, meaning that there are houses and other structures directly positioned on the SL.

The last sector under analysis is in the far eastern area. The data regarding the analysis of the variation rates of the SL in this sector, using field monitoring and images, demonstrates an opposite trend compared to what was observed in sector 2 to the south. Even though this sector shows the greatest total retreat of the SL, 85.8 m, it differs from the observations made between 2002 and 2016 when it was noted that this sector was dominated by erosive trends, as highlighted by Lacerda Barros (2018). Currently, this area presents a short-term progradational trend.

The relationship between a relatively flat beach and the encroachment of development towards the SL has consequently made this point vulnerable to erosion in the past, resulting in a series of damage already inflicted on the constructed structures. Several buildings have been destroyed by erosion; additionally, a school had to be demolished due to the risk of collapse to make way for the rock revetment to curb erosion and protect the houses located further inland. The population was relocated to a nearby area; however, the construction carried out for the purpose ended up exacerbating erosion in areas downstream (Lacerda Barros, 2018).

Figure 20 shows the changes in the SL at Barrinha Beach (sector 3) between 2002 and 2022, based on field monitoring and satellite images. The highest erosion rates and the greatest number of indicators of coastal erosion were observed in the central and western sections of this sector. These areas had frontal dunes that were present and eroded during this analysis period.

Figure 20. Damage caused by coastal erosion to accommodations at Praia da Barrinha between 2002 and 2010. Source: Blog "A Cidade Icapuí."

The presence of an "L"-shaped rock revetment in the area, made of limestone material that is quite prevalent in the area and extremely fragile against the action and intensification of erosive processes, has worsened erosion throughout the stretch down-drift of the structure, according to Lacerda Barros (2018). It was constructed to stabilize the SL and thus contain the encroachment of tides under the buildings installed there. However, there is now a tendency for accretion precisely in the stretch where the SL had previously receded more significantly, in the center of the sector (Figures 21 and 22).

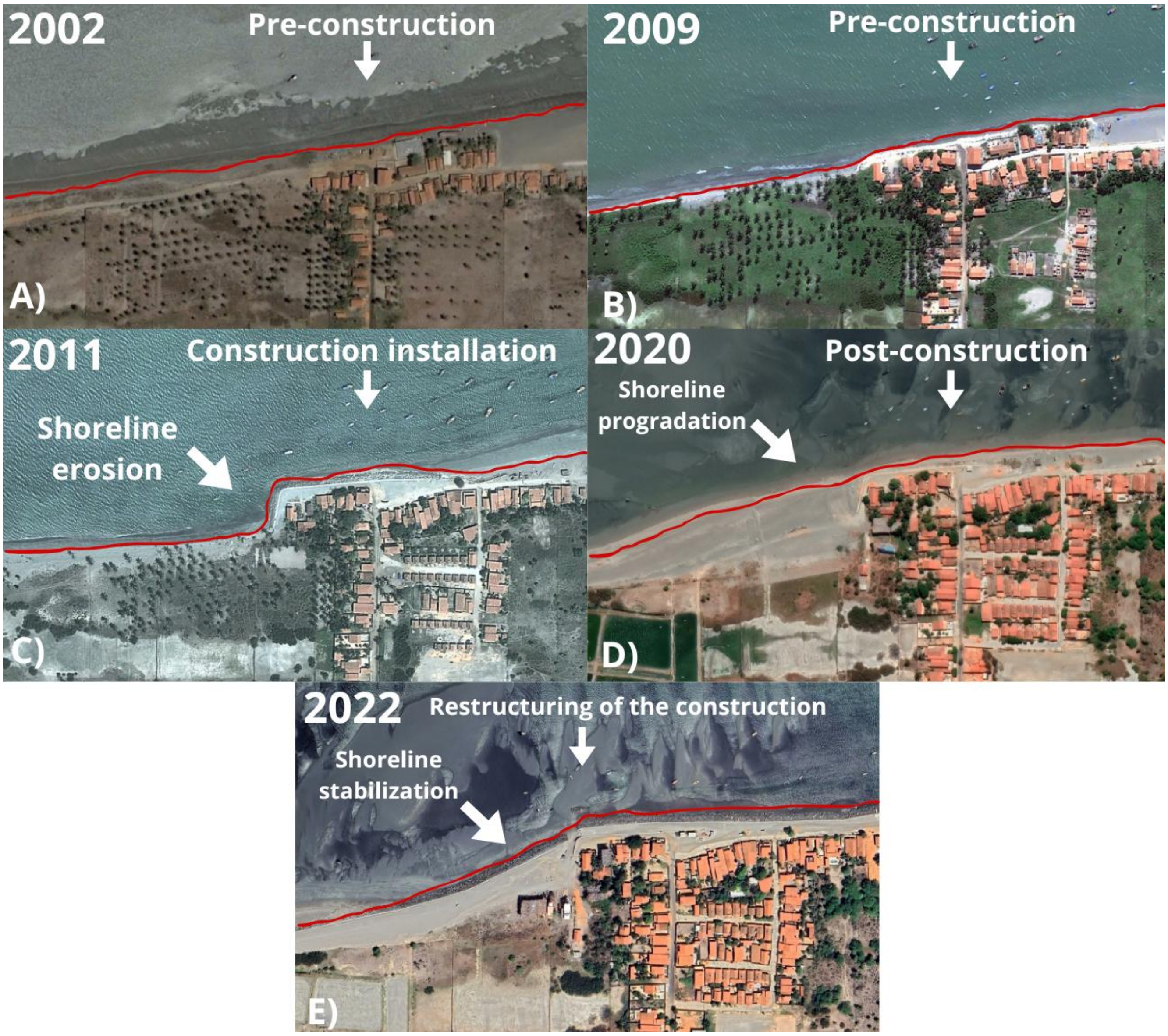

Figure 21. Evolution of a stretch of the shoreline in sector 3 analyzed between the years 2002 and 2022. A) Situation of the shoreline at Praia da Barrinha in 2002; B) Situation of the shoreline at Praia da Barrinha in 2009, highlighting the pronounced erosive process in the area with shoreline retreat and the beginning of construction for stabilization with limestone blocks; C) Completion of the stabilization, relocation of the affected community, and exacerbation of the shoreline retreat in the stretch to the west of the structure; D) Beginning of a process of accretion in the stretch to the west of the structure; E) Replacement of the limestone stabilization structure with a rock revetment made of granite blocks and extension of the structure to the east and west of the most populated stretch. Source: Adapted from Google Earth Pro 2023.

Figure 22. Evolution of a stretch of analyzed shoreline in sector 3. A and B) Photographic records from the period of intense erosive processes and the consequent damage to the structures built in the area in 2010; C, D, and E) Photographic records from 2024 obtained in the same stretch.

It was also possible to observe through satellite image analyses that there was progradation of the SL in the area downdrift adjacent to the revetment around 2019/2020, even without the construction of the revetment in the area, indicating a possible previous cycle of erosion followed by deposition in the area, similar to other areas along the coast of the state of Ceará (Pinheiro *et al.*, 2008; Duarte, 2018).

The area has undergone a series of modifications in recent years; however, during field activities, several indicators of erosion were observed, such as erosional scarps, exposed coconut tree roots, steep and completely eroded foredunes, damage to urban infrastructure, and the presence of erosion control measures, such as the use of wooden structures to minimize the impact of tides and waves in the area.

The use of structures such as revetments for the stabilization of the SL becomes a viable option not only for this purpose but also for the protection of the urban infrastructure built in the area. However, it is essential to exercise caution when choosing this option, as monitoring studies of the area are necessary before, during, and after construction, as well as medium-to-long-term studies and maintenance of the structure. This approach is crucial to avoid situations like those previously observed in the sector 3 stretch at Praia da Barrinha. Currently, the retreat of the SL in this section of Icapuí's SL is either stabilized or experiencing accretion due to the construction of the revetment that replaced the previously installed structure.

Containment measures in the area are crucial, especially in light of the forecasts from the Sixth Assessment Report (AR6) of the IPCC, which indicate a global average sea-level rise of approximately 3.7 mm per year since 2006, with projections of an increase between 0.43 m and 0.84 m by the end of the century, depending on greenhouse gas emission scenarios.

However, when analyzing these projections, it is essential to also consider the local scale, as the behavior of the SL does not directly correlate with sea level but is closely linked to sediment supply. Even with rising sea levels, a high sediment supply in areas influenced by rivers can lead to SL accretion, as observed in the deltas along Brazil's eastern coast, where coastal erosion occurs in Atafona (Machado *et al.*, 2024), while accretion is seen in Gargaú. The same phenomenon is identified in the Jequitinhonha delta, reinforcing that sediment supply is essential for understanding coastal dynamics and SL evolution, regardless of variations in sea level (Fernandez and Rocha, 2015).

5. Conclusions

Sandy beaches play a crucial role in protection against extreme events and provide significant socioeconomic value, including recreation, tourism, and ecosystem services. However, these coastal areas are constantly subject to changes due to natural and anthropogenic factors, often resulting in coastal erosion and retreat of the SL. This study revealed that approximately 63.2% of the analyzed SL has been stabilized by protection structures, especially in critical sectors observed during field data collection activities. Despite this, coastal erosion remains a significant concern for Icapuí and other municipalities in the state of Ceará, particularly in light of climate change and the rising sea levels projected by the IPCC.

The results presented show variations in the SL in both the short and long term, with more pronounced retreat trends in areas lacking adequate protection. Sectors such as Barreiras de Cima and Barrinha stood out for having the highest rates of erosion and accretion. These variations underscore the importance of continuous monitoring and the implementation of effective containment measures. Additionally, future projections indicate that without appropriate interventions, some areas may face significant SL retreat, directly impacting local communities and infrastructure.

The study highlights the urgent need for an effective participatory master plan, currently under development for the municipality, aligned with instruments such as a Municipal Climate Change Adaptation Plan and the Integrated Coastal Management Plan (PGI), associated with the Orla Project, considering the trends in SL variation, especially in vulnerable areas. Projections for 2034 and 2044 suggest that, without preventive actions, erosion could worsen, negatively affecting the environment, society, and the local economy. Therefore, it is recommended to adopt constant monitoring measures, maintain existing protection structures, and conduct ongoing studies to adapt coastal management strategies to the dynamics observed in the SL.

Thus, the information generated by this work is of utmost importance for decision-makers in actions aimed at urban planning and local coastal management. This study provides valuable insights into coastal changes over time, essential for planning and implementing adaptation and mitigation measures against the worsening of erosion processes in the analyzed locations. Such measures aim to protect coastal communities, infrastructure, and ecosystems vulnerable to coastal transformations.

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