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SPATIO-TEMPORAL ANALYSIS OF COASTAL VULNERABILITY IN ITAPOÁ, SC, BRAZIL

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ABSTRACT: Coastal vulnerability manifests along the shoreline due to the high sensitivity of the environment and the complexity of its hydrodynamic and sedimentological processes, making the coastal environment susceptible to constant changes that can result in erosion. The objective of this study is to analyze the spatio-temporal evolution of coastal vulnerability and erosive processes in Itapoá, Brazil. The study uses two existing tools that allow for a rapid analysis of the state and evolution of vulnerability in any coastal environment. The analysis of vulnerability evolution was conducted using the Cassie Engine System, which examined the time series from 1985 to 2022 through automated analysis. For the assessment of the current state of vulnerability, the Vulnerability Index and in situ analyses were used. Coastal vulnerability was assessed based on physical, morphological, and anthropogenic components, including drybeach width, presence of protection structures, wave dynamics, and impacts on infrastructure. The beaches of Itapoá were divided into nine points (P01-P09), from north to south, and visually characterized according to the erosion pattern. Results revealed that 4 points (P03, P06, P07 and P08) exhibited intense erosion, with alteration rates exceeding 1000 m/year, these four sectors share common characteristics, such as a narrow or absent dry beach, the presence of coastal protection structures, and strong exposure to wave energy. In addition, four sectors were classified as stable (P02, P04, P05, and P09), while one sector showed accretion (P01). The results highlight priority areas for coastal management and reinforce the need for integrated planning strategies in response to advancing erosive processes.

Keywords: Coastal Erosion, Coastal Vulnerability, Climate Changes, Remote Sensing.

RESUMO: *A vulnerabilidade costeira manifesta-se ao longo da linha de costa devido à elevada sensibilidade do ambiente e à complexidade dos seus processos hidrodinâmicos e sedimentológicos, tornando o meio costeiro suscetível a mudanças constantes que podem resultar em erosão. O objetivo deste estudo é analisar a evolução espaçotemporal da vulnerabilidade costeira e dos processos erosivos em Itapoá, Brasil. O estudo utiliza duas ferramentas existentes que permitem uma análise rápida do estado e da evolução da vulnerabilidade em qualquer ambiente costeiro. A análise da evolução da vulnerabilidade foi realizada por meio do sistema Cassie Engine, que examinou a série temporal de 1985 a 2022 através de análise automatizada. Para a avaliação do estado atual de vulnerabilidade, utilizou-se o Índice de Vulnerabilidade e análises in situ. A vulnerabilidade costeira foi considerada a partir de componentes físicos, morfológicos e antrópicos, incluindo largura da faixa de areia, presença de estruturas de contenção, dinâmica de ondas e impactos sobre a infraestrutura. As praias de Itapoá foram divididas em 9 pontos (P01-P09), de norte a sul, e caracterizadas visualmente de acordo com o padrão de erosão. Os resultados revelaram que 4 pontos (P03, P06, P07 e P08) apresentaram erosão intensa, com taxas de alteração superiores a 1000 m/ano, estes quatro setores apresentam características comuns, como faixa de areia reduzida ou ausente, presença de estruturas de contenção e forte exposição à energia de ondas. Além disso, quatro pontos foram classificados como estáveis (P02, P04, P05 e P09), enquanto um ponto apresentou acreção (P01). Os resultados destacam áreas prioritárias para gestão costeira e reforçam a necessidade de estratégias integradas de planejamento frente ao avanço dos processos erosivos.*

Palavras-chave: *Erosão Costeira, Mudanças Climáticas, Sensoriamento Remoto, Vulnerabilidade Costeira.*

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1. INTRODUCTION

Coastal vulnerability arises from the environmental sensitivity and the complexity of hydrodynamic and sedimentary processes that control beach morphodynamics. When high-energy events, relative sea-level rise, or astronomical and/or meteorological tide events impact beach environments—either individually or in combination—the coastline becomes highly susceptible to morphological and structural changes. Under such forcing conditions, coastal systems may experience significant profile adjustments, shoreline retreat, and sediment redistribution, reflecting the dynamic response of beaches to ongoing environmental pressures (Vousdoukas *et al*. 2020; Ranasinghe 2020).

Recent studies emphasize that coastal erosion results from the complex interaction between wave climate, rising sea level, longshore sediment transport, and variations in sediment supply. These processes operate across multiple temporal and spatial scales and can intensify under climate change scenarios (Vitousek *et al*. 2023; Toimil *et al*. 2020). Coastal erosion is therefore understood as a dynamic and often natural geomorphological process, characterized by modifications in the beach profile and potential landward shoreline migration. However, its frequency and magnitude are being amplified in several regions due to accelerated sea-level rise and increased storm intensity (Barnard *et al*. 2023; IPCC 2021).

The coastal zone holds strategic importance for society due to its role in global trade and transportation networks, food security through fisheries and aquaculture, regulation of ocean circulation processes, tourism and recreation, and the provision of critical ecosystem services. Coastal areas host densely populated regions and economically vital infrastructure, while also supporting highly productive and environmentally significant ecosystems that contribute to biodiversity conservation and climate regulation (IPCC 2022; Neumann *et al*. 2022).

Recent studies emphasize that coastal systems function as socioecological interfaces where economic development, environmental services, and climate-related processes intersect. These regions play a key role in maritime logistics, blue economy activities, nutrient cycling, carbon sequestration, and shoreline protection, reinforcing their global strategic relevance (Bennett *et al*. 2021; UNCTAD 2023).

With global trends of rising average sea levels, coastal erosion is becoming an emergent and worrying risk, as the population in coastal areas is larger compared to other regions. It is commonly recognized as a public management issue, frequently mitigated through the implementation of engineered coastal protection structures, including jetties, groins, and rock revetments. However, these structures not only alter the beach profile but can also cause various other impacts and, crucially, often worsen the problem instead of solving it (Gracia *et al*. 2018; Castillo, 2023).

According to estimates from the Intergovernmental Panel on Climate Change (IPCC), sea level rise could reach rates of 0.13 to 0.50 mm/year by 2100 (IPCC 2021). The World Meteorological Organization reports that sea level rise over the past decade was 4.5 cm, and global temperature increased by 1.1°C. As a consequence of these events, it is expected that coastal erosion processes will intensify (WMO 2022).

Recent studies indicate that coastal erosion has increasingly become a significant socio-environmental challenge, largely driven by rapid population growth in coastal zones and expanding urbanization. The construction of residential areas, transport infrastructure, and recreational facilities along shorelines frequently occurs without adequate consideration of local hydrodynamic and sedimentary processes that govern beach morphodynamics. This mismatch between coastal development and natural dynamics often exacerbates shoreline retreat, infrastructure vulnerability, and environmental degradation, particularly when compounded by extreme climatic events and sea-level rise (Vitousek *et al*. 2023; Castillo, 2023, Ranasinghe 2020; Vousdoukas *et al*. 2020).

Urban expansion in low-lying coastal areas has been identified as a key factor increasing exposure to coastal hazards, intensifying socio-environmental risks and amplifying the impacts of storm surges and high-energy wave events under climate change scenarios (Neumann *et al*. 2022; IPCC 2022).When coastal risk becomes imminent, the search for technologies and methodologies to measure, monitor, and devise containment strategies becomes critically important. One of the main problems with erosion assessment methods is the failure to consider the drainage basin and the sediment supply in the environment, which would require more in-depth studies for proper assessment. Remote sensing has become a beneficial tool for numerous studies, as it provides spatial and temporal coverage that would be difficult to achieve through monitoring studies. Currently, the Cassie Engine platform offers simplified remote sensing for automatic DSAS analysis, allowing for the assessment of vulnerability and coastal advancement using satellite databases in a simplified manner (Almeida *et al*. 2021).

By combining simple techniques, it is possible to obtain fast and efficient coastal assessment methods, allowing the implementation of coastal risk assessments and making vulnerability maps available to the public. Therefore, the aim of this study is to understand coastal vulnerability and the evolution of erosive processes in Itapoá, on the northern coast of Santa Catarina, Brazil. In this context, the aim of this study is to analyze the spatiotemporal evolution of coastal vulnerability and erosive processes along the shoreline of Itapoá, Santa Catarina.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the city of Itapoá, located on the northern coast of the state of Santa Catarina (Latitude 26°07'01" S and Longitude 48°36'58" W) in the southern region of Brazil. Itapoá has approximately 30 km of beach line (Figure 1). The estimated population of Itapoá is 21,177 inhabitants as of 2021 (IBGE 2021). Figure 1 shows the spatial distribution of the nine beach sectors analyzed in this study. The sectors were defined according to the criteria used by Ângulo & Souza (2002), who analyzed shoreline conditions using satellite imagery, and by the Itapoá City Hall (2021), which monitored the beach profile for two years using topographic profilesurvey techniques.

2.2 Characterization of the Beach Profile and Coastal Vulnerability Index (Erosional State)

The characterization of the erosional state of each beach was obtained through descriptions and visual analysis in the field. The characterization of the beach profile was conducted in two campaigns, in September 2021 and June 2022, observing depositional characteristics to identify the erosional state of each beach, including the presence of rock revetments, pavement, mangroves, coastal vegetation, and other general aspects. The methodological framework which was adopted in this analysis based on the geoindicators presented in the study by Perinotto *et al*. (2012), with each geoindicator assigned a specific weight that is subsequently entered into the table for the vulnerability

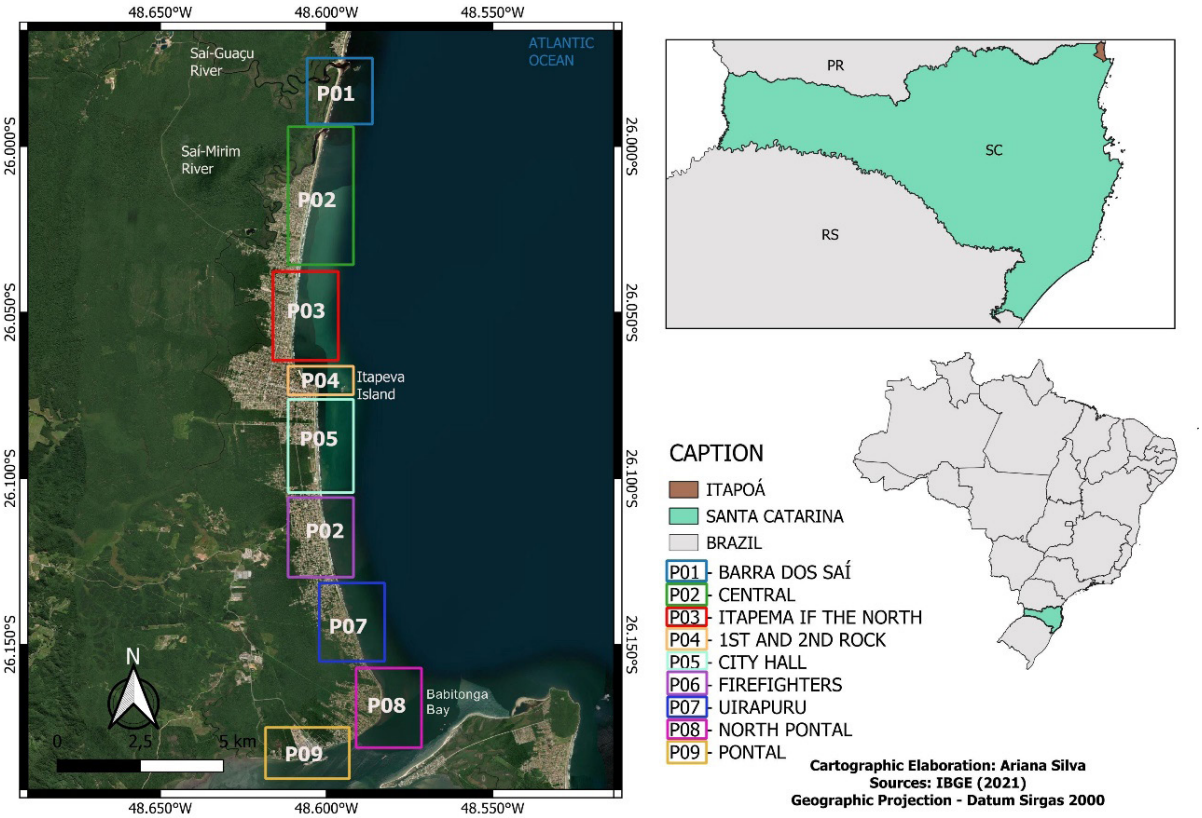


Figure 1. Study Area and Delimitation of Points - Itapoá-SC.

assessment. This characterization was also used for the analysis of the Coastal Vulnerability Index (CVI), which took into account the beach profile and the erosional state of each beach, based on descriptions of the presence of rock revetments, pavement, mangroves, coastal vegetation, and other general aspects (Table I). This index was chosen due to its simplicity and suitability for understanding subtropical environments, having been previously applied on the coast of Santa Catarina.

The study area was divided into 9 beach points, subdivided according to geomorphological divisions from north to south of the city, and subsequently, each point was analyzed, and the index was applied based on the geoindicators. After data collection, a score was assigned to each geoindicator. The final sum of this score was applied to understand and characterize the erosional state of each point, based on the following determinations: sum greater than 5 = "severe erosion"; sum between 2 and 5 = "erosion"; sum less than 2 = "stability or accretion." Topographic profiles of the most relevant areas were also obtained using the evaluation method based on Emery Markers, which consists of two markers, each 1.5 m long (Kowmann 1970).

2.3 Evolution of Coastal Vulnerability

2.3.1 Cassie Engine

The Cassie Engine system was used for the characterization and variation of the coastline over the years through the principles of Digital Shoreline Analysis System (DSAS). The Cassie Engine is a simplified simulation and analysis system that utilizes advanced computational methods to model complex phenomena in natural environments, such as fluid dynamics and the interaction between different ecological elements. DSAS is a technical tool used to measure and analyze changes in the coastline over time, calculating rates of variation to understand processes such as erosion and accretion.

The system begins with the definition of a baseline, which is generally drawn along the coastline. From this line, a series of transects (perpendicular lines) is projected to intercept the various coastline positions over time (historical lines). Each transect serves as the basis for calculating the variation and change in the position of the coastline. The End Point Rate (EPR) calculates the rate of change between two positions of the

Table I. Indicators and variables used to classify the erosional state of the Itapoá beaches, SC, Brazil.

Erosional State	Indicators/Variables	INDICATOR	WEIGHT
SEVERE EROSION	Active wave-cut escarpment in the post-beach frequent	1.1	2
	Evident beach escarpment (due to waves and tides)	1.2	2
	Absence of dry beach	1.3	2
	Many properties or structures impacted and/or with retaining structures	1.4	4
	Peat and/or mud exposed on the beach or along the escarpment in the post-beach	1.5	2
	Uprooted vegetation or exposed roots along the escarpment in the post-beach	1.6	2
EROSION	Localized (point) wave-cut escarpments in the post-beach	2.1	1
	Sparse, localized beach escarpment	2.2	1
	Narrow strip of dry beach	2.3	1
	Some properties or structures impacted, with retaining structures	2.4	1
	Localized retaining structures	2.5	2
STABILITY OR ACCRETION	Well-developed frontal dune, high and/or with well-established vegetation	3.1	-2
	Wide, well-developed strip of dry beach	3.2	-2
	Presence of a well-developed berm on the beach, without escarpments or erosion	3.3	-2

Source: Adapted from Perinotto *et al.* (2012).

coastline (an initial and a final one), representing the variation over a specific period (equation 1):

$$EPR = \frac{Dfinal - Dinicia}{Tfinal - Tinicia} \quad (1)$$

Where:

EPR - is End Point Rate;

$Dfinal$ - is the distance from the most recent coastline along the transect;

$Dinicial$ - is the distance from the oldest coastline along the same transect;

$Tfinal\ e\ Tinicial$ - are the years corresponding to each coastline.

The Linear Regression Rate (LRR) uses linear regression to calculate the average rate of variation across multiple coastlines at different dates. This allows for the smoothing of extreme variations and provides a more stable trend. The LRR calculation follows a regression line (equation 2):

$$y = mx + b \quad (2)$$

Where:

y - is the position of the coastline along the transect;

x - is time (years);

m - is the slope of the line (representing the rate of variation over time);

b - is the regression intercept.

The DSAS also calculates uncertainties in the measurements, taking into account positioning errors of the coastlines and data variability by calculating the minimum, maximum, mean, and standard deviation for each transect. The predefinition of the transects can be chosen according to the need, maintaining the same distance across the selected area. The automated system has been evolving and demonstrating significant consistency in its analyses; more information can be obtained through Almeida *et al*. (2021).

For this analysis, a cartographic survey was conducted using the database from Landsat 5, 6, 7, and 8 satellites within the Cassie system to analyze the time series of coastline positions over the years. Images from the years 1985, 1995, 2005, 2015, and 2022 were used to complete the chronology for analyzing coastline variation. From this system, 10 images (2 for each year) of satellite data with up to 2.5% cloud cover were selected, considering possible periods without detection of meteorological tide, configuring the processing in transects spaced 100 m apart, with threshold number 0 and a length of 800 m for each transect (Almeida *et al*. 2021).

3. RESULTS

Points P01 and P02 exhibited no or very mild erosion symptoms, with these beaches showing greater stability in their profiles and wider sand strips. At P02, the vegetation line of the coastal vegetation can be observed to be well stabilized. In contrast, point P03 showed extreme coastal erosion, with sections lacking a sand strip and many containment structures, as well as pavements and residences being directly affected. At point P04, the two beaches are characterized by arcs defined by rocky points. Erosion occurs on these two beaches but is less severe compared to point P03. At P05, the intensity of erosion decreases, demonstrating various points with stability and/or accretion, along with the presence of stabilized coastal vegetation. Only in some areas were rock armoring strips found near the houses. At P06, an advanced stage of coastal erosion is noted, with significant direct impact on residences and pavements, along with the presence of rock armoring as a containment measure, with armoring heights of about 2.5 m. Furthermore, ruptures are occurring in some areas, forming small pocket beaches. Subsequently, points P07 and P08 are under greater stability along their entire length. Some areas in P07 show the presence of rock armoring and debris, with evident scarps (steps) in their profile caused by erosion. Lastly, P09, which is characterized by the direct action of Babitonga Bay, has a stable profile, although some areas have little sand strip; however, it is a location with lower hydrodynamic force and is only more sensitive to seasonal changes, such as tides. The points can be visualized in Figure 2.

The general characterization of each type of beach can be observed in Table II. The beaches are generally composed of fine sand, commonly found in sandy beaches, and are mostly reflective or mixed with high energy, with one dissipative profile beach having less energy.

According to Table III, the scores obtained at each designated point and their respective calculations can be observed, and with the final sums, the erosional pattern of each point can be determined. From this analysis, 2 points of stability (P01 and P04), 4 points with erosion (P02, P05, P07, and P08), and 3 points with severe erosion (P03, P06, and P09) were identified. In the points that exhibited severe erosion, the erosion is in an advanced state (except for point P09), with the presence of many rock armoring structures as a containment measure to prevent damage to the surrounding houses. In the points that resulted in erosion, erosion can be observed in specific sections. Meanwhile, the points that showed stability exhibit slight stability, with very few well-established dunes present.



Figure 2. Images of the Points from Itapoá beaches, SC, Brazil. A - Point 01; B - Point 02; C - Point 03; D - Point 04; E - Point 05; F - Point 06; G and H - Point 07; I - Point 08; J - Point 09.

Table II - Division and characterization of the beaches in Itapoá-SC, Brazil.

POINT	LOCATION	DESCRIPTION
P01	Barra do Saí	Mixed/Intermediate Profile (Masselink & Short 1993) Free/Open Beach (Gallop *et al*. 2020) Influence of the mouths of the Saí-Guaçu and Saí-Mirim rivers Oceanic or open sea beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson 2013; Short 1980; Wright & Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P02	Central	Reflective Profile (Masselink & Short 1993) Free/Open Beach (Gallop *et al*. 2020) Alignment in beach topography Oceanic or open sea beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson 2013; Short 1980; Wright & Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P03	Itapema of the North	Reflective Profile (Masselink & Short 1993)) Enseada Beach (Gallop *et al*., 2020) Beach with the presence of 1 rocky outcrop Oceanic or open sea beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson 2013; Short 1980; Wright & Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)

Table II - Division and characterization of the beaches in Itapoá-SC, Brazil.

POINT	LOCATION	DESCRIPTION
P04	First Stone and Second Stone	Mixed/Intermediate Profile (Masselink & Short 1993) Pocket Beach or Enseada - (Gallop *et al*. 2020) Beach with a beach arc (2 rocky outcrops) Oceanic or open sea beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson, 2013; Short 1980; Wright & Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P05	Municipality	Reflective Profile (Masselink & Short 1993)) Enseada Beach (Gallop *et al*. 2020) Beach has the presence of a rocky outcrop Oceanic or open sea beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson 2013; Short 1980; Wright & Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P06	Firefighters	Reflective Profile (Masselink & Short 1993)) Free/Open Beach (Gallop *et al*. 2020) Alignment in beach topography Mouth beach (Angulo & Souza 2002) Dominated by waves (Short & Jackson 2013; Short 1980; Wright &Short 1984) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P07	Uirapuru	Reflective Profile (Masselink & Short 1993)) Free/Open Beach (Gallop *et al*. 2020) Alignment in beach topography Dominated by waves (Short & Jackson 2013; Short 1980) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P08	North Pontal	Mixed to Dissipative Profile (Short & Jackson 2013) Bay Beach (Gallop *et al*. 2020) Beach with direct influence from the estuarine mouth (Babitonga Bay) Mouth beach (Angulo & Souza 2002) Modified by tides (Short & Jackson 2013; Short 2006) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)
P09	Pontal	Dissipative Profile (Short & Jackson 2013) Bay Beach (sheltered) (Gallop *et al*. 2020) Sheltered beach with direct influence from the estuarine mouth (Babitonga Bay). Estuarine beach (Angulo & Souza 2002) Dominated by tides (Short & Jackson 2013; Short 2006) Granulometry: Fine Sand (Post-Beach; Beach Face; Medium Beach) (Porpilho 2012)

3.1 Evolution of Coastal Vulnerability

According to the DSAS analysis of the beaches of Itapoá based on satellite images (Figure 3), the rate of change over the period from 1985 to 2022 was observed for all 284 transects obtained in the analysis (Figure 4). The results of the transects along the coastline of Itapoá demonstrated patterns very similar to the characterization of the beach profile. The results showed that the most intense erosional states are located at points P03, P06, P07, and P08. Stable profiles and/or those exhibiting accretion were observed at points P01 and P02. Points P05 and P09 showed stability throughout their profiles.

Point P01, with 43 transects, showed stability in 26 locations and an accretion section in 16 locations throughout the entire

Table III. Result of the characterization of the erosional state of the 9 beach points from Itapoá beaches, SC, Brazil.

INDICATOR	1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	SUM	Erosional State Result
WEIGHT	2	2	2	4	2	2	1	1	1	2	2	-2	-2	-2		
Location/Points	indicators of severe erosion						indicators of erosion					stability				
P 01								1				-2	-2	-2	–5	Stability
P 02							1	1					-2	-2	-2	Erosion
P 03	2	2	2	4							2	-2			10	Severe Erosion
P 04													-2		-2	Stability
P 05								1			2				3	Erosion
P 06	2	2	2	4							2				12	Severe Erosion
P 07		2				2			1		2	-2	-2		3	Erosion
P 08		2					1		1	2	2	-2	-2		4	Erosion
P 09		2	2			2			1	2	2				11	Severe Erosion

Source: Adapted from Perinotto et al. (2012).

stretch, varying only at the mouth of the Saí Mirim River. At point P02, 42 transects were identified, demonstrating stable locations; however, it recorded minor negative values, indicating sediment loss in this area. Nevertheless, since the analysis focuses on the rate of change, even with sediment departures, these departures indicate small changes or seasonal variations over the period. Point P03 was characterized by larger negative variation rates, representing a point with 20 transects, of which 11 locations identified critical erosion, 7 locations of erosion, and 2 locations demonstrated stability. Point P04 was characterized by 12 transects, of which 8 were stable, 3 showed accretion, and 1 location indicated critical erosion, representing outlier areas. Point P05 was determined by 27 transects, of which 26 locations were stable and 1 location showed accretion. Point P06 is represented by 42 transects, which represents the point with the most variation in erosion stages, with 9 stable locations, 1 location in accretion, 26 locations in an erosional state, and 6 locations in a critical erosional state. Point P07 was identified as the point with the most erosion stretch among the 37 transects, with 22 locations in critical erosion, 9 in an erosional state, and 6 stable locations. Point P08 has 18 transects, with 3 stable locations, 2 locations in erosion, and 13 locations in critical erosion. Point P09 comprised 43 transects, with 40 locations in a stable state and 3 locations in accretion.

Table IV shows the representation of the minimum, maximum, mean, and standard deviation of the annual variation rates for each point between the years 1985 and 2022. The negative numbers in the minimum, maximum, and mean may indicate sand loss over the years, while the positive numbers may represent stability and/or sand gain over the years. The averages across each point demonstrated that points P01 and P09 (Figure 5) experienced accretion over the years, yielding high variation rates. Point P02 and P05 showed stability; despite the mean being negative, the variation rate was small over the years, unlike point P04, which exhibited stability but had a positive mean. Points P03, P06, P07 (Figure 5), and P08 demonstrated erosion with high sediment loss rates over the years. The greatest variation among the points over the years, according to the standard deviation of the transects, was observed at P01 (accretion), P03 (erosion), and P08 (erosion), with variation rates exceeding 1000 m/year. In order to contribute to coastal management in Itapoá, SC, Brazil, the results have been simplified into a thematic conceptual map regarding vulnerability in the region (Figure 6).

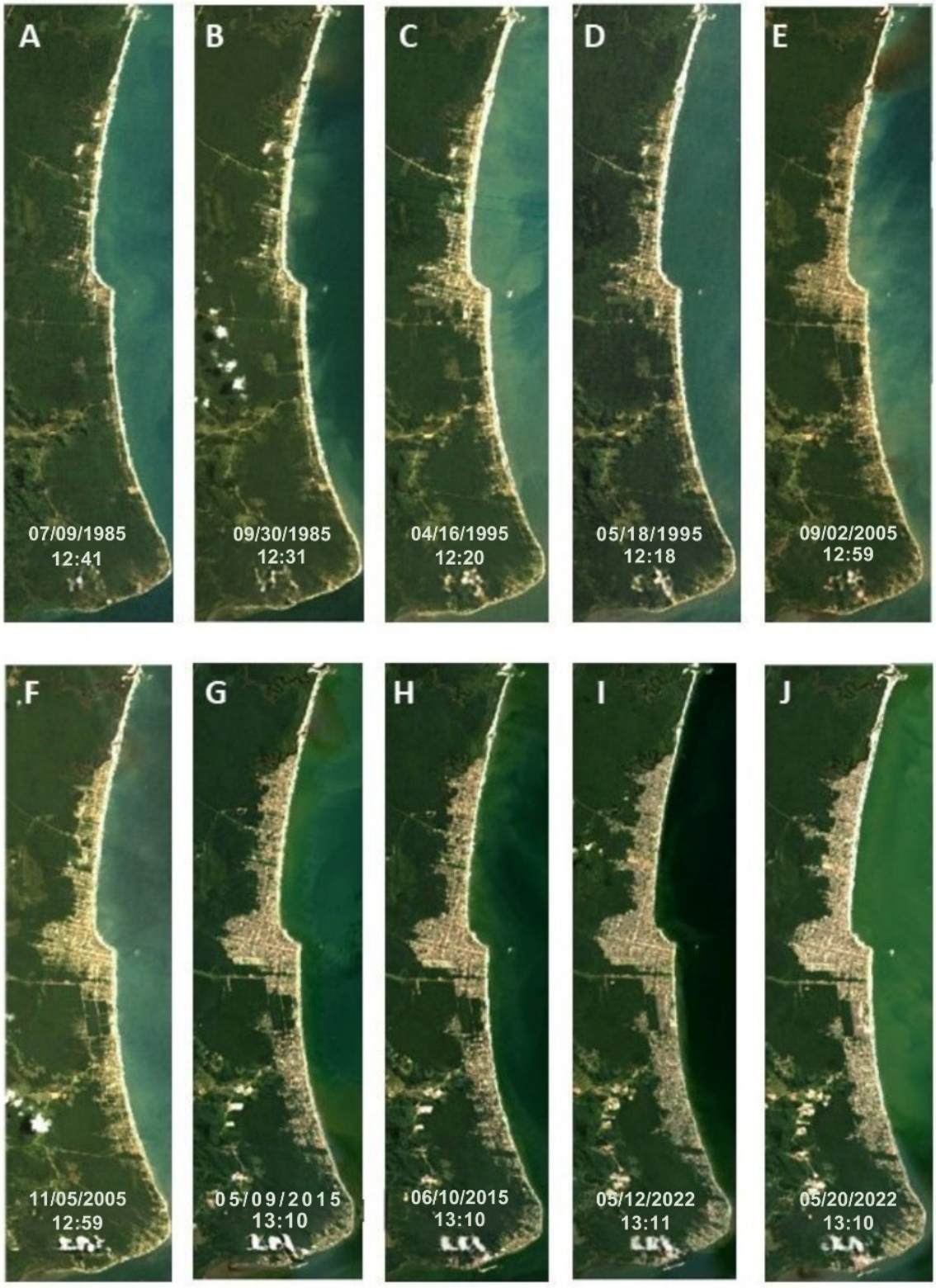


Figure 3. Satellite images used in the automated processing of the DSAS analysis from Itapoá beaches, SC, Brazil. Source: The author (2023).

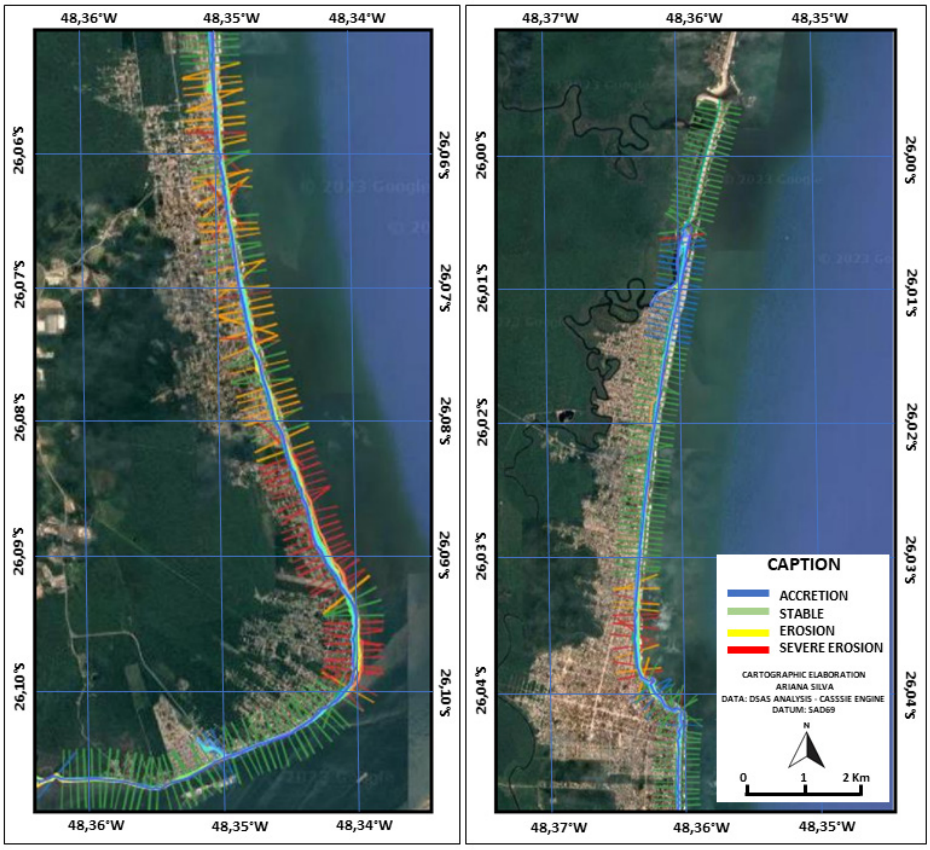


Figure 4. Image of the 284 transects obtained in the DSAS analysis from Itapoá beaches, SC, Brazil. Source: The author (2023).

Table IV. Minimum, maximum, and true averages of the variation rates for each point in meters from Itapoá beaches, SC, Brazil.

RESULT OF THE ALTERATION RATE - LRR					
POINT	NUMBER OF TRANSECTS	MINIMUM	MAXIMUM	AVARAGE	SD
P01	43	-0.0954	6.264	698.40	1567.10
P02	42	-0.0015	0.4702	-0.1000	0.2353
P03	20	-7,2010	0.0000	-1,075.00	1641.80
P04	12	-0.0991	0.9524	0.21515	0.4066
P05	27	-0.0999	0.5601	-0.10361	0.2200
P06	42	-1,571	0.9946	-179.33	451.60
P07	37	-2.710	-0.1130	-1099.02	992.90
P08	18	-3.060	-0.0581	-1480.05	1119.80
P09	43	-0.0084	4.680	108.78	713.60
9 points	**284 transects**		Result of the LRR in m/year		

Note: Mouth locations were disregarded.

Note: possible outliers were removed from the analysis so that the alteration rates could be compared with erosion rather than with other seasonal environmental processes.

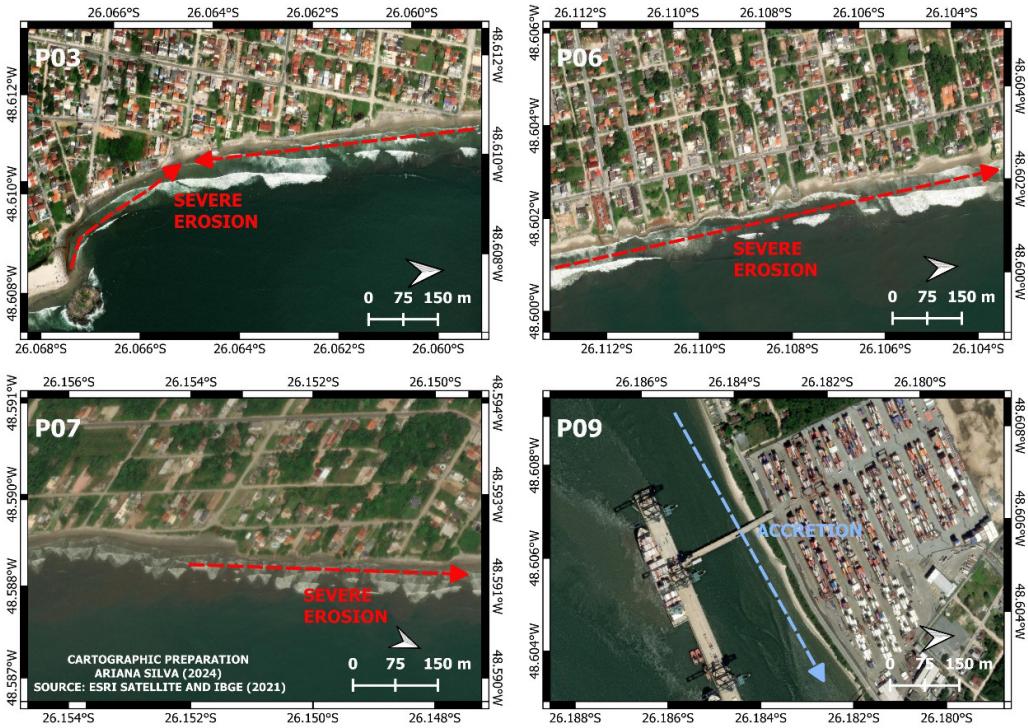


Figure 5. Erosion at points P03, P06, P07, and accretion at point P09. Evident severe erosion at these points and accretion found at P09 in the port area. Source: The author (2023).

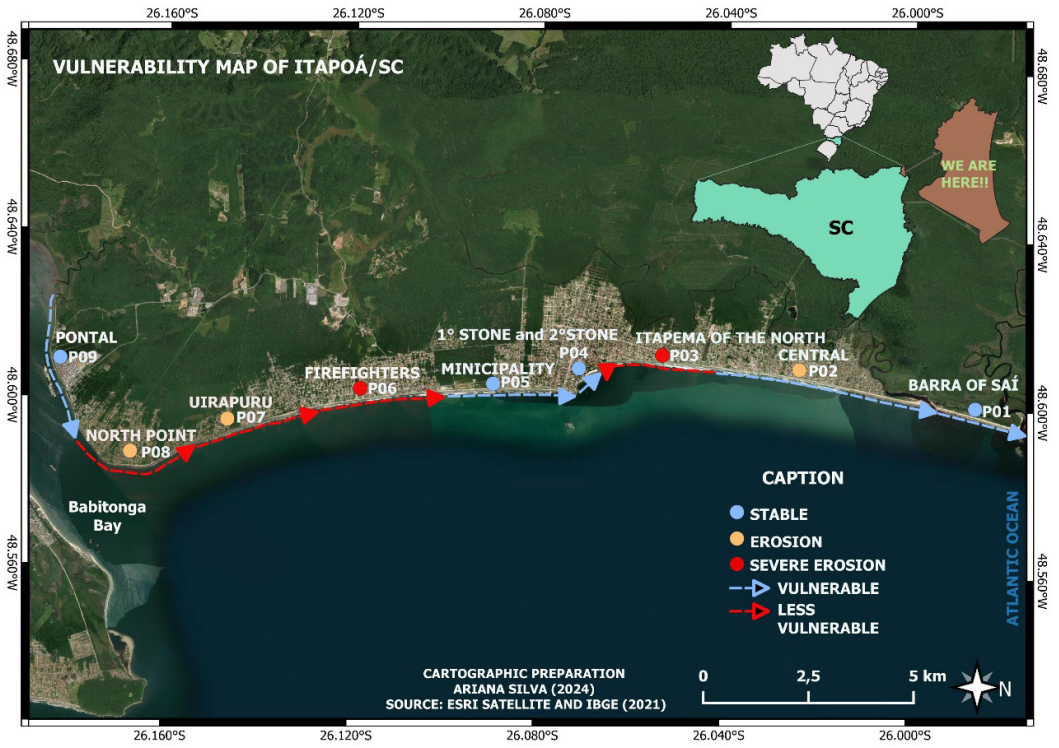


Figure 6. Conceptual Thematic Map of Coastal Vulnerability Based on the Results. Source: The authors (2023).

4. DISCUSSION

In comparison to the results of the topographic profiles conducted by the Municipality of Itapoá in 2020 and 2021 (Municipality of Itapoá 2022), it was observed that the characterization carried out using the Coastal Vulnerability Index (CVI) and represented by the Erosional State Result, yielded similar results to those observed in situ. This is an extremely satisfying finding, as it indicates that the methodologies employed were effective in assessing the coastal vulnerability of the studied region.

Points P01, P03, P04, and P06 demonstrate the same sedimentary patterns, both over the decades and in their current state. Specifically, P01 and P04 have remained stable over the years, with some areas experiencing accretion. At P01, certain transects resulted in very high rates of accretion, which can be attributed to the influence of the mouths of the Rio Saí-Guaçu and Rio Saí-Mirim. Depending on seasonal variations, the position of the river mouth may change, directly influencing the analyses. Nevertheless, the region remains stable.

According to Castelle & Masselink (2022), sandy beaches tend to maintain their equilibrium and persist over time, remaining in the same location for extended periods. This allows these beaches to be considered as systems that oscillate around an underlying static equilibrium state in the short to medium term (from days to years), enabling a better understanding of the equilibrium environment, as highlighted by Hunt *et al*. (2023). The assertion that sandy beaches often maintain their equilibrium and persist over time does not imply that all beaches are immutable.

In contrast, P03 and P06 have consistently shown patterns of severe erosion over the years, which continue to be evident today. On the other hand, points P02, P05, P07, P08, and P09 exhibit different patterns compared to their current state. At P02 and P05, signs of erosion can be observed in various areas. However, despite the ongoing erosion, analyses over the years indicate that there has been no significant progression of this process. At points P07 and P08, the Vulnerability Index analysis revealed erosion in many locations, but the DSAS analysis indicated critical erosion states over the years. This means these points have been experiencing erosion for an extended period. Currently, erosion is not as severe in most areas; however, some locations at point P07 are experiencing severe erosion, particularly near P06.

According to Cowell & Thom (1994), the evolution of coastal forms is inherently nonlinear and time-dependent, resulting from the combined effects of morphodynamic feedback and the introduction of uncertainties into the system (Markovian behavior). Thus, the details of coastal evolution are unpredictable, unrepeatable, and irreversible. In this sense, this complex geomorphological system develops its landform features influenced by both natural and anthropogenic forcing (Van Maanen *et al*. 2016). This is confirmed by the results of the DSAS analysis, which indicates that there have been significant sediment losses over the years (greater in points of severe erosion), and that sediments in Itapoá are indeed being trapped out of the system.

Point P08, specifically, has shown the greatest significant loss of sediments over the years, but it does not currently exhibit severe erosion. This is due to fewer constructions and more vegetation, resulting in a larger spreading zone in this area. Another important aspect of P08 is its location at the “pontal” (point) of the mouth of the Bay of Babitonga, where it is strongly influenced by the flooding and flow of the bay. Therefore, this considerable variation in erosive patterns over the years is a natural characteristic of the environment. Point P09 has shown patterns of severe erosion in the current analysis; however, it has remained stable over the years and appears visually stable today. P09 represents a beach directly related to the action of the bay, characterized by very calm hydrodynamics. Thus, despite exhibiting severe erosion in the Vulnerability Index, the DSAS analysis indicates that the beach has remained stable over the years.

According to Gobbi (1997), the waves in the northern coastal region of Santa Catarina primarily act in the ENE and SSE/SE directions, and it is observed that winds parallel to the coast are the main driving force behind meteorological tides (Melo Filho 2017). Therefore, sediment exchanges tend to move from south to north, with some periods of movement from north to south; however, the predominance is towards the north (in most seasons of the year). This trend is evident in the results from points P01, P02, P04, and P05, which are more stable because they are located further north and, in conjunction with the geology of the beaches, exhibit a greater depositional tendency than erosion, allowing for a balance in sediment supply during seasonal events.

Regarding geology, point P05 is located near point P04, where a “step” forms in the linearity of the beach. P05 is considered to have a stable depositional pattern due to its geological location and arrangement along the beach. P04 refers to two arched beaches formed by rocky headlands. Arched or embayed (cove)

beaches exhibit distinct depositional and morphodynamic behavior due to the oblique and spatially variable incidence of waves along their shoreline. This non-linear wave approach is primarily controlled by patterns of wave refraction and diffraction around rocky headlands, which redistribute wave energy and sediment transport within the embayment. As a result, sediment accumulation and erosion patterns are strongly influenced by the geometric configuration of coastal promontories and the associated gradients in longshore sediment transport (Short & Masselink 2021; Harley *et al*. 2022; Castelle *et al*. 2021).

Recent studies emphasize that headland-bay systems tend toward equilibrium shoreline configurations governed by wave climate, sediment availability, and coastal boundary conditions, with morphodynamic adjustments occurring under changing storm regimes and sea-level rise (Splinter *et al*. 2020; Toimil *et al*. 2020).

From P03 (Figure 5), one can understand a natural tendency pattern of the environment, as the coastline exhibits a "step" concerning the direction of the continental drift. This occurs mainly due to the local geology, where interference caused by two rocky headlands (referred to as the 1st and 2nd stones) leads to a pattern of sediment deposition upstream of the flow (related to P05) and a tendency for erosion downstream of the flow (related to P03). Clearly, this pattern could be minimized with a robust sediment supply. Therefore, when a coastal system experiences limited sediment supply or a persistent sediment deficit, geological controls become the primary determinants of shoreline evolution, interacting with local hydrodynamic forcing. Under such conditions, lithological framework, headland configuration, and antecedent morphology exert stronger influence on sediment distribution and beach stability, particularly where longshore transport gradients and wave energy variability constrain natural replenishment processes (Vitousek *et al*. 2023; Castelle *et al*. 2021; IPCC 2022). Consequently, shoreline response becomes increasingly dependent on the inherited geological setting combined with site-specific wave climate and sediment transport dynamics. Furthermore, the beaches of Itapoá tend to have extensive backshore and post-beach zones, with their origins associated with the presence of coastal vegetation, which are natural forms of beach protection. If these beaches were uninhabited, with no nearby constructions and still maintained the protection of the coastal vegetation, the tendency would be that erosion would not occur at the most affected points, as the sediments would tend to remain more trapped along the coast (Zasso *et al*. 2013). It is also noted that points such as P01, P02, and various locations of P05 have poorly developed vegetation along the coast, as these points also exhibit greater stability in their profiles. The degradation or removal of coastal vegetation for urban expansion, infrastructure development, or tourism-related activities can significantly intensify coastal erosion processes. Coastal vegetation—such as dune grasses, mangroves, and other shoreline plant communities—acts as a primary natural defense by stabilizing sediments, attenuating wave energy, and reducing storm surge impacts. The loss of these biophysical buffers compromises sediment retention capacity and increases shoreline vulnerability to erosion and coastal flooding, particularly under conditions of rising sea levels and more frequent extreme events (Temmerman *et al*. 2023; Menéndez *et al*. 2020; IPCC 2022).

At the mouth of Babitonga Bay, there is the formation of an ebb-tidal delta, commonly found on the front lobe of the delta, which results in shallower waters and causes breaking waves, facilitating sediment transport (Ângulo & Souza 2002). Therefore, in the estuarine beaches, even though there is erosion and a narrow beach profile, point P09 remains relatively stable along most of its beach profile, while points P08 and P07, despite experiencing sand loss, still have sediment supply close to the profile. This delta formed by sedimentation results in sediment supply for the balance of these points, creating greater sediment equilibrium through the exchange and refuge of sediments. However, due to the relatively close location of the dredged channel, it may be influencing the refuge of sediments, even when there is an ebb-tidal delta forming very close by or because the weak hydrodynamics are not capable of directing sediment to the beach (Siemes *et al*. 2025).

Another important characteristic refers to some locations in P09 near the ship platform of the Port of Itapoá, where signs of accretion have been observed in nearby areas that function as a form of sediment containment (Figure 5).

Recent studies indicate that the presence of deep tidal channels—whether naturally occurring or maintained through recurrent dredging—can significantly alter sediment budgets in adjacent coastal systems. Channel deepening enhances sediment trapping efficiency and promotes offshore export of material transported by longshore drift, often resulting in sediment deficits along nearby beaches. Numerical and field-based investigations have demonstrated that dredging activities in estuarine inlets modify hydrodynamic circulation, increase ebb-dominant conditions, and shift sediment deposition toward offshore or channel-confined sinks, limiting sediment

return to the littoral system (Van Maren *et al*. 2022; Luan *et al*. 2023). Persistent maintenance dredging, common in port-access channels, may therefore contribute to long-term negative sediment trends, influencing shoreline stability and dune development. In some sectors, partial sediment retention within incipient dune systems suggests localized storage; however, when offshore trapping dominates, the overall system reflects a morphodynamic adjustment driven by both anthropogenic interventions and natural hydrosedimentary processes (Jiang *et al*. 2021).An

On the beach of Itapoá, since 1996 (or even earlier), there has been a presence of structures made from various materials to block the advancement of erosion. However, according to Van Maren *et al*. (2022), these structures are very harmful to the environment and to the erosion processes themselves; when sediments of higher hardness or larger grain sizes are placed, the tendency is to increase the sediment deficit in the region and provoke intense erosion in adjacent areas. According to Schmidt *et al*. (2012), the northern coast of Santa Catarina is responsible for 11.4% of all coastal dam works in Brazil aimed at containing coastal erosion. Additionally, it has intensified the influence of river mouths (dredging of the ports of São Francisco do Sul and Itapoá) and the anthropogenic occupation of the coastline as the main causes of advancing erosion in the Itapoá region.

The lack of sediment in the region and meteorological forces disrupt the cyclical feedback system, causing erosion that becomes evident each year as coastal erosion evolves in the area (Vitousek *et al*. 2023). Not only dredging in the region but also extensive urban occupation very close to or within the beach profile has been the main problem faced by the city of Itapoá. Considering the new climate data and sea-level rise projections, specifically, the city of Itapoá/SC must take immediate containment and/or relocation measures for residences in points P03, P06, and P07 (Figure 5) within the next 30 years. The results from the IPCC (2021) and WMO (2022) report projections indicate a relative sea-level rise of 0.13 to 0.50 cm/year by 2100, demonstrating the importance of monitoring updated meteorological information and being prepared to face potential risk situations arising from adverse weather conditions.

FINAL CONSIDERATIONS

Coastal erosion along the beaches of Itapoá (SC) results from the interaction of natural dynamics and anthropogenic pressures. Regional hydrodynamic processes, combined with frequent storm events affecting southern Brazil, play a central role in shoreline variability. Dredging operations may also contribute to sediment deficits by redistributing material offshore, while long-established rocky revetments can intensify local erosive patterns by altering sediment transport pathways.

Three sites (P03, P06, and P07) exhibit severe erosion, and three additional points (P02, P05, and P08) show clear erosive trends, highlighting the need for targeted coastal management strategies. Only P01 and P09 present relatively stable conditions. At P01, native vegetation, setback constructions, and fluvial sediment inputs contribute to a more favorable sediment balance, reinforced by longshore drift deposition. In contrast, P02 lacks vegetation and has buildings closer to the shoreline, showing emerging instability despite an overall stable pattern.

Point P03 experiences intense erosion due to its downdrift position relative to longshore currents, while P04, characterized by an arc-shaped and geologically controlled profile, remains relatively stable. P05 maintains a near-equilibrium condition but shows localized erosion and sparse vegetation. Linear beaches at P06 and P07, where constructions are located close to the shoreline, exhibit pronounced sediment loss and limited dry sand areas. Although P07 and P08 show advanced erosive patterns, sediment strips persist in some sectors due to weaker, more estuarine hydrodynamics influenced by the Babitonga Bay. P09, also estuarine, remains stable despite a narrow profile.

While erosion is a natural coastal process, unplanned occupation and vegetation removal increase vulnerability to storm impacts. Integrated and sustainable coastal management is therefore essential. Future studies should prioritize detailed transect monitoring at the most critical sites to better understand hydrodynamic responses and sediment feedback mechanisms.

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