Publication status: This preprint has not been published elsewhere.

MULTICRITERIA ANALYSIS OF VULNERABILITY TO COASTAL EROSION IN THE ATLANTIC COAST OF PARAENSE, EASTERN AMAZON

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https://doi.org/10.1590/SciELOPreprints.15853

Submitted on: 2026-04-16
Posted on: 2026-04-17 (version 1)
(YYYY-MM-DD)

MULTICRITERIA ANALYSIS OF VULNERABILITY TO COASTAL EROSION IN THE ATLANTIC COAST OF PARAENSE, EASTERN AMAZON

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ABSTRACT

Coastal erosion has emerged as a critical environmental challenge for coastal societies worldwide, particularly under accelerating climate change and sea-level rise. These processes intensify shoreline retreat, increasing pressure on coastal ecosystems, infrastructure, and local economies. This study evaluates coastal erosion vulnerability along the beaches of Bora, Crispim, and Marudá, located in the northern sector of the municipality of Marapanim, northeastern Pará State, Brazil. A multi-criteria decision-making framework based on the Analytic Hierarchy Process (AHP) was applied to integrate seven key physical variables: shoreline change, geomorphology, soil types, proximity to the CL, coastal vegetation, elevation, and slope. The criteria were selected according to data availability and their relevance for coastal vulnerability assessment. Spatial modeling results reveal a clear concentration of high vulnerability zones, covering approximately 0.4 km² (11%) of the study area, predominantly located along Marudá and Crispim beaches. Moderate vulnerability occupies 2.1 km² (57%), while low vulnerability corresponds to 1.2 km² (32%). These findings provide critical scientific support for coastal risk mitigation, territorial planning, and the development of adaptive coastal management strategies.

Keywords: Eastern Amazon; Coastal Vulnerability; GIS; AHP Method, Remote Sensing.

INTRODUCTION

Global coastal erosion is an alarming issue for societies residing in these zones (Fogarin et al., 2023; Queiroz et al., 2022; Toure et al., 2019). Thus, coastal erosion has become an immediate concern due to the large population that utilizes this area through urban activities, industrial endeavors, transport networks, and tourism, which serves as a population attractor (Barragán; De Andrés, 2015). Rapid climate change and rising sea levels can accelerate coastal erosion in this region. Consequently, the increase in coastal erosion can severely damage coastal environments, hinder commercial activities, and disrupt the tourism sectors.

Over the past decades, coastal erosion has increased in magnitude along many shorelines worldwide. Nearly 30% of homes located within 200 m of low-lying coasts may be significantly affected by erosion processes (UN-HABITAT, 2010). In this context, coastal erosion directly affects human well-being and local economies, particularly in regions experiencing rapid urban expansion.

In Brazil, the intensification of urbanization and the increasing frequency of extreme climatic events contribute to rising socio-environmental vulnerability in coastal areas (Iwama et al., 2014; Lins-de-Barros, 2017). The Brazilian Amazon contains an extensive coastline (CL) (~3,044 km), representing approximately 35% of the national CL (Braga et al., 2019; MMA, 2018), This region includes diverse coastal ecosystems with distinct levels of vulnerability influenced by both anthropogenic pressures and physical coastal dynamics (Braga; Pimentel, 2019; Negrão et al., 2022).

Mapping coastal erosion vulnerability is therefore an important tool for supporting mitigation strategies and coastal management planning (Liu et al., 2022). Geospatial techniques, particularly remote sensing and spatial analysis, enable the efficient identification and evaluation of vulnerable coastal sectors (Ahmed et al., 2021; Menezes et al., 2018). Within this context, multicriteria approaches have become widely applied to integrate different environmental variables in coastal vulnerability assessments.

The weighting and ranking become substantial in this spatial assessment, where it can incorporate and evaluate multiple criteria from the perspective of erosive vulnerability (Menezes et al., 2018; Stathopoulos et al., 2017). The Analytic Hierarchy Process (AHP) is a tool efficient in integrating multiple criteria for a spatial decision-making process (Malczewski, 2006, 2010). AHP uses a hierarchical structure to assign weighting and ranking, incorporating the opinions of experts and users (Ahmed et al., 2021).

The focus on evaluating coastal vulnerability based on multi-criteria analysis has been highlighted in recent years (Ahmed et al., 2021; Hoque, Muhammad Al Amin et al., 2019; Thakare; Shitole, 2021). In Brazil, several manuscripts have addressed this theme (De Paula; De Souza, 2011; Lins-de-Barros et al., 2019; Paula; Silva, 2023; Queiroz et al., 2022). In the Brazilian Amazon, the use of multi-criteria-based methods has been applied in assessments for the creation of an environmental impact potential index (Progênio et al., 2021), in addition to some studies aiming to determine the Coastal Vulnerability Index in response to sea-level rise (Braga et al., 2019). Despite their scientific relevance, these studies present some gaps regarding processes related to coastal erosion, especially using the AHP method in the Amazon region of Pará, to evaluate potential vulnerability indices.

Thus, this study aims to analyze the vulnerability to coastal erosion at the Bora, Crispim, and Marudá beaches, in the northern part of the Marapanim municipality, northeastern Pará State (Brazil). This area was chosen due to its significant tourist importance and its location within the Marine Extractive Reserve (RESEX) Mestre Lucindo, with the intent of supporting measures to mitigate the impacts of coastal erosion.

Thus, irregular occupation of the beach environment and the construction of residential and commercial buildings in mangrove areas (recurring problems), have contributed to vulnerability to coastal erosion classified as moderate to high, especially on Crispim and Marudá beaches, whereas Bora Beach is less anthropized and presents moderate vulnerability (Santos et al., 2023). Although erosion and accretion are natural processes, particularly in coastal environments, factors such as urban expansion and population growth intensify these processes.

The specific objectives of this study include: (1) to develop indices of physical vulnerability from the impacts of coastal erosion using a multi-criteria decision-making approach based on AHP; (2) to produce a vulnerability index that integrates physical criteria to examine the spatial pattern of vulnerability from the impacts of coastal erosion, and finally, (3) to weigh the spatialized results within the scope of coastal vulnerability in the northern coastal portion of the Marapanim Municipality.

STUDY AREA

The research focused on the region that includes the coastal zone of the northeastern coast of the State of Pará, specifically the coastal zone of the Marapanim municipality. The main beaches are Crispim, Marudá, and Bora, which are the focus of this manuscript (Figure 1).

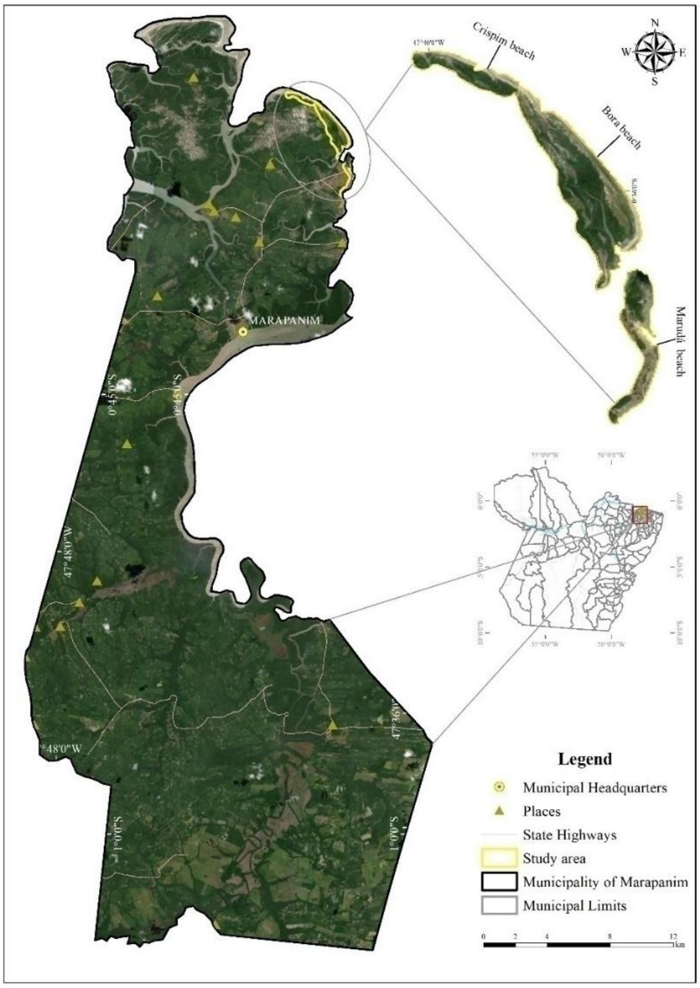

Figure 1 - Location of the study area, Crispim, Bora, and Marudá beaches, Marapanim Municipality, Pará. Source: Authors.

The study area is influenced by a semidiurnal macrotidal regime (above 5m) (Berrêdo et al., 2008) and contain mangrove environments that are affected by both fluvial and oceanic influences, as well as tidal currents (Baía et al., 2021). This geographic area consists of a coastal, estuarine, and alluvial plain; undergoing a process of transformations in the occupation scenario, stemming from urban expansion and ventures arriving in the region (Silva, 2009). Temperatures remain constant throughout the year, with an annual average around 27.7°C (INMET, 2020). The relative humidity ranges between 80-85% (annual average), which is associated with the annual rainfall amount (Martorano, 2020).

MATERIALS AND METHODS

The methodological procedure used to assess the vulnerability to coastal erosion in the beaches of Crispim, Marudá, and Bora was the multi-criteria evaluation through AHP and geoprocessing techniques. The flow of the methodological procedures can be observed in Figure 2.

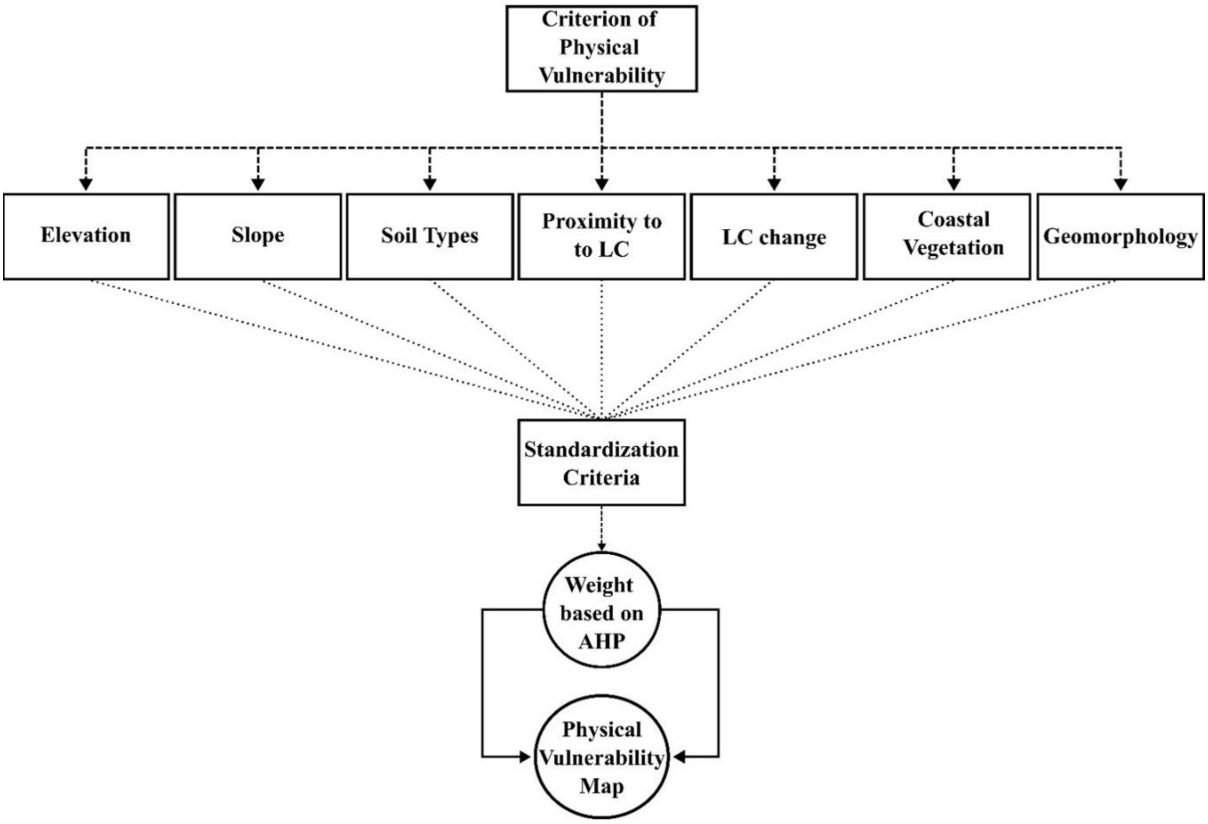

Figure 2 - Flowchart used to assess coastal erosion vulnerability in this study. Source: Authors.

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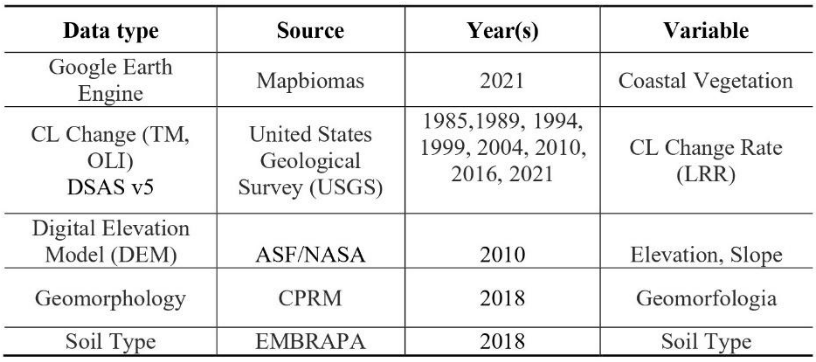
DIVISION OF THE STUDY AREA

Due to the dynamic complexity of the study area and for a better understanding of the results, it was chosen to divide this area into six distinct sectors, namely: Crispim Beach sectors I and II; Bora Beach, sectors III and IV; and finally, Marudá corresponding to sectors V and VI. All these sectors are highlighted in Figure 3.

Figure 3 - Sectorization map of the study area. Source: Authors.

DATA SET AND SOURCES

Data were selected that influence vulnerability to coastal erosion in the study area. Thus, the data used in this compilation were gathered from various sources, considering the existing literature, the availability of data (vector and raster) (Table 1), and, finally, a field survey. The field survey primarily served to evaluate the results of the desktop processing and to investigate areas affected by coastal erosion, as well as to assess the prediction and success rates of the generated data. In this way, three field campaigns were carried out (22/10/2024 to 24/10/2024), one at each beach in the study area.



Data type	Source	Year(s)	Variable
Google Earth Engine	Mapbiomas	2021	Coastal Vegetation
CL Change (TM, OLI) DSAS v5	United States Geological Survey (USGS)	1985,1989, 1994, 1999, 2004, 2010, 2016, 2021	CL Change Rate (LRR)
Digital Elevation Model (DEM)	ASF/NASA	2010	Elevation, Slope
Geomorphology	CPRM	2018	Geomorfologia
Soil Type	EMBRAPA	2018	Soil Type

Table 1 - Types of data and sources used for coastal erosion assessment. Organization: Authors.

VULNERABILITY ASSESSMENT CRITERIA, ALTERNATIVES, AND MAPPING

Geoprocessing and remote sensing techniques were employed to generate the geospatial layers pertaining to the selected criteria, using ENVI 5.4 and ArcGIS 10.8 software. The cell size of each spatial raster layer was 12.5 m × 12.5 m. This composition utilized natural break statistical methods to classify the products produced and to present the spatial pattern of vulnerability to erosion (Ahmed et al., 2021; Hoque, Muhammad Al-Amin et al., 2018) (Table 2).

Criteria	Creation Method	Rationale for Coastal Erosion Vulnerability
CL Change	Digital Shoreline Analysis System (DSAS) no ArcGIS	Areas experiencing coastal retreat are more likely to continue being eroded in the future
Coastal Proximity	Euclidean distance from the CL	The distance from the coastal base provides greater protection against erosive risks
Geomorphology	Geomorphology classification in the study area	Geomorphology is of great importance, as the tabuleiros (terrace lands) will be less vulnerable compared to the coastal mangrove and rias areas
Soil Type	Soil classification in the study area	The soil texture includes the coastal mangrove and rias areas, which have medium resistance to coastal erosion, while the indiscriminate mangrove is mainly erodible
Coastal Vegetation	Raster calculation of coastal vegetation	Vegetation cover plays a significant role in mitigating coastal erosion
Elevation	Elevation = natural break classification of DEM values	Coastal erosion is constantly affected by variations in the elevation of the earth's surface
Slope	Slope percentage = rise/run × 100	One of the main contributors to assessing the physical vulnerability of coastal beaches to erosion. In steep slopes, there is a higher vulnerability to coastal erosion

Table 2 - Description of selected. Organization: Authors.

CRITERIA FOR VULNERABILITY MAPPING

The selected criteria were elevation, slope, geomorphology, soil texture, proximity to the CL, coastal vegetation, and changes in the CL. The Normalized Difference Water Index (NDWI) (Gao, 1996) was used because it provided more satisfactory results than other methods, and also offered a more refined technical content for detecting the CL from 8 Landsat images (Table 3) (Do et al., 2019). Where,

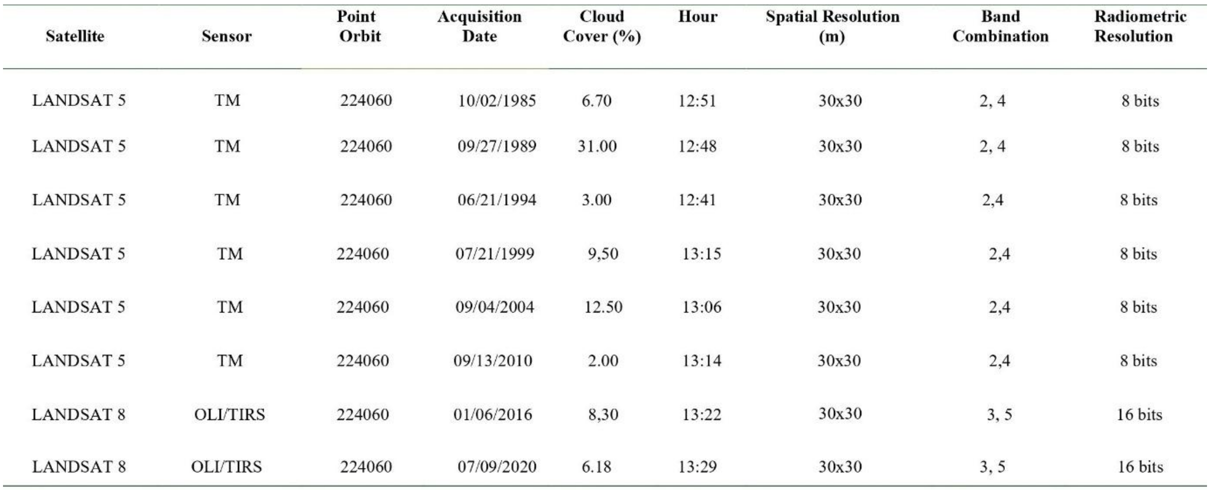
Equation 1 - Calculation of the Normalized Difference Water Index (NDWI)

$$NDVI = \frac{\rho NIR - \rho RED}{\rho NIR + \rho RED}$$

The rate of CL change (m/year) was calculated using the DSAS v5 plugin (Digital Shoreline Analysis System) of ArcMap 10.8 software, from 93 transects, which were divided for each beach in the study area. In this study, the Linear Regression Rate (LRR) method was used (Almonacid-Caballer et al., 2016). The LRR has as its main features: 1) all data are used, regardless of changes in trend or precision, 2) the method is purely computational, 3) the calculation is based on accepted statistical concepts, and 4) the method is easy to use (Honeycutt et al., 2001). The results of this processing and data compilation are found in table 4 and figure 4.

To generate the proximity to the CL, defined as the coast–water interface, the Euclidean Distance tool available in ArcGIS was used. This tool calculates the shortest straight-line (planar) distance from each cell (or location) in the analysis area to the nearest segment of the CL, producing a continuous distance raster that represents how close each area is to the CL.. Manual digitization on the screen of the ALOS/PALSAR mosaic images from 2010 was used to draw the CL using the Euclidean distance tool, thereby generating the distances in the onshore direction. (Ahmed et al., 2021).

The characteristics of the Geomorphology were developed from the database available at the Geological Service of Brazil (CPRM) with a scale of 1:250,000 (Lacerda et al., 2008). The vector dataset corresponding to soil texture was obtained from the Brazilian Agricultural Research Corporation (EMBRAPA) through its soil mapping website. For coastal vegetation, the Semi-Automatic Classification Plugin (SCP) was used, extracting the classification from Landsat 8 OLI images (CONGEDO, 2021). The slope was calculated using the Digital Elevation Model (DEM), and slope maps were generated from acquisitions at the Alaska Satellite Facility (ASF/NASA), using the Synthetic Aperture Radar (SAR) ALOS from the PALSAR sensor with a resolution of 12.5 m, corrected for radiometric terrain for each available polarization, where the pixel values are zero gamma power in 32-bit floating point format (Rosenqvist et al., 2007) (Figure 5)



Satellite	Sensor	Point Orbit	Acquisition Date	Cloud Cover (%)	Hour	Spatial Resolution (m)	Band Combination	Radiometric Resolution
LANDSAT 5	TM	224060	10/02/1985	6.70	12:51	30x30	2, 4	8 bits
LANDSAT 5	TM	224060	09/27/1989	31.00	12:48	30x30	2, 4	8 bits
LANDSAT 5	TM	224060	06/21/1994	3.00	12:41	30x30	2,4	8 bits
LANDSAT 5	TM	224060	07/21/1999	9,50	13:15	30x30	2,4	8 bits
LANDSAT 5	TM	224060	09/04/2004	12.50	13:06	30x30	2,4	8 bits
LANDSAT 5	TM	224060	09/13/2010	2.00	13:14	30x30	2,4	8 bits
LANDSAT 8	OLI/TIRS	224060	01/06/2016	8,30	13:22	30x30	3, 5	16 bits
LANDSAT 8	OLI/TIRS	224060	07/09/2020	6.18	13:29	30x30	3, 5	16 bits

Table 3 - Passive Sensors and Spatial Resolution. Organization: Authors.

Figure 4 - Expanded view of selected locations. Source: Authors.

	SECTORS	**CRISPIM**		**BORA**		**MARUDÁ**		**TOTAL**
		I	**II**	**III**	**IV**	**V**	**VI**	
ESTATÍSTICA DESCRITIVA	ID do Transect	1-11	12-25	26-39	40-61	1-12	13-32	93
	Total Number of Transects	11	14	14	22	12	20	
	CL Length (km)	1,2	1,4	1,5	2,4	1,4	2,1	10
	Total Number of Transects Where Erosion Was Recorded	0	9	0	0	0	7	16
	Total Number of Transects Where Accretion Was Recorded	11	5	14	22	12	13	77
	Total Number of Transects Where Statistical Uncertainty ($R^2 > 0.5$) Was Recorded	5	0	14	22	7	0	48
	Total Number of Transects Where Statistical Uncertainty ($R^2 < 0.5$) Was Recorded	6	14	0	0	5	20	45
	% of the Total Number of Transects Where Erosion Was Recorded	0	65	0	0	0	35	***
	% of the Total Number of Transects Where Accretion Was Recorded	100	35	100	100	100	65	
	% of the Total Number of Transects Where Statistical Uncertainty ($R^2 > 0.5$) Was Recorded	45	0	100	100	58	0	
	% of the Total Number of Transects Where Statistical Uncertainty ($R^2 < 0.5$) Was Recorded	55	100	0	0	42	100	
	Average CL Change (m/year)	4,11	-0.68	12,7	25,19	3,09	0,3	45,01
	Maximum Positive CL Change (m/year)	9,37	3,38	18,36	28,41	5,8	1,43	***
	Maximum Negative CL Change (m/year)	0	-2,56	0	0	0	-0,94	
	Average Accretion Rate (m/year)	4,11	1,4	12,7	25,19	3,09	0,72	47,21
	Average Accretion Rate (m/year)	0	-1,8	0	0	0	-0,47	-2,27

Table 4 - Calculated Summary of CL Change Rates. Source: Authors.

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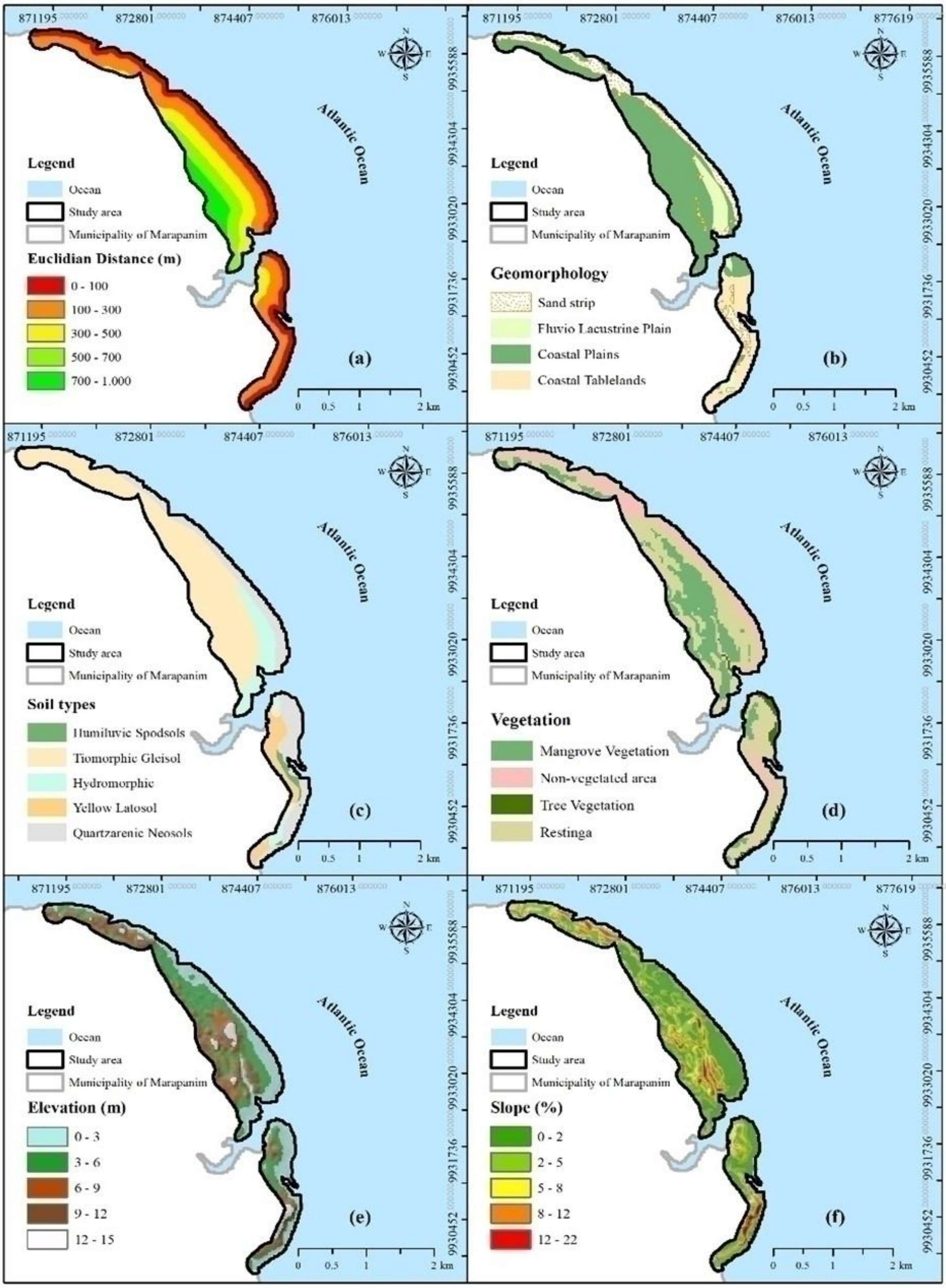

Figure 5 - Layers of physical vulnerability criteria: (a) proximity to the coast, (b) geomorphology, (c) soil types, (d) coastal vegetation, (e) elevation, and (f) slope. Source: Authors.

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STANDARDIZATION OF CRITERIA LAYERS

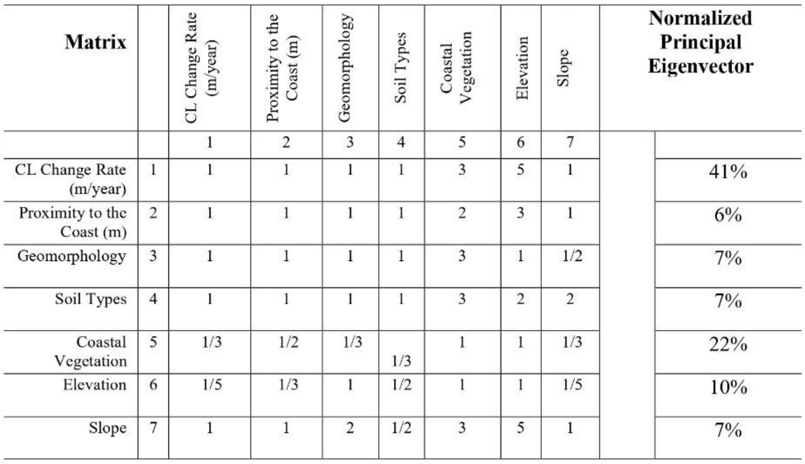
The standardization process reclassified the thematic classes into 5 classes of influence on vulnerability to erosion, namely: Very Low; Low; Moderate; High; Very High (Table 5). Each vulnerability class was associated, defined from five assigned points, and ranked respectively with the values 1, 2, 3, 4, and 5, for weighted calculation needs by the AHP (Analytic Hierarchy Process) that was be carried out.

Criteria	Ranges	Classification	Vulnerabilities	GIS Data Type	Classification Methods	%
CL Change Rate (m/year)	> 20	1	Very Low	Scale	Manual Classification	41
	10 – 20	2	Low			
	3 – 10	3	Moderate			
	–1 – 3	4	High			
	–3 – –1	5	Very high			
Proximity to the Coast (m)	700 – 1.000	1	Very Low	Scale	Manual Classification	6
	500 – 700	2	Low			
	300 – 500	3	Moderate			
	100 – 300	4	High			
	0 – 100	5	Very High			
Geomorphology	Plateaus of Pará	2	Low	Polygon	Geomorphological Classification	7
	Fluvio-Lacustrine Plain	3	Moderate			
	Coastal Plains	4	High			
	Beach Strip	5	Very High			
Soil Types	Yellow Latosol	1	Very Low	Polygon	Soil Type Classification	7
	Humiluvic Spodosols	2	Low			
	Thionic Gleysol	3	Moderate			
	Hydromorphic	4	High			
	Quartzarenic Neosols	5	Very high			
Coastal Vegetation	Arboreal Forest Formation	1	Very Low	Scale	Vegetation Density Classification	22
	Mangrove Vegetation	2	Low			
	Coastal Vegetation	3	Moderate			
	Non-vegetated area	4	High			
Elevation (m)	12 – 15	1	Very Low	Scale	Natural Breaks Elevation	10
	9 – 12	2	Low			
	6 – 9	3	Moderate			
	3 – 6	4	High			
	0 – 2	5	Very high			
Slope (%)				Scale	Manual Classification	7
	2 – 5	2	High			
	5 – 8	3	Moderate			
	8 – 12	4	Low			
	12 – 22	5	Very Low			
						100

Table 5 - Classification of alternative criteria according to their contribution to vulnerability to coastal erosion. Source: Authors.

WEIGHING THE CRITERIA USING AHP

From the compilation of data and the estimation of weights used, the AHP decision-making algorithm was employed to weigh the criteria of the two vulnerability indices and develop a general vulnerability map (Malczewski, 2006, 2010). All criteria were analyzed by the authors, who have extensive analytical experience on each criterion, establishing the weights from the justification of the factor with the greatest interference in natural processes under the parameter of coastal dynamics and its consequence from this modification processed in the study area. The composite score for each vulnerability component was 1 (Table 6).



Matrix		CL Change Rate (m/year)	Proximity to the Coast (m)	Geomorphology	Soil Types	Coastal Vegetation	Elevation	Slope		**Normalized Principal Eigenvector**
		1	2	3	4	5	6	7		
CL Change Rate (m/year)	1	1	1	1	1	3	5	1		41%
Proximity to the Coast (m)	2	1	1	1	1	2	3	1		6%
Geomorphology	3	1	1	1	1	3	1	1/2		7%
Soil Types	4	1	1	1	1	3	2	2		7%
Coastal Vegetation	5	1/3	1/2	1/3	1/3	1	1	1/3		22%
Elevation	6	1/5	1/3	1	1/2	1	1	1/5		10%
Slope	7	1	1	2	1/2	3	5	1		7%

Table 6 - Analytic Hierarchy Process (AHP) Matrix (multiple EVM inputs).

OVERALL VULNERABILITY ASSESSMENT

The assessment of vulnerability to erosion was carried out using a weighted overlay technique in ArcGIS 10.8 software with layers of physical criteria and their assigned weights. This process produced indices of physical vulnerability to erosion. The generated indices were grouped into five vulnerability classes (very low, low, moderate, high, and very high).

ASSESSMENT OF THE EFFICIENCY OF THE RESULTS OF VULNERABILITY TO PHYSICAL EROSION

To validate the physical vulnerability data to coastal erosion, the Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC) were used. The ROC curve assesses the model’s ability to distinguish between locations affected by coastal erosion and those not affected by comparing the true positive rate (sensitivity) with the false positive rate (1 − specificity) across different decision thresholds. The AUC summarizes this performance into a single metric ranging from 0 to 1, where values closer to 1 indicate higher predictive accuracy, whereas values close to 0.5 reflect performance similar to random classification. (Ahmed et al., 2021). In October 2022, the study area was visited by the authors, where they identified areas affected by coastal erosion and collected GPS (Global Positioning System) points of areas subject to erosion dynamics to verify and assess the accuracy of the coastal erosion vulnerability results (Figure 6).

In total, 11 locations highly affected by erosion were identified, whereupon the collected points were plotted using ArcGIS 10.8 (Figure 7). Thus, fieldwork was carried out at these specific points, where the main objective was to characterize the vulnerable areas based on the prepared erosion vulnerability map, by photographing these areas and observing the real context of vulnerability to coastal erosion. Out of the total 27 sites collected, the training data sets resemble 70% of the erosion points, while the validation data sets only present 30%.

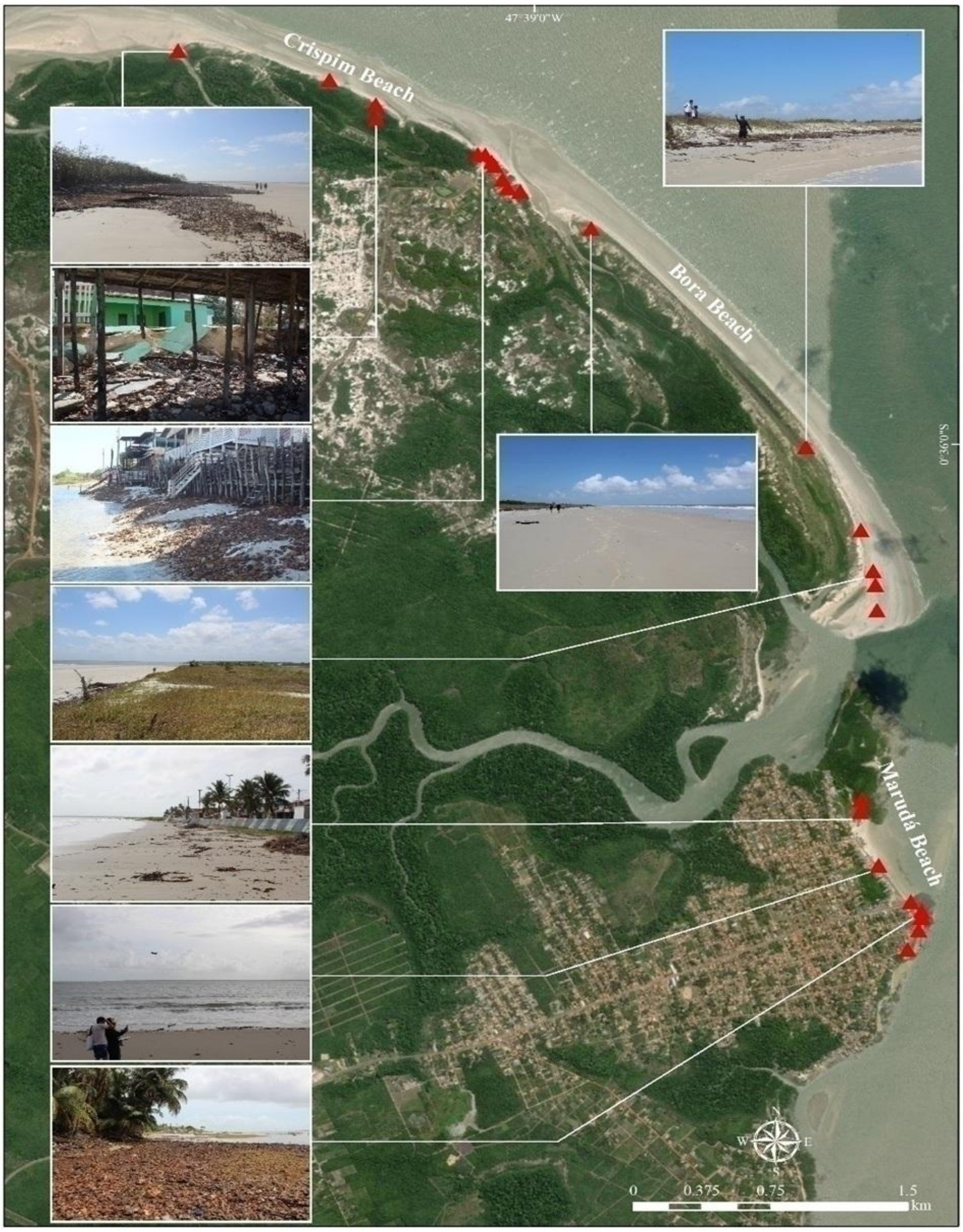


Figure 6 - Field visit sites for validating the results of vulnerability to erosion in the study area. Source: Authors.

RESULTS

VULNERABILIDADE COSTEIRA DAS PRAIAS DO BORA, CRISPIM E MARUDÁ

The results of the analysis are presented in Figure 7 and Table 7, which provide an integrated overview of the spatial distribution and magnitude of vulnerability to coastal erosion in the study area. Together, they synthesize the multicriteria analysis based on the AHP method by delineating the vulnerability classes and their respective areal proportions, which enabled a direct comparison among the evaluated sectors (I–VI). This information supports the identification of the most critical zones and provides a basis for prioritizing management and mitigation actions.

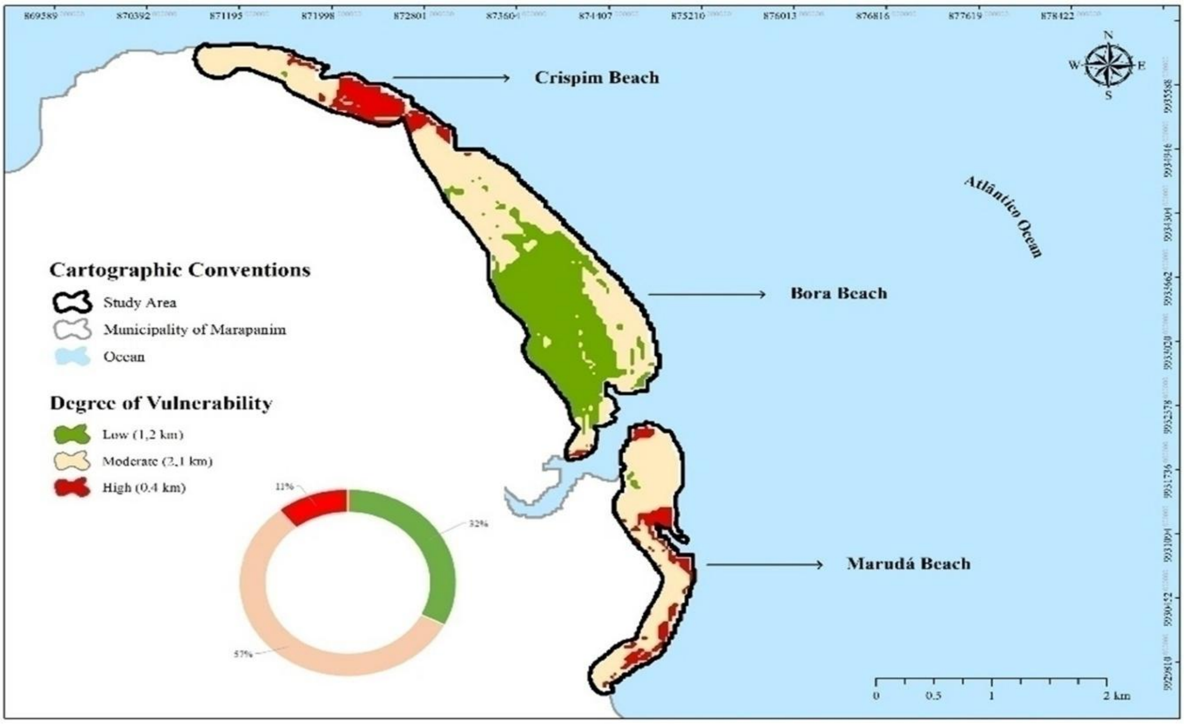


Figure 7 - Physical vulnerability map showing spatial pattern and degree of vulnerability to coastal erosion. Source: Authors.

Beaches	Sectors	Low (km^2)	Moderate (km^2)	High (km^2)
Crispim	I	0	0,4	0,1
	II	0	0,2	0,1
Bora	III	0,5	0,5	0
	IV	0,6	0,3	0
Marudá	V	0,1	0,4	0,1
	VI	0	0,3	0,1
Total		1,2	2,1	0,4

Table 7 - Distribution of sectors in different vulnerability classes in km^2. Source: Authors.

The levels of high vulnerability to erosion in the study area cover approximately 0.4 km², which comprises 11% of the total study area, being concentrated mainly on Marudá and Crispim beaches. Specifically, sectors I, II, V, and VI, where there is a high pattern of urbanization near the coast, enhance the vulnerability indices (Figure 8-a). The areas of moderate physical vulnerability total 2.1 km² of the study area and are present in all sectors/beaches, representing 57% of the study area (Figure 8-b). The levels of low physical vulnerability total 32% (1.2 km²) of the mapped area (Figure 8-c).

Figure 8 - (a) Beach feature of Crispim Beach, PA. (b) Beach feature of Marudá Beach, PA. (c) Beach feature of Bora Beach, PA. Source: author's collection (2023).

ASSESSMENT OF THE EFFICIENCY OF THE EROSION VULNERABILITY APPROACH

The efficiency of the data is demonstrated by the success and prediction rate curves (Figure 9) of the model's performance employed for the work carried out. Thus, a success rate of 0.801 was achieved, which translates to an 80.1% success accuracy AUC for the applied AHP model. Conversely, the AUC for the prediction rate reached a value of 0.791, corresponding to a 79.1% prediction accuracy for the results of physical vulnerability to coastal erosion in the study area. It is important to note that AUC values range between 0.5 and 1, given that values above 0.8, nearing 1, represent a higher precision within the scope of the obtained results (AHMED et al., 2021a). Therefore, the AUC values for prediction rate (79.1%) and success rate (80.1%) (Figure 9).

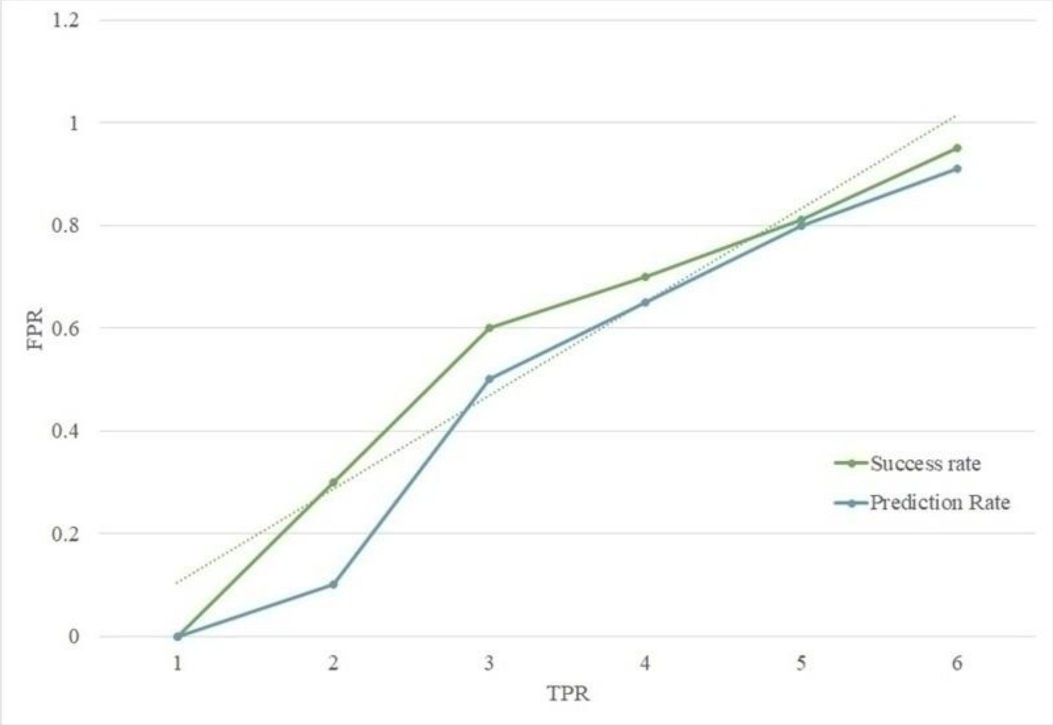


Figure 9 - Area under the curve for success rate (80.1%) and prediction rate (79.1%). Source: Authors.

DISCUSSION

Coastal zones are strategically important at the global scale because they concentrate population, infrastructure, and economic activities. However, coastal erosion has intensified in many regions, and the expected effects of climate change and sea-level rise tend to amplify erosional impacts. In this context, vulnerability mapping based on physical criteria is a practical way to support preventive planning and to reduce potential social, environmental, and economic losses.

Several approaches have been used to assess physical vulnerability and coastal risk, most of which integrate geomorphological and topographic controls with indicators of shoreline behaviour (Ahmed et al., 2021; Braga; Pimentel, 2019; Hoque, Muhammad Al Amin et al., 2019; Lins-de-Barros, 2017). Building on this literature, this study applied a GIS-based multicriteria framework and used AHP to assign weights to seven physical criteria, with particular emphasis on shoreline change over a multi-decadal period.

At the study site, the resulting index indicates that high physical vulnerability represents 11% of the mapped area (0.4 km²), moderate vulnerability 57% (2.1 km²), and low vulnerability 32% (1.2 km²). Beyond these overall proportions, the spatial pattern shows a consistent sector-to-sector contrast: sectors I, II, V, and VI concentrate higher vulnerability levels, while sectors III and IV exhibit comparatively lower scores. This contrast reflects the combined influence of shoreline-change rates and the reduction of natural buffers in areas where urban occupation approaches the active beach zone.

In the Amazonian coast of Pará, previous studies have advanced coastal vulnerability assessments despite limitations in databases and field logistics (Braga; Pimentel, 2019; Neves et al., 2019; Santos, Marcos Ronielly da Silva et al., 2017). All these authors consider physical elements (low elevation, steep slope, absence or degradation of mangroves, high population density, vulnerable soil cover class) as factors that render their geographical spaces of analysis vulnerable. In the case of Braga & Pimentel (2019), the CL and sea level were used as central elements of their analysis. However, they did not utilize the Digital Shoreline Analysis System (DSAS v5), which encompasses more concise and efficient statistical calculations (Nassar et al., 2019).

Thus, among all criteria under the scope of physical vulnerability, the rate of CL change, based on the DSAS LRR parameter, was considered the most important factor in assessing physical vulnerability to erosion. The 36 years analyzed between 1985 and 2021 showed that the rate of CL change varies from -2.56 m/year to 28.41 m/year (Table 4), similar to the results found in the study by Baía et al. (2021). Such erosive processes are considered of utmost importance in the process of understanding and spatializing vulnerable locations, based on the analysis of multiple criteria using the AHP method. Thus, the proposed integrated model can be applied by coastal planners in an attempt to contain coastal erosion and maintain a sustainable scenario.

However, this study was limited by the availability of information and data for various criteria. For example, some essential criteria could be considered to assess the impacts of climate change on coastal erosion, such as sea-level rise, tidal range, and significant wave height. Additionally, the authors also had to overcome various challenges in managing data quality and providing updated data because the study site lacks refined data from state agencies.

In this scenario, research that fostered more robust analyses might consider and use high-resolution satellite images, high-resolution DEMs, such as Light Detection and Ranging (LiDAR), and/or use images from Unmanned Aerial Vehicles (UAVs) and better scale criteria and other variables to refine the performance and assessment of vulnerability to coastal erosion.

The current composition was carried out using a single model (AHP). However, there are applications of different multi-criteria decision analysis (MCDM) models (Fuzzy-AHP, Fuzzy Logic), statistical models (bivariate and multivariate), artificial neural network (ANN), and machine learning models that can provide better results.

Given the above, future literary compositions may consider various models to compare among them as many other studies considering multiple models to assess other emerging natural risks, such as floods, landslides, droughts, etc. As a result, the best model can be assigned by public policy makers and non-governmental initiatives to try or succeed in inhibiting the drastic future consequences that may arise from coastal erosion.

CONCLUSION

In this study, we developed a comprehensive and nuanced approach to assessing vulnerability to coastal erosion. This effort culminated in a broad-ranging analysis based on the integration of seven key physical parameters in the northern part of Marapanim-PA municipality.

Our methodological framework leveraged the robust capabilities of Geographic Information Systems (GIS), enabling a precise and thorough evaluation of the data collected. This rigorous analysis was further validated by extensive fieldwork, during which the dynamic and erosive processes shaping the geographic area under study were directly observed and documented.

This manuscript stands out for its eminent potential to inform and guide coastal planning and the implementation of strategic mitigation measures. These measures, ranging from immediate actions to long-term initiatives, aim to significantly reduce or ideally eliminate the physical vulnerability of the coastal regions in the northern part of Marapanim-PA. By doing so, we hope to safeguard these areas against the ongoing and future impacts of coastal erosion, thus preserving their ecological integrity and the livelihoods of the communities that depend on them.

Furthermore, the methodologies and insights presented in this study have broader implications, potentially informing effective mitigation strategies in coastal regions across the Amazon, Brazil, and globally. Such areas, often marked by their vulnerability, can benefit from the application of the comprehensive methodological framework we have outlined.

By tailoring our approach to the specific characteristics and needs of each geographical area, we can better diagnose, understand, and address the natural processes driving coastal erosion. Ultimately, this study not only sheds light on the challenges faced by coastal regions but also offers a pathway towards more resilient and sustainable futures for these critical ecosystems and the communities they support.

ACKNOWLEDGEMENTS

To the Coastal Management Observatory of the State of Pará for funding the research.

AUTHOR’S CONTRIBUTIONS

Barros, V.H.C. - The author contributed to data preparation and handling, as well as writing and final revision of the manuscript.

Menezes, R.A.A. - The author contributed to data preparation and handling, as well as writing and final revision of the manuscript.

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Paula, E.M.S. - The author contributed to final revision of the manuscript.

Veloso, G.A. - The author contributed to final revision of the manuscript

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

RESEARCH DATA AVAILABILITY

All the data supporting the results of this study were published in the article itself.

USE OF AI

No Artificial Intelligence tools were used.

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