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Coastal Vulnerability in the Stretch Between Beaches of Peroba and Redonda in the Municipality of Icapuí-Ceará, Brazil

Vulnerabilidade Costeira no Trecho entre as Praias de Peroba e Redonda no Município de Icapuí-Ceará, Brasil

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Abstract: Coastal zones are dynamic regions whose morphology is directly influenced by natural or anthropic physical factors. Depending on the level of occupation and stage of development, these areas may be subject to risks associated with floods or erosive processes that make them vulnerable. Considering this context, this work quantified the relative vulnerability of the coast to physical changes between the Peroba and Redonda beaches in the municipality of Icapuí, east coast of Ceará, highlighting the stretches of beach where the effects on the coastline can be extreme. The natural variables geomorphology, slope, shoreline variation rate, mean tidal range, significant wave height, and mean sea level variation were used to implement the Coastal Vulnerability Index. The results indicated the occurrence of three vulnerability classes, ranging from moderate to very high. About 2,940 m (58%) were recorded as moderate vulnerability, 2,100 m (41%) as high vulnerability, and about 30 m (1%) as very high vulnerability. The most vulnerable stretches are associated with sandy beaches. The less vulnerable ones are with active cliffs that are part of the coastal tablelands and conservation areas.

Keywords: Coastal Erosion; Risk; CVI.

Resumo: Zonas costeiras são regiões dinâmicas cuja morfologia é diretamente influenciada por fatores físicos naturais ou de origem antrópica. A depender do nível de ocupação e do estágio de desenvolvimento, estas áreas podem estar sujeitas a riscos associados à ocorrência de inundações ou processos erosivos que as tornam vulneráveis. Considerando esse contexto, este trabalho quantificou a vulnerabilidade relativa da costa quanto às alterações físicas entre as praias de Peroba e Redonda no município de Icapuí, litoral leste do Ceará, destacando os trechos de praia onde os efeitos na linha costa pode ser extremos. Na implementação do Índice de Vulnerabilidade Costeira, foram utilizadas as variáveis naturais geomorfologia, declividade, taxa de variação da linha de costa, amplitude média de maré, altura significativa de onda e variação do nível médio do mar. Os resultados indicaram a ocorrência de três classes de vulnerabilidade, desde moderada a muito alta. Cerca de 2.940 m (58%) foram registrados como trecho de moderada vulnerabilidade, 2.100 m (41%) de alta vulnerabilidade e cerca de 30 m (1%) muito alta vulnerabilidade. Os trechos com maior vulnerabilidade estão associados a faixas de praias arenosas e os de menor vulnerabilidade a falésias ativas constituintes dos tabuleiros costeiros e áreas de conservação.

Palavras-chave: Erosão; Risco; IVC.

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1. Introduction

Coastal zones are highly dynamic due to their interaction between the sea, the continent and the atmosphere. Their high dynamism is generally influenced by physical agents that can act alone or together, making them vulnerable to the occurrence of floods, changes in the position of the coastline, or the salinization of aquifers (KANTAMANENI et al., 2018; GHOUSSEIN et al., 2018). The constant changes taking place in coastal zones are also strongly influenced by anthropogenic activity due to the growing occupation of land resulting from population growth, increased urbanization, and industrialization, among other development activities, and accentuate the problem of coastal erosion (DEL RÍO & GRACIA, 2009; MUTMAINAH, 2022).

The vulnerability of these areas varies according to the occupation related to the safe distance from the beach (NEVES et al., 2010; MUEHE, 2011; KOROGLU, 2019; KOVALEVA et al., 2022). In situations where extreme events occur, such as spring tides, coastal areas with lower slopes tend to present a greater potential risk of flooding and rapid shoreline retreat (DENNER et al., 2015; LOPES, 2021). In coastal geology, the challenge generally lies in determining the physical response of the coast to sea level rise and predicting the retreat of the coastline in the face of the growing vulnerability associated with the occupation of coastal land (THIELER & HAMMAR-KLOSE, 2000).

Currently, the assessment of coastal vulnerability has been widely used in various studies due to its importance in identifying, in the first instance, coastal segments susceptible to the risk of exposure to different natural factors (APPEANING ADDO, 2013; KOVALEVA et al., 2022). Several studies have already applied the Coastal Vulnerability Index (CVI) on a regional and local scale to different coastlines around the world, using various natural and socio-economic variables to assess the susceptibility of the coast to disasters in the face of rising sea levels (THIELER & HAMMAR-KLOSE, 2000; MUEHE et al., 2011; LINS-DE-BARROS, 2017; PANTUSA et al., 2018; KOMI et al., 2022; LOPES et al., 2022). Vulnerability studies have already been applied to beaches in the coastal zone of north-eastern Brazil, such as Araújo et al. (2019), who estimated the coastal vulnerability index on the coast of Piauí. Lopes (2021) studied vulnerability on the coast of the São Gonçalo do Amarante municipality in Ceará. Amaro et al. (2021) established the index of coastal vulnerability to erosion based on natural and environmental variables, considering the dynamics of climate change for different future scenarios established by the Intergovernmental Panel on Climate Change, for the Barreira do Inferno/RN region. Queiroz et al. (2022) applied global indicators to the study of coastal vulnerability for erosion management on the north coast of Pernambuco. Lacerda et al. (2022) assessed natural variables to determine coastal vulnerability before and after installing a wind farm in Pedra Grande and São Miguel do Gostoso/RN.

The occurrence of erosion processes observed in the coastal zone of the municipality of Icapuí, on the east coast of the state of Ceará, has been widely described by Barros et al. (2020), Silva (2021), Chacanza et al. (2022) and Chacanza et al. (2023). Given the erosion phenomenon identified, this study aimed to map and quantify the areas of relative vulnerability of the coast that are susceptible to physical alterations between the Peroba and Redonda beaches in the municipality of Icapuí, highlighting the stretches of beach where natural or anthropogenic risks on the shoreline that could be extreme and environmentally impactful.

2. Methodology

2.1. Study area

The research area is the region on the coast of the municipality of Icapuí, in the extreme east of Ceará, northeast Brazil, between the beaches of Peroba and Redonda (Figure 1). Two beaches comprise the research area: Peroba Beach (sector 1) to the east and Redonda Beach (sector 2) to the west. Active cliffs that produce promontory-shaped landforms, particularly near the eastern end of Sector 1 and between the two sectors, are the area's defining topography. In Sector 2, dune fields are visible to the west.

Figure 1 – Study area in the municipality of Icapuí-Ceará, Brazil, consisting of Peroba Beach (site 1) and Redonda Beach (site 2).
Source: They are prepared based on IBGE cartographic data and RapidEye/REIS image of 27/06/2015 made available by the MMA.

2.2. Coastal vulnerability index (CVI)

Six physical variables were chosen to calculate the Coastal Vulnerability Index, using the approaches of Thieler & Hammar-Klose (2000), Ghoussein et al. (2018), and Pantusa et al. (2018) as references. The variables applied were geomorphology, coastal slope, shoreline variation rate, mean tidal range, significant wave height, and mean sea level. To quantify coastal vulnerability, following Thieler & Hammar-Klose (2000), individual classifications were assigned to each variable, with values from 1 to 5, where 1 indicates the lowest risk, and 5 is the highest risk in the face of rising sea levels (Table 1). A percentage was then assigned to each class, indicating the specific impact; in other words, each parameter's response level on a given stretch of beach. The weighting values were 0.2 for very low vulnerability, 0.4 for low, 0.6 for moderate, 0.8 for high, and 1.0 for very high.

Table 1 - Ranking of the Coastal Vulnerability Index (CVI).

Reference	**Variable**	**Weight (x)**	**Very low**	**Low**	**Moderate**	**High**	**Very high**
			1	**2**	**3**	**4**	**5**
Thieler & Hammar-Klose (2000); Pantusa *et al.* (2018)	Shoreline change rate (m/yr)	15%	> 2.0 Accretion	1.0 – 2.0	-1.0 – 1.0 Stability	-1.0 – -2.0	< -2.0 Erosion
Ghoussein *et al.* (2018)	Coastal slope (%)	25%	> 45	30 – 45	15 – 30	8 – 15	< 8
Thieler & Hammar-Klose (2000)	Geomorphology	10%	-	Cliff coast	-	-	Send beach, dunes
Thieler & Hammar-Klose (2000)	Mean tide range (m)	30%	> 6.0	4.0 – 6.0	2.0 – 4.0	1.0 – 2.0	< 1.0

Thieler & Hammar-Klose (2000)	Significant wave height (m)	15%	< 1.1	1.1 – 2.0	2.0 – 2.25	2.25 – 2.60	> 2.60
Thieler & Hammar-Klose (2000)	Relative sea-level change (mm/yr)	5%	< -1.21	-1.21 – 0.1	0,1 – 1,24	1.24 – 1.36	> 1.36

Source: Author (2023)

The variables defined were given a specific risk value that indicates their influence on the coastal stretch. All the points of intersection between the transects generated and the coastline in August 2021 were used as a spatial reference for thematic mapping and calculating coastal vulnerability. The CVI was computed using the expression proposed by Denner et al. (2015) and Mutmainah (2022), consisting of the sum of the product of the variables involved in the analysis with their respective weight (Equation 1).

Equation 1 Coastal vulnerability index

$$CVI = (a * x_1) + (b * x_2) + (c * x_3) + (d * x_4) + (e * x_5) + (f * x_6)$$

where a = rate of shoreline change, b = coastal slope, c = geomorphology, d = mean tidal range, e = significant wave height and f = mean sea level. The x values represent the weights of the variables. x1 = weight of the rate of change of the coastline, x2 = weight of the slope of the coastline, x3 = weight of the geomorphology of the coastline, x4 = weight of the mean tidal range, x5 = weight of the significant wave height and x6 = weight of the mean sea level.

Geomorphology: This was defined through field observations and the orthomosaic generated from the high-resolution images collected by a remotely piloted aircraft (RPA) between August 2020 and August 2021. In this context, the value corresponding to this variable was extracted based on the shape of the local relief, considering the method described by Thieler & Hammar-Klose (2000). The regional geomorphology of the study area encompasses pre-littoral tablelands and the coastal plain. The latter comprises beaches, dunes, coastal and interdune lagoons, the estuarine-lagoon system, and marine terraces. At the same time, the pre-littoral tablelands make up a large part of the territory of Icapuí, extending into the regions adjacent to the coast where, in some areas, it is covered by ancient dunes, limited inland by dead cliffs and by living cliffs when they reach the coast (MEIRELES & SANTOS, 2012).

Coastal slope: The slope variable is considered a primary indicator of flood risk or the speed of shoreline retreat (HEGDE & REJU, 2007). This variable was calculated from values extracted from the digital elevation model (DEM) generated from data collected in the field in August 2021 using an RPA. The variable was expressed as a percentage (%), and the class value ranges were defined according to Ghoussein et al. (2018). The data extracted took into account the slope present on the coastline in August 2021, where all values above 45% indicate very low sensitivity and values below 8% indicate very high sensitivity to the occurrence of erosion.

Shoreline change rates: The values were obtained from the short-term history based on the linear regression rate (LRR) resulting from five scenes from the composition of images collected quarterly by RPA between August 2020 and August 2021. The images were processed using Agisoft Metashape Pro software, ultimately generating the orthophoto mosaic. It was exported to ArcGIS 10.8 software, where five shorelines were vectorized, and then the Digital Shoreline Analysis System (DSAS) tool, version 5.0, was applied. The average rate of change for the entire length of the coastline was 1.15 meters per year. The vulnerability classes were based on Thieler & Hammar-Klose (2000) and Pantusa et al. (2018). Predicting coastal retreat rates, sediment loss, and cliff erosion is essential for better planning coastal management (THIELER & HAMMAR-KLOSE, 2000). The rate of change of the shoreline is a variable that also validates the CVI calculation methodology (MANNO et al., 2013).

Average tidal range: The tidal variable is linked to the risk of permanent and episodic flooding (THIELER & HAMMAR-KLOSE, 2000). The average tidal range was calculated from 15-year historical values between January 2006 and December 2021, made available by the Directorate of Hydrography and Navigation (DHN), referring to the records of the Port of Areia Branca-RN, the closest to the study area. The annual average was 1.83 meters, which falls into the high vulnerability class, according to the classification by Thieler & Hammar-Klose (2000).

Significant wave height (SRH): Significant wave height is a variable used as an indicator of the energy of waves hitting the coast, as it is a significant influencer of coastal processes that drive sediment transport, resulting in coastal erosion (GAKI-PAPANASTASSIOU et al., 2010). In this case, the average Hs value presented by Barros (2018) was used, corresponding to a period of ten years (10) between January 2006 and December 2016, in which the waves arriving in Icapuí have an average Hs of 1.64 m, with maximums of 3.1 m and minimums of 0.80 m and an average period of 8.2 s, maximum of 17.9 s and minimum of 4.6 s. This value falls within the range of coastal erosion. This value falls within the range of 1.1 to 2.0 and is classified as low vulnerability. Pinheiro et al. (2016) measurements in the region closest to Icapuí (neighboring municipality of Aracati) showed Hs values with frequencies that varied between 1.3 and 1.73 m. In five field campaigns, wave height measurements in the surf zone showed average values between 0.8 and 1.0 m with periods between 3.72 and 6.56 s (CHACANZA et al., 2023).

Mean sea level: The sixth IPCC (Intergovernmental Panel on Climate Change) report predicts a rise in sea level by 2100, with a probable range between 0.26 and 0.55 m for an optimistic estimate (average of 0.40 m). For variations between 0.58 and 1.07 meters in a pessimistic estimate, the average increase will be 0.81 meters (IPCC, 2021). Any erosion or visible advance on the coast is directly related to sea level variation (GHOUSSEIN et al., 2018). On this basis, more than 1.36 mm/year variations fall into the very high vulnerability class (THIELER & HAMMAR-KLOSE, 2000). According to Lopes (2021), all the scenarios proposed by the IPCC report show more than 1.36 mm/year variations.

3. Results and discussion

3.1. Results

The rates of variation of the shoreline and the coast slope showed CVI values ranging from very low to very high vulnerability. As for the geomorphology variable, only two features were classified as low and very high vulnerability (Table 2). As for the hydrodynamic variables, the values were constant, with the mean tidal range showing an average corresponding to high vulnerability, the significant wave height showing an average corresponding to low vulnerability, and the mean sea level with a value corresponding to very high vulnerability.

Table 2 – Vulnerability values by variable

Variable	Minimum	Average	Maximum	Standard Deviation
Shoreline change rate	0.2	0.48	1.0	± 0.21
Coastal slope	0.2	0.39	1.0	± 0.24
Geomorphology	0.4	0.93	1.0	± 0.19

Source: Author (2023)

The variables involved in the process showed different vulnerability index values along the coastline (Table 3).

Table 3 – Coastal Vulnerability Index values along the shoreline

Variáveis	Vulnerability ranking									
	Very low (1)		Low (2)		Moderate (3)		High (4)		Very high (5)	
	m	%	m	%	m	%	m	%	m	%
Shoreline change rate (m/yr)	1,550	30.57	560	11.05	2,530	49.90	330	6.51	100	1.97
Coastal slope (%)	2,770	54.63	650	12.82	970	19.13	520	10.26	160	3.16
Geomorphology	-	-	620	12.23	-	-	-	-	4,450	87.77
Mean tide range (m)	-	-	-	-	-	-	5,070	100	-	-
Significant wave height (m)	-	-	5,070	100	-	-	-	-	-	-
Relative sea-level change (mm/yr)	-	-	-	-	-	-	-	-	5,070	100

Source: Author (2023)

Once the CVI was implemented, the vulnerability levels found ranged from moderate to very high (Figure 2A), where the values varied between 0.47 and 0.85, with an average of 0.61 ±0.07. This value indicated a classification of high coastal vulnerability between the Peroba and Redonda beach stretches in the municipality of Icapuí. The stretches with very high vulnerability are in the eastern part of Peroba Beach, and the values ranged from 0.82 to 0.85.

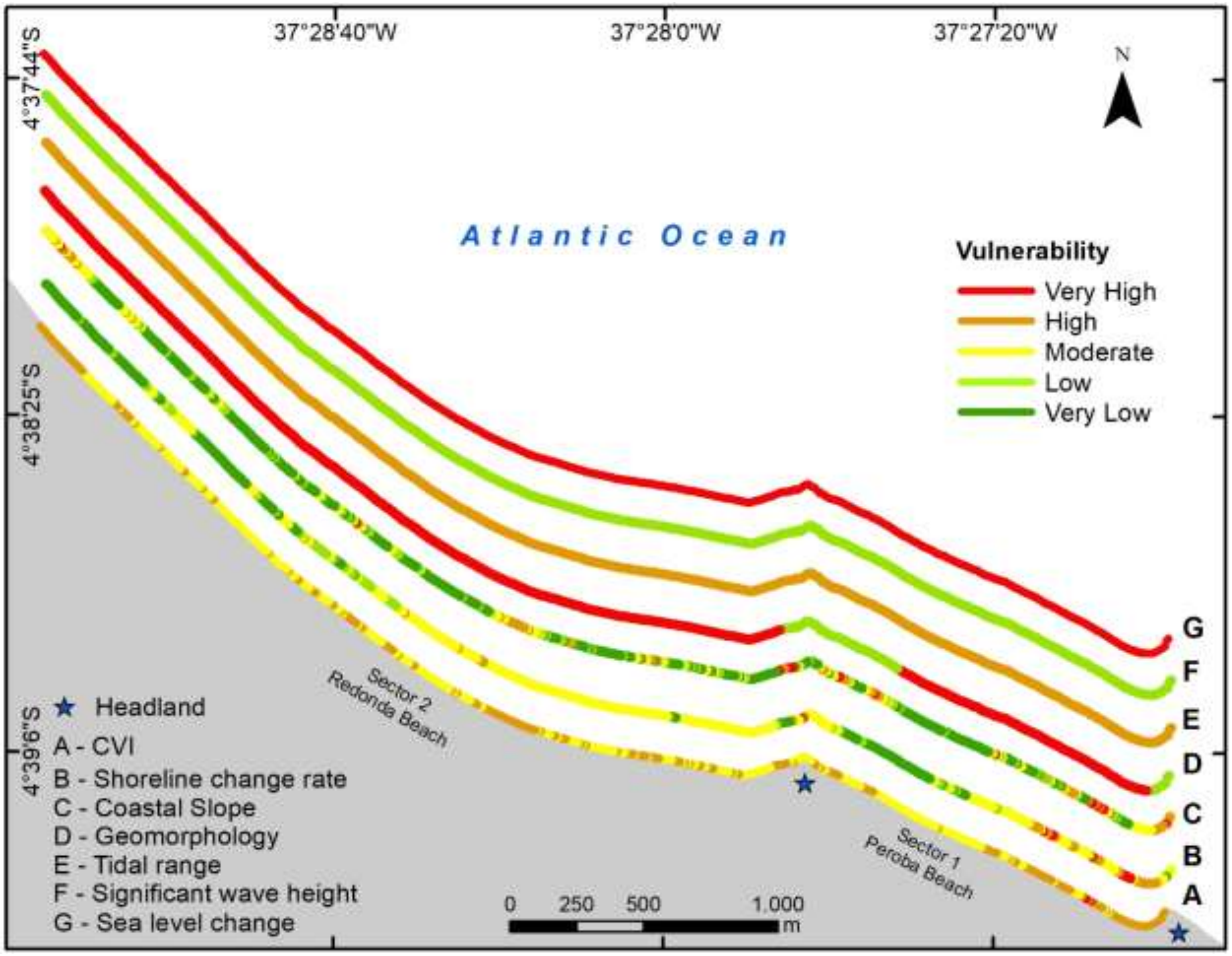

Figure 2 – (A) CVI: Coastal vulnerability index between Peroba and Redonda beaches; (B - G) Coastal vulnerability index classes by variable. LC: shoreline.
Source: Author (2023)

Figure 3 shows the distance and percentage of coastal vulnerability graphs. Of the 5,070 m of coastline in the analyzed stretch, around 2,940 m (58%) were recorded as moderately vulnerable, 2,100 m (41%) as highly vulnerable, and around 30 m (1%) as very highly vulnerable.

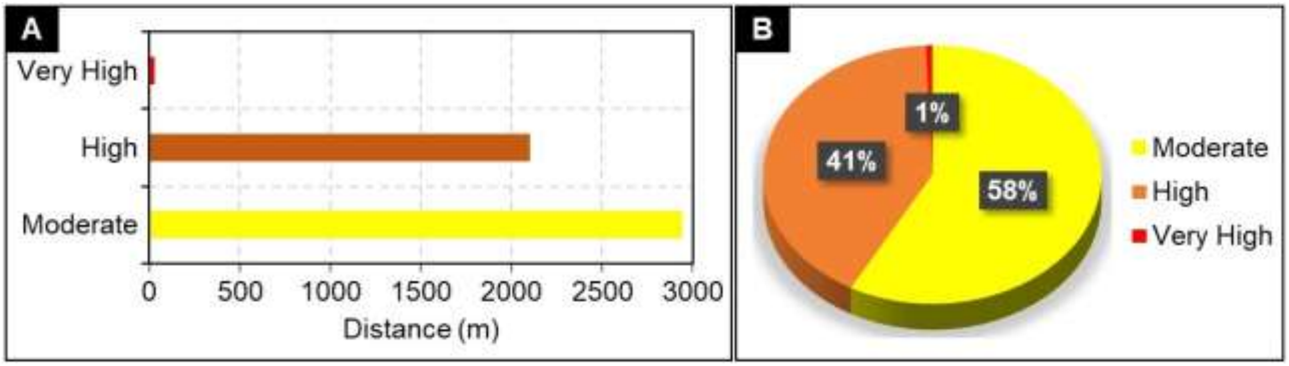

Figure 3 - Coastal vulnerability classes: (A) Distance from the coastline; (B) Percentage of vulnerability along the analyzed stretch.
Source: Author (2023)

The highest vulnerability index is concentrated east of sector 1, coinciding with the most significant negative variations in the coastline (Figures 2A and 4B, C, and D). In Sector 2, the stretches of high vulnerability are distributed along the eastern subsector, an area with erosion containment structures (Figures 2E 4F and G). In contrast, the western subsector shows moderate vulnerability with localized stretches of high vulnerability.

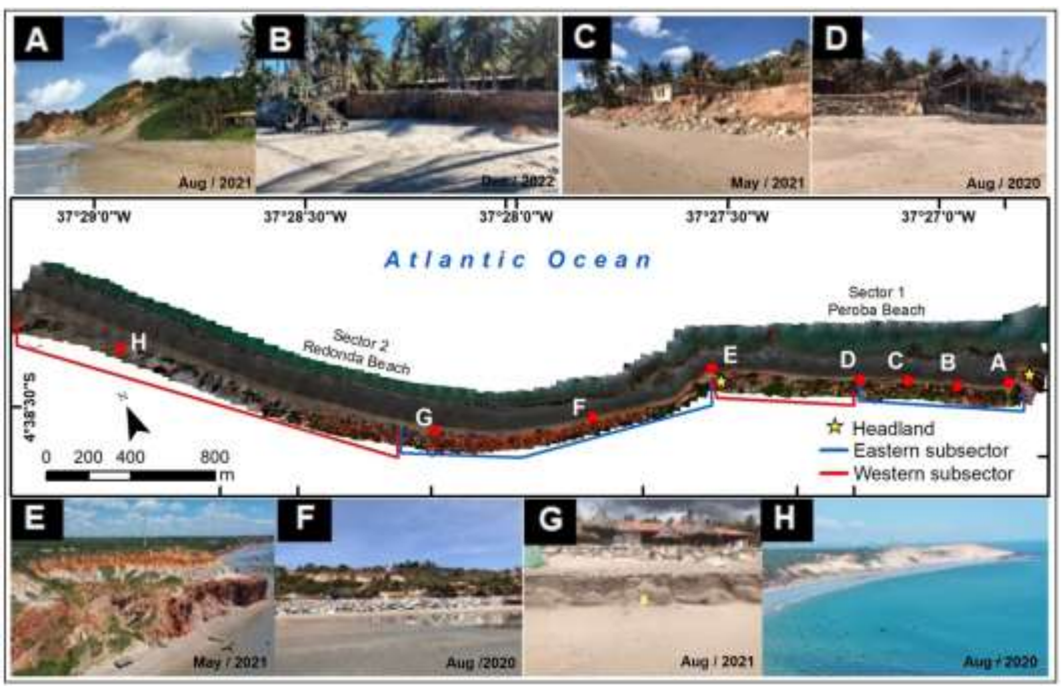

Figure 4 - Stretches of beach representing different morphologies in relation to the shoreline's response level to physical risks due to interaction with the sea. (A) Rocky headland at the eastern end of Sector 1; (B, C, and D) Sections of sector 1 that represent high coastal vulnerability; (E) Active cliff area with rocky headland between sectors 1 and 2; (F and G) Sections of sector 2 with high vulnerability and temporarily controlled due to the erosion containment structure; (H) Section with an extensive back beach area (conservation area).
Source: Author (2023)

3.2. Discussion

The moderate vulnerability class coincides with stretches of beach where there are higher rates of shoreline progradation, mainly in the western portions of the two sectors analyzed. The stretches of coast with high vulnerability are concentrated in the easternmost portions, coinciding with the highest rates of shoreline retrogradation. The shoreline varied at a rate corresponding to 1.15 m/year, where sector 1, the most vulnerable, showed an average rate equivalent to 0.87 m/year, and in sector 2, the average rate was 1.27 m/year. Meireles et al. (2020) described the stretch between Peroba beaches and the eastern part of Redonda as a critical stage of erosion and the western part of Redonda as temporarily stable in the face of rising sea levels. This study also found the temporarily stable stage along the stretch west of Peroba Beach (Figure 2A).

The geomorphology variable shows stretches with low and very high vulnerability. The low-vulnerability stretches are associated with active cliffs, and the high-vulnerability stretches with sandy beaches (Figure 2D). The geomorphology of the cliffs provides a high slope on the coastline near the foot of the cliff, and this means that vulnerability to sea level rise is minimized in the stretches with very steep slopes. However, the values point to classifications of moderate to high vulnerability. Although erosion processes are at a progressive stage, the speed of erosion is minimized in areas of steep slopes due to the presence of active cliffs (HEGDE & RUJU, 2007; MEIRELES et al., 2020). Localized points of active cliff showed high vulnerability, and these values coincided with shoreline retreat rates equal to or greater than 2 m/year. Erosion processes on cliffs in the area analyzed were reported by Silva (2021) in his analysis of cliff erosion vulnerability in eastern Ceará.

In the western portion of Redonda Beach, an area characterized by dune fields that are part of the Ponta Grossa state marine reserve, there is a vast back beach region made up of frontal dunes and mobile and fixed dune fields that interact directly with the beach, exchanging sediment in the dune-beach direction or vice versa, making the high vulnerability rate of this sandy beach, in practice, very low about the risk of losing built heritage as a result of erosion impacts. The absence of urban pressure on this subsector of Redonda Beach also minimizes local vulnerability and social effects.

The high tidal range (1.83 meters) combined with the low slope of the beach strip are the variables that contribute most to the variation of the CVI in the area. Combined with the significant wave height, they can increase coastal vulnerability to sea level rise in response capacity in a scenario of extreme events. Anthropogenic actions have strongly influenced coastal processes and, in the case of sandy beaches, have often been the leading cause of coastal vulnerability, such as construction in areas close to the coastline, as well as sand mining and landfill in new locations, construction of erosion containment structures without due respect for geological processes (THIELER & HAMMAR-KLOSE, 2000; GHOUSSEIN et al., 2018). In the field, this situation was widely verified in sector 1, especially when compared to sector 2, with a vast presence of infrastructures in a stage of high to very high vulnerability, located less than 20 meters from the coastline and, in some cases, next to the current coast (Figure 4B, C, and D). This local scenario devalues infrastructure in the property market.

To minimize the levels of risk exposure, some countries have established minimum distances from the coastline. According to Dronkers (2022), several Latin American countries have established setback distances between 20 and 80 meters from the coastline, except the Bahamas and Venezuela, with distances of less than 20 meters, and Brazil and Costa Rica, with distances of 50 and 200 meters. The distance established in Brazil, 50 m, was defined for urbanized areas and 200 m for non-urbanized areas Ministry of the Environment (MMA, n.d.). This minimum distance was not verified in the study area, especially on Peroba Beach and in the eastern subsector of Redonda, except for the stretches with active cliffs. The distance was only verified in the western subsector of Redonda Beach, where there are no occupations because it is a conservation area (Figure 5). In addition to the setback distances, it is essential to include tourism in the coastal management plan, especially in municipalities with beaches with high tourism potential, as this activity contributes to the degradation of coastal environments (LINS-DE-BARROS, 2017). This tourist potential can be found at Peroba and Redonda beaches.

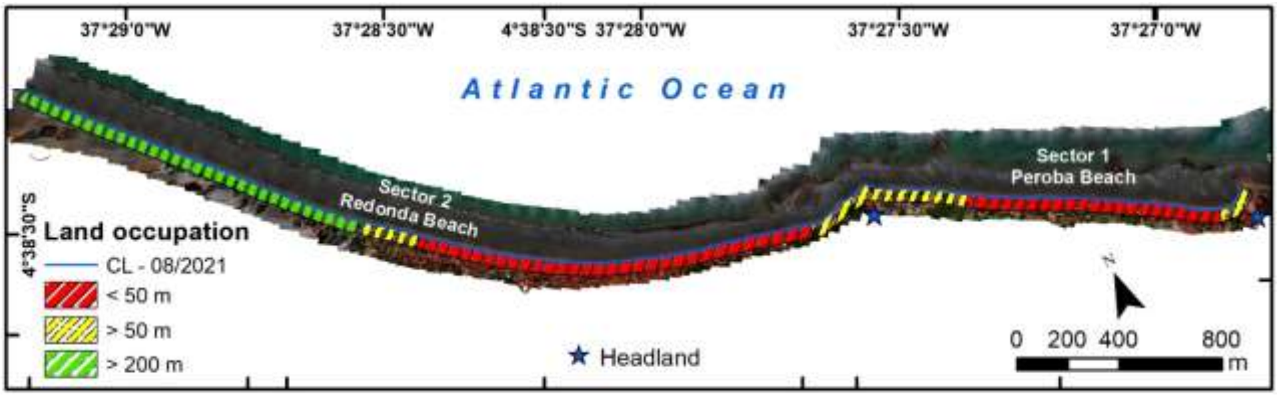

Figure 5 - Use and occupation of coastal land according to distance from the coastline. Red indicates occupation at a distance of fewer than 50 meters from the coastline, yellow is an occupation at a distance of more than 50 meters, and green means no occupation at a radius of more than 200 meters (conservation area).
Source: Author (2023)

The implementation of actions aimed at minimizing coastal vulnerability is in line with SDG 13 (Sustainable Development Goals), which states: "strengthen resilience and adaptive capacity to climate-related risks and natural disasters in all countries; integrate climate change measures into national policies, strategies and planning" United Nations (UN, 2018). Failure to take action could result in environmental and socio-economic damage (SANTOS et al., 2015).

4. Conclusions

The methodology applied in this study made it possible to determine in detail the coastal vulnerability of around 5 kilometers of the Peroba and Redonda beaches to physical changes along the shoreline, where the average vulnerability value was classified as high (IVC 0.61). The beaches above had three levels of vulnerability: moderate with 58% (2,940 m), high with 41% (2,100 m), and very high with 1% (30 m).

Peroba Beach was classified as having all three levels of vulnerability, while Redonda Beach had two levels, moderate and high. The most vulnerable stretches are associated with sandy beaches and dunes, while the least vulnerable stretches are associated with active cliffs, as the erosion process is slower on active cliffs.

The natural vulnerability presented in this study can be related to socio-economic variables from the perspective of coastal land use and occupation, considering that the data applied in the vulnerability analysis of the coastline was based on high spatial resolution products. As a result, this study provides managers with vital information to help them make decisions regarding coastal land management, which can reduce vulnerability to erosion risks and loss of property in coastal areas.

With this in mind, two strategies can be applied, especially in site 1: (1) Building an erosion containment structure with nature-based solutions; (2) Relocating at-risk infrastructure to safe areas so the beach can establish a new stage of natural equilibrium. For any action that local managers can take to reduce local coastal vulnerability associated with the progressive erosive stage, especially in site 1, it is necessary to carry out a thorough analysis of the costs and benefits of implementing and maintaining a coastal protection structure compared to the costs of relocating people in a situation of vulnerability. Concerning site 2, an essential detailed analysis needs to be made of the resources to be invested in maintaining the existing protection structure in the area.

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