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Socio-environmental vulnerability in coastal areas: a case study in the municipality of Macau-RN, Brazil

Vulnerabilidade socioambiental em áreas costeiras: um estudo de caso no município de Macau-RN, Brasil

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Abstract: The analysis of socio-environmental vulnerability in Macau-RN, Brazil, highlights the challenges arising from the interaction between social factors and physical-natural conditions in coastal areas. This study aimed to assess the socio-environmental vulnerability in the municipality, focusing on its urban center and the districts of Barreiras and Diogo Lopes. Using Geographic Information Systems (GIS) and factor analysis, a Social Vulnerability Index (SVI) was developed, incorporating socioeconomic and urban infrastructure variables. Additionally, a Physical-Natural Vulnerability Index (PNVI) was created, based on elevation, slope, and proximity to drainage channels. The results indicate that the most vulnerable neighborhoods, such as Navegantes, Valadão, and Porto São Pedro, face greater exposure to floods and landslides, revealing an unequal risk distribution. The municipal center, located in the Piranhas-Açu River delta, is directly exposed to extreme climatic events, exacerbated by its geography and precarious infrastructure. The proposed methodology integrates social and environmental dimensions into a Socio-Environmental Vulnerability Index (SAVI), providing a basis for public policies and risk management at the local scale. It is concluded that targeted interventions are essential to mitigate vulnerabilities and promote resilience in Macau's coastal context.

Keywords: Natural Disaster; Geotechnologies; Risk Management.

Resumo: A análise da vulnerabilidade socioambiental em Macau-RN, Brasil, reflete os desafios da interação entre fatores sociais e condições físico-naturais em áreas costeiras. Este estudo objetivou avaliar a vulnerabilidade socioambiental no município, com enfoque em seu centro urbano e distritos de Barreiras e Diogo Lopes. Utilizando Sistemas de Informações Geográficas (SIG) e análise fatorial, foi elaborado um Índice de Vulnerabilidade Social (IVS), que considerou variáveis socioeconômicas e de infraestrutura urbana. Em complemento, foi gerado o Índice de Vulnerabilidade Físico-Natural (IVFN), com base em altimetria, declividade e proximidade de canais de drenagem. Os resultados demonstram que os bairros mais vulneráveis, como Navegantes, Valadão e Porto São Pedro, apresentam maior exposição a inundações e movimentos de massa, evidenciando uma distribuição desigual dos riscos. A sede municipal, localizada no delta do Rio Piranhas-Açu, está diretamente sujeita a eventos climáticos extremos, agravados por sua geografia e infraestrutura precária. A metodologia proposta integra dimensões sociais e ambientais em um Índice de Vulnerabilidade Socioambiental (IVSa), fornecendo subsídios para políticas públicas e gestão de riscos em escala local. Conclui-se que intervenções direcionadas são essenciais para mitigar as vulnerabilidades e promover resiliência no contexto costeiro de Macau.

Palavras-chave: Desastre Natural; Geotecnologias; Gestão de Riscos.

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1. Introduction

The study of disaster risks—referred to in Portugal as *cindínic sciences*—began to gain prominence in the 1920s, with the contributions of Gilbert F. White, Ian Burton, and Robert W. Kates, geographers from the renowned Chicago School (USA), who developed studies and concepts around *Natural Hazards* (MARANDOLA JR. & HOGAN, 2004). Initially, analyses focused on understanding and controlling the natural phenomena associated with disasters. Over time, the emphasis shifted toward risk and the mitigation of its negative impacts.

Socio-environmental disasters are, according to Pelling (2014), the result of a "sum of failures in the development of a society." Nevertheless, they are still commonly referred to as "natural disasters," especially in media outlets that prioritize the speed of information over its accuracy. This article adopts a critical perspective of that naturalization, emphasizing the central role of society in the processes that generate disasters: natural phenomena such as floods, droughts, and heat waves become disasters due to social vulnerability—that is, the propensity of people, societies, and ecosystems to be harmed (RAJU, BOYD & OTTO, 2022).

The continued use of the term natural hazard may contribute to the idea that disasters are merely products of natural dynamics, ignoring their social origins. As Quarantelli (1998) asserts, disasters are discrete events, but risk and its management are part of an ongoing process and, as such, are linked to human accountability. In this same vein, Saavedra and Marchezini (2020) argue that disasters result from a socially constructed risk process. Risk—and its management—is therefore a dimension that can be analyzed and controlled through mitigation strategies.

The risk analysis and assessment methodologies adopted in this study share a common foundation: the construction of indicator systems composed of categorized and weighted variables, resulting in a synthetic index. At the global level, the World Risk Index (WELLE & BIRKMANN, 2015) stands out; in Brazil, the Disaster Risk Indicators in Brazil (DRIB), proposed by Almeida, Welle, and Birkmann (2016), is a key reference. At the state and municipal levels, relevant contributions include the works of Medeiros (2014; 2018), Macedo (2015), Oliveira (2018), Aguiar et al. (2018), Macedo et al. (2020; 2021), and Araújo (2020) and Araújo et al. (2021).

According to a recent survey by the Federal Government, 1,942 Brazilian municipalities (34.9% of the total) are "more susceptible to the occurrence of landslides, flash floods, and riverine floods" (BRASIL, 2023), encompassing approximately 73% of the country's population. In the state of Rio Grande do Norte, 31 municipalities were identified with such susceptibility, including Macau, which is the focus area of this study.

Macau has 27,369 inhabitants (IBGE, 2022) and a semi-arid climate, with an annual average rainfall of 537.6 mm. It is the driest coastal municipality in Brazil and the country's largest producer of sea salt (DINIZ & PEREIRA, 2015). Located on the northern coast of Rio Grande do Norte, its territory is characterized by the Piranhas-Açu River delta. The municipal seat is situated on an island surrounded by estuarine channels and salt production structures (reservoirs, decanters, and evaporators), forming a densely urbanized area. This physical-natural configuration, coupled with the low elevation of the urbanized areas—mostly below 5 meters—intensifies the municipality's exposure to flooding caused both by river overflow and sea-level rise (ARAÚJO et al., 2021).

Despite being in a semi-arid region, the municipality has recorded significant water-related disasters. According to the Brazilian Atlas of Natural Disasters (UFSC-CEPED, 2013), Macau experienced flash floods in 2004 and riverine floods in 2006, 2008, and 2009, displacing 359 people in the last two of those years. The intense rainfall, totaling 565 mm, led to the overflow of the Armando Ribeiro Gonçalves Dam, located upstream, thereby increasing the water level of the Piranhas-Açu River.

Previous studies have already identified flood risks in the municipality. Silva (2019) analyzed vulnerability and risk perception, while Araújo et al. (2021) conducted a mapping of areas susceptible to tidal flooding, considering climate change scenarios based on astronomical and meteorological tide data, integrated into a Digital Elevation Model (DEM) derived from LiDAR technology. Although statistically robust, that analysis addressed vulnerability solely based on land use and land cover.

In light of this, the main objective of the present study is to analyze the socio-environmental vulnerability of the municipality of Macau/RN, focusing on the urban center and the districts of Barreiras and Diogo Lopes—the most urbanized areas of the municipality—in order to understand the interrelations between social vulnerability and exposure to natural hazards, such as floods and landslides.

2. Methodology

The concept of risk adopted in this article is defined as a function of social vulnerability and natural hazards in a given location: R = f(P, V), where R represents risk, P the hazard, and V vulnerability. Thus, the concepts of risk, hazard, and vulnerability form the theoretical and methodological foundation of this study. It is therefore essential to understand both the dynamics of environmental elements—natural and anthropogenic—that shape a territory, as well as the social conditions that expose certain population groups to situations of risk. From this perspective, risk can be interpreted in a socio-environmental sense, often considered synonymous with socio-environmental vulnerability (ALVES, 2006; MENDONÇA & LEITÃO, 2008; ESTEVES, 2011; FREITAS et al., 2012; ZANELLA et al., 2013; MACEDO et al., 2015; MACEDO, 2018; GIRÃO, RABELO & ZANELLA, 2018; ARAÚJO, 2020; ARAÚJO et al., 2021).

Risk is a social construct, directly linked to the population's perception of potential hazards capable of causing physical damage and significant material losses. In many cases, communities may not even perceive that they are at risk. Within the scope of this study, the most relevant category of environmental risk corresponds to what Veyret (2007, p. 24) classifies as "man-exacerbated natural risks"—those resulting from natural hazards whose impacts are intensified by human activity and land use, such as erosion, desertification, wildfires, pollution, and flooding.

Hazard, in turn, is understood as the agent capable of causing material and/or immaterial damage. In this study, the definition adopted follows Smith (2001), who argues that hazards are an inevitable part of life and represent a potential threat to people and their property, while risk is the probability of a hazard occurring and leading to losses (SMITH, 2001, p. 392).

Vulnerability refers to the capacity of individuals or groups to prepare for, respond to, withstand, and recover from a hazard. From this perspective, it is understood as a condition of susceptibility to events that may cause material and physical harm to the population. According to Blaikie et al. (1994), this condition encompasses social and economic characteristics that influence a community's ability to anticipate, cope with, and recover from the impacts of natural hazards. It is shaped by a combination of factors that determine the extent to which lives and livelihoods are put at risk by specific events in nature or society.

The relationship between risk and vulnerability, as considered in this study, follows the approach of Almeida, Welle, and Birkmann (2016), who propose that risk consists of two dimensions: one natural and one social. The natural dimension refers to exposure to hazards that may trigger disasters, while the social dimension is linked to vulnerability, which is further broken down into three core components: susceptibility, coping capacity, and adaptive capacity.

From this perspective, risk assessment in this study was operationalized through the construction of two specific indices—one representing social vulnerability and the other addressing the physical-natural aspects of the study area. These were then integrated into a third, composite index. This methodological approach is fully aligned with the adopted concept of risk as a function that combines natural hazards (physical sphere) and vulnerability (social sphere).

2.1 Social Vulnerability Index (SVI)

The first index developed in this study is the Social Vulnerability Index (SVI), structured based on socioeconomic variables provided by the Brazilian Institute of Geography and Statistics (IBGE, 2013), at the scale of census tracts. Only the tracts corresponding to the study areas were considered. The analysis was carried out in a Geographic Information System (GIS) environment, using the ArcGIS 10.1 software, which was also employed in all cartographic production and spatial analysis throughout the study.

To construct the SVI for the municipality of Macau, the methodology proposed by Almeida (2010) was adopted, which is based on the São Paulo State Social Vulnerability Index, developed by the State System for Data Analysis Foundation (Fundação SEADE, 2008), from São Paulo State. The index is composed of 21 variables, organized into five thematic vulnerability indicators: (i) Household heads by gender and age / Children; (ii) Income; (iii) General characteristics of households; (iv) Illiteracy; and (v) Surrounding area characteristics.

The selection of these variables, as well as the aspects of vulnerability they represent, is aligned with theoretical and methodological frameworks commonly used in disaster risk assessment studies, as discussed by Almeida, Welle, and Birkmann (2016); Medeiros (2014; 2018); IPCC (2007; 2012); Rosendo (2014); Rosendo et al. (2017); Oliveira (2018); Veyret (2007); Olímpio and Zanella (2017); Cutter (1996); and Cutter et al. (2006), among others. Table 1 presents the grouping of variables under their respective vulnerability indicators.

Table 1 – Social vulnerability assessment indicators.

Indicators	Variables
General Characteristics of Households	V1 – Permanent private households with water supply or well/spring on the property
	V2 – Households with bathrooms lacking adequate sanitary sewage
	V3 – Permanent private households without exclusive-use bathrooms or toilets for residents
	V4 – Households without garbage collection
	V5 – Households without electricity or with illegal connections
	V6 – Households with 6 to 10 residents
	V7 – Permanent private households headed by male residents
	V8 – Households headed by women with 5 or more residents
	V9 – Permanent private households classified as “other dwelling types”
Household Heads by Gender and Age / Children	V10 – Household heads who are female
	V11 – Household heads aged 10 to 19 years
	V12 – Children aged 0 to 9 years
	V13 – Total number of improvised private households
Income	V14 – Households with per capita nominal monthly income of 0 to 2 minimum wages
	V15 – Female-headed households with income of 0 to 2 minimum wages
Surrounding Area Characteristics	V16 – Households in areas without public lighting
	V17 – Households in areas without paved roads
	V18 – Households on streets without storm drains
	V19 – Households on streets with open sewage
	V20 – Households on streets with accumulated garbage
Illiteracy	V21 – Total number of illiterate individuals per census trac

Source: Macedo et al. (2012). Adapted from ALMEIDA (2010).

For the statistical analysis of the data, factor analysis was applied to the variables using the R software (R CORE TEAM, 2021). This is a multivariate statistical technique that, based on the dependency structure among the variables (correlation or covariance matrix), allows for the reduction of data dimensionality by grouping correlated variables into factors that explain a significant portion of the total observed variability.

The study sample comprises census tracts from the urbanized areas of the municipality of Macau, located in the state of Rio Grande do Norte (RN), Brazil. Considering that the study area is situated on the northern coast of the state—a region characterized by high levels of socioeconomic vulnerability—the values obtained for the Social Vulnerability Index tend to be relatively higher compared to other regions of the state.

In this research, the results of the factor analysis were based on the correlation matrix of the variables, adopting the following matrix notation model:

$$\mathbf{X - \mu = L\,F + \varepsilon}$$
$$\mathbf{(pX1)\ (pXm)\ (mX1)\ (pX1)}$$

Where:
X – Vector of item responses;
μ – Vector of item means;
L – Matrix of weights of variables Xi on factor Fj (factor loadings);
F – Vector of unobservable random variables called common factors;
ε – Vector of unobservable random variables called specific factors;
p – Number of items;
m – Number of factors, with $m \leq p$, where p is the total number of variables.

At the end of this procedure, a score was generated for each variable, resulting in the extraction of four factors that explained 69.4% of the total data variability. The Social Vulnerability Index (SVI) was calculated as the mean of these scores. Subsequently, using ArcGIS 10.1 software, the SVI was classified into five vulnerability categories for spatialization and cartographic analysis: Very High, High, Moderate, Low, and Very Low.

The classification method adopted was the equal interval, which consists of dividing the range of index values into equal intervals. This approach allows for a balanced visualization of the spatial variation of social vulnerability across the municipality of Macau.

2.2 Physical-Natural Vulnerability Index (PNVI)

The second phase of disaster risk assessment in the municipality of Macau consisted of the development of the Physical-Natural Vulnerability Index (PNVI), structured based on variables related to the physical-natural characteristics of the study area. These characteristics are essential for evaluating two main types of risk: flooding and mass movement (landslides). Considering the scale of analysis and data availability, the PNVI was composed of three variables: elevation, slope, and proximity to rivers and drainage channels. Slope is associated with susceptibility to mass movements, while elevation and proximity to watercourses are directly related to flood occurrences.

The elevation and slope variables were derived from a Digital Elevation Model (DEM) generated using high-resolution LiDAR (Light Detection and Ranging) technology. This remote sensing technology, deployed on an aerial platform, detects the Earth's surface based on the reflectance of laser pulses. The data obtained were calibrated, resampled, and classified within a GIS environment, following the methodology proposed by Araújo et al. (2018).

Also within this digital environment, the variable representing proximity to drainage channels and the Piranhas-Açu River was incorporated, as these areas are naturally more exposed to flooding events. The channels were mapped based on a survey conducted during by Araújo (2020) doctoral research and made available in a vector format compatible with the software (.shp), allowing the generation of buffers—zones of influence calculated from the distance to water bodies.

Once the data acquisition phase was completed, each variable was categorized and classified into five risk levels (very low, low, moderate, high, and very high), using the same criteria adopted in the construction of the SVI, thus standardizing the analysis. Table 2 presents the grouping and classification of the three variables used in the creation of the PNVI.

Table 2 – Categorization of variables and classification by levels of physical-natural vulnerability.

Vulnerability Classes	Elevation (m)	Slope (°)	Proximity to Channels (m)
Very High	0 – 2.572	45 – 76.90	40
High	2.572 – 6.038	30 – 45	80
Moderate	6.038 – 11.442	20 – 30	120
Low	11.442 – 17.49	10 – 20	160
Very Low	17.49 – 25.194	0 – 10	200

Source: Authors (2025).

The classification method for the variables varied according to the data distribution or established legal parameters. For the elevation variable, the natural breaks method was adopted, as it provided better segmentation of the data based on the natural distribution patterns of the values. This method groups class intervals according to frequency and inflection points in the data series, making it more suitable for revealing topographic variation patterns.

The slope variable was manually classified in accordance with legal criteria. Slopes greater than 45° are considered permanent preservation areas, as defined by the Brazilian Forest Code (Law No. 12,651/2012). The proximity to drainage channels and the river variable was also manually classified, based on 40-meter equidistant intervals, determined according to the characteristics and scale of the study areas.

Based on these classifications, a raster surface was generated representing the three variables, with pixel values ranging from 1 to 5, corresponding respectively to very low to very high vulnerability classes.

At the end of the categorization process, within the GIS environment, the raster surface was converted to vector format (.shp). The three vector layers were then overlaid into a single file, in which the vulnerability values were summed using the Field Calculator tool. The final result was classified into five classes with defined intervals of 3 units (3, 6, 9, 12, and 15), using the defined interval method.

2.3 Socio-Environmental Vulnerability Index (SEVI)

After generating the cartographic products for the Social Vulnerability Index (SVI) and the Physical-Natural Vulnerability Index (PNVI)—both classified into five vulnerability levels—the two raster layers were overlaid in a GIS environment to construct the Socio-Environmental Vulnerability Index (SEVI). In this step, the rasters were summed using the Raster Calculator tool, resulting in a composite raster that integrates both the social and physical-natural dimensions of vulnerability.

The final product was subsequently classified into five categories—very high, high, moderate, low, and very low vulnerability—using the natural breaks method, in line with the procedures adopted for the previous indices.

3. Results and Discussion

In previous studies, Araújo et al. (2021) and Silva (2019) had already identified critical areas of exposure and vulnerability to flooding, respectively. The research presented in this article, however, expands that approach by including not only the municipal seat but also the urbanized districts of Diogo Lopes and Barreiras, and by adopting an integrated socio-environmental risk analysis perspective. In this regard, the SEVI developed in this study represents a synthesis between the socioeconomic indicators generated from the SVI and the main physical-natural characteristics associated with flood and mass movement processes.

The inclusion of mass movement risk represents a novel contribution of this research to the municipality, as there were no previous records or studies on this type of hazard. Although less common in flat areas such as Macau, these events can still occur in specific locations, especially on urbanized slopes.

To facilitate the understanding and organization of the results, the presentation is structured into three stages: first, the results of the Social Vulnerability Index (SVI); followed by the Physical-Natural Vulnerability Index (PNVI); and finally, the Socio-Environmental Vulnerability Index (SEVI).

3.1 Social Vulnerability Index (SVI)

Based on the factor analysis, four main factors were identified, together explaining 69.4% of the variability in the SVI data. These are: F1 – Income and Gender; F2 – Sanitation and Education; F3 – Basic Sanitation; F4 – Sanitation, Youth Age Group, and Gender. These factors represent the most relevant components of social vulnerability in Macau and therefore require greater attention in planning disaster risk reduction (DRR) strategies and mitigation actions in the municipality.

Among the 28 census tracts included in the sample area of this study, only one was classified as having very high social vulnerability, corresponding to the Navegantes neighborhood, located in the urban core (4%) (Figure 1). No tracts were classified as high vulnerability. Five sectors (18%) were identified with moderate vulnerability, all located in the municipal seat, covering parts of the Valadão, Porto São Pedro, and Centro neighborhoods. An additional fifteen sectors (53%) were classified as having low social vulnerability, distributed between the urban center and the districts of Diogo Lopes and Barreiras. Finally, seven sectors (25%) presented very low vulnerability, one located in the central area and the others in the aforementioned districts. Figure 2 presents the spatial distribution of the SVI across the study areas.

These results largely reflect the quality of urban infrastructure in the analyzed areas at the time of the 2010 Demographic Census, which served as the reference base for this study.

Figure 1 – Aerial view of the Navegantes neighborhood, Macau – RN.
Source: Authors (2025).

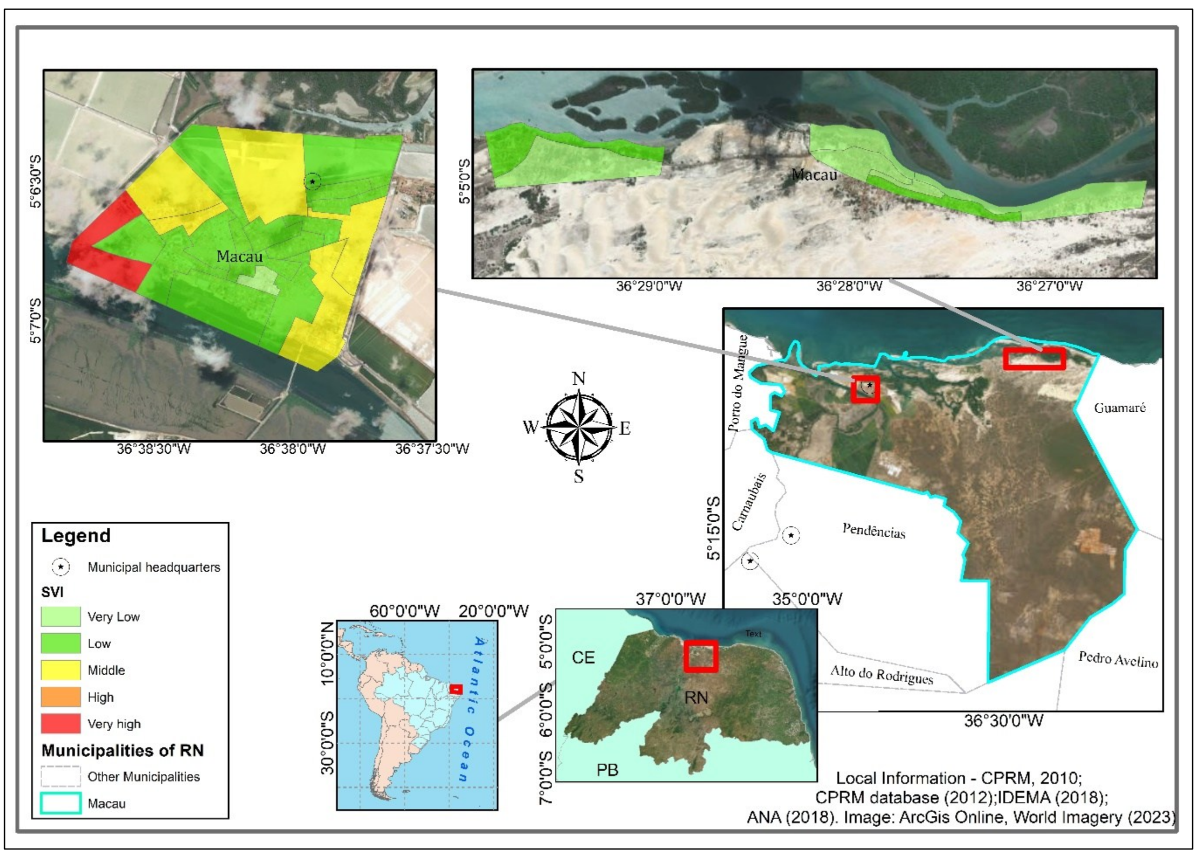

Figure 2 – Spatial distribution of the Social Vulnerability Index in Macau – RN.
Source: Authors (2025).

In this context, the districts of Diogo Lopes and Barreiras demonstrated lower levels of vulnerability compared to the municipal seat, mainly due to the variables V18 – Households on streets without storm drains, V19 – Households on streets with open sewage, and V20 – Households on streets with accumulated garbage. At the time, a significant portion of the urban center still lacked these basic sanitation infrastructures.

Additionally, several census tracts within the study areas exhibited high and very high social vulnerability for variables such as: V6 – Households with 6 to 10 residents; V8 – Female-headed households with 5 or more residents; V10 – Female household heads; and V12 – Children aged 0 to 9 years. These variables reflect socioeconomic conditions that increase the population's susceptibility to damage caused by adverse events. Furthermore, they reveal limitations in the community's ability to respond to and recover from potential disasters.

3.2 Physical-Natural Vulnerability Index (PNVI)

The spatial analysis of the results obtained through the Physical-Natural Vulnerability Index (PNVI) highlights the strong influence of proximity to drainage channels and rivers in the study areas of Macau—including the municipal seat, Barreiras, and Diogo Lopes—which contributed to the classification of several regions as having high and very high physical-natural vulnerability. Additionally, in Barreiras and Diogo Lopes, areas of high and very high vulnerability were identified on steep slopes with high residential density. These characteristics reinforce the exposure of these localities to hazards associated with mass movements and floods (Figure 3). Figure 4 presents the spatial distribution of the PNVI across the study areas.

Figure 3 – Sectors with steep slopes in Macau-RN: A) and B) excerpts from Barreiras; C) and D) excerpts from Diogo Lopes.
Source: Authors (2025).

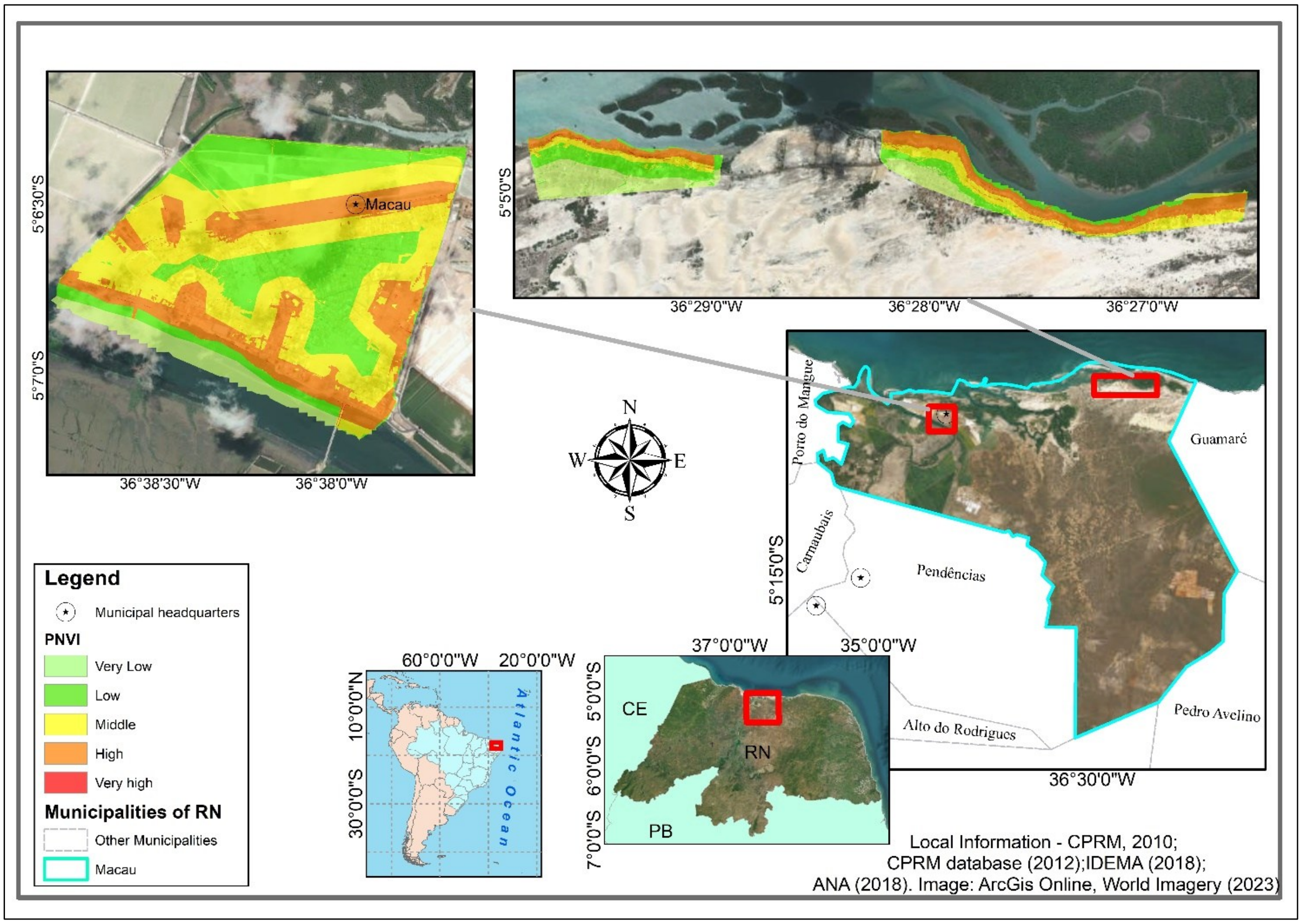

Figure 4 – Spatial distribution of the Physical-Natural Vulnerability Index in Macau – RN.
Source: Authors (2025).

The municipal seat of Macau is located in the Piranhas-Açu River delta and is surrounded by drainage channels and tanks used for sea salt production. It is the most urbanized sector of the municipality and is directly exposed to flood events, sea-level rise, and stochastic tidal fluctuations. In addition, the urban center is intersected by urban drainage channels responsible for the runoff of rainwater toward the river and salt ponds. The areas surrounding these channels were classified as having high physical-natural vulnerability in the PNVI, due to their increased exposure to flooding. These regions represent the main pathways for riverine backflow during flood events, as also analyzed by Araújo et al. (2021).

3.1 Socio-Environmental Vulnerability Index (SEVI)

The results of the Socio-Environmental Vulnerability Index (SEVI) for the municipality of Macau provide important guidance for the planning of public policies and disaster mitigation actions, by identifying priority areas according to socio-environmental vulnerability levels, with emphasis on flood and mass movement hazards. The research revealed areas at risk of mass movements in the studied districts, as well as zones susceptible to flooding and inundation in the municipal seat. Figure 5 presents the SEVI assessment results applied to the study areas.

The neighborhoods of Navegantes (classified as very high vulnerability), Valadão, and Porto São Pedro (both classified as high vulnerability) were identified as the areas within the municipal seat with the highest levels of socio-environmental vulnerability, and are therefore priorities for mitigation actions. These results primarily reflect the combination of three risk dimensions: exposure (proximity to drainage channels and the river), susceptibility, and coping capacity, the latter being closely tied to adverse socioeconomic conditions. These neighborhoods had already been identified as critical areas in previous studies (ARAÚJO et al., 2021; SILVA, 2019), which reinforces the reliability and consistency of the results obtained in this research.

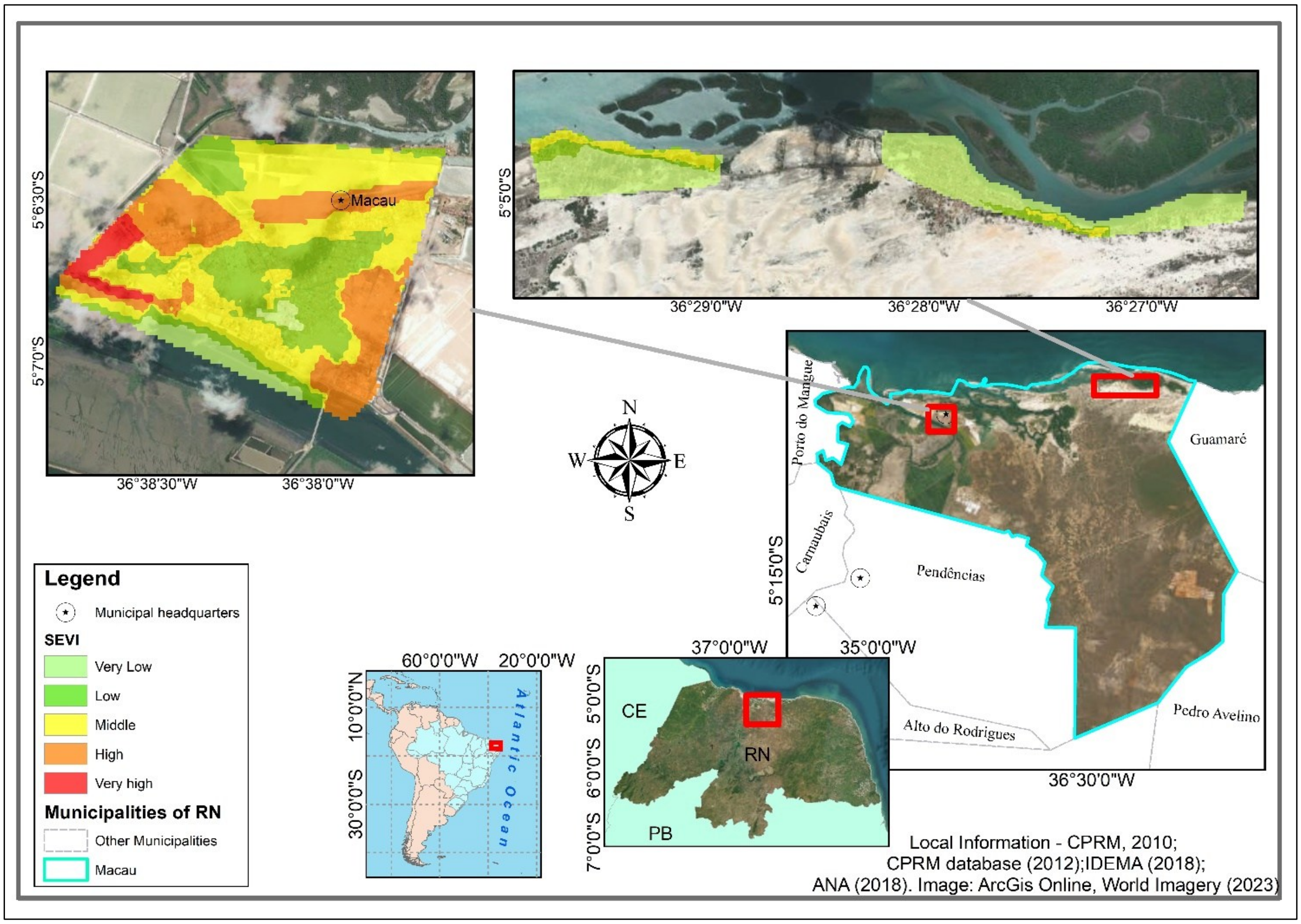

Figure 5 – Spatial distribution of the Socio-Environmental Vulnerability Index in Macau – RN.
Source: Research Data (2025).

In this context, various mitigation actions can be implemented, particularly in the most vulnerable areas, including improvements in urban infrastructure, basic sanitation, women's empowerment policies, and social assistance programs aimed at children and adolescents. It is worth noting that since the reference date of the data used in this study (2010 Demographic Census), improvements have been identified in certain infrastructure components, especially in basic sanitation. With the release of the 2020 Census data (conducted in 2022), it will be possible to compare progress and reassess vulnerability levels using more up-to-date information.

Among the coping strategies, special attention should be given to actions targeting female-headed households, such as the expansion of municipal early childhood education centers (CMEIs), which enable mothers in vulnerable situations to pursue technical training and enter the labor market. These measures directly contribute to reducing vulnerability by enhancing the population's adaptive and coping capacities in the face of risk situations.

In addition to structural and social interventions, it is essential to invest in Disaster Risk Reduction (DRR) education. Awareness must be promoted transversally and continuously, from schools to labor unions, non-governmental organizations (NGOs), and public institutions, fostering knowledge about risks, exposure, and vulnerability conditions associated with human occupation. The development of a culture of prevention strengthens social empowerment and better prepares communities to respond to adverse situations.

In this sense, actions such as evacuation drills, early warning systems, risk area signage, and the designation of safe meeting points are examples of coordinated measures aimed at building resilient cities, in accordance with the Sendai Framework for Disaster Risk Reduction 2015–2030, under the umbrella of the United Nations Office for Disaster Risk Reduction (UNDRR, 2015), in partnership with Brazil's National Secretariat for Civil Protection and Defense (SEDEC), through the Making Cities Resilient 2030 initiative.

4. Final Considerations

The objective of this study was to propose a plausible and simplified methodology for analyzing socio-environmental vulnerability at the municipal scale, in a way that could be applied not only in academic contexts but also by civil society organizations and government agencies. The proposed approach consisted of the integration between the Social Vulnerability Index (SVI) and the Physical-Natural Vulnerability Index (PNVI), resulting in the Socio-Environmental Vulnerability Index (SEVI). This index proved to be a robust and effective methodology to support public policies, institutional actions, and collective initiatives aimed at Disaster Risk Reduction (DRR).

The assessment of disaster risk, its dissemination, and the proposition of mitigation measures are aligned with the principles of DRR established by the National Secretariat for Civil Protection and Defense (SEDEC), under the Ministry of Regional Development (MDR). It is also in line with projects supported by the United Nations Development Programme (UNDP), such as the Project for the Enhancement of Risk and Disaster Management in Brazil. Furthermore, the proposed methodology aligns with the growing urgency of climate change research, as events such as floods and landslides reinforce the ongoing warnings in reports by the Intergovernmental Panel on Climate Change (IPCC, 2023), which indicate the increasing frequency and intensity of extreme weather events.

This research is directly connected to the Sustainable Development Goals (SDGs), particularly SDG 6 – Ensure availability and sustainable management of water and sanitation for all, and SDG 11 – Make cities and human settlements inclusive, safe, resilient, and sustainable. The latter includes a target to implement integrated policies and plans for climate change mitigation and adaptation, promoting urban resilience in accordance with the Sendai Framework for Disaster Risk Reduction 2015–2030. In the Brazilian context, this goal is set to be achieved by 2030, with the commitment to "significantly increase the number of cities with developed and implemented policies and plans for climate change mitigation, adaptation, resilience, and integrated disaster risk management" (BRASIL, 2019).

Although the 2010 Demographic Census conducted by the Brazilian Institute of Geography and Statistics (IBGE) remains the most recent source available at the census tract level, it still represents the most detailed dataset for local-scale analyses. While the 2022 Census has been conducted, its detailed data have not yet been fully released. Therefore, the 2010 data continue to serve as the most accurate reference for studies requiring information at the census tract level.

Based on fieldwork and the development of the socio-environmental vulnerability map for the municipality of Macau-RN, the proposed methodology was found to accurately reflect the local reality, without significant distortions. Nevertheless, it is important that the theoretical-methodological framework, variable selection, and data processing techniques be continuously discussed and improved to obtain even more refined results in future research efforts.

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