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Socio-environmental Vulnerability to Floods Including Technological Factors: Cases from Bezerros, Caruaru, Escada, and Sanharó - Pernambuco, Brazil.

Vulnerabilidade socioambiental a inundações com inclusão de fatores tecnológicos: Casos de Bezerros, Caruaru, Escada e Sanharó, em Pernambuco.

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Abstract: Floods are among the most frequent hydrological disasters in Brazil and affect several municipalities in the state of Pernambuco. Numerous events have occurred, particularly since the 2000s, and due to climate changes experienced worldwide, their frequency and intensity may increase. Although of natural origin, the consequences of this phenomenon vary according to the vulnerability of the communities. In this context, this study analyzed socio-environmental vulnerability to floods in four municipalities located in the Ipojuca River basin: Bezerros, Caruaru, Escada, and Sanharó. The methodology involved three main stages: identification of variables; development of social, environmental, and technological indicators; and calculation of the socio-environmental vulnerability index (IVS) with and without the inclusion of technological factors, using a spatial analysis model. The results showed that the areas with the highest vulnerability are located in densely populated urban zones and their surroundings, and that the lack of infrastructure intensifies this fragility. The inclusion of technological factors in flood vulnerability analysis provides a more comprehensive understanding and can support public policies aimed at reducing vulnerability in critical areas.

Keywords: Hydrological disasters; Climate change; Sustainability.

Resumo: Inundações estão entre os desastres hidrológicos mais frequentes no Brasil e afetam diversos municípios em Pernambuco. Diversos eventos ocorreram, especialmente, após os anos 2000 e, devido a mudanças climáticas experimentadas em todo mundo, sua frequência e intensidade podem crescer. Embora de origem natural, as consequências desse fenômeno variam conforme a vulnerabilidade das comunidades. Desta forma, este artigo analisou a vulnerabilidade socioambiental a inundações em quatro municípios pertencentes à bacia hidrográfica do rio Ipojuca: Bezerros, Caruaru, Escada e Sanharó. A metodologia envolveu três etapas básicas: identificação de variáveis; proposição de indicadores sociais, ambientais e tecnológicos; e cálculo do índice de vulnerabilidade socioambiental com e sem a inclusão de fatores tecnológicos, por meio de um modelo de análise espacial. Os resultados demonstraram que as áreas com maior vulnerabilidade estão localizadas em zonas urbanas densamente povoadas e próximas a elas, e que a falta de infraestrutura acentua esta fragilidade. A inclusão de fatores tecnológicos na análise de vulnerabilidade a inundações oferece uma compreensão abrangente e pode orientar políticas públicas voltadas para redução da vulnerabilidade em áreas críticas.

Palavras-chave: Desastres hidrológicos; Mudanças climáticas; Sustentabilidade.

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1 Introduction

Floods are among the disasters that occur most frequently and cause significant damage in Brazil. Although related to natural factors, several elements are identified as aggravating the impacts of these events, such as uncontrolled land use, rapid urbanization, environmental degradation, and the worsening of poverty conditions (Tasantb, 2019). These conditions, combined with natural hazards, influence the capacity for prevention, response, and recovery in the face of disasters, making urban concentration areas particularly vulnerable to extreme hydrological conditions (Cho; Chang, 2017).

The report of the Intergovernmental Panel on Climate Change (IPCC, 2022) indicates that by 2050, 68% of the world's population may be living in urban areas, and more people will be forced to leave their homes due to climate-related disasters, particularly floods. In this context, the concept of vulnerability has become increasingly important and urgent for disaster management and climate change studies, as it provides analytical tools to assess risk, powerlessness, and marginalization within physical and social systems, thereby contributing to the reduction of damages and the improvement of the population's quality of life (Cho; Chang, 2017).

Although this is a global issue, the distinct characteristics of each population influence the degree to which it is vulnerable. Thus, the interaction between an adverse event and a more vulnerable ecosystem tends to produce more severe impacts (Freire; Bonfim; Natenzon, 2014). In addition to environmental and climatological factors, the lack of infrastructure, low socioeconomic conditions, the absence or inadequate implementation of public policies and environmental and urban legislation, as well as the process of urbanization itself, also influence the magnitude of the impacts generated (Fragoso; Silva, 2019)

The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change – IPCC, 2007) defined vulnerability as a function of exposure, sensitivity, and adaptive capacity. This framework enables both the standardization and the adoption of different indicators and variables to analyze the specific characteristics of each region. This multidimensional concept has been adopted by several studies (Aktar et al., 2021; Chang et al., 2021a; Cho; Chang, 2017; Hamstead; Sauer, 2021; Turner et al., 2003) to integrate the socioeconomic, demographic, physical, natural, cultural, and institutional contexts of populations (Adeleye et al., 2019; Freire; Bonfim; Natenzon, 2014; Guimarães et al., 2014; Hamidi et al., 2020; Salami; Von Meding; Giggins, 2017).

Exposure is related to the level of risk experienced by society and can be expressed by the number of individuals or structures exposed; therefore, their location as well as their physical and temporal conditions must be considered (Andrade; Szlafsztein, 2018). Sensitivity refers to the likelihood that a community will be affected and is associated with its internal characteristics, such as socioeconomic factors. Adaptive capacity, or adaptability, refers to the potential for adjustment under the influence of hazards in order to reduce their impacts, and is also understood as resilience (Chang et al., 2021a; Hamidi et al., 2020).

Thus, vulnerability encompasses multiple dimensions and should not be studied in isolation from socioeconomic and environmental aspects (Cho; Chang, 2017). For a more comprehensive assessment, it is important to incorporate technological aspects into this concept, as they may contribute to either increasing or reducing vulnerability (Markolf et al., 2018). Studies highlight the importance of including technological factors, despite the challenges involved in identifying and measuring them, considering society and technology as mutually constitutive (Andrade; Szlafsztein, 2018; Grabowski et al., 2017).

Nevertheless, few studies consider the social, environmental, and technological domains in an unpacked and integrated manner, which would help to effectively identify the intersectional factors of vulnerability (Sauer et al., 2023) and, thus, contribute to the formulation of policies and interdisciplinary actions capable of addressing the challenge in an effective, realistic, and systemic way. This assessment of vulnerability is crucial for understanding how different communities or sectors—considered complex and integrated systems—will be impacted by extreme flood events (Kim et al., 2021).

In the state of Pernambuco, some regions, such as the Zona da Mata Sul and the Agreste, experienced an intensification of floods and inundations between 2000 and 2010 (Fragoso; Silva, 2019; Silva, 2019). In the following decade (2010–2020), other disasters affected the region, leaving several municipalities in a state of emergency or public calamity (Ferraz, 2019). The most significant events occurred in 2000, 2004, 2005, 2010, 2011, 2017, and 2020 (Silva, 2019), affecting various municipalities, including Bezerros, Caruaru, Escada, and Sanharó. In this context, this study proposes to analyze socio-environmental vulnerability to floods, including technological factors, in these four municipalities located within the Ipojuca River Basin.

2 Study area

The municipalities analyzed were selected based on the occurrence of floods since 2000, the flood vulnerability classification established by the Agência Nacional de Águas (ANA), and the analytical units described in the Hydro-Environmental Plan (PHA) of the Ipojuca River Basin, with one municipality representing each of these units (Table 1). Climatic, environmental, and risk-exposure criteria enable a more comprehensive analysis of socio-environmental vulnerability to flooding.

Table 1 – Municipalities selected for the study and the criteria used.

Municipalities selected for the study and the criteria used			
Municipality	**Unit of analysis (PERH, 2010)**	**Vulnerability classification (ANA, 2014)**	**Flood events (2000–2022)**
Bezerros	UA 3	Moderate	2000, 2010, 2018
Caruaru	UA 2	Moderate	2004, 2009, 2011, 2017, 2020
Escada	UA 4	High	2005, 2010, 2011, 2017
Sanharó	UA 1	Low	2019, 2020, 2021

Source: Author (2024).

Bezerros, Caruaru, Escada, and Sanharó (Figure 1) are part of the Ipojuca River Basin and present different social, economic, environmental, and climatic characteristics. Thus, it becomes possible to conduct an analysis at different levels regarding these factors and their impact on vulnerability. The basin has an elongated shape, with an extension of 3,435 km and an area of 3,587.24 km² (Pernambuco, 2022). Due to its large extent, it crosses the regions of the Sertão, Agreste, Zona da Mata, and the Pernambuco Coast (CONDEPE/FIDEM, 2005). As a result, its climatic characteristics are considered intermediate, including cities with humid climates, such as those in the Zona da Mata, and hot and dry climates in the Agreste and Sertão regions.

Bezerros is located in the Agreste region of Pernambuco and has a population of 61,694 inhabitants (IBGE, 2022). Caruaru is one of the most important municipalities in the Agreste region of Pernambuco, with a population of approximately 380,000 inhabitants (IBGE, 2022). Its area of 921.2 km² is characterized by the presence of mountains, valleys, and rivers, which makes it susceptible to extreme weather events such as intense rainfall and flooding (CPRM, 2005).

Escada is a municipality located in the Zona da Mata Sul region of Pernambuco, with an area of about 470 km² and a population of approximately 60,000 inhabitants (IBGE, 2022). The Zona da Mata Sul of Pernambuco is a region prone to extreme weather events, such as intense rainfall and floods (Fragoso; Silva, 2019). Sanharó is a municipality located in the Agreste region of the state of Pernambuco, with a population of 18,624 inhabitants (IBGE, 2022). The four municipalities included in this study are among those monitored by the Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN).

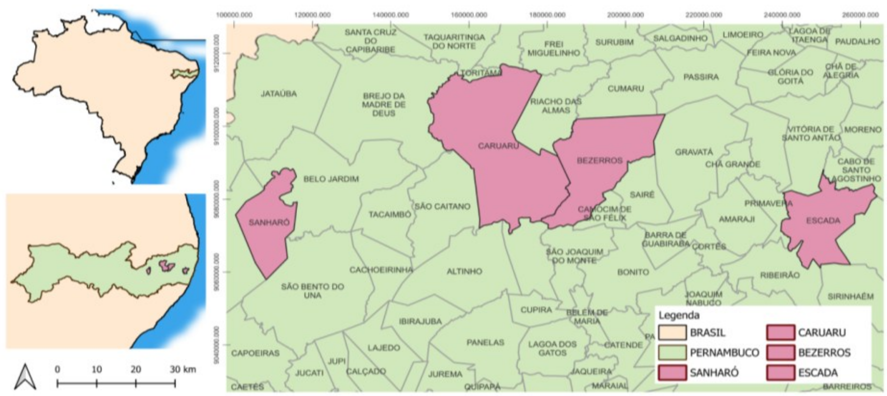
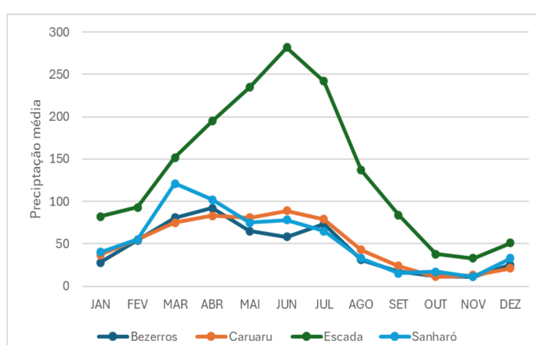


Figure 1: Location map of the study municipalities. Source: Author (2024).

In 2023, the municipalities of Sanharó, Caruaru, Bezerros, and Escada showed an increase in the accumulated rainfall volume. In March of that year, rainfall exceeded 100 mm in Sanharó. A similar pattern was observed in Escada; however, precipitation levels remained above 100 mm and continued to increase until September 2023, with the highest value recorded in July, when approximately 300 mm of rainfall accumulated (Graph 1). This scenario of climatic variability, isolated rainfall events, and accumulated precipitation above the monthly average plays a fundamental role in the occurrence of floods and disasters.



Graph 1: Monthly accumulated precipitation in 2023. Source: Author (2024)[1].

3 Methodology

3.1 Vulnerability Indicators

This study proposes a set of social, environmental, and technological indicators based on three dimensions of vulnerability: exposure, sensitivity, and adaptive capacity. The variables selected to compose the social indicators were obtained from data from the 2010 Census of the Instituto Brasileiro de Geografia e Estatística (IBGE), at the census tract scale. For the environmental variables, the data were obtained from the Instituto Nacional de Pesquisas Espaciais (INPE), the Fundação Brasileira para o Desenvolvimento Sustentável (FBDS), and the Serviço Geológico do Brasil (CPRM). The technological variables were obtained from the Agência Nacional de Águas (ANA), the Instituto Nacional de Estudos e Pesquisas Educacionais Anísio Teixeira (INEP), and the Ministério dos Transportes and Ministério da Saúde.

The social variables were normalized using the min–max linear scaling method, similar to the approach adopted by Chang et al. (2021a) and Hamidi et al. (2020), which generated values between zero and one. The procedure consisted of subtracting the minimum value of the variable from its actual value when the variable increases vulnerability (Equation 1), and subtracting the actual value of the variable from its maximum value (Equation 2) when the variable decreases vulnerability.

$$V_i = \frac{X_i - X_{imín}}{X_{imax} - X_{imín}} \qquad [1]$$

$$V_i = \frac{X_{imax} - X_i}{X_{imax} - X_{imín}} \qquad [2]$$

Where Xi represents the indicator, Vi the normalized value, and Xi max and Xi min the maximum and minimum values of the indicator, respectively. The resulting values, ranging from 0 to 1, were divided into five equal-interval classes, which were assigned values from 1 to 5 to represent the degree of exposure, sensitivity, or adaptive capacity (Table 2. The environmental and technological variables followed a similar classification process, with scores ranging from 1 to 5 assigned to their respective classes (Table 3).

It is important to note that, for the adaptive capacity variables, level 5 represents the class with very high adaptive capacity, corresponding to the most favorable situation, whereas level 1 represents the class with very low adaptive capacity, corresponding to the least favorable situation.

[1] Data extracted from the APAC website – Climatology – Average preciptation by municipality. Available at: https://www.apac.pe.gov.br/193-climatologia/521-climatologia-por-municipio. Accessed on: 08/01/2024.

Table 2: Normalization and classification of social variables.

Normalization and classification of social variables.		
Normalized value	**Weight**	**Level**
0	1	Very Low
0.25	2	Low
0.50	3	Medium
0.75	4	High
1	5	Very High

Source: Author (2024).

Table 3 – Normalization and Classification of Environmental and Technological Variables.

Normalization and Classification of Environmental and Technological Variables			
Variable	**Classes**	**Weight**	**Level**
Precipitation	800 a 1100 mm	1	Very Low
	1100 a 1400 mm	2	Low
	1400 a 1700 mm	3	Medium
	1700 a 2000 mm	4	High
	> 2000 mm	5	Very High
Distance from Water Resources	> 400 m	1	Very Low
	400 m	2	Low
	300 m	3	Medium
	200 m	4	High
	100 m	5	Very High
Slope	> 20%	1	Very Low
	8 - 20%	3	Medium
	0 -8%	5	Muito Alto
Elevation	> 829 m	1	Very Low
	572 a 829 m	2	Low
	314 a 572 m	3	Medium
	58 a 314 m	4	High
	< 58 m	5	Very High
Land Use and Land Cover	Water	5	Very High
	Forest	4	High
	Non-Forest	3	Medium
	Anthropized area	2	Low
	Urban/built-up area	1	Very Low
Soil Types	Oxisols (Latosols)	5	Very High
	Planosols	4	High
	Podzolic soils	3	Medium
	Regosols and Lithosols	2	Low
	Vertisols	1	Very Low
Flood-Prone Sections	Low risk	1	Very Low
	Medium risk	3	Medium
	High risk	5	Very High
Infrastructure (Roads)	< 200 m	1	Very Low
	200 a 400 m	2	Low
	400 a 600 m	3	Medium
	600 a 800 m	4	High
	> 800	5	Very High
Emergency Services (Hospitals)	> 2,5 Km	5	Very High
	2,5 a 5 Km	4	High
	5 a 7,5 Km	3	Medium
	7,5 a 10 Km	3	Low
	> 10 Km	1	Very Low
Shelter Capacity (Schools)	< 250 m	5	Very High
	250 a 500 m	4	High
	500 a 750 m	3	Medium
	750 a 1000 m	3	Low
	> 1000 m	1	Very Low

Source: Author (2024).

3.2 Vulnerability Indices

To construct the vulnerability indices, the variables were grouped into three indicators: social, environmental, and technological (Table 4). The indicators were composed with equal weighting through map overlay using Equation 3. Based on these indicators, the socio-environmental vulnerability index (IVSA) was calculated, considering social and environmental factors, as well as the integrated vulnerability index (IVSAT), which includes technological factors in the calculation using the same method (Aktar et al., 2021; Chang et al., 2021a; Hamidi et al., 2020).

Table 4: Variables grouped into indicators.

Variables grouped into indicators.		
Indicator	Variable	Grouped Variables
Social	$\frac{Social\ Exposure\ \times Social\ Sensibility}{Social\ Adaptation\ Capacity}$	$\frac{(Pop) \times (Dep + Pob)}{(Edu + Ren)}$
Environmental	$\frac{Environmental\ Exposure\ \times\ Environmental\ Sensibility}{Environmental\ Adaptation\ Capacity}$	$\frac{(Precip + Rec. Híd.) \times (Dec + Ele)}{(T. Solos + C. Solo)}$
Technological	$\frac{Technological\ Exposure\ \times\ Technological\ Sensibility}{Technological\ Adaptation\ Capacity}$	$\frac{(T. inun) \times (Infra)}{(Emerg + Abrigo)}$

Source: Autora (2024).

$$IV_d = \left(\frac{\sum E \times \sum S}{\sum A}\right)^{1/3} \quad [3]$$

Where IV represents the index value and *d* the domain representing the social, environmental, or technological dimensions. E, S, and A represent the factors of exposure, sensitivity, and adaptive capacity, respectively.

4 Results

4.1 Flood Vulnerability Indicators

Regarding social vulnerability (Figure 2 and Graph 2), Caruaru was the only municipality that presented areas of moderate (4.76%) and low vulnerability (11.31%), while Bezerros presented a small region of low vulnerability corresponding to only 1.21% of its territory. The other two municipalities have predominantly very low vulnerability areas.

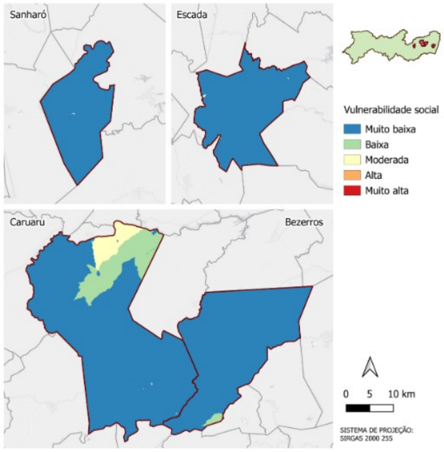
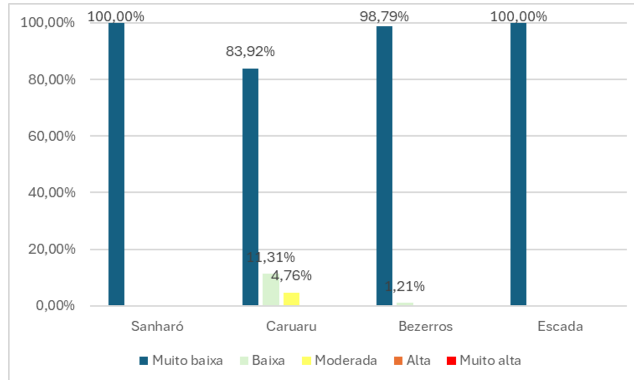


Figure 2: Social Vulnerability Indicator.
Source: Author (2024).



Graph 2: Percentages of the Social Vulnerability Indicator.
Source: Author (2024).

In the exposure dimension, the municipalities analyzed did not present areas of high vulnerability. This behavior is related to the population being distributed over a large territorial area, resulting in lower population density. Sanharó, Bezerros, and Escada have urbanization rates below 30%, unlike Caruaru, which has an urbanization rate above 80% (IBGE, 2020). However, the urban areas of these municipalities are crossed by the Ipojuca River (Figures 3, 4, 5, and 6), which increases their exposure.

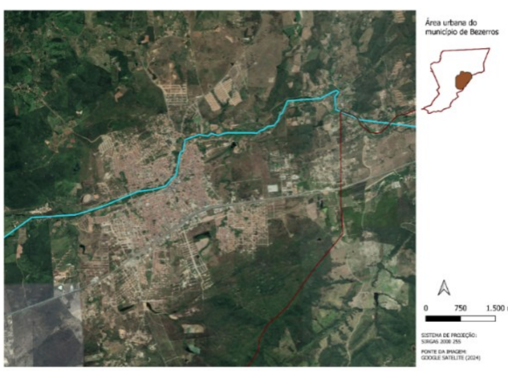


Figure 3:Urban concentration area of the municipality of Bezerros.
Source: Author (2024).

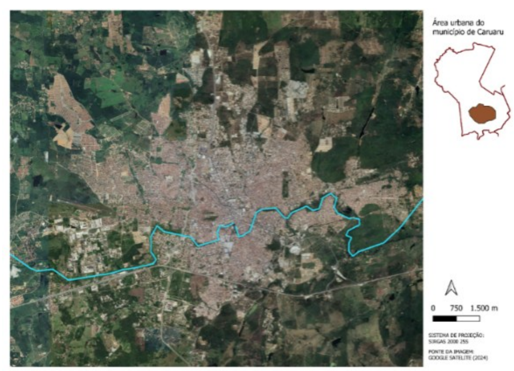


Figure 4: Urban concentration area of the municipality of Caruaru.
Source: Author (2024).

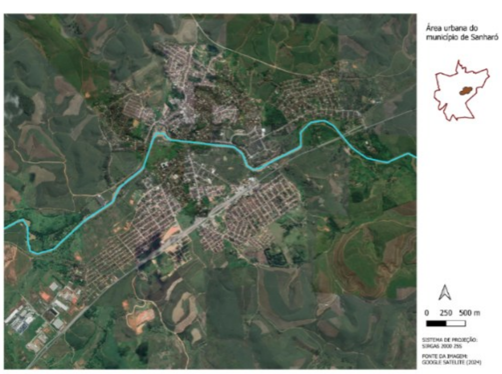


Figure 5: Urban concentration area of the municipality of Escada.
Source: Author (2024).

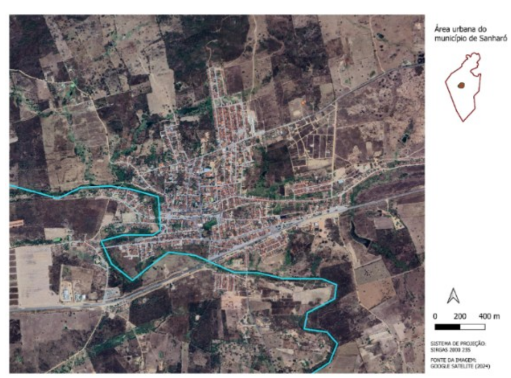


Figure 6: Urban concentration area of the municipality of Sanharó.
Source: Author (2024).

Regarding sensitivity, the municipalities presented moderate to high vulnerability in some areas. This occurred due to the overlap of areas with greater vulnerability related to poverty (Figure 7), with a predominance of households with per capita income below one-quarter of the minimum wage, and a higher number of dependents (Figure 8), whose residents are younger than 14 years or older than 60 years. These areas are located in the northwestern part of the municipality of Caruaru and in the southern part of the municipality of Bezerros.

Adaptive capacity showed heterogeneous results in relation to income (Figure 9). Caruaru has areas of very low adaptive capacity in this aspect (income). However, Bezerros and Escada have only small areas with moderate to low levels. Regarding education (Figure 10), the municipalities show most of their territory with areas ranging from very low to moderate adaptive capacity. Areas with greater adaptive capacity are located closer to urban centers.

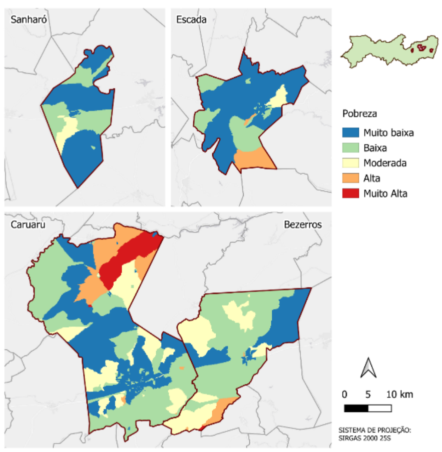


Figure 7: Social sensitivity variable: poverty.
Source: Author (2024).

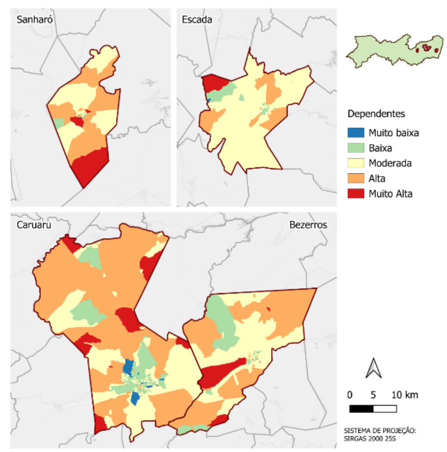


Figure 8: Social sensitivity variable: dependents.
Source: Author (2024).

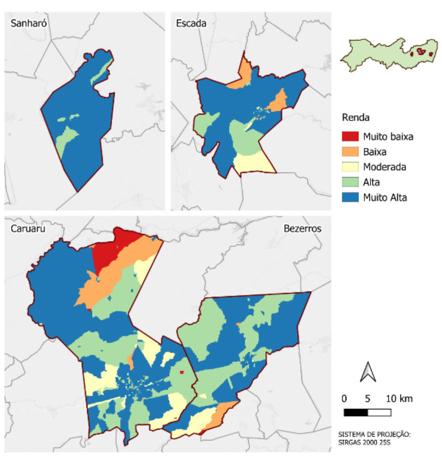


Figure 9: Social adaptive capacity variable: income.
Source: Author (2024).

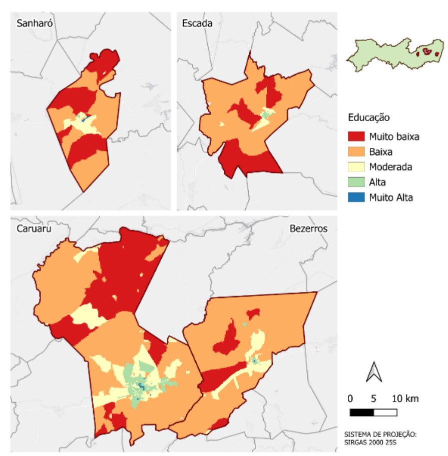


Figure 10: Social adaptive capacity variable: education.
Source: Author (2024).

Environmental vulnerability (Figure 11) resulted mainly in low and moderate vulnerability values. The municipality of Escada presented areas of high (5.09%) and very high (0.15%) vulnerability because it is the municipality most affected by rainfall and has elevation conditions favorable to flooding. Points of high vulnerability were also observed in Bezerros (0.71%) and Caruaru (0.13%) (Graph 3).

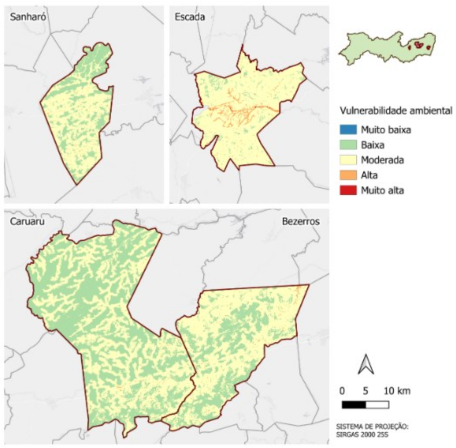
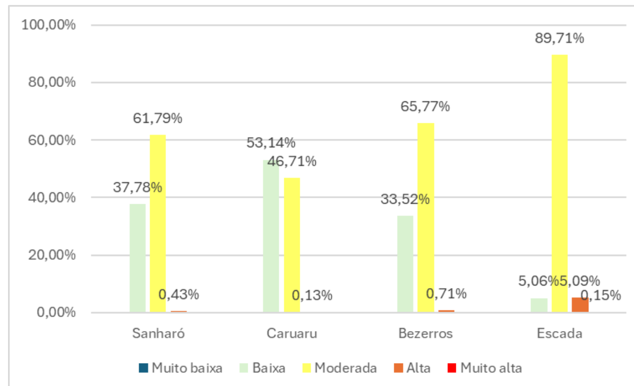


Figure 11: Environmental Vulnerability Indicator.
Source: Author (2024).



Graph 3: Percentages of the Environmental Vulnerability Indicator.
Source: Author (2024).

Regarding exposure, the municipalities are located in different regions of the state, which results in high variation in rainfall indices throughout the year (Lacerda et al., 2015). The municipality of Escada has the highest precipitation levels (Figure 12) among the four because it is part of the Zona da Mata region, which has a hot and humid climate and high rainfall. Despite the high density of water bodies (Figure 13), which is a factor of exposure, Sanharó, Caruaru, and Bezerros are located in the Agreste region of Pernambuco, characterized by a hot and dry climate with limited rainfall throughout the year.

In the sensitivity dimension, all municipalities present areas of moderate to high vulnerability. Slope (Figure 14) can hinder drainage in flatter terrains (Pathan et al., 2022), as can elevation (Figure 15) in the case of low-lying areas. Thus, Sanharó presents lower vulnerability because it is located in the Borborema Plateau, a region with altitudes ranging from 650 to 1,000 meters. Caruaru and Bezerros have areas of low to moderate vulnerability, while Escada presents the highest environmental exposure due to its location in predominantly flat terrain (CPRM, 2005)

Regarding adaptive capacity, the municipalities presented varied indices related to soil types (Figure 16). However, the municipality of Escada is predominantly composed of latosol, a porous soil with good drainage capacity that can absorb water more quickly (Ouma; Tateishi, 2014), therefore presenting very high adaptive capacity. Regarding land use and land cover (Figure 17), there was a greater occurrence of areas with moderate adaptive capacity, mainly because most of the municipalities' territory consists of anthropized areas.

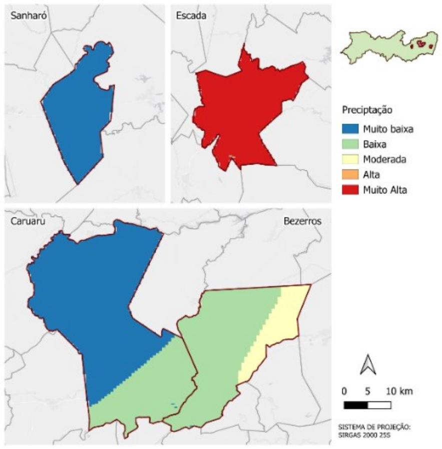


Figure 12: Environmental exposure variable: precipitation Source: Author (2024).

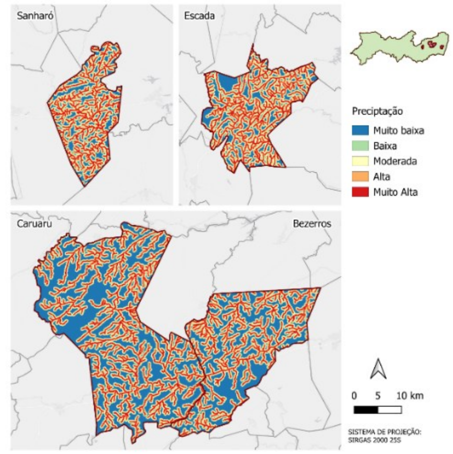


Figure 13: Environmental exposure. variable: distance from water resources. Source: Author (2024).

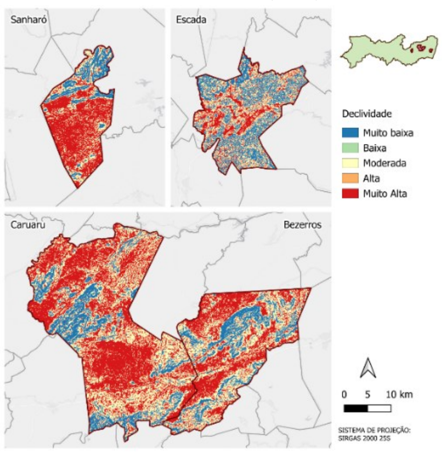


Figure 14: Environmental sensitivity variable: elevation. Source: Author (2024).

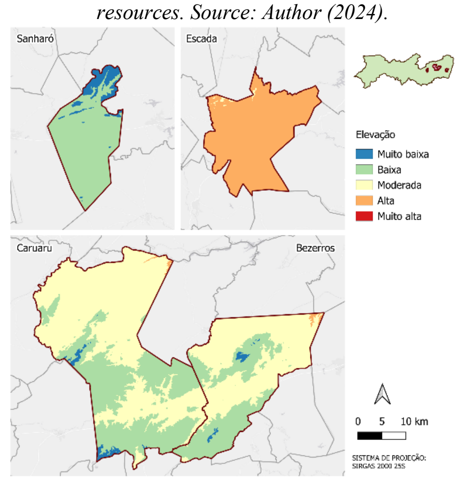


Figure 15: Environmental sensitivity variable: slope. Source: Author (2024).

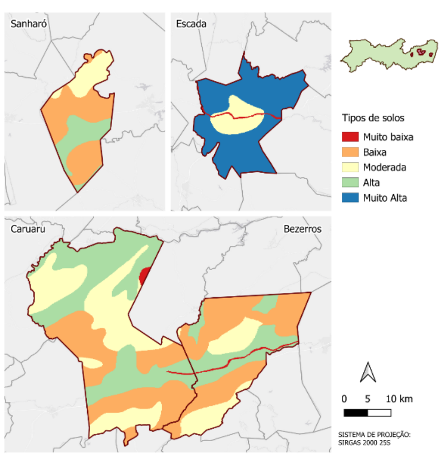


Figure 16: Environmental adaptive capacity variable: soil types. Source: Author (2024).

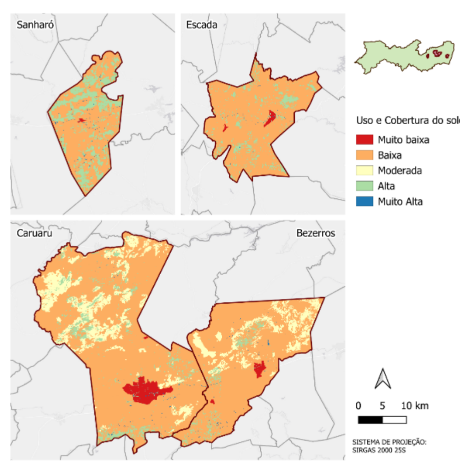


Figure 17: Environmental adaptive capacity variable: land use and land cover. Source: Author (2024).

Regarding technological vulnerability (Figure 18), Caruaru presented 1.38% of areas with high vulnerability and 1.33% with very high vulnerability. Escada had a higher percentage of areas with high and very high vulnerability, 5.81% and 2.76%, respectively. These areas are mainly located near the municipal boundaries, farther from urban centers. The other municipalities and remaining areas showed low to moderate vulnerability. Areas of very low vulnerability related to technological factors occurred in all four municipalities but were limited to small areas located in their urban centers: 0.11% in Sanharó, 0.41% in Caruaru, 0.31% in Bezerros, and 0.14% in Escada (Graph 4).

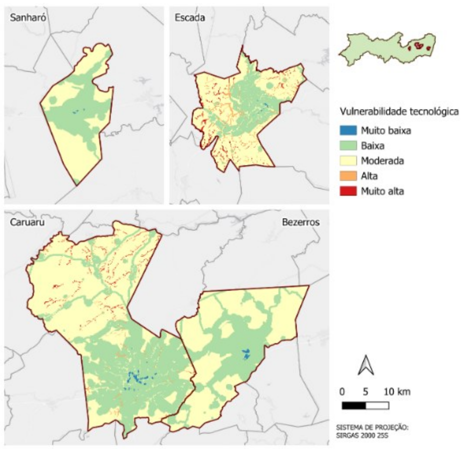
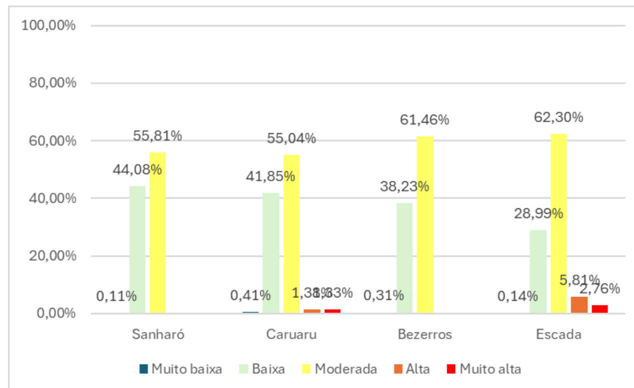


Figure 18: Technological Vulnerability Indicator. Source: Author (2024).



Graph 4: Percentages of the Technological Vulnerability Indicator. Source: Author (2024)

Regarding exposure (Figure 19), the municipalities of Bezerros and Sanharó presented only areas of very low vulnerability because no sections classified as flood risk areas appear in the flood risk map produced by the Agência Nacional de Águas (ANA). However, Bezerros experienced flooding events in 2018, and Sanharó in 2020 and 2021. According to Andrade and Szlafsztein (2018), the absence of areas classified as risk zones or the lack of previous disaster experiences may influence community risk perception and knowledge regarding prevention and response actions in the event of disasters.

Regarding the sensitivity dimension (Figure 20), the road and highway network of a region is an important factor in flood vulnerability analysis because it serves both as an evacuation route from risk areas and as access routes for rescue and emergency services (Pathan et al., 2022). The studied municipalities presented very low or low sensitivity due to the presence of a dense road network in the state; however, regions farther from urban centers show very high vulnerability regarding this factor

Regarding adaptive capacity, the indices are better near urban centers due to the location of emergency services (Figure 21), such as health facilities, and greater shelter capacity (Figure 22) due to the concentration of schools. Thus, regions farther from urban centers have lower adaptive capacity, as their populations have greater difficulty accessing services that are important for disaster prevention and response.

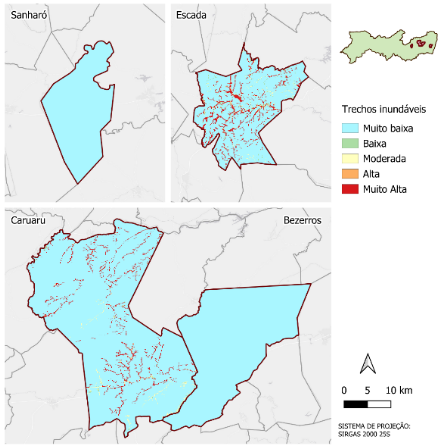


Figure 19: Technological exposure variable: flood-prone sections. Source: Author (2024).

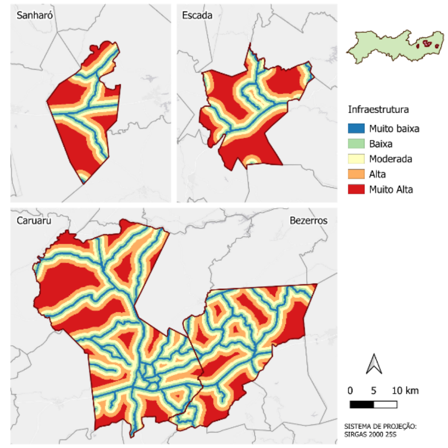


Figure 20: Technological sensitivity variable: infrastructure. Source: Author (2024).

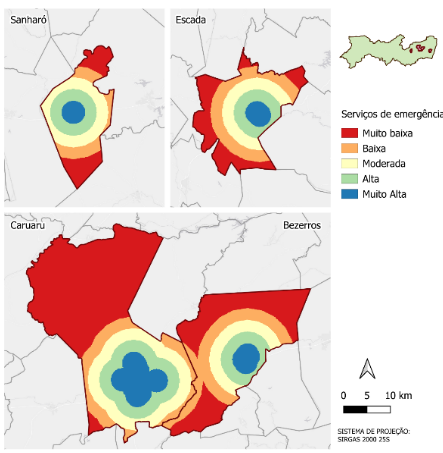


Figure 21: Technological adaptive capacity variable: emergency services. Source: Author (2024).

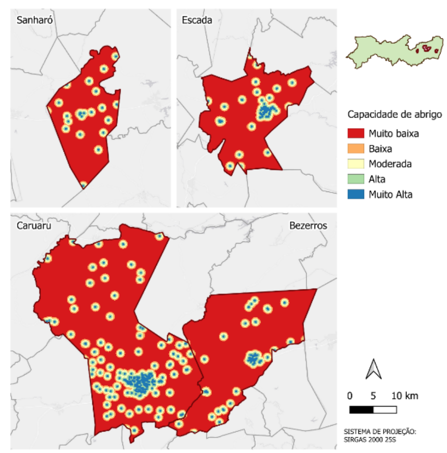


Figure 22: Technological adaptive capacity variable: shelter capacity. Source: Author (2024).

4.2 Flood vulnerability indices

The results of the IVSA and IVSAT showed similar spatial patterns. However, with the inclusion of technological factors, a reduction in areas classified as low and moderate vulnerability was observed, while areas classified as high vulnerability increased. A similar small variation between indices was also observed in the study by Barros, Mendes, and Castro (2015), which evaluated socio-environmental flood vulnerability in the urban area of Londrina, Paraná, considering infrastructure aspects.

In that study, it was observed that the highest vulnerability values were located in areas farther from urban concentrations. When infrastructure variables were included, vulnerability increased in those areas (Barros; Mendes; Castro, 2015). Similar to the case analyzed in Londrina, the increase in vulnerability with the inclusion of technological factors also occurred in the municipalities analyzed in this study. In Caruaru, areas of high vulnerability increased from 8% to 12.4%; in Bezerros, from 5% to 9.6%; and in Escada, from 13.4% to 25.7% (Table 1 and Table 2).

Sanharó did not present areas of high or very high vulnerability in the IVSA. However, in the IVSAT, approximately 6% of the municipality presented high flood vulnerability. The class of very high vulnerability did not appear in the socio-environmental index, while the index including technological factors indicated approximately 1% of areas with very high vulnerability in Caruaru.

Table 1 – List of areas by vulnerability class (IVSA).

List of areas by vulnerability class (IVSA)								
Vulnerability Class	Sanharó		Caruaru		Bezerros		Escada	
	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)
Very Low	-	-	-	-	-	-	-	-
Low	38,27	14,42	135,54	14,81	21,96	4,51	306,63	90,96
Medium	247,91	93,42	757,31	82,76	459,07	94,26	30,47	9,04
High	-	-	22,21	2,43	6,01	1,23	-	-
Very High	-	-	-	-	-	-	-	-

Source: Author (2024).

Table 2 – List of areas by vulnerability class (IVSAT).

List of areas by vulnerability class (IVSAT)								
Vulnerability Class	Sanharó		Caruaru		Bezerros		Escada	
	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)	Área (Km²)	Perc. (%)
Very Low	-	-	-	-	-	-	-	-
Low	0,02	0,01	13,42	1,47	203,05	60,23	0,02	0,01
Medium	366,92	75,34	697,55	76,23	132,52	39,31	249,88	94,14
High	120,08	24,66	196,74	21,50	1,53	0,46	15,54	5,86
Very High	0,01	0,00	7,35	0,80	-	-	-	-

Source: Author (2024).

For the IVSA (Figure 23), vulnerability areas are scattered throughout the territory, making it difficult to identify clear concentrations of highly vulnerable areas. In the IVSAT (Figure 24), with the emergence of higher index values, it becomes possible to identify the most vulnerable regions in Caruaru, Bezerros, and Escada. The highest values are mainly located in Escada and Caruaru, revealing that technological variables played a significant role, as the areas with increased vulnerability are primarily those with the poorest conditions regarding flood-prone sections and distances from roads, hospitals, and schools.

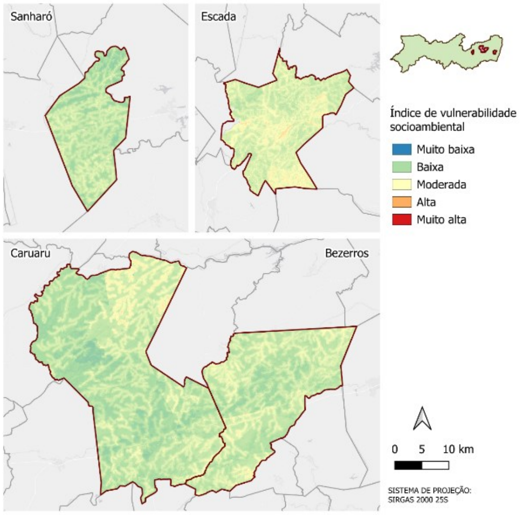


Figure 23: Socio-environmental vulnerability index. Source: Author (2024).

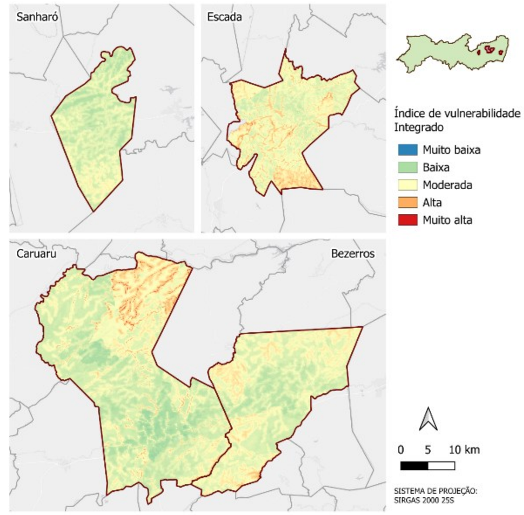


Figure 24: Integrated socio-environmental vulnerability index. Source: Author (2024).

Areas classified as having high and very high vulnerability were further analyzed using satellite images (Google Earth), which allowed a detailed assessment of the current situation in these regions. The analysis revealed that, in the four municipalities, the areas classified as most vulnerable are predominantly located in rural and sparsely populated areas that lack infrastructure.

The analysis of satellite images also identified areas of high vulnerability within urban environments or areas with greater housing density in Caruaru and Escada. Although these areas appear in smaller numbers and cover smaller portions of the territory, their identification is highly important because they represent specific locations where interventions aimed at reducing vulnerability may be particularly effective.

In Caruaru, the critical areas distributed within the urban area are located in Alto do Moura and nearby neighborhoods such as Rendeiras, Salgado, Indianópolis, Cedro, Riachão, and Deputado José Antônio Liberato (Figures 25 and 26). In Escada, critical areas are located in the industrial district, the Alvorada neighborhood, and the city center surrounding the Ipojuca River (Figures 27 and 28). These are densely built areas that contain important facilities such as industries, educational centers, and cultural infrastructure.

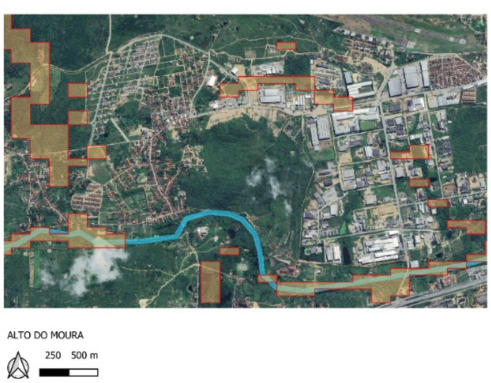


Figure 25: Most vulnerable areas in Caruaru: Alto do Moura. Source: Author (2024).

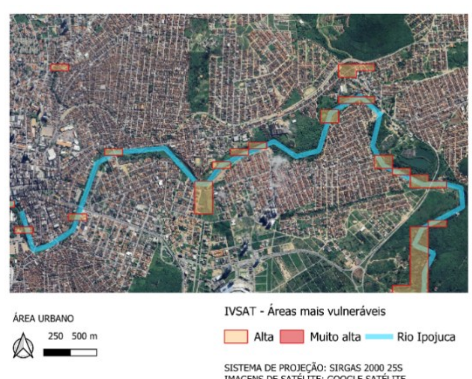


Figure 26: Most vulnerable areas in Caruaru: City center. Source: Author (2024).

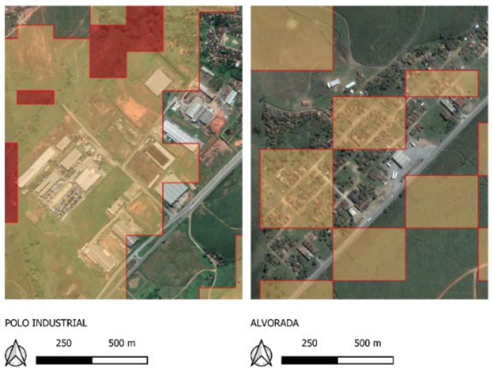


Figure 27: Most vulnerable areas in Escada.
Source: Author (2024).

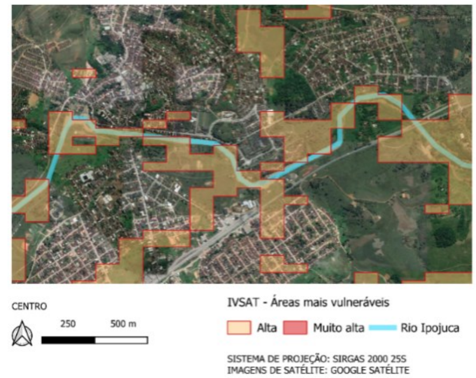


Figure 28: Most vulnerable areas in Escada.
. Source: Author (2024).

5 Final Considerations

Disasters related to flooding can be reduced through the ability to identify, measure, and assess different forms of vulnerability. Although some studies point to the limited availability of adequate frameworks for vulnerability assessment that incorporate technological factors, several studies provide approaches that can be used to structure and evaluate the effectiveness of such models.

Through the literature review, it was possible to identify social, environmental, and technological variables for analyzing socio-environmental vulnerability to flooding and the relationship between infrastructure availability and vulnerability. The inclusion of technological factors enables a comprehensive analysis that can not only identify areas requiring more urgent intervention but also indicate which vulnerability mitigation measures may be replicated.

The comparison between IVSA and IVSAT demonstrated that technological factors have a measurable impact on increasing or reducing vulnerability. This pattern suggests that prioritizing measures involving technological factors—whether structural or non-structural—may mitigate vulnerability and increase community resilience. Such actions may include educational and awareness campaigns, risk mapping, river and rainfall monitoring, and early warning systems, while also considering drainage, transportation, sanitation, and housing infrastructure to better prepare populations for disaster response.

Thus, the results highlight the importance of a multifactorial approach in assessing flood vulnerability, demonstrating that the inclusion of technological factors is essential for a more accurate evaluation. Furthermore, vulnerability indices can be integrated into public policies related to urban planning, risk management, and infrastructure development, aiming to effectively mitigate flood impacts and strengthen community resilience.

Acknowledgments

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