

Spatial distribution of socio-environmental vulnerability in urban flood-prone areas in the Municipality of Araruama-RJ

Distribuição espacial da vulnerabilidade socioambiental em áreas de inundação urbana no município de Araruama-RJ

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ABSTRACT

This study analyses socio-environmental vulnerability in Araruama, a municipality in the Lagos São João Hydrographic Region, in Rio de Janeiro, with a history of hydrometeorological disasters and a high number of homeless people. Based on 2010 Census data integrated with the flood susceptibility zone of the SGB and official and media flood records, thematic maps were developed in a GIS environment and crossed with official and media flood records between 2009 and 2023. Twenty-four affected neighbourhoods were identified. The spatialisation of exposure, combined with social vulnerability, enables the identification of the location of the most affected population. Proximity to water bodies was common among the most critical sectors. Areas of extreme socio-environmental vulnerability are located near a river and exhibit low response capacity. The study highlights the need to adopt monitoring and forecasting systems and public policies for the adaptation of the most affected neighbourhoods

Keywords: Vulnerability. Flood. Socio-environmental.

RESUMO

Este estudo analisa a vulnerabilidade socioambiental em Araruama, município da Região Hidrográfica Lagos São João, no Rio de Janeiro, com histórico de desastres hidrometeorológicos e elevado número de pessoas desabrigadas. A partir de dados do Censo 2010 integrados à mancha de suscetibilidade à inundação do SGB e registros de inundações oficiais e midiáticos, foram elaborados mapas temáticos em ambiente SIG e cruzados com registros oficiais e midiáticos de inundações entre 2009 e 2023. Foram identificados 24 bairros atingidos. Os resultados da espacialização da exposição, junto com a vulnerabilidade social, permitem identificar a localização da população mais atingida. A proximidade a corpos de água foi comum entre os setores mais críticos. Áreas de vulnerabilidade socioambiental extrema localizam-se próximas a um rio e apresentam baixa capacidade de resposta. O estudo ressalta a necessidade de adotar sistemas de monitoramento e previsão, e políticas públicas direcionadas para adaptação dos bairros mais atingidos.

Palavras-chave: Vulnerabilidade. Inundação. Socioambiental.

1 INTRODUCTION

Climate change and its effects, intensified by human activities, have increased the occurrence of disasters, and in Brazil, this is also a reality. The National Centre for Monitoring and Early Warning of Natural Disasters (Cemaden) (Ministry of Science, Technology and Innovation, 2024) pointed out an increase in the occurrences of hydrometeorological disasters since 2011, among them floods.

In Brazilian territory, floods represent one of the main socio-environmental challenges. From this perspective, understanding the distribution of socio-environmental vulnerability in areas with the potential to be flooded is essential to guide mitigation and adaptation policies. The occupation of areas with the potential to be flooded by vulnerable populations aggravates the impacts of floods (De Andrade Cristo *et al.*, 2022; Macedo, 2015; Zanetti *et al.*, 2016).

The definition of socio-environmental vulnerability can be understood as the coexistence or spatial overlap of poor, discriminated, and highly deprived population groups (social vulnerability) who live or circulate in risk or environmentally degraded areas (environmental vulnerability) (Cartier *et al.*, 2009). This definition aligns with the vulnerability and exposure framework for climate change in the Sixth Report of the Intergovernmental Panel on Climate Change (IPCC, 2023). Since vulnerability is understood as the combination of the degree of alteration the system may undergo (directly, indirectly, positively or negatively) with the degree to which the system's elements (institutions, people and organisations) are prepared for possible climatic impacts. And exposure is understood as the presence of people; livelihoods; species or ecosystems; functions, services and environmental resources; infrastructure; or economic, social or cultural assets in locations and environments that may be negatively affected (AdaptaBrasil, 2025; IPCC, 2014, 2023).

This study aimed to investigate the spatial distribution of socio-environmental vulnerability in the municipality of Araruama-RJ and answer the question: how is socio-environmental vulnerability distributed in urban areas subject to flood risks in Araruama?

The study area is located in the Lagos São João Watershed Hydrographic Region, where the municipality of Araruama presents recurrent impacts related to floods. Until 2014, Araruama was the municipality with the highest number of affected people in the region, with extreme events recorded in 2007, 2010 (Coppetec, 2014) and 2016, according to the Integrated Disaster Information System – S2ID, a platform associated with the National Secretariat for Protection and Civil Defense (Sedec) of the Ministry of Integration and Regional Development (Brazil, 2024). This history of recurrence and event intensity highlights the need to analyse socio-environmental vulnerability, thereby justifying the development of this study.

1.1 DISASTER, RISK AND VULNERABILITY: CONCEPTUAL FRAMEWORK AND STATE OF THE ART

Disasters can have various effects on society, with impacts that can manifest in the short or long term (Freitas, 2020; Inouye *et al.*, 2015). The definition of disasters in this study aligns with the United Nations Department for Disaster Risk Reduction's Global Assessment Report (UNDRR, 2022), which defines disasters as “serious disturbances that affect the functioning of communities or societies at any scale.” In this study, the term “natural disaster” is not used, as it perpetuates the blame of nature for disasters and removes anthropogenic responsibility (Raju *et al.*, 2022).

From 2001 to 2020, the number of disasters worldwide increased from 350 to 500 per year and will continue to increase (UNDRR, 2022). This scenario is similar in Brazil, where the National Centre for Monitoring and Early Warning of Natural Disasters (Cemaden) recorded the highest number of disaster occurrences in Brazilian territory from 2011 to 2023 (MCTI/Cemaden, 2024). The research pointed to a significant concentration of events in the southeast and south, with predominance of hydrometeorological events.

These occurrences reflect the regions' susceptibility to disasters related to intense rainfall driven by climate change, deficient infrastructure, and municipalities' low adaptive capacity (Ribeiro Gomes *et al.*, 2021). These results indicate a trend of increasing extreme events in Brazil over recent years, particularly since 2017 (Cemaden, 2024), reinforcing the need for urgent actions to reduce the frequency of disasters and risk exposure.

Risk is defined as the potential for a hazardous event for humans that can cause harm (IPCC, 2023). The risk framework addresses the intersection or interaction among exposure, vulnerability, and hazard. This definition of risk takes into account social and environmental dimensions, thereby enabling its analysis and assisting decision-makers in developing strategies to mitigate disasters (Barendrecht *et al.*, 2017).

Disasters tend to be more impactful for the most vulnerable people who are exposed to an extreme event. The vulnerability presented by the IPCC (2007, 2014, 2023) refers to vulnerable, sensitive and exposed people to climate change. Thus, vulnerability is presented as the degree or magnitude of systems that are exposed, sensitive and with low adaptive capacity to climate change and its effects.

In the current context of climate risk, especially based on the Fifth and Sixth IPCC Reports (2014, 2023), vulnerability and exposure begin to be understood as different but interconnected dimensions. Vulnerability indicates the level at which individuals, organisations or systems may be affected, taking into account their sensitivity and ability to adapt. On the other hand, exposure refers to the presence of populations, infrastructures, environmental services and economic activities in regions prone to damage (IPCC, 2012, 2023).

However, separating these components rigidly, as proposed in earlier versions, may complicate communication with managers and decision-makers in complex socio-environmental contexts (Ishtiaque *et al.*, 2022). Thus, this study adopts the integrated approach suggested by Cartier *et al.* (2009) and Goerl (2012), which states that socio-environmental vulnerability arises from the intersection between socially vulnerable groups and environmentally delicate or exposed areas. This strategy aligns with the IPCC's “climate risk flower,” in which socio-environmental vulnerability arises from the intersection of the petals of vulnerability and exposure. This guides the creation of indicators that capture these two dimensions simultaneously.

Socio-environmental vulnerability is an important concept for understanding the relationship between the environment and society (Siqueira Malta, 2017).

Socio-environmental vulnerability aims to understand the response capacity of socially vulnerable individuals exposed to damaging disturbances in the face of climate change and its effects (Alves, 2021; Cartier *et al.*, 2009).

The assessment of socio-environmental vulnerability must address the interdependence between social, economic and environmental factors. Quantitative and spatial approaches, using Geographic Information Systems (GIS) for the integrated analysis of census, environmental and remote sensing data, assist in this task (Mattedi *et al.*, 2024).

Socio-environmental vulnerability can be assessed from the spatial overlap between population groups exposed to hazards (Cardoso, 2017; Cartier *et al.*, 2009; Krellenberg *et al.*, 2014). Social inequality plays an important role in increasing population exposure to extreme events, such as floods (Cardoso, 2017; Krellenberg *et al.*, 2014). In this sense, it should be highlighted that the location of the poorest population in hazardous areas is a structural characteristic of many Brazilian cities (Cardoso, 2017).

The estimation of exposure of vulnerable populations results from the juxtaposition of physical and social data (Chand *et al.*, 2024). The integration of social vulnerability with flood or terrain-susceptibility data highlights how the intersection of poverty and exposure can redefine the geography of risk (Fox, 2024; Goerl, 2012). In this way, at the municipal scale, vulnerability can be defined as inversely proportional to municipalities' response capacity and resilience (Gupta *et al.*, 2020).

Through spatial methodologies to map areas susceptible to hydrometeorological events that use GIS and remote sensing data, it is possible to identify system exposure, allowing efficient public policies to be based on detailed spatial analyses (Lins-de-Barros, 2010; Mattedi *et al.*, 2024; Silva *et al.*, 2018; Zanetti *et al.*, 2016).

Urban infrastructure also influences the spatial distribution of socio-environmental vulnerability. The precariousness of drainage, transportation and sanitation infrastructure amplifies the impacts of adverse hydrological events, reinforcing the need for adaptive urban policies (Cardoso, 2017; Chaves *et al.*, 2022; Gaedke *et al.*, 2020).

The study of socio-environmental vulnerability converges towards the need for interdisciplinary approaches and integrated methodologies. The use of GIS, census data and remote sensing techniques is widely employed to identify spatial patterns of vulnerability and support adaptation strategies. Furthermore, the relationship between social vulnerability and exposure is further reinforced, demonstrating that economically disadvantaged populations are disproportionately affected by disasters and requiring structural and social interventions.

2 METHODOLOGY AND STUDY AREA

2.1 STUDY AREA

The Lagos São João Hydrographic Region is composed of 9 municipalities in the state of Rio de Janeiro, among them Araruama. This municipality covers 639 km², with 5 districts, 59 neighbourhoods, and 312 census sectors (Figure 1) (IBGE, 2010). This region is coastal, with a tropical climate characterised by hot, humid summers and dry winters.

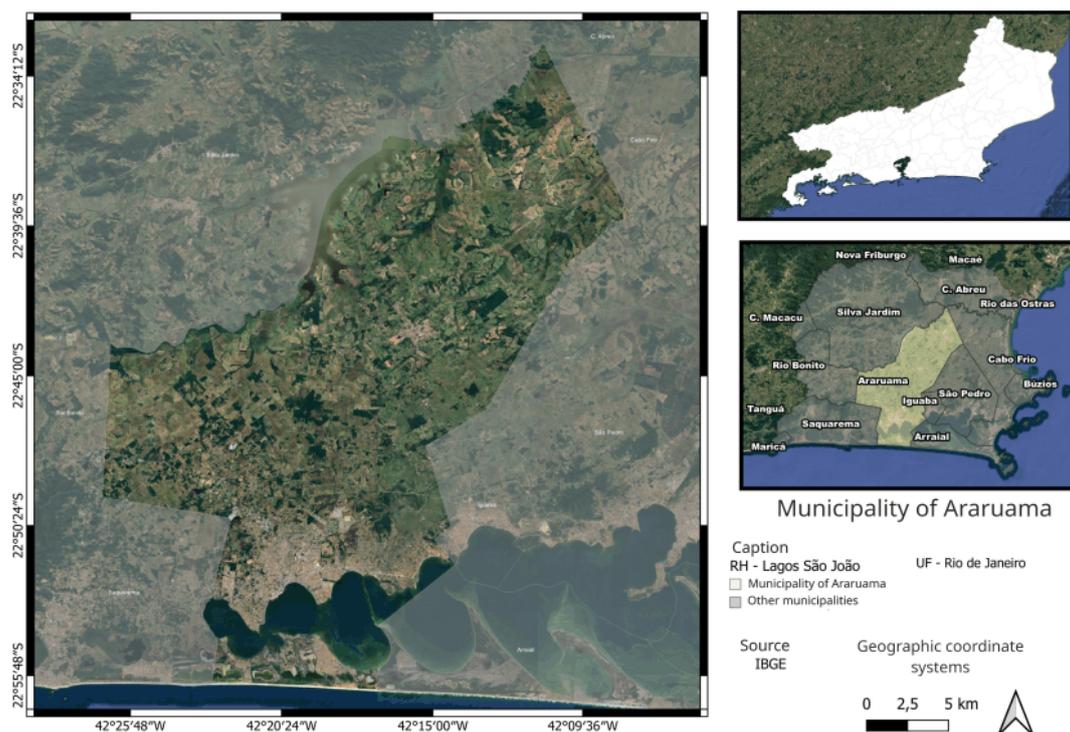


Figure 1 – Location of the Municipality of Araruama-RJ

Source: The authors, 2025

The Integrated Disaster Information System (S2ID, 2024) database records 2 flood events in the city of Araruama. The first record corresponds to the 2010 event, with 122 millimetres of precipitation in 4 hours and a total of 100 homeless people. The second record corresponds to 2016, with precipitation of 148 millimetres in 6 hours, leaving more than 2,500 people displaced (G1, 2016).

The technical report of the State Water Resources Plan of Rio de Janeiro (Perh-RJ) (Coppetec, 2014) presents records of disasters in Araruama between 2000 and 2012. The report highlights two significant flood records: the first in January 2007, which affected 18,000 people, and the second in April 2010, which affected 20,000 people (Coppetec, 2014, p.114).

Perh-RJ and S2ID have only the 2010 record in common. Regarding the locations affected by floods, according to the Basic Sanitation Plan of Araruama (Serenco, 2014), the region presents five flood scenarios: slow or fluvial floods in flat regions, rapid floods or torrential rains, floods due to urban runoff in small basins up to 10 km², floods by torrents in areas with slopes above 6%, and backwater flooding from the stormwater drainage network. The document states that until 2014, there were eight neighbourhoods with flood records, but it does not classify the scenario. The neighbourhoods affected until 2014 were: Bananeiras, Sapolândia, Iguabinha, Coqueiral, Clube dos Engenheiros, Vila Capri, Fazendinha, Park Hotel (Serenco, 2014, p. 144).

2.2 RESEARCH STAGES

For the development of the study, a GIS database was constructed that allowed the generation and application of a synthetic indicator to assess socio-environmental vulnerability in flood areas in Araruama. For the execution of the research, census sector data from the 2010 Demographic Census (IBGE, 2010) and the Susceptibility Map of the Geological Survey of Brazil from 2018 (SGB, 2018) were collected for analysis in a GIS environment.

To adapt the proposed methodology to the theoretical framework of climate risk (IPCC 2014, 2023), it would be necessary to reformulate it as follows:

Climate impact risk: hazard (in this case, floods); vulnerability (sensitivity; adaptive capacity); exposure (demography and density). Thus, the proposed IVS indicators would be partly linked to sensitivity (txd, E, R and IDHM) and partly linked to exposure (nm, mm, dd), together with the floodable percentage indicators (PI), to provide the socio-environmental vulnerability index, while respecting the updated analytical framework.

The adaptive capacity indicators are absent in the study, classically defined by the existence of municipal contingency plans, early warning systems, institutional capacity, etc. Since the study concerns only the municipality of Araruama, the adaptive capacity factor should not vary spatially, which in this case makes the sensitivity factor equivalent to vulnerability.

2.3 VULNERABILITY INDEX

The research began with the collection of quantitative data and cartographic bases to be processed in the GIS environment. The quantitative data are georeferenced census variables that allow for verifying the exposure and response capacity of the local population. These variables are used to estimate the Social Vulnerability Index (IVS) in each census sector (Equation 1), as proposed by Goerl (2012).

$$IVS = \frac{Nm+Mm+Dd+Txd+E+R}{IDHM} \text{ Equation (1)}$$

In the estimation of IVS, Nm is the number of residents of the census sector, Mm is the average number of residents per sector, Dd is the demographic density, Txd is the dependency rate corresponding to the percentage of elderly above 65 years and children below 12 years, E (Education) is the percentage of illiterate people above 12 years, R (Income) is the sum of the percentage of heads of household without income and with income up to 1 minimum wage. IDHM is the Municipal Human Development Index published by the Institute of Applied Economic Research (Ipea, 2015; Ipea, 2023). The statistical normalisation technique (Equation 2) was applied to all indicators, since the magnitudes and dimensions of the indicators that comprise IVS are not homogeneous. The indicators of the index characterise each census sector, except for IDHM, which corresponds to the municipality level.

$$Vescalonado = \frac{Vobservado - Vmínimo}{Vmaior - Vmínimo} \text{ Equation (2)}$$

The normalisation of Equation 2 standardised the six indicators in the numerator of IVS to obtain results between 0 and 1. The normalised indicators were classified according to the Atlas of Social Vulnerability of Brazilian Municipalities (Ipea, 2017) into: very low (0 to 0.2), low (> 0.2 to 0.3), medium (> 0.3 to 0.4), high (> 0.4 to 0.5) and very high (> 0.5 to 1). The indicators were organised to be integrated in GIS with the vector of census sectors from IBGE (IBGE, 2010), which has the original scale of 1:250,000, as described in the technical documentation of IBGE for the 2010 census grid, using the SIRGAS 2000 Geodetic System. The municipal-level extraction allowed detailed analysis of the area of interest.

2.4 FLOODABLE PERCENTAGE

The SGB (2014), in the Susceptibility Map to mass gravitational movements and flooding, defines areas susceptible to flooding as resulting from natural topographic influence. The identification of areas susceptible to flooding was based on the HAND algorithm (Rennó *et al.*, 2008). This algorithm calculates the height of a given point of the terrain relative to the nearest drainage network. It thus generates an

indicator of hydrological connectivity between the slope and the channel, which can be used as a tool to assist in the topographic analysis aimed at flood susceptibility (Rennó *et al.*, 2015). The SGB defines three degrees of flood susceptibility, according to the HAND value of the terrain: low (high terrace), medium (low terrace) and high (alluvial plain) (SGB, 2014).

In the present research, the “Susceptibility Map to mass gravitational movements and flooding: Municipality of Araruama, RJ” developed by Pedrazzi and Lana (2018) was used to extract the Floodable Percentage (Equation 3) of the exposed sectors. Thus, PI indicates the degree of impact in each sector. For this analysis, all susceptible areas were considered, without differentiation of susceptibility degrees.

$$PI = \frac{AI}{AT} \text{ Equation (3)}$$

Where AI is the area with potential to be flooded of the sector at the sectoral scale, AT is the total area of the sector according to IBGE, and PI is the Floodable Percentage (%) of the sectoral area.

2.5 SOCIO-ENVIRONMENTAL VULNERABILITY INDEX (IVSA)

Socio-environmental vulnerability was determined by the integration between the Social Vulnerability Index (IVS) and the Floodable Percentage (PI). It is considered that socio-environmental vulnerability manifests when IVS is exposed to areas susceptible to flooding. The spatial analysis of this interaction is enabled through GIS, allowing the integrated spatialization of vulnerable areas and terrain susceptible to flooding.

The calculations were performed in the field calculator in the vector layer with the indicators already georeferenced. To obtain the results, Equation 4 was applied, where IVSA represents Socio-environmental Vulnerability, which combines the Social Vulnerability Index (IVS) and the Floodable Percentage (PI).

Both IVS and PI were previously normalised also in the field calculator, presenting rescaled values in the continuous interval from 0 to 1, where 1 represents the extreme of vulnerability. In this research, exposure, which integrates the definition of risk (UNDRR, 2022) and the definition of vulnerability by IPCC (2014, 2023), is highlighted as a key factor in socio-environmental studies.

$$IVSA = IV \times PI \text{ Equation (4)}$$

The result of applying IVSA was compared with information on flood events in the study region, obtained from records in newspapers, electronic magazines, social networks and official documents related to the Basic Sanitation report of the Municipality of Araruama (Serenco, 2014). The media data collection covered the period from 2007 to 2023 and was complemented with information provided by the Araruama City Hall through the Serenco document, by S2ID (2024) and by Fundação Coppetec (2012).

The year 2007 was adopted as the beginning of the time interval due to the first official record presented by Coppetec (2012). For the selection of media records, the keywords “flood”, “flooding”, “inundation”, and “Araruama” were used, associated with the respective years in the analysed interval. Based on the collected information, a database on flood events recorded in the media was developed. This database allowed comparing and validating the areas identified by the media records with the occurrence of events documented in the region.

3 RESULTS AND DISCUSSION

3.1 VULNERABILITY INDEX

The results obtained were georeferenced products of the social and environmental spectrum in relation to the area of the sector in terrain with potential to be flooded, and finally, the socio-environmental vulnerability map. The first product refers to the IVS of the Municipality of Araruama (Figure 2) integrated with the locations where the city administration indicated flood records up to the year 2014. It was verified the occurrence of 60 sectors in the Very High class, 60 sectors in the High class, 105 in the Medium IVS class, 52 in the Low class and 20 in the Very Low class. It is noted that the Medium, High and Very High classes of social vulnerability are distributed near the Limão and Araruama Lagoon rivers, and also near areas with flood records up to 2014 (Serenco, 2014).

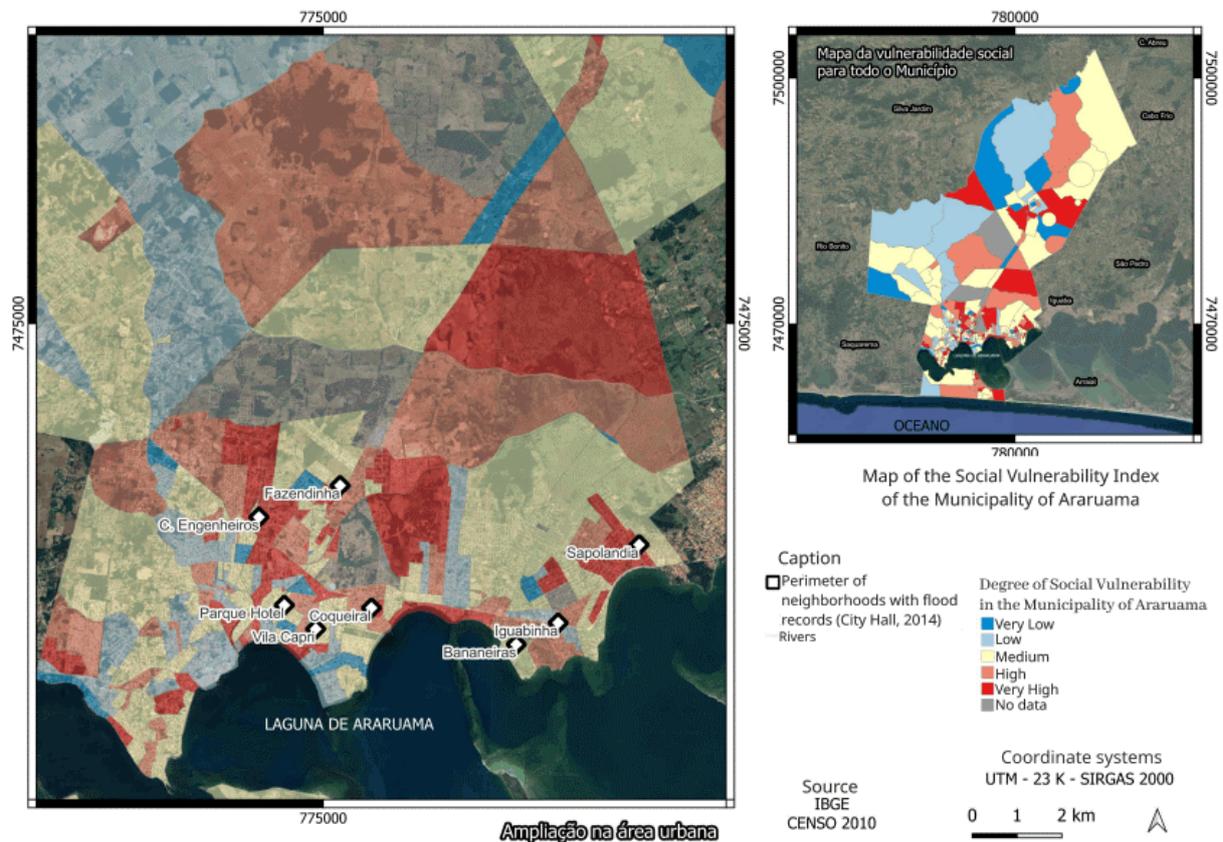


Figure 2 – Vulnerability Map of the social spectrum of the municipality of Araruama

Source: The authors, 2025

With the Number of Residents indicator, it is possible to quantify how many people are present per class. It can be observed that the Medium IVS class has the highest number of people (34,467), followed by the Very High IVS class (32,675), High IVS (25,971), Low IVS (10,417), and Very Low IVS (4,240). The Very High and High IVS classes correspond to 52.7% of the population of Araruama. This magnitude highlights the concerning situation of social vulnerability in the municipality.

In addition to identifying the spatial distribution of social vulnerability, it is important to identify the processes or dimensions of the problem that contribute to the results in the different sectors. For this purpose, a statistical analysis was conducted of the six indicators that characterise each census sector in the IVS. The contribution is obtained by dividing the average of the indicator by the sum of the averages of all indicators. The analysis highlights the Dependency indicator as the one with the highest contribution, 40%, in the IVS index in Araruama (Table 1).

Table 1 – Contribution of the dimensions to the IVS of Araruama-RJ

<i>Variables</i>	<i>Average</i>	<i>Sum of averages</i>	<i>Contribution (Average/Σ Average)</i>
Population Density (Dd)	0,03	1,6	0,018
Number of Residents (Nm)	0,20		0,125
Average number of residents (Mm)	0,21		0,131
Education (E)	0,15		0,093
Income (R)	0,36		0,225
Dependency ratio (Txd)	0,65		0,406

Source: The authors, 2025

In the sector with the highest IVS, the indicators with the greatest contribution were Education, Income and Dependency. Although Dependency is the variable with the greatest overall influence on IVS in Araruama, in the extreme sector of the Very High IVS class, it was Education that contributed the most after normalisation. Nevertheless, Income and Dependency are also in the Very High class, leading to an increase in the IVS value.

Table 2 – Characteristics of the extreme sector of the Social Vulnerability Index

<i>Location: Limão River</i>
IVS VERY HIGH
Km ² : 0,443
Dd: 0,005
Nm: 478
Mm: 3,51
E: 1 (35%)
R: 0,8 (80%)
Txd: 0,6 (25%)

Source: The authors, 2025

The indicators for the sector classified as extreme Very High, located in the Rio do Limão neighbourhood, showed that 80% of residents had an income of at most one minimum wage or had none. Furthermore, it was observed that 35% of the resident population in the sector consisted of illiterate individuals, while 25% had some form of dependency, such as children or elderly persons. Retired elderly may be the only source of income due to retirement; however, the elderly and children may compromise rapid decision-making in the face of a hazardous event (Saito *et al.*, 2021).

3.2 FLOODABLE PERCENTAGE

The result of the floodable percentage of each sector in Araruama (Figure 3) was extracted in the GIS environment using the flood susceptibility vector of the SGB overlaid on the census vector grid. Sectors located within the area with potential to be flooded were considered exposed sectors. The percentage of the area of intersection between the sector and the flood susceptibility indicates exposure. The degree of exposure (Figure 3) is classified following the vulnerability symbology of the Social Vulnerability Atlas

(Ipea, 2015), considering the thresholds: 0 – 0.2, very low; > 0.2 – 0.3, low; > 0.3 – 0.4, medium; > 0.4 – 0.5, high; and > 0.5 – 1, very high.

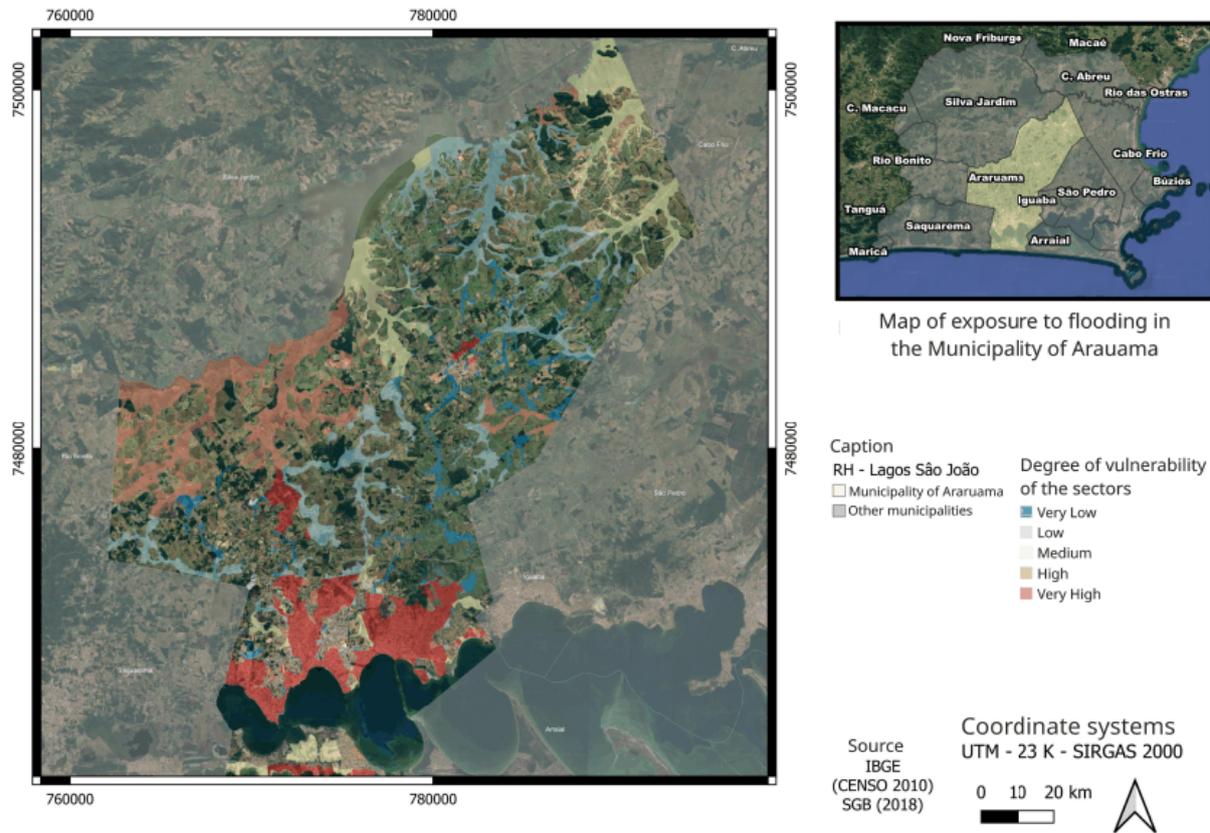


Figure 3 – Map of exposure to flooding in Araruama-RJ

Source: The authors, 2025

Of the 312 sectors of Araruama, 88.1% are exposed to flooding to some degree. Approximately 57.08% were found in the Very High exposure class, 6.7% in the High class, 6.7% in the Medium class, 10.07% in the Low class, and 23.3% in the Very Low class. The High and Very High exposure classes affect 55.6% of the population, more than half of Araruama’s population, highlighting the concerning situation of the municipality.

The spatial distribution of exposure (Figure 3) shows that the most exposed sectors are those in the urban area near the Araruama Lagoon shore, Mataruna River and Limão River. The sector with the highest exposure to flooding is located in the Parque Mataruna neighbourhood and has an IVS value of 0.4, within the Medium IVS class. The evaluation of the flood event databases shows no occurrence records for this neighbourhood (Serenco, 2014).

The different flood record databases in Araruama do not show consistency in relation to the number of disasters that occurred. While the Integrated Disaster Information System (S2ID, 2024) presents records of flood occurrences in 2010 and 2016, the State Water Resources Plan of the State of Rio de Janeiro presents records in the years 2007 and 2010 (Coppetec, p. 48). Seeking to consolidate flood event data, the year of occurrence and the affected locations, a media survey was conducted on websites, newspapers, reports and social networks to compare with existing data. The survey identified 24 neighbourhoods with media-recorded flooding events from 2009 to 2023 (Table 3). In 2016, the record for the most neighbourhoods affected in a single event was 11. All neighbourhoods affected in 2016 are included in the SGB flood susceptibility map, but are not indicated in the Serenco (2014) report.

Table 3 – Media records of floods in the Municipality of Araruama in the time interval 2009–2023

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Total of neighbourhoods	1	5	0	4	1	0	1	11	6	0	3	8	3	8	5

Source: The authors, 2025

Over the years, there has been significant variability in the number of affected neighbourhoods and precipitation totals since 2016. However, the 2016 event was too impactful and was considered the worst disaster since 2009. In this event, the Araruama police station and the Regional Hospital (G1, 2016) were affected, causing disruption in access to public services.

3.3 SOCIO-ENVIRONMENTAL VULNERABILITY AND INTEGRATION WITH MEDIA RECORDS

Exposure is of great importance in building the IVSA in the research and has resulted in the product shown in Figure 4. The spatial distribution of IVSA results from the crossing of IVS with PI of the terrain that can be flooded (Figure 4). The spatial distribution shows that the Very Low and Medium IVSA classes are predominant in Araruama and distributed throughout the urban area. Additionally, it is possible to note that the Very High IVSA class moves away from the city centre, heading toward the periphery.

In Figure 4, the sectors in red represent the most critical locations in terms of socio-environmental vulnerability, since they bring together social and exposure factors that may amplify flood impacts. The locations of neighbourhoods with flood records identified in the media survey are shown in Figure 4. The neighbourhoods that presented records, along with the number of events recorded in the media, are listed in Table 4.

Table 4 – Neighbourhoods with media records between 2009 and 2023

Neighborhoods	Number of events by neighbourhood
Parque Mataruna	8
Centro	6
Rio do Limão	6
Bananeiras	5
Areal	4
Boa perna	4
Havai	3
Clube dos Engenheiros	3
Parque Hotel	3
Vila Capri	3
Parati	2
Praia do Hospício	2

Neighborhoods	Number of events by neighbourhood
Sapolandia	2
Ponte dos Leites	1
Praça da Bandeira	1
Pontinha	1
Quinze de novembro	1
Iguabinha	1
São Vicente	1
Barbudo	1
Fazendinha	1
Jardim São Paulo	1
Novo Horizonte	1
Mutirão	1

Source: The authors, 2025

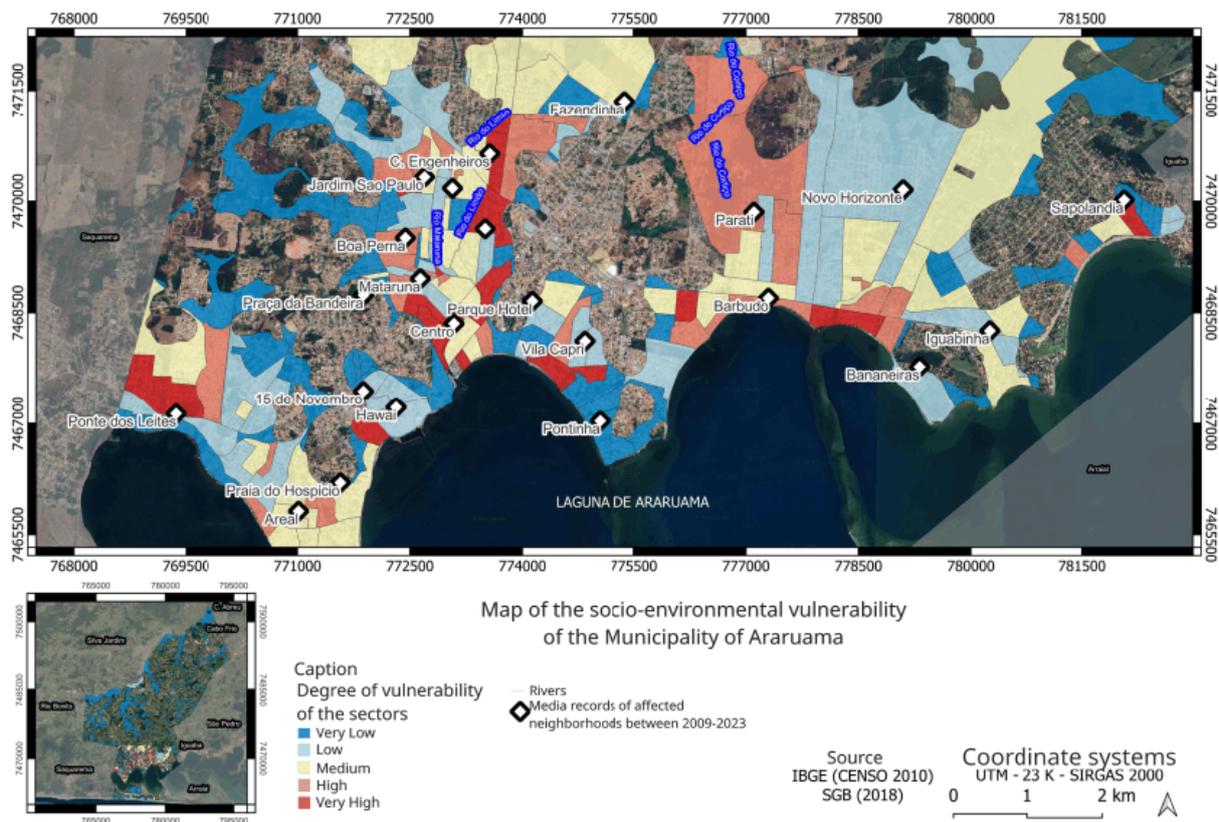


Figure 4 – IVSA and integration with records of flood occurrences in Araruama-RJ

Source: The authors, 2025

The locations affected by floods identified in the media survey are found in susceptible areas. The data from Araruama indicate 8 critical neighbourhoods with flood records (Serenco, 2014), but the media survey identified 24 neighbourhoods. A similar result was found by Farias and Mendonça (2022) in their study in Francisco Beltrão, a municipality located in the state of Paraná, identifying a greater

number of locations with flood susceptibility than those officially recorded by the government and government agencies.

The highest IVSA value (1.00) was observed in only one sector, the Clube dos Engenheiros neighbourhood, which Serenco (2014) cited as having flood records. Table 5 presents the indicators of the sector with extreme IVSA Very High value, along with the corresponding IVS and PI. The sector confirms the relevance of the Education, Income and Dependency indicators, with Income being the one with the greatest influence on the sector's IVSA index. The Dependency indicator reflects that 29% of the residents of the sector are elderly or children. In the sector located near a river, this indicator suggests a concerning situation, as these more vulnerable groups are concentrated in areas of high socio-environmental vulnerability and require priority attention in flood events.

Additionally, 62% of the heads of household in this sector have an income of at most one minimum wage, which indicates that most of the population may not have the resources to replace the goods lost in case of a disaster. These data reinforce the study by Rentschler *et al.* (2022), which showed, on a global scale, that poorer populations are the most impacted by floods, highlighting the socioeconomic fragility of this portion of the population. These results are aligned with the reality observed in Araruama, confirming the relationship between vulnerability, poverty and exposure, and exacerbated by the dependency of part of the population.

Table 5 – Table of the dimensions of extreme IVS, P.I and IVSA sectors

<i>Indexes and Variables</i>	<i>Sector with extremely very high IVS</i>	<i>Sector with very high extreme PI</i>	<i>Sector with very high extreme IVSA</i>
IVS	1	0,4	0,9
IVSA	0,5	0,6	1
Nm	478	527	1050
Mm	3,5	3,23	3,41
R %	80%	36%	62%
E %	35%	3%	21%
Txd%	25%	19%	29%
Area km ²	0,4	0,01	0,09
Area i km ²	0,2	0,01	0,09
Pi %	58%	100%	99%
Neighborhoods	Rio do Limão	Parque Mataruna	Clube dos Engenheiros
Floods	6	8	3

Source: The authors, 2025

When compared, in the sectors that present extreme values in each of the indicators, IVS, PI and IVSA (Figure 5), it is possible to verify the importance of considering the overlap of vulnerability and exposure in the assessment. The sector with extreme Very High IVS value presents a high percentage of people with income equal to or less than half a minimum wage and other indicators of social exclusion, such as the high illiteracy rate and dependency. The population is smaller than the other indices and is located in a neighbourhood with 6 media-recorded flood events.

In the sector with extreme Very High PI value, the numbers reflect a sector with 100% of the area exposed to floods. The number of residents is even higher than in the sector with extreme Very High IVS value. The exposure of dependents in the sector to the flooded area is still of serious concern.

However, income in this sector is higher, indicating that this group is in a situation of exposure but with a more favourable economic situation, suggesting a greater capacity to adapt or replace what was damaged, perhaps more quickly than in sectors with extreme Very High IVS and Very High IVSA values. In addition to income, the low illiteracy rate shows a higher level of education than in the other two sectors. The low illiteracy rate suggests that the residents of this sector may understand what is happening around them more quickly, favouring rapid decision-making regarding flooding and an efficient response to the event. This sector is located in the Parque Mataruna neighbourhood, which suffered 8 floods, the highest number of events among the neighbourhoods found in the media survey. This reinforces the idea that it is a critical zone from the exposure point of view, but not from the social spectrum. In addition, the exposed population is small, which favours a reduction in IVSA.

The sector with extreme Very High IVSA value identified presents the highest Dependency indicator among the other extreme sectors (Table 3), but Income was the most influential indicator in the IVSA of this sector. Additionally, the extreme IVSA sector also presented the largest number of people in the sector among all extreme sectors, indicating that the interaction between IV with a high number of exposed people, among them dependents, increases its degree of socio-environmental vulnerability. This sector is located in the Clube dos Engenheiros neighbourhood.

The comparison between the three indicators suggests that analysing exposure or social vulnerability separately may neglect assistance to the most vulnerable in the event of floods. The joint assessment of these dimensions allows for better targeting of efforts and resources to serve the population exposed to the disaster and with lower response capacity.

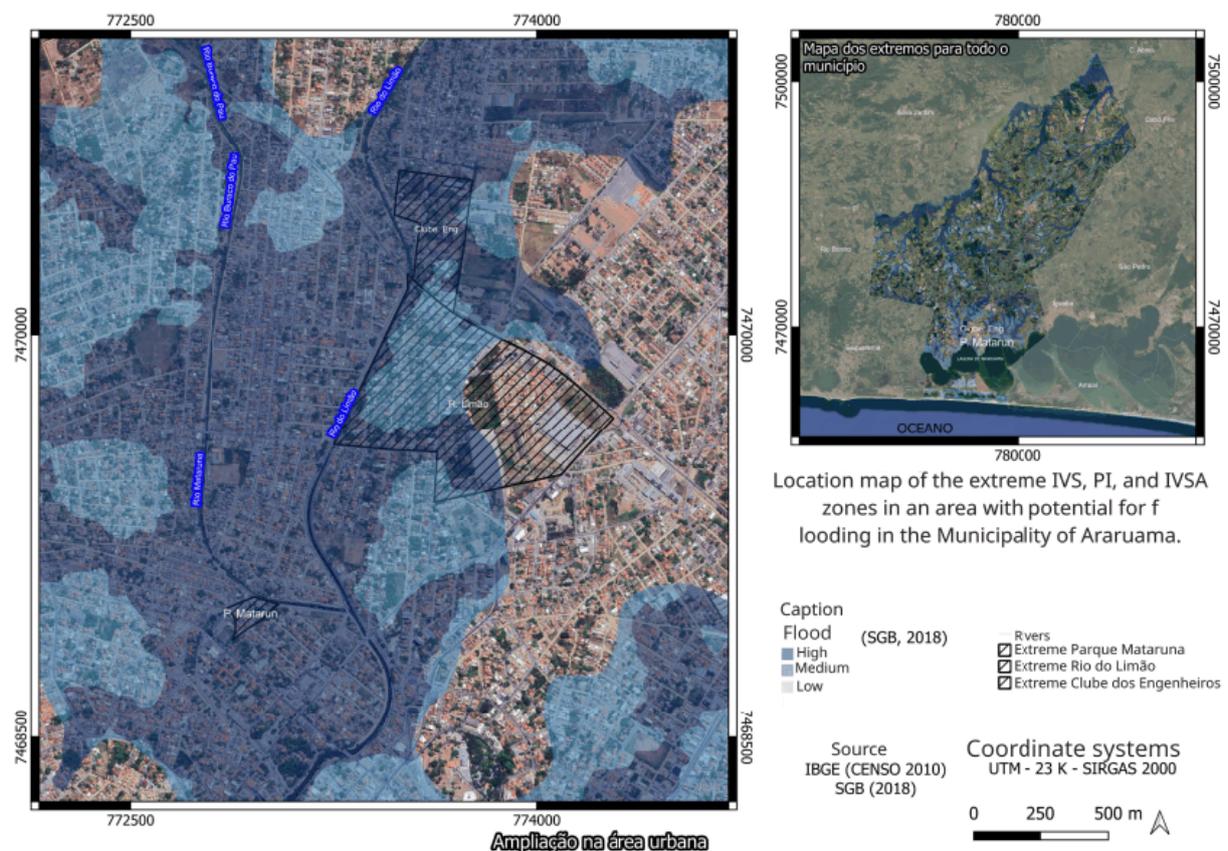


Figure 5 – Location of the sector with extreme IVS, PI and IVSA in Araruama-RJ

Source: The authors, 2025

The sector with extreme Very High IVSA value is located near the sector with extreme Very High IVS value, and both have in common their proximity to the Limão River (Figure 5). The sector with

extreme Very High PI value is located near the Mataruna River. The research showed that socio-environmental vulnerability in Araruama is concentrated mainly in areas close to rivers and within the flood susceptibility zone delimited by SGB (2018). More than half of the municipality's population is exposed to flooding, exceeding the percentage of those classified in high social vulnerability.

The Rio do Limão neighbourhood presented the highest Social Vulnerability Index (IVS), influenced by the income, education and dependency dimensions, which indicates the need for public policies aimed at education and the protection of dependent groups. The Parque Mataruna neighbourhood, although with better socioeconomic indicators, stood out as the most exposed, presenting frequent flood records and demanding improvements in urban infrastructure.

The combination of the social vulnerability index (IVS) and the floodable percentage (PI), forming the Socio-environmental Vulnerability Index (IVSA), confirmed that the most critical sectors are located in flat regions and near water bodies.

The important influence of Income and Dependency was recurring among the extreme IVS and IVSA, reinforcing the importance of specific actions for the elderly and children in risk contexts. These results are aligned with the definition of socio-environmental vulnerability by Cartier (2009) and the definition of risk and vulnerability by IPCC (2014, 2023), by showing that the interaction between exposure to climate change, its effects and social factors can intensify the occurrences of disasters. In this scenario, the most important thing is to prioritise those who suffer most from the temporal records found: the poorest, the elderly and children. In addition, the research highlighted the inconsistency of flood records. These gaps in records may compromise the efficient targeting of adaptive resources in the municipality.

4 CONCLUSION

The study enabled understanding the distribution of socio-environmental vulnerability in Araruama, highlighting the integration of social factors and exposure to floods in understanding risks in the municipality. In general, the most sensitive sectors are located near water bodies, which highlights the importance of public policies that combine urban planning, social inclusion and risk management. The results highlight the importance of accounting for social dimensions when developing adaptive strategies, prioritising the groups most vulnerable to the consequences of extreme events.

The inconsistency in official disaster records points to a significant limitation of the study, indicating the need to improve monitoring systems and to periodically update the number of neighbourhoods with flood records, with easy public access. In addition to inconsistency in disaster data, the temporal gap of the 2010 census may not reflect the contemporary reality of 2025, as the 2022 census data, at the time of the production of the research, were still considered preliminary.

Finally, it is important to highlight that the expansion of the affected area over time underscores the need for ongoing investments in prevention, infrastructure, and technology to reduce flood impacts and decrease the number of affected neighbourhoods.

Therefore, the mapping of the spatial distribution of socio-environmental vulnerability integrated with updated flood records can help decision-makers direct resources to the population with lower capacity to cope with events in the municipality of Araruama. In addition, this study can be applied in other locations subject to flood risk.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (OpenAI, versão 5.1) for language editing and stylistic polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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