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Flooding and inundation risk areas at the mouth of the Cachoeira River in Ilhéus (Bahia – Brazil)

Áreas de risco a alagamento e inundação na foz do rio Cachoeira, em Ilhéus (Bahia – Brasil)

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Abstract: Hydrometeorological phenomena have been increasingly recurrent due to urban growth, since this waterproofs the soil, intensifies surface runoff, and increases the accumulation of water on the surface. This work aimed to map the areas at risk of flooding at the mouth of the Cachoeira River in Ilhéus - BA, where several neighborhoods are in its surroundings and are frequently affected by these natural phenomena. For this, a multicriteria spatial analysis was carried out using the Analytic Hierarchy Process (AHP) method, where environmental covariates were combined using map algebra in the QGIS 3.26 software. RStudio was used to create graphics. It was possible to identify with the maps and graphs how each environmental covariates and their respective classes are distributed in each risk class. The results showed that more than 75% of the area is subject to Moderate, High, and Very High risk, and that the Urban Area is highly inserted in Very High-Risk zones, where flat relief and mangroves predominate. The information generated can be used by the Secretariat of Civil Defense to guide actions that minimize the negative impacts caused by flooding, for example, occupation plans, recovery of riparian forest, drainage works, among other alternatives.

Keywords: Spatial Analysis; Multicriteria Analysis; Natural disasters.

Resumo: Fenômenos hidrometeorológicos têm sido cada vez mais recorrentes por conta do crescimento urbano que, por sua vez, impermeabiliza o solo, intensifica o escoamento superficial e aumenta o acúmulo de água na superfície. Esse trabalho objetivou mapear as áreas de risco a inundações e alagamentos na foz do Rio Cachoeira em Ilhéus – BA, em que estão localizados vários bairros que são atingidos por esses fenômenos naturais frequentes. Foi realizada uma análise espacial multicritério pelo método *Analytic Hierarchy Process (AHP),* combinando-se covariáveis ambientais por Álgebra de mapas no software QGIS 3.26. O *RStudio* foi utilizado para elaborar gráficos. Foi possível identificar com os mapas e gráficos como cada covariável ambiental e suas respectivas classes estão distribuídas em cada classe de risco. Os resultados apontaram que mais de 75% da área está sujeita a riscos Moderado, Alto e Muito Alto, e que a Área Urbana está altamente inserida em zonas de Risco Muito Alto onde predominam relevo plano e manguezais. As informações geradas podem ser utilizadas pela Secretaria de Defesa Civil para nortear ações que minimizem os impactos negativos causados pelas inundações e alagamentos, como planos de ocupação, recuperação da mata ciliar, obras de drenagem, dentre outras alternativas.

Palavras-chave: Análise Espacial; Análise Multicritério; Desastres naturais.

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1. Introduction

Floods and inundations are natural processes that occur due to the environmental characteristics of each location (climate, soil, topography, vegetation). However, they are exacerbated by unplanned urban development (VESTENA; ALMEIDA; GESTER, 2020). In coastal areas, the risks of flooding are even higher, especially due to their predominantly flat relief characteristics, and there is also the influence of sea level rise, which can have various environmental and socioeconomic impacts (TUCCI, 2012; SILVA et al., 2021).Floods occur when there is an accumulation of water on the surface according to the relief characteristics and soil impermeability; in urban areas, they are aggravated due to the deficiency of the drainage system (CASTRO et al., 2005; SILVA, 2015; DUARTE; SANTOS; CASTELHANO, 2021). On the other hand, inundations are related to precipitation events, in which the flow of a river channel exceeds its capacity and overflows onto floodplains (CALDANA et al., 2018; SILVA; LAMMLE; PEREZ FILHO, 2021).

The mouth of the Cachoeira River is composed of Atlantic Forest and Mangrove areas, and over the years, these environments have been reduced due to human occupation (SILVA, 2021; PATERNOSTRO et al., 2022). It is worth noting that mangroves are naturally flooded ecosystems where the transition between continental and oceanic waters occurs. Their vegetation acts as a natural barrier against phenomena such as floods and inundations (ENGELBRECHT et al., 2019; ALVES; GONÇALVES; NASCIMENTO, 2022).

The Atlantic Forest also plays an important protective role by providing soil stability and reducing surface runoff volume. Consequently, it mitigates the impacts caused by heavy rains (NETO, 2019; CALDEIRA; LIMA, 2020; VERÇOSA et al., 2023). The suppression of this vegetation represents a high risk to the population, especially those living along riverbanks. Thus, the conservation of these environments becomes crucial for maintaining a balance between environmental and socioeconomic factors (DOS SANTOS et al., 2020; NASCIMENTO, 2022; SANTOS et al., 2022).

The implementation of efficient drainage systems helps prevent and mitigate flood events (MENGE, 2017; CALDEIRA; LIMA, 2020; FERREIRA; REIS; OLIVEIRA, 2023). However, the majority of Brazilian cities lack efficient drainage systems and often fail to conduct risk characterization studies, which hinders effective interventions with infrastructure and systems to mitigate these natural phenomena, further endangering the population (CREPANI et al., 2001; SILVA; NUNES, 2009; MARTINS; VAZ, 2015).

During periods of high precipitation rates, the lack of an efficient drainage system intensifies and prolongs these hydrometeorological phenomena, causing damages on various fronts, such as mobility, accessibility, quality of life, and also contributing to the proliferation of pathogens (CANUTO, 2021; FREITAS, 2022; JUNIOR, 2022).

In the last decades, Geotechnologies have gained prominence in terms of territorial planning and environmental management (RIBEIRO; LIMA; SOUZA, 2017; BEVILACQUA, 2023). Through the integration of geoprocessing techniques in Geographic Information Systems (GIS), it is possible to collect, store, and process data, thus generating insights about specific phenomena occurring in the study area, making them indispensable for risk mapping (MOURA, 2020; OLIVEIRA, 2022).

Risk mapping allows for the identification of both areas that should not be occupied and those that are already occupied, providing a definition of their risk situation (DE LIMA; DE SOUSA; 2023; SANTOS; SILVA; VITAL, 2023). This information can assist in urban planning by providing a foundation for interventions, such as the implementation of drainage systems, conservation of remaining vegetation, and the restoration of riparian forests.

The use of multicriteria analysis in conjunction with the Analytic Hierarchy Process (AHP) allows for generating responses to complex studies that involve multiple environmental variables, such as the present work, and facilitates decision-making based on scientific knowledge (SAATY, 1991; PIMENTA et al., 2019; PRUDENTE, 2019; MÁRIO; UACANEM, 2023).

With the information provided, the aim of this study was to identify the areas exposed to the risk of floods and inundations, and to understand how environmental characteristics contribute to this issue in the vicinity of the Cachoeira River mouth in Ilhéus, Bahia.

2. Methodology

2.1. Study area

The Cachoeira River mouth is in the Pontal Bay, in the municipality of Ilhéus, Bahia. Surrounding the area are the neighborhoods of Centro, Pontal, Banco da Vitória, Princesa Isabel, Nelson Costa, Teotônio Vilela, and Av. Esperança, as illustrated in "Figure 1." The vegetation found in the study area consists of a combination of Atlantic Forest and the Cabruca Agroforestry System (SAF) due to the strong influence of cocoa farming in the region. In this SAF, cocoa grows under the shade of native trees from the original forest, making it an important factor for biodiversity conservation by preventing deforestation practices.

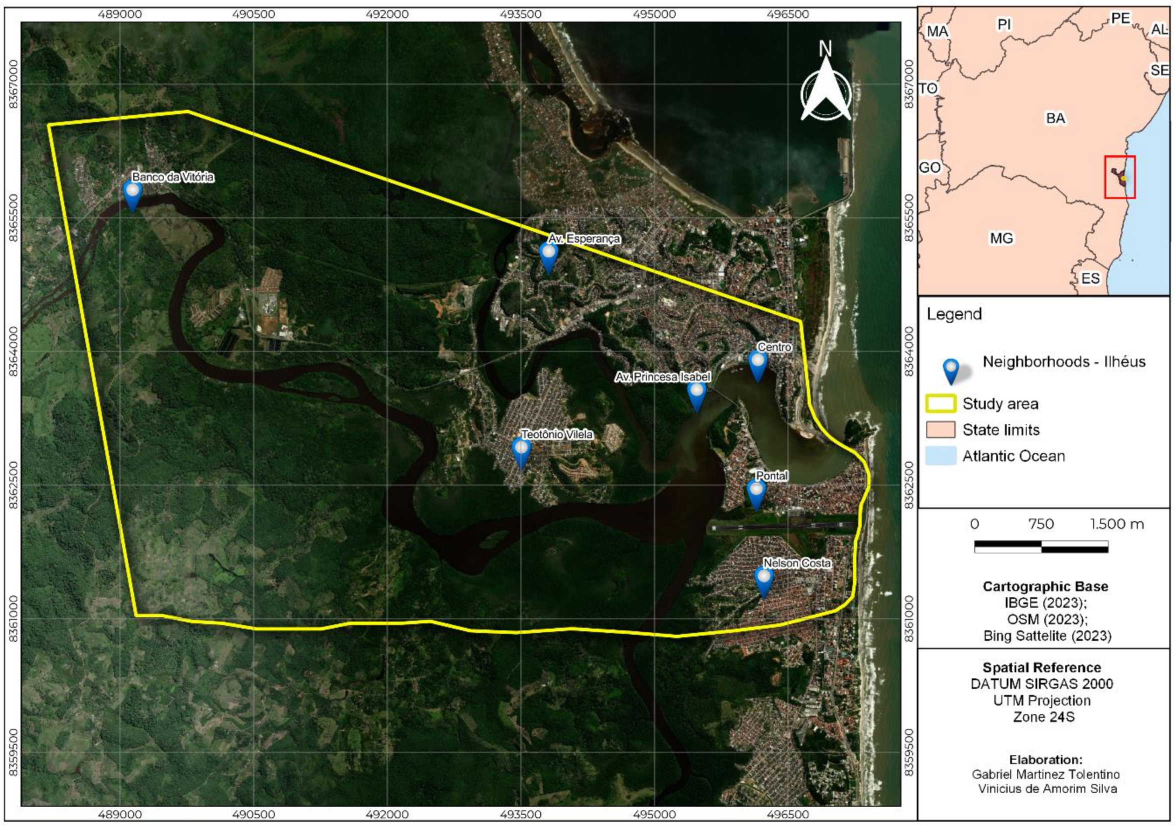

Figure 1 – Location map of the mouth of Cachoeira River in Bahia.
Source: The authors (2023).

2.2. Data base building

The mapping of flood and inundation risk was conducted using the free software QGIS, version 3.26. The preparation of the database was carried out in two stages. The first stage involved determining the polygon that encompasses the study area, considering the human settlements located along the banks of the Cachoeira River estuary. The second stage involved the assembly of georeferenced database containing the elements analyzed in this study.

According to Mantis and Vaz (2019), the most influential aspects in flood and inundation risk studies are geomorphological factors (altitude and slope), land use and land cover, and soil characteristics. The rainfall factor was also considered, which refers to the accumulation of precipitation over a specific period and influences the occurrence and intensity of these events. All the data used in this study were obtained as follows:

- Soil Map at a scale of 1:250.000: acquired through the Environmental Information Database (BDiA) of IBGE (2021).
- Altitude Map: derived from the Digital Terrain Model (MDT) from the Japanese Aerospace Exploration Agency (JAXA), using the Advanced Land Observing Satellite/Phased Array L-band Synthetic Aperture Radar (ALOS Palsar) with a spatial resolution of 12.5 meters (JAXA, 2021).
- Slope Maps: derived from the Altitude Map using the Slope tool in QGIS.
- Land Use and Land Cover Map: obtained from the MAPBIOMAS database (2019), derived from images captured by the Operational Land Imager (OLI) sensor on the Landsat 8 satellite, with a spatial resolution of 30 meters.
- Rainfall Map: developed by interpolating data from the historical series of average annual precipitation from rainfall stations in the municipality of Ilhéus, available in the metadata catalog of the National Water Resources Information System (SNIRH), managed by the National Water Agency (ANA, 2021).

2.3. Multicriteria risk analysis of flooding and flooding

After the construction of the database, a multicriteria analysis was carried out to determine the flood and inundation risks, following the Analytic Hierarchy Process (AHP) methodology proposed by Saaty (1991), which studies the interactions between components of a system and their impacts on the integrated system.

The first phase of the multicriteria analysis involved the reclassification of the maps (covariates) based on individual scores on a scale of 0 to 10. according to the risk that each class represents (for example, a score of "one" for forests and a score of "ten" for urban areas). The information plan of the covariates used for the multicriteria analysis and mapping of flood and inundation risks is illustrated in Figure 2.

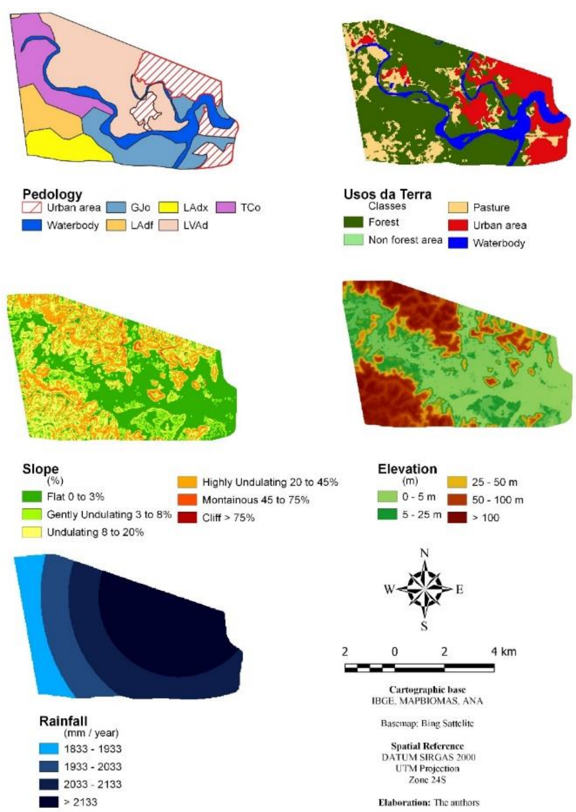

Figure 2 – Covariate information plan
Source: The authors (2023).

In the Pedology layer, soil classes (Ferralsols, Gleysols, Luvisols) and classes such as Water Bodies and Urban Areas were identified. The assigned scores for each class considered the moisture and drainage characteristics of each soil, which directly impact the risk of flooding and inundation in a particular location (EMBRAPA, 2018). The scores obtained for each class in the Pedology layer are described in Table 1.

Table 1 – Grades for pedology classes

Pedology	**Grades**
Ferralsols	2
Gleysols	6
Luvisols	4
Urban Area	10
Waterbodies	10

Source: The authors (2023).

According to the Brazilian Soil Classification System by Embrapa (2018), Gleysols are considered poorly drained. Ferralsolss, on the other hand, are classified as well or strongly drained. Luvisols range from imperfectly drained to well drained. These drainage characteristics were taken into consideration as they are important in determining the system's vulnerability, and accordingly, scores were assigned to each soil type.

In the slope, land use and land cover, altitude, and rainfall maps, the scores were assigned through reclassification using the "Reclassify by Table" tool in QGIS.

Table 2 presents the scores assigned to the slope, matched with the relief classes established by Embrapa (2018).

Table 2 – Grades for relief classes

Relief type	**Slope (%)**	**Grades**
Flat	0 – 3	10
Gently Undulating	3 – 8	9
Undulating	8 – 12	5
Strongly Undulating	20 – 45	3
Mountainous	45 – 75	1
Strongly montainous	> 75	1

Source: The authors (2023).

For the flat relief and gently undulating relief classes, scores of 10 and 9 were assigned, respectively. For the intermediate relief classes, such as undulating and strongly undulating, scores of 5 and 3 were assigned, respectively. For the mountainous and steep relief classes, a score of 1 was assigned. The scores were assigned taking into consideration the influence of the relief on flooding and inundation events, which are more frequent and intense in areas with lower slopes.

The altitude map was reclassified, and the scores assigned to each altitude interval are detailed in Table 3. Following the same criterion adopted for the slope map, areas with lower altitudes tend to represent a higher risk of flooding and inundation, particularly due to the increase in sea level.

Table 3 – Grades for Elevation intervals

Elevation (m)	Grades
0 – 5	10
5 to 25	7
25 to 50	3
50 to 100	2
> 100	1

Source: The authors (2023).

Regarding the Land Use and Land Cover map, initially divided into classes such as Forest, Pasture, Urban Area, and Water Bodies, the map needed to be reclassified in order to assign scores to each class, corresponding to the level of risk they pose for flooding and inundation issues (Table 4).

Table 4 – Grades for land use classes

Land use classes	Classes
Forest	1
Pasture	7
Urban area	10
Waterbodies	10

Source: The *authors* (2023).

The score assigned to the Urban Area class is related to the fact that these areas have little to no permeability, increasing the likelihood of flooding. This risk can be minimized through drainage works. As for the score given to the Pasture class, it is due to the reduced permeability caused by soil compaction resulting from cattle movement. Regarding the high score assigned to the Water Bodies class, it is because these areas represent naturally flooded areas that are occasionally subject to flooding events in their surroundings.

The Rainfall map, ranging from 1833 mm/year to 2246 mm/year in the study area, had its values reclassified using the "Reclass by Table" tool, where a table is provided to input the value ranges of the data and assign them a corresponding score, which reflects their strength in causing flooding and inundation.

Table 5 – Grades for Rainfall

Rainfall (mm/year)	Grades
1833 – 1933	7
1933 – 2033	8
2033 – 2133	9
> 2133	10

Source: The authors (2023).

The decision was made to define the Rainfall classes with variations of 100 mm/year, with higher scores assigned to classes with higher rainfall levels.

The second phase of the study consisted of determining the weights, which were obtained by inputting the factors into a pairwise comparison matrix. For each pair, the prevailing feature and the degree of prevalence were defined on a scale ranging from 1 to 9, following Saaty's (1991) guidelines. The description of what each value represents is presented in Table 6 as follows:

Table 6 – Comparative values of AHP matrix

Scale of importance	Description
1	Same importance, meaning the factors contribute equally to the objective
3	Slight importance of one factor over the other, slightly favoring the chosen factor as a priority
5	Great importance or essential, strongly favoring the chosen factor over the other
7	Very high importance, strongly favoring one factor over the other
9	Absolute importance, favoring one factor over the other with the highest degree of certainty
2, 4, 6 e 8	Represent intermediate values between adjacent values, used when the evaluator finds it difficult to define between two of the values above.

Source: Saaty (1991).

In this way, obtaining the weights was done by inserting the comparative values on the scale of importance into the AHP matrix, as shown below (Table 7):

Table 7 – Matriz AHP

	Pedology	Land use	Elevation	Slope	Rainfall	Weight
Pedology	1	1/3	1/5	1/7	1/5	0.042
Land use	3	1	1/3	1/5	1/4	0.100
Elevation	5	3	1	1/3	1/2	0.206
Slope	7	5	3	1	3	0.397
Rainfall	5	4	2	1/3	1	0.258

Source: The authors (2023).

The weights obtained for the Pedology map were 0.042, for the Land Use and Land Cover map it was 0.1, while the Altitude map had a weight of 0.206. The Slope and Rainfall had the most significant weights, with values of 0.397 and 0.258, respectively.

After determining the scores and weights, the variables were processed using map algebra in the QGIS raster calculator, as defined by the equation below, where Flood and Inundation Risk (RiskFI) is equal to the sum of the products of each layer's values multiplied by their respective weights.

$$\text{RiskFI}^* = \text{Soil} \times 0.042 + \text{Land Use} \times 0.1 + \text{Altitude} \times 0.206 + \text{Slope} \times 0.397 + \text{Rainfall} \times 0.258$$

The resulting layer, with a risk scale ranging from 1 to 10. was reclassified according to Table 8 as follows:

Table 8 – Risk Classes and their scale intervals

Risk Scale	Risk Classes
1 – 3	Very low
3 – 5	Low
5 – 7	Moderate
7 – 9	High
9 – 10	Very High

Source: The authors (2023).

2.4. Graphing in R

The covariates maps and the resulting Flood and Inundation Risk layer were stacked using R version 4.2.2 in the RStudio interface version 2022.12.0.353. The attributes of each layer (covariates and final map) were transformed into a dataframe using the dplyr package to facilitate data cleaning (POSIT TEAM, 2022).

The cleaned dataframe was then used to create histogram-type graphs using the ggplot2 package. Each covariate (represented in columns) was crossed with the Flood and Inundation Risk information, enabling the visualization of how each class of each covariate is distributed within the risk classes.

Additionally, a histogram was created to represent the Land Use classes, showing their frequencies and stylized according to the type of relief in which they are presented.

3. Results and discussion

According to Figure 3, the highest risk classes are located near the banks of the Cachoeira River mouth, where the largest urban areas are situated, falling into the High and Very High-risk categories. Examples of such areas include the Teotônio Vilela, Pontal, Nelson Costa, Banco da Vitória neighborhoods, and a significant portion of the city center. Most of these neighborhoods are entirely situated in mangrove areas and have experienced rapid growth in recent decades, particularly the Teotônio Vilela neighborhood, leading to the suppression of these ecosystems and increasing the susceptibility to flooding and inundation in these areas.

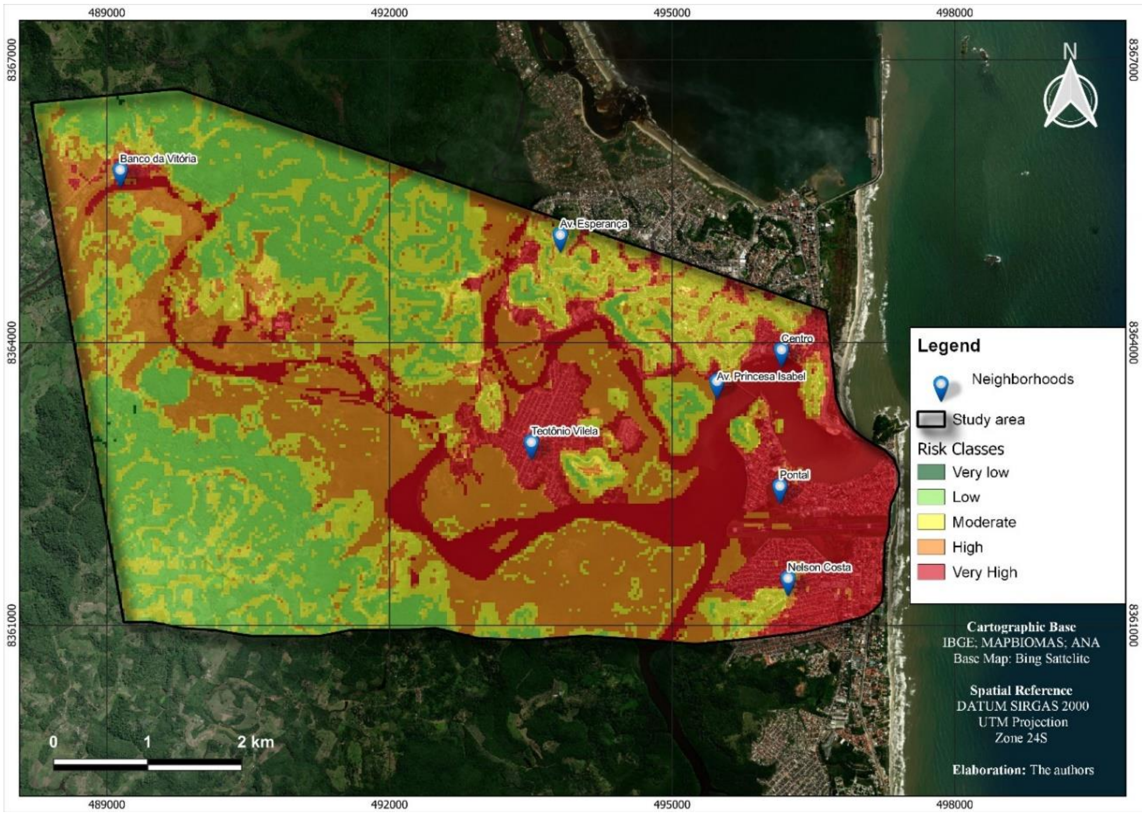

Figure 3 – Flood and Inundation Risk Map at the mouth of the Cachoeira River.
Source: The authors (2023).

It is important to highlight that the population has already suffered from flooding and inundation events caused by the Cachoeira River. The year 2021 stands out, as heavy rainfall flooded the city, leaving several areas isolated, people displaced from their homes, disrupting urban mobility, and leading to fatalities. As the study area is in a coastal region, there is a risk of sea-level rise, which could further intensify the hydro-meteorological processes, exacerbating the potential for flooding and inundation.

In Table 9, the results of the area relationships for each risk class are presented, revealing that only 0.04% of the study area (equivalent to 20 m²) falls under the Very Low risk class. The Low-risk class covers 23.34% of the area. Subsequently, the mapping also showed that 24.69% of the area is classified as Moderate risk, 23.12% as Very High risk, and most of the area is susceptible to High risk, accounting for 28.31%.

Table 9 – Area relation for each risk class

Risk Class	**Area (km²)**	**Area (ha)**	**Percentage**
Very low	0.02	1.53	0.04%
Low	9.12	911.58	23.34%
Moderate	9.64	964.40	24.69%
High	11.25	1125.46	28.81%
Very High	9.03	903.22	23.12%
Total	39.06	3906.19	100%

Source: The authors (2023).

In a general aspect, it is shown in Table 9 that only 23.38% of the area is not seriously susceptible to flooding or flooding, while 76.62% are associated with a situation of Moderate, High or Very High risk.

The set of histograms illustrated in Figure 3 shows how the classes in each covariate are distributed within each degree of risk mapped in the study area. Thus, it is possible to visualize in the histogram (1) and (4) that the areas with flat relief and low altitudes are predominantly distributed in places with High and Very High risk of susceptibility to flooding and/or flooding.

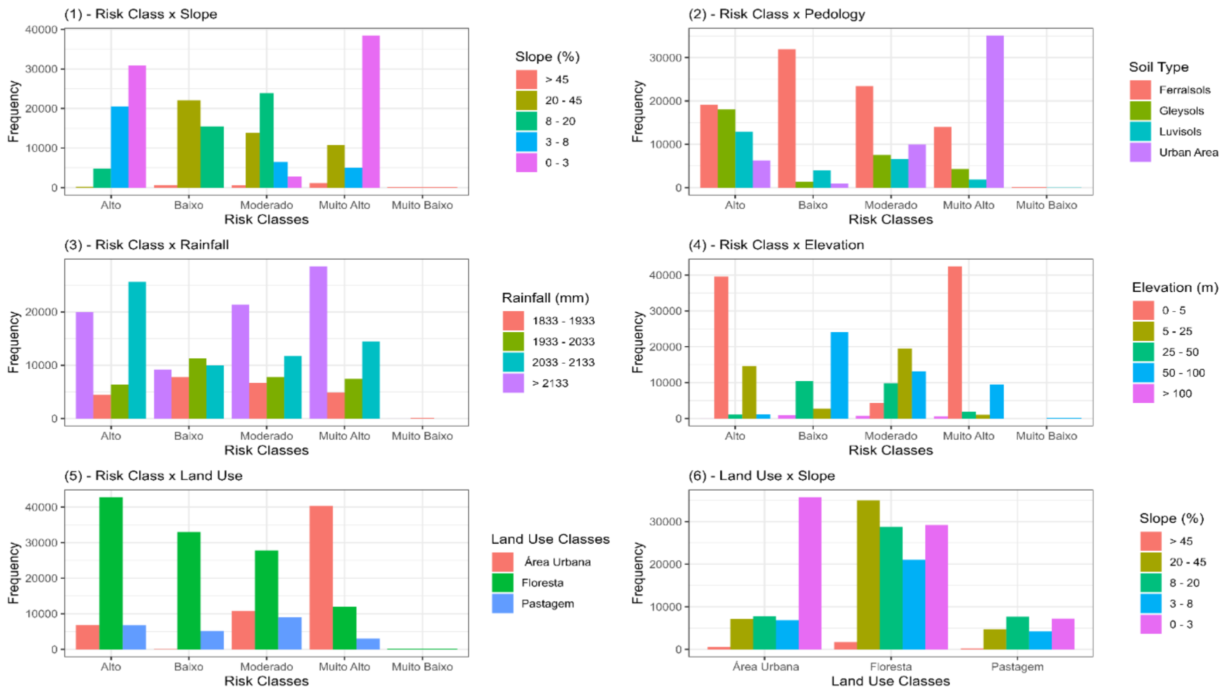

Figure 4 – Histograms of covariates and response variable.
Source: The autors (2023).

A similar situation occurs with the Urban Area classes in the histogram (5), which are mostly located in zones of very high risk. It is also noticeable that the Vegetation class is widely present in areas of high risk, which can be attributed to their location in flat terrains near rivers, such as the remaining mangroves and riparian forests.

Regarding the soil covariate, it is possible to identify a frequency between 10000 - 20000 for the pedological classes "Gleysols," "Ferralsols," and "Luvisols" located in high-risk zones. Nevertheless, there is a predominance of "Ferralsols" in low-risk areas, which may be linked to the influence of other environmental factors, such as the presence of vegetation.

It is worth noting that the absorptive action of roots confers vegetation an important role in flood and inundation containment, as leaves naturally retain part of the rainwater on their surfaces, favoring evapotranspiration and reducing surface runoff and erosive processes (GUERRA, 2012; TUCCI, 2012; KÖNIG, 2022).

Observing the last histogram (6), it is possible to identify how the "Uso da Terra" (Land Use) classes are distributed across different types of terrain found in the area. In this sense, it is evident that the "Urban Area" class is densely present in flat terrains, which are highly susceptible to flooding (near the riverbanks) and inundation. These areas are mostly concentrated around the rivers, and the population of Ilhéus has developed in these surroundings over the years, leading to the suppression of gallery forests and mangroves.

According to data from the Demographic Census (IBGE, 2023), the population of the city of Ilhéus was around 108 thousand inhabitants in 1970. and in 2022, estimates suggest a population of around 200 thousand inhabitants. This indicates that the city's population has doubled in 50 years, with particular emphasis on the Teotônio Vilela neighborhood, which has experienced significant development over the years and is now almost entirely distributed in an area that was previously occupied by mangroves. In addition to Teotônio Vilela, other neighborhoods are also in a similar situation and as mapped, are subject to suffering from increasingly frequent rains.

4. Final considerations

It was possible to identify flood and inundation risk areas around the mouth of the Cachoeira River in Bahia, evaluate the elements that compose the study area, and how they influence the risk classes. The results showed that flat and urbanized areas with little permeability have higher risk values, while locations with more pronounced terrain and vegetation presence are integrated into low-risk categories.

The information derived from mapping and graphs revealed that the urban area is mostly situated in flat terrain near the river, where mangroves naturally develop, but have been reduced over the years. It is essential to note that mangroves are naturally flooded environments that buffer the impacts of natural phenomena, and their removal has significant consequences for the population residing nearby.

It is worth emphasizing that this study can be updated over the years due to changes in land use, such as the suppression of native vegetation and the soil's impermeabilization caused by urban growth processes, which are a reality in the municipality of Ilhéus.

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