ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 9, nº 1 (2023)

https://doi.org/10.21680/2447-3359.2023v9n1ID31523

Physical characterization and susceptibility to erosive processes in the municipality of Ilhéus-Bahia

Caracterização física e suscetibilidade aos processos erosivos do município de Ilhéus-Bahia

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Abstract: Analyzing susceptibility provides the basis for risk prevention policies. The objective was to characterize the environmental conditions of Ilhéus that contribute to erosion processes. In addition to assessing the susceptibility of slope, geology, soil, rainfall intensity, coverage, use and occupation factors and identifying areas at risk by creating a database containing classes and values of stability/vulnerability to erosion. To develop the research it was necessary to collect bibliographic data; treatment of digital images for the map of slope, geology, soils, and land use, occupation and cover using geoprocessing techniques via GIS, in addition to average annual precipitation values (mm) and duration of the rainy season (months) ; it involved analysis based on the Crepani methodology (1996; 2001), the degree of stability of the environmental conditions, combined with the weights of the environmental conditions by the AHP Calculator (SAATY, 1991); creation of a multicriteria equation to generate the final map. The results indicate the characterization of the environmental constraints and their degree of stability, in addition to the areas of very high, high, average, low and very low vulnerability to erosion processes produced with the integration of the mappings. Average to very high vulnerability was obtained in 19% of the studied area, and very low to low vulnerability adds up to 82%.

Keywords: Multicriteria analysis; Remote sensing; Environmental constraints.

Resumo: Analisar a suscetibilidade fornece base para políticas de prevenção de riscos. O objetivo foi caracterizar os condicionantes ambientais de Ilhéus que contribuem para os processos erosivos. Além de avaliar a suscetibilidade dos fatores declividade, geologia, solos, intensidade pluviométrica, cobertura, uso e ocupação e identificar áreas em risco mediante elaboração de banco de dados contendo classes e valores de estabilidade/vulnerabilidade à erosão. Para desenvolver a pesquisa foi necessário o levantamento de dados bibliográficos; tratamento de imagens digitais para a carta de declividade, geologia, solos, e o uso, ocupação e cobertura da terra com uso de técnicas de geoprocessamento via SIG, além de valores da precipitação média anual (mm) e duração do período chuvoso (meses); envolveu análise baseada na metodologia Crepani (1996; 2001), o grau de estabilidade das condicionantes ambientais, aliado aos pesos dos condicionantes ambientais pela AHP Calculator (SAATY, 1991); elaboração de equação multicritério para gerar o mapa final. Os resultados indicam a caracterização dos condicionantes ambientais e seu grau de estabilidade, além das áreas de vulnerabilidade muito alta, alta, média, baixa e muito baixa aos processos erosivos produzida com a integração dos mapeamentos. Obteve-se 19% da área estudada, vulnerabilidade média a muito alta, e vulnerabilidade muito baixa a baixa soma-se 82%.

Palavras-chave: Análise multicritério; Sensoriamento remoto; Condicionantes ambientais.

Received: 15/02/2023; Accepted: 24/04/2023; Published: 26/06/2023.

1. Introduction

The erosive processes consist of the movement of soil, rock, or vegetation due to gravity action along a slope or hillside. This process occurs due to water infiltration that, when mixed with soil, reduces its resistance, inducing its fragmentation and fluidity. Wind action is also one of the causes of erosion.

According to MARTINI et al. (2006), erosive processes consist of the movement of soil, rock, or vegetation due to gravity along a slope. This process occurs due to the infiltration of water that, when mixed with the soil, reduces its resistance, inducing fragmentation and fluidity. Wind erosion is also one of the causes of erosion.

Anthropogenic activities accelerate this process, and erosion occurs due to the action of water and wind, and its magnitude is directly influenced by soil factors, relief, and mainly vegetation cover. The consequences of erosion on the soil surface are called laminar, gullies, or gullies. The dragging of soil particles in varying amounts has long-lasting effects on the landscape, modifying relief, agricultural areas, or urban areas. According to Tominaga et al. (2009), mass movements related to slopes are based on criteria such as speed, geometry of the displaced mass, and the type of material. The most adopted classification system divides mass movements into creeping, sliding, falls, and flows.

In addition to implications for agricultural areas, erosive processes lead to the transport of sediment to water bodies, with consequences for the quality of water resources, siltation of rivers and reservoirs, for example. Mass movements, particularly landslides, can pose risks to populated areas and environmental catastrophes. Thus, "risks exist when there is a set of natural and social variables that culminate in irregular occupation in environments whose physical-natural conditions tend to be fragile," (GIRÃO et al., p. 72, 2018). However, to obtain the risk of the occurrence of a given phenomenon, it is necessary to know the probability of temporal incidence for an area to be affected by a hazardous event or process in a determined period or time, (ZÊZERE et al., 2004).

Occupation in these areas requires organization and planning in its process of use and occupation. The elaboration of public policies and management aims to reduce degradation and increase conservation. The southern region of Bahia, where Ilhéus is located, still preserves part of its natural vegetation, an important endemic region that has heterogeneous fauna and flora and is considered an important area for the development of conservation actions. The municipality of Ilhéus shows a trend towards expanding its territory and the danger of becoming a place of recurrent environmental and economic disasters if these occupations occur improperly and in terrain unsuitable for anthropogenic activities. The inadequate occupation of areas such as slopes that have pronounced natural fragility creates situations of risk to erosive processes and landslides. The urbanization process of Ilhéus is characteristic of the colonial period, and the main occupation area is on its coastal strip and hills without concern for the consequences for the environment and the population. This work allows guiding activities to be developed by knowing the environmental fragilities and potentialities of the study area. Lobo de Paiva et al. (2022) explain that environmental potentiality involves environmental resources or services, in relation to soil components, relief, rocks, minerals, water, climate, flora, and fauna. Fragility can be represented by the susceptibility of the intrinsic characteristics of the environment that, when undergoing negative changes, must be evaluated in an integrated manner.

2. Study área

Located in the south of the state of Bahia, Ilhéus is part of the Itabuna-Ilhéus microregion (Figure 1). The municipality has a territory of approximately 1,585 km² and has the longest coastline in the state, measuring 84 km. Its coastline features areas with different levels of occupation and types of use, including urbanized areas, areas undergoing development, and non-urbanized areas. The cultivation of cocoa stands out in the municipality's agriculture, along with other small-scale agricultural activities. The municipality is divided into ten districts, including its headquarters with 27 neighborhoods, as well as 49 other urban nuclei such as district headquarters, villages, and hamlets.

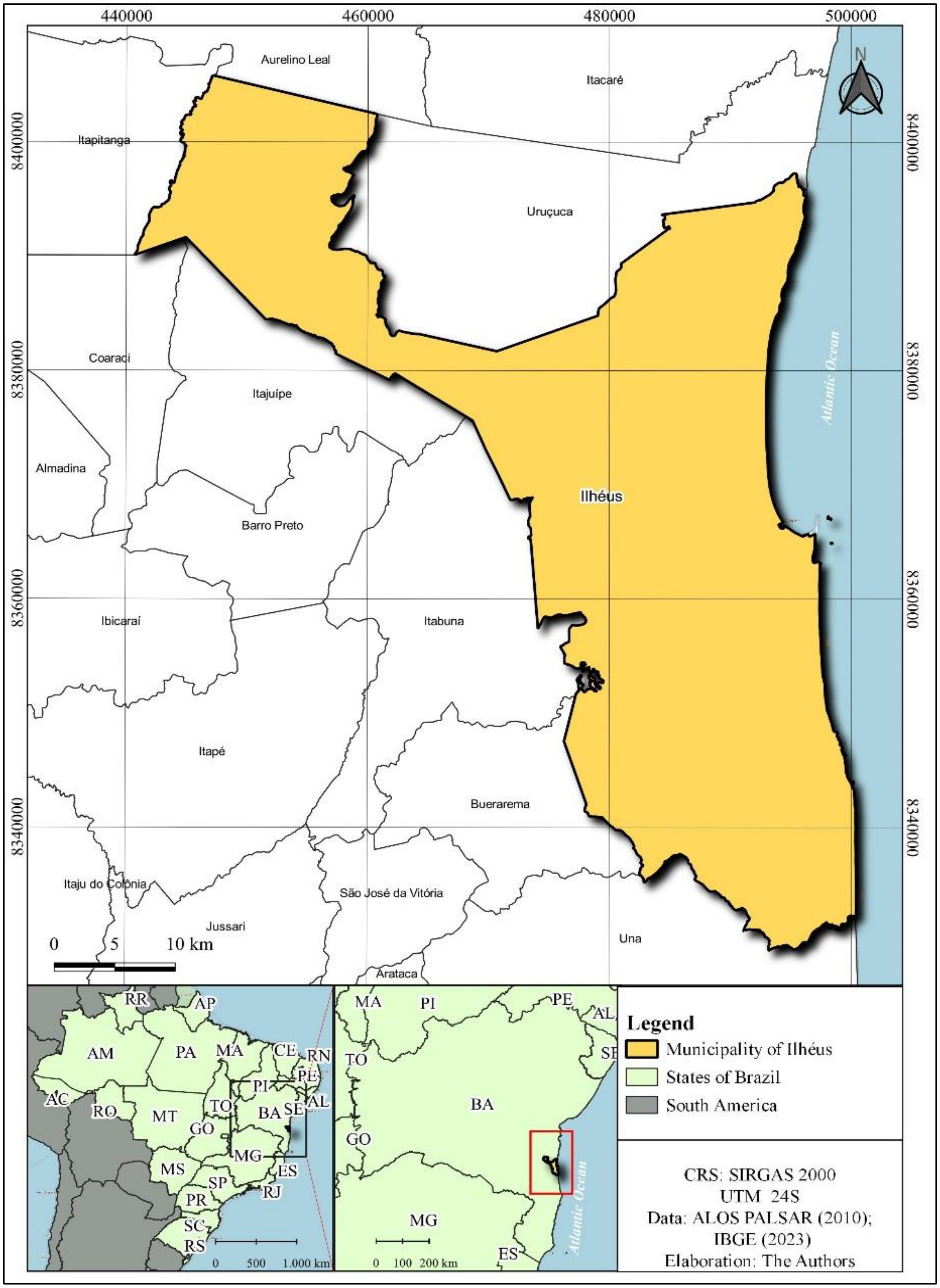

Figure 1– Location of the municipality of Ilhéus
Source: IBGE (2023)

3. Physical Environment

3.1 Climate

The climatic type that acts on Ilhéus is classified as humid tropical, with an average annual temperature higher than 24º. The accumulated annual rainfall between 1,900 and 2400 mm well distributed in the year, with the months between December and March being the rainiest, and September and October the least rainy).

According to data from the Climate-Data Org., the municipality's climate information shows the lowest value for relative humidity in the month of September (81.68%). The relative humidity of the air is highest in June (86.68%). On average, the least rainy days are measured in September (17.87 days). The month with the wettest days is March (25.03 days). Ilhéus has a tropical climate, where there is significant rainfall throughout the year. Even the driest month there is still a lot of rainfall. This location is classified as an average temperature of 23.9 °C. In a year, the average rainfall is 1325 mm. The driest month is September and there is 74 mm of precipitation. With an average of 139 mm, the most precipitation falls in April. The difference in precipitation between the driest month and the wettest month is 65 mm. Throughout the year, temperatures vary by 3.9 °C.

3.2 Vegetation

The Atlantic Forest is the predominant vegetation, in addition to it, the restingas and mangroves stand out. It has an estuary where the Cachoeira River, the Santana River and the Itacanoeira River (or Fundão) meet. In addition to these rivers, the Almada River basin is part of its hydrographic network. The municipality has two conservation units, the Permanent Protection Area (APA) of Lagoa Encantada and the Boa Esperança Municipal Park.

3.3 Topography, Geology and Soils

With regard to geomorphology, this region has an elevation of up to 52 m and several forms ranging from the Mares de Morros to the Coastal Plain (AB'SÁBER, 2003) that impose restrictions for urban expansion. The topography is characterized by the geomorphological characteristics of hills or hills, which are undulating areas with rounded tops, of smooth slope, and trays that correspond to the highest places with almost flat tops and cut by deep valleys excavated by ancient river beds, which originate a thick clayey mantle, formed by gneisses, granulites and basic rocks, What forms clay-sandy soils, such soils are very susceptible to landslides and erosive processes, as they expand when saturated causing their instability and vulnerable to the danger of landslides in the hills and floods in the plain, also as coastal erosion.

Its urban center presents occupied by slopes that often occur landslides, this form of the relief is characterized by rocks of the crystalline basement (FRANCO, 2008). To the south there are fragments of the Barreiras Group that are clay-sandy sediments of the Tertiary period. In the areas near the rivers and under the influence of the tide, fluviolacustres sediments predominate, which are clayey sediments associated with mangroves. Already in the coastal portion are beach sediments of the current coastline. Because it is characterized as a tropical and humid sub-region, the climate is fundamental in the definition of the natural framework, as it configures the types of soil and the shape of the relief, variety of vegetation and the river system.

4. Historical, socioeconomic and demographic aspects

According to data from the IBGE Census (2010), Ilhéus had 184,236 inhabitants, of which 89,440 were men and 94,796 women. In 2019 the estimated population fell to 162,327 people and 159,923 in the year 2020. Population density: 99.5 inhabitants per km². In comparison with the Ilhéus-Itabuna Microregion and the State of Bahia, Ilhéus ranks 2nd and 7th in relation to population; the percentage of the population with a nominal monthly per capita income of up to 1/2 minimum wage (below the poverty line) was 40.4% and with an average monthly salary of formal workers (2017) of 2.5 minimum wages and a percentage of the employed population of only 19.4%. The percentage of declared color/race of the population in 2010 is: mulatto 58.6%; white 19.5%; black 18.7%; indigenous 2.1%; yellow 0.9%.

After the 1990s, the crisis occurred in the production of cocoa, resulting from the spread of the witch's broom fungus (*Crinipellis perniciosa*), decimated most of the cocoa crop in the southern region of Bahia, there was a need for alternatives for economic development, among which tourism and small commercial and industrial activity (Informatics pole) stand out.

5. Methodology

5.1 Evaluation of the degree of susceptibility to erosive processes

The evaluation of susceptibility to erosive processes and mass movements is related to the conditioning factors of these processes linked to slope, geology, soil, land use and land cover. In general, the degree of stability in relation to morphogenesis and pedogenesis is combined with other restrictive factors such as rainfall intensity and the capacity or suitability of land use is obtained (Chart 1).

Chart 1 – Criteria for assessing environmental constraints

Variables	Criteria
Geology	Geological time and cohesion
Alone	Pedogenetic maturity
Slope	Slope variation
Vegetation/land use	Landscape protection
Rainfall intensity	Erosividade

Source: Crepani et al. (1996; 2001)

This stage evaluates the degree of stability to erosive processes, the characteristics are evaluated individually according to the reinterpretation of pre-existing thematic data (slope, soils, precipitation, cover, land use and occupation, rainfall intensity and geology), which will employ a model capable of evaluating possible soil losses. Each characteristic will be assigned a stability value in order to produce a scale.

This methodology was developed from the Ecodynamics of Tricart (1977), applied by Crepani et al. (1996; 2001) the integrated studies of the AHP method – Analystic Hierarchy Process, which consists of an integrated analysis of the environment by evaluating multiple variables that relate to other systems, creating a decision hierarchy that allows a broader view.

Crepani et al. (1996; 2001) confers the morphodynamic categories developed based on the principles of Tricart Ecodynamics (1977), in which each category receives stability values ranging from 1.0 to 3.0 given the Pedogenesis/Morphogenesis relationship. As the values approach 1.0, stability in the environment is conferred, while as the value approaches 3.0, instability is conferred on the environment, as can be seen in Table 1.

Table 1 – Evaluation of the stability of morphodynamic categories

Category morfodinâmica	Pedogenesis/Morphogenesis Relationship	Value
Stable	Pedogenesis prevails	1,0
Intermediate	Balance Pedogenesis/Morphogenesis	2,0
Unstable	Morphogenesis prevails	3,0

Source: Tricart (1977)

5.2 Stability/vulnerability of rainfall intensity

In the erosive processes are involved some physical characteristics of the rainfall, such as the amount or total rainfall, the rainfall intensity and the seasonal distribution. Among these, it is important to know the rainfall intensity, because when there is a high annual rainfall, but with significant distribution over the long period, the erosive power becomes lower than a more concentrated annual precipitation in reduced periods, that is, the rainfall intensity represents the relationship between the amount of rain (mm) and the period that there was precipitation. To calculate the rainfall intensity of an area (Equation 1), simply divide the value of the average annual precipitation (in mm) by the duration of the rainy season (in months).

Equation 1 Rainfall index

$$PMA/DPC=IP$$

Where: PMA= average annual precipitation divided by DPC= duration of the rainy season, which results in rainfall intensity (PI) values.

The stations chosen as the database were the Provision station (01439000), responsible and operator of the National Agency of Water and Basic Sanitation (ANA), located Lat. 14.63º Long. 39.11º, altitude of 30 m and the station Cocoa Research Center CEPEC (01439058), responsible and operator linked to CEPLAC - Executive Committee of the Cocoa Crop Plan, located Lat. 14.75º Long. 39.23º, altitude of 50 m, historical series from 1945 to 1978. Both belong to the Atlantic Basin, eastern stretch and the basins of the Pardo, Cachoeira, Almada and other Rivers.

In the absence of more accurate information, simple linear regression correlates data from two stations. This method fills the gap by performing an estimate with data obtained from rainfall stations located in the study area, it was possible to perform the reconstruction of historical series that are useful for characterization of rainfall intensity. The application was performed using: the data available on the Hidroweb platform of the National Water Agency (ANA); o Hydro 1.4 and Excel 2016 to process the rainfall data, generate the graphs and apply the simple linear regression method.

The modeling for data completion was necessary to obtain the estimate of rainfall in missing periods, identified with more failures between the years 1945 to 1963 and 1976 to 1978. Data from more recent years showed a wide discontinuity in years and months of collection followed. More concise and complete data were found between the years 1945 and 1978.

5.3 Multicriteria evaluation

Since several elements intervene in erosive processes, for the identification of susceptible areas alternatives must be available to combine them in a coherent way. Therefore, multicriteria evaluation is an appropriate option to support decision making.

The Multicriteria Evaluation stands out as a technique to aid environmental planning and decision-making for strategies for prioritization of areas, since it allows the analysis of different geophysical, social, economic, etc. information. The method is based on the contextualization and structuring of a problem, followed by analysis in a GIS environment and formulation of the most appropriate decision to the reality of the area under study. Some studies have been conducted using the Multicriteria valuation such as DE ALMEIDA et al. (2020); SARTORI (2010); SILVA et a. 2014; BRAVE 2017; VETTORAZZI 2006.

To establish the relative importance of each factor in the hierarchy, comparison matrices are elaborated for each factor, where the results of the matrices are weighted against each other. The hierarchical model of Saaty (1991) is a process of choice based on the logic of pairwise comparison, where different factors that influence decision making are organized hierarchically, compared with each other and a value of relative importance (weight) that is attributed to the relationship between these factors, according to a predefined scale that expresses the intensity of the predominance of one factor over the other, (Chart 2).

Chart 2 – Values of the AHP method for paired correlation between variables

Degree of importance	Definition and Explanation
1	Equal Importance - the two variables contribute equally to the phenomenon.
3	Moderate importance - one variable is slightly more important than the other.
5	Essential importance - one variable is clearly more important than the other.
7	Demonstrated importance - a factor is strongly favored and its relevance has been demonstrated in practice.

9	Extreme importance - The evidence differentiating the variables is of the highest possible order.
2,4,6 e 8	Intermediate values between judgments.

Source: Adapted from Saaty (1991).

5.4 Selection of criteria

The municipality of Ilhéus is located on the coast of the state of Bahia, its urban area highlighted on all maps, is inserted between the Coastal Plain and the Seas of Morros (AB'SÁBER, 2003), due to its environmental characteristics of altimetric variation and slope, dominant presence of Atlantic Forest vegetation, as well as mangrove and restinga, make the municipality the target of environmental studies for being characterized as a region of contrast between urban development and areas of permanent preservation (APP).

Given the study situation, the criteria described in Chart 3, slope, soil, land use and cover, and rocks were judged as of greater importance, respectively. The relative factors (soil type, rock types, cover, use and occupation and slope) and the restrictive factor (rainfall intensity).

Chart 3 – Criteria for assessing environmental constraints

Factors	**Criteria**
Geology	Geological time
Alone	Pedogenetic maturity
Slope	Slope variation
Vegetation/land use	Landscape protection
Rainfall intensity	Erosiveness

Source: Crepani et al. (1996; 2001).

The criteria, factors and characteristics are listed in Table 2, to each factor it is possible to assign a relative importance, represented by the weights. It can be observed that the sum of the weights is equal to 1, distributed as follows: 0.29 (29%) for the slope criterion; 0.21 (21%) for soils; 0.13 (13%) for land cover; 0.23 (23%) for rocks and 0.14 (14%) for rainfall.

Considering all the factors, the one with the highest weight is the slope (0.29), followed by rocks (0.23), soils (0.21), rainfall intensity 0.14 and vegetation use and cover (0.13). The vegetation cover factors have lower relative weights, since they assume greater importance when combined mainly with the slope and soil factors. Table 2

Table 2 – Criteria, factors and indicator characteristics adopted in the classification regarding susceptibility to erosive processes in the municipality of Ilhéus-BA

Factors	**Indicator characteristics**	**Scale**	**Weight**
Slope	Plan (0-5%) Soft wavy (5-15%) Wavy (15-30%) Very wavy (>30%)	1,0 2,0 3,0 3,0	0,29
Alone	Ferralsols Acrisols Podzosols Luvisols Gleysols	1,0 2,0 2,0 2,0 3,0	0,21
Coverage and use	Plant formation Savanic Formation Mango Flooded field and marshy area	1,0 1,0 1,0 1,0	0,13

	Beach, dune and sand Sandbank Other non-forest formations Built-up area Agriculture Pasture Mosaic of agriculture and pasture Other non-vegetated areas	1,0 1,0 2,0 2,0 2,0 3,0 3,0 3,0	
Geology	Mesoarchaean Archean. Proterozoic Paleoproterozoica Riaciano. Cryogenic Neoproterozoic Proterozoic. Proterozoic Paleoproterozoic Siderian. Phanerozoic Cenozoic Neogeno M. L. Upper Cretaceous Mesozoic Phanerozoic. Phanerozoic Mesozoic Lower Cretaceous B. Upper Jurassic Mesozoic Phanerozoic. Phanerozoic Cenozoic Quaternary P. Phanerozoic Cenozoic Quaternary H.	1,0 1,3 1,5 1,5 2,7 2,8 2,9 2,9 3,0 3,0	0,23
Rainfall intensity	0,0-3,0 4,0-0,7 7,0- >	1,0 2,0 3,0	0,14

Source: Authors (2022)

According to Silva et al. (2009) the AHP technique is based on a square matrix of n x n, of comparison between the n criteria, where the rows and columns correspond to the criteria, the result being equal to the relative importance of the row criterion compared to the column criterion.

In this context, the input values in the matrices were obtained based on the two-by-two comparison (for pair) of the factors that influence environmental fragility. From the paired comparison, the criterion of relative importance between the factors was defined, according to a predefined scale from 1 to 9, where the value 1 is equivalent to the minimum, and 9 the maximum importance of one factor over the other.

From each paired comparison matrix, its eigenvectors were extracted, which correspond to the weight of relative importance for each factor considered. The eigenvectors resulting from the attribute comparison matrix are called weights. This technique for obtaining weights is described in detail in Saaty, 1991, Eastman et al. (1995) and also in Ferraz and Vettorazzi (2003).

5.5 Elaboration of the natural vulnerability to erosion map

The Linear Weighted Combination (CLP) is one of the most widely used methods in multicriteria analysis. From the CLP, the factors are combined by assigning, to each of them, a weight of relative importance previously calculated in the AHP.

From the determination of the individual values of vulnerability to erosive processes of each environmental conditioning in relation to Declivity, Pedology, Cover, Land use and occupation, Geology and Rainfall Intensity, it can be defined, empirically and relatively, through Equation 2.

The raster calculator was used in QGIS 3.10, and the map algebra equation was elaborated for the generation of the map. The Weighted Linear Combination (PLC) is the method of integrating the factors. It consists of multiplying each map by the sum of its respective weight and average of the vulnerability acquired in Crepani (2001) by the product of all these weighted factors. Thus, the equation that describes the erosion potential will be:

Equation 2 Potentiality to erosive processes

"Va = (Declivity *P1) + (Pedology * P2) + (Cover, use and occupation * P3) + (Geology*P4) + (Rainfall intensity * P5)"

Where: Va = Environmental vulnerability and P1, P2, P3, P4, P5 = Weighted Hierarchical Analysis weights.

For the crossing of the maps we opted for matrix data, because in this format each pixel of the resulting map is the result of the crossing of the pixels of the other existing mappings in the same x, y coordinate. To this end, it was necessary to transform the maps from the vector format to the matrix format. The result of this crossing is the Vulnerability Chart to Erosive Processes, a product of analysis that seeks to integrate the environment by approaching the region as a system composed of multiple variables that interrelate.

6. Results and discussion

6.1 Declivity

The relief of the municipality of Ilhéus is mostly within low hypsometric amplitudes of up to 250 m (Figure 2), but with average to high slope amplitudes, between 15 and 30%, with a predominance of slope above 30%, which corresponds to low stability.

According to the mapping, approximately 40.36% of the municipality has high and very high vulnerability, with slope above 30%, predominantly present in the urban area highlighted on the map (Figure 3), limit percentage for the parceling of the soil according to Law No. 6,766 of 1979 (BRAZIL, 1979) that provides for the Parceling of Urban Land.

In addition to these values, the municipality has 28.91% slope between 0 – 5%; 30.73% slope between 5-15%; 27.86% slope between 15-30%; and 12.50% of slope above 30% (Table 3). As the slope increases, so does the vulnerability, due to the greater potential for generating runoff and, consequently, greater susceptibility to erosion and risk of mass movements.

Table 3 – Area of the municipality in relation to the classes of Declivity

Relief Class	**Declivity %**	**Hierarchical Class**	**Area in km²**	**Area in %**
Plan	0-5%	Very Low/Low	467,51	28,91%
Soft wavy	5-15%	Average	496,92	30,73%
Wavy	15-30%	Loud	450,39	27,86%
Very wavy	>30%	Very high	202,08	12,50%

Source: IBGE (2001)

The mapping of the slope demonstrates the dissection of the relief of this region. It is worth mentioning that this classification considers the environmental/natural vulnerability of the slope, which is directly influenced by the form of use and occupation given its surface, so that the more devoid of vegetation, the more vulnerable the soil is to erosive effects.

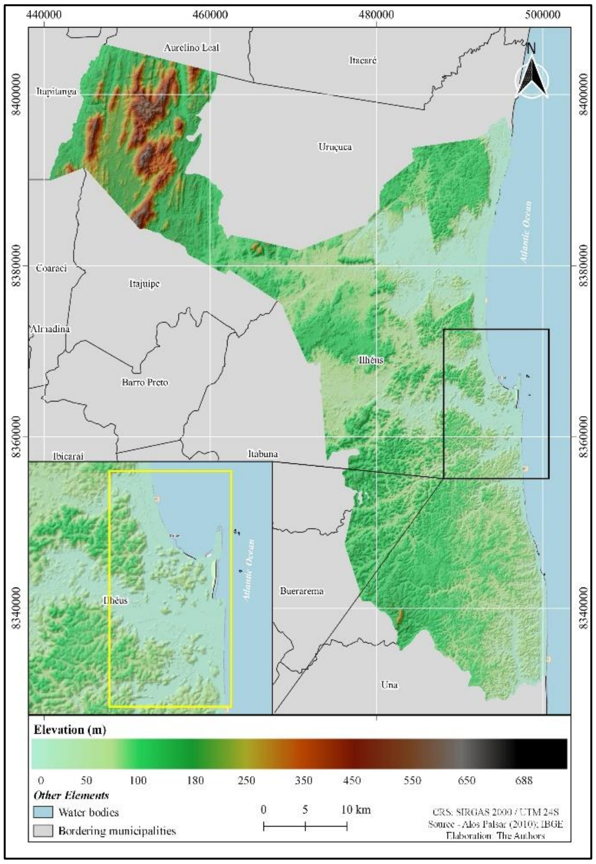

Figure 2 – Hypnometry Map of the municipality of Ilhéus Fonte: Alos Palsar (2010); IBGE (2023).

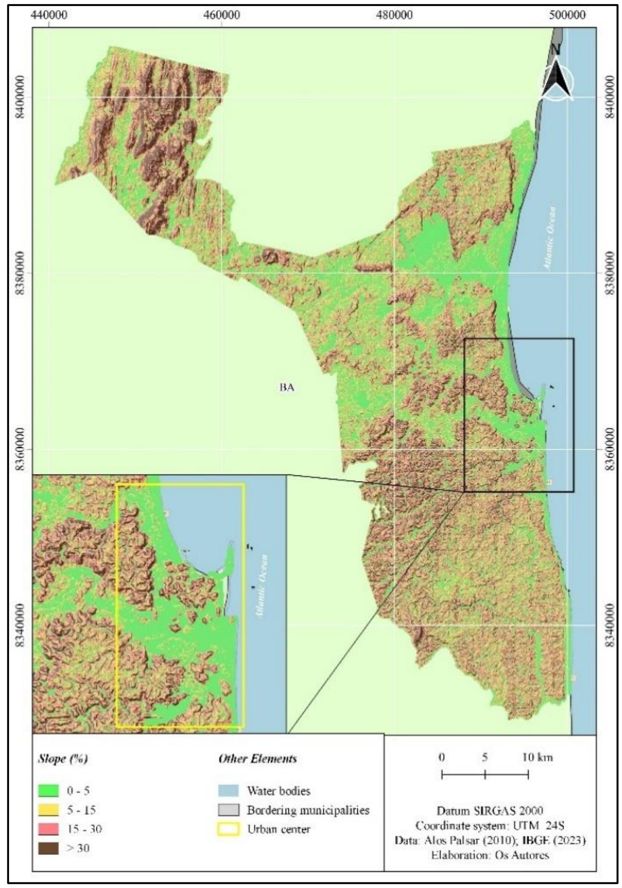

Figure 3 – Declivity Map of the municipality of Ilhéus
Source: Alos Palsar (2010); IBGE (2023).

6.2 Pedology

In the urban area highlighted on the map, latosols predominate (Figure 4), classified with a stability value of 1.0 and 52% of the area of the municipality, deep soils, but associated with slope, rain and deforestation, become more susceptible to erosion.

The latosols tend to be found in more stable and developed relief areas (flat to gently undulating), usually dystrophic, that is, the vertical flow of water prevails, intensifying the weathering, formation and homogenization of the pedological material, these aspects favor pedogenesis. The segments in question correspond to the interfluvium (watershed) and convex slopes, that is, at the top of the hills.

In contrast, in the most unstable and therefore younger segments, usually eutrophic, there is a predominance of erosive processes: slopes with rectilinear and convex slopes, a characteristic that is present in the relief of the urban area besides being densely occupied; or depositional reliefs: concave segments and colluvial/alluvial slopes, these aspects favor morphogenesis, where the soils tend to be younger and more diverse, such as the Acrisols and Gleysols, corresponding to 9% and 2% of the area of the municipality and stability value 2.0 and 3.0 respectively.

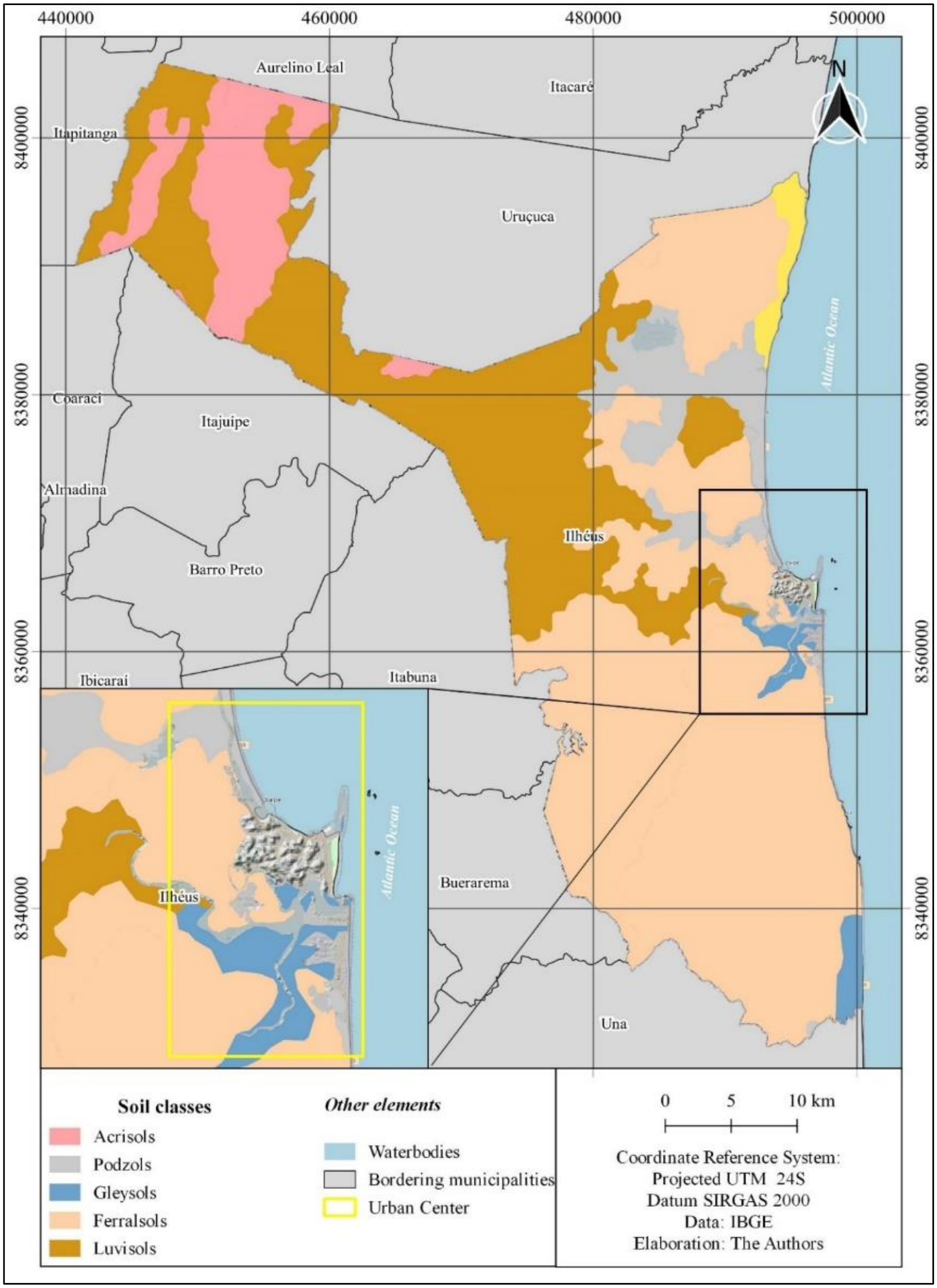

Figure 4 – Pedology Map of the municipality of Ilhéus
Source: IBGE (2023).

The Acrisols when located in sloped areas present greater susceptibility to erosive processes, due to the high concentration of clay that hinders infiltration processes and the saturation of the upper horizon favor the development of floods (laminar slippage), and when these areas present urban occupations without planning, associated with: inadequate interventions are factors that potentiate the occurrence of erosive processes and landslides, as already identified by Franco (2008).

Luvisols with a stability value of 2.0 also predominate, occupying 30% of the municipality's area. The Luvisols is an order of soil consisting of clays of high and eutrophic activity, that is, environments that have a predominance of erosive processes.

This type of soil occurs mainly on young surfaces. In this environment, such soils occur commonly associated with Plansols and Neosols (not identified in the mapping), which covers 1% of the area of the municipality, obtains the value 3.0 of stability and class High/Very High. Only the predominant soil classes were considered for reclassification in the matrix format according to the values shown in Table 4.

Table 4 – Area assigned to soil classes

Soil Class	Associated relief (IBGE)	Hierarchical Class	Area in km²	Area in %
Ferralsols	Corrugated/strong wavy	High/Very High	809,44	52%
Acrisols	Undulating/mountainous	Average	140,94	9%
Podzols	Plan	Very low/low	94,95	6%
Luvisols	Smooth wavy and wavy	Average	468,56	30%
Gleysols	Plan	Very low/low	26,27	2%
Neosols	Flat/wavy	Very low/low	18,87	1%

Source: Crepani et al. (1996; 2001). Data: IBGE (2001).

6.3 Coverage, use and occupancy

Based on the Charter of Coverage, use and occupation it was possible to observe that this region has been suffering a process of imbalance of its environmental functions caused by deforestation for civil construction, it is observed the almost complete urban occupation in the coastal area of the municipality. According to this mapping, the main class of land use and land cover (Table 5) is Forest Formation (71.59% of the total area), followed by Mosaic of agriculture and pasture (13.22%) and pasture (11.15%), and only 0.70% of Mangrove vegetation, 0.55% of wooded restinga if compared to the extension of the coast (Figure 5).

Table 5 – Area of the municipality in relation to Coverage, use and occupation

Coverage, use and occupancy	Hierarchical Class	Area in km²	Area in %
Savanic Formation	Low	0,39244	0,00%
Beach, Dune, Areal	Low	0,92425	0,00%
Other non-forest formations	Average	104,147	0,07%
Flooded field and marshy area	Low	142,254	0,09%
Other non-vegetated areas	Loud	156,801	0,10%
Sandbank	Low	872,246	0,55%
Mango	Low	1.115,041	0,70%
River, Lake, Ocean	-	1.584,221	1,00%
Built-up area	Average	2.458,555	1,55%
Pasture	Loud	17.725,592	11,15%
Mosaic of agriculture and pasture	Loud	21.016,407	13,22%
Forest training	Low	113.820,473	71,59%
TOTAL		158.995,737	100%

Source: MapBiomas, 2020.

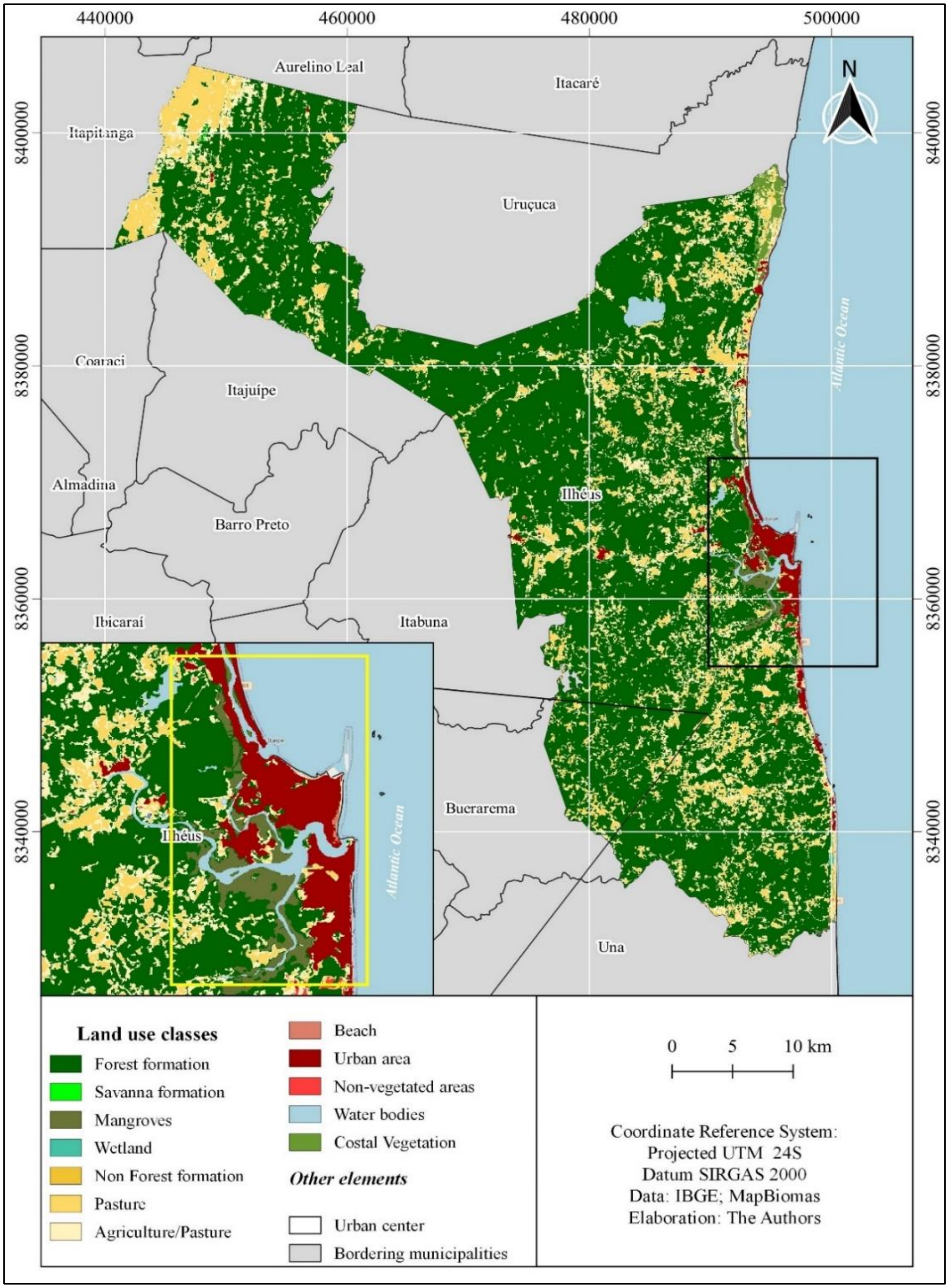

Figure 5 – Use and coverage Map of the municipality of Ilhéus
Source: IBGE, 2023.

In the high densities of vegetation cover the values attributed in the stability scale approach 1.0, for the intermediate densities intermediate values are attributed around 2.0, and for low densities of vegetation cover values close to 3.0 of stability.

6.4 Geology

In the urban area, the Proterozoic Paleoproterozoic Riacian formations predominate, rocks of the granulite gneiss type, metagabronorite, Enderbito, Metabasalt, Metadiorite, Metanorite and Metagabbro (Figure 6), classified as Igneous and Metamorphic rocks.

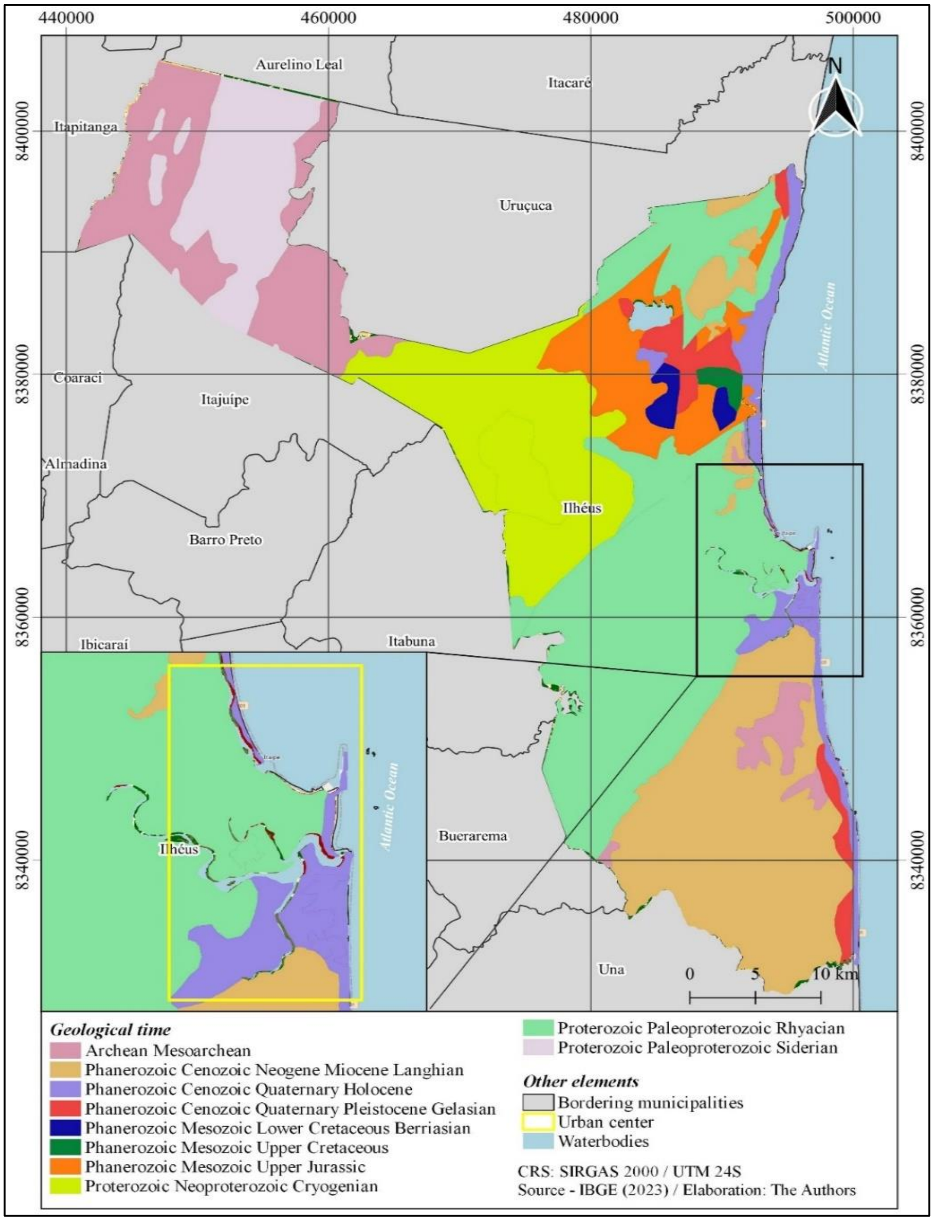

Figure 6 – Geology Map of the municipality of Ilhéus
Source: IBGE (2023)

These rocks have low vulnerability, in the value of 1.3 and area 457.13 km², despite the low value of vulnerability, that is, high stability, this formation gave rise to the hills of average to high slope, predominance of morphogenetic processes, such as greater flow of surface runoff and, that is, more susceptible to erosion. Also predominate the Phanerozoic Cenozoic Quaternary Holocene formations, rocks formed by deposits of clay, sand and silt, classified by sedimentary rock, has low stability, in the value of 4.6 and area 60.94 km², in compensation has flat relief, characteristic that predominates pedogenesis in relation to morphogenesis.

Older formations, of the granitic and gneissic types with igneous and metamorphic rocks receive lower vulnerability values, because they have greater resistance to erosive processes and mass movements. In order to assign a value within a vulnerability scale, the most commonly found lithologies were gathered in Table 6, which considers the aspects regarding the degree of cohesion of igneous, metamorphic and sedimentary rocks.

Table 6 – Area assigned to rocks

Geologic Time	Rocky Class	Hierarchical Class	Area in km²	Area in %
Mesoarchaean Archean.	Igneous, metamorphic	Very Low	204,19	12,99
Paleoproterozoic R.	Igneous, metamorphic	Very Low	457,13	29,09
Proterozoic Neoproterozoic C.	Igneous	Low	232,54	14,80
Proterozoic Paleoproterozoic S.	Metamorphic	Low	134,13	8,54
Cenozoic Phanerozoic N. M. L.	Sedimentary rock or sediments	Average	324,59	20,66
Phanerozoic Mesozoic Cretáceo S.	Sedimentary (or Sediments)	Average	6,81	0,43
Phanerozoic Mesozoic Cretaceous Lower Berriasian.	Sedimentary (or Sediments)	Average	13,21	0,84
Late Jurassic Mesozoic Phanerozoic.	Sedimentary (or Sediments)	Average	95,77	6,09
Phanerozoic Cenozoic Q. Pleistocene.	Sedimentary rock or sediments	Very high	42,07	2,68
Phanerozoic Cenozoic Q. Holocene.	Sedimentary rock or sediments	Very high	60,94	3,88

Source: Crepani et al. (1996; 2001). Data: CPRM (2003).

6.5 Stability/vulnerability of rainfall intensity

The rainfall intensity values shown in Figure 7 represent the values of potential energy available to transform into kinetic energy responsible for Erosivity, therefore, the higher the values, the greater the Erosivity, being possible to create an Erosivity scale that represents the influence of precipitation on erosive processes and mass landslide.

According to Crepani et. al. (1996;2001) on the scale of Erosivity: it can be constructed in such a way as to accommodate 21 classes of Erosivity and associate values, relative and empirical, of natural vulnerability to soil loss, since the higher the Erosivity the greater the soil loss of the natural landscape units.

Thus, regions with lower annual rainfall rates and longer duration for the rainy season will receive values close to stability of 1.0, intermediate values are associated with values of vulnerability/stability around 2.0, and regions with higher annual rainfall rates and shorter duration of the rainy season are attributed values close to vulnerability 3.0.

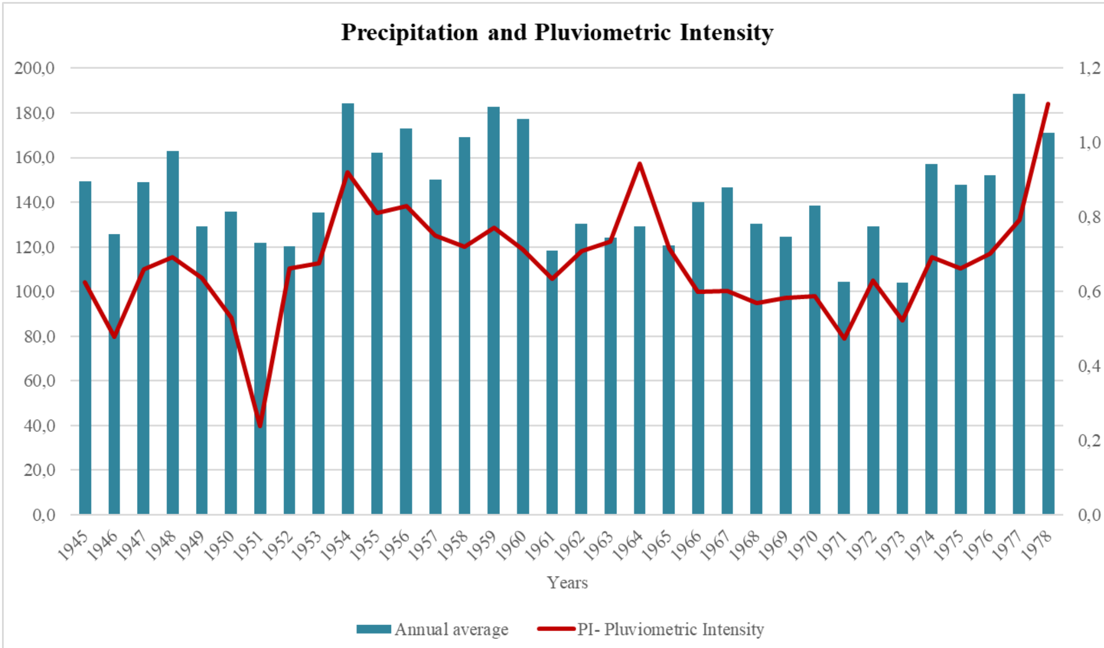

Figure 7 – Precipitation and Rainfall Intensity
Source: National Agency for Water and Basic Sanitation (ANA)

The rainfall intensity values calculated in this way are in Table 7 below, which presents the result of the ratio between average annual precipitation (PMA) and duration of the rainy season (DPC), which results in values of rainfall intensity (PI) and their respective values of stability/vulnerability for the municipality of Ilhéus.

Table 7 – Stability/vulnerability values attributed to rainfall intensity

Year	PMA	DPC	IP	E/V	Hierarchical Class
1945	149,3	239	0,6	2,0	Average
1946	125,6	263	0,5	2,0	Average
1947	149,0	226	0,7	2,0	Average
1948	162,9	235	0,7	2,0	Average
1949	129,2	203	0,6	2,0	Average
1950	135,6	256	0,5	2,0	Average
1951	121,8	512	0,2	1,0	Low
1952	120,4	182	0,7	2,0	Average
1953	135,2	200	0,7	2,0	Average
1954	184,1	200	0,9	3,0	High
1955	162,2	200	0,8	3,0	High
1956	173,2	209	0,8	3,0	High
1957	150,3	200	0,8	3,0	High
1958	169,2	235	0,7	2,0	Average
1959	182,6	237	0,8	3,0	High
1960	177,3	249	0,7	2,0	Average
1961	118,5	187	0,6	2,0	Average
1962	130,4	184	0,7	2,0	Average
1963	124,0	169	0,7	2,0	Average
1964	129,3	137	0,9	3,0	High

1965	120,7	169	0,7	2,0	Average
1966	140,1	234	0,6	2,0	Average
1967	146,8	244	0,6	2,0	Average
1968	130,2	229	0,6	2,0	Average
1969	124,7	214	0,6	2,0	Average
1970	138,6	236	0,6	2,0	Average
1971	104,1	220	0,5	2,0	Average
1972	129,1	205	0,6	2,0	Average
1973	103,9	199	0,5	2,0	Average
1974	157,1	227	0,7	2,0	Average
1975	147,6	223	0,7	2,0	Average
1976	152,2	217	0,7	2,0	Average
1977	188,6	238	0,8	3,0	High
1978	171,2	155	1,1	3,0	High

Source: National Agency for Water and Basic Sanitation (ANA)

Where: PMA= Average annual rainfall; CPD= Duration of the rainy season; IP= Rainfall intensity; E/V= Stability/vulnerability values.

6.6 Vulnerability Map to erosive processes

It is analyzed that the places with very high vulnerability are located in the urban area highlighted on the map, also in water bodies and areas of wooded restinga. There is also the presence of high vulnerability in coastal areas, non-vegetated, pastures and agricultural mosaics. That is, they present the highest vulnerabilities in areas where there is a high risk not only of erosion, but where the loss of biodiversity already occurs, such as in urban areas, water bodies and areas with a predominance of pastures. The average vulnerability class is mainly found in the Luvisols areas, while the very low and low vulnerability class is located in the Acrisols and Ferralsols areas.

When the Equation of Potentiality to the erosive processes to obtain the environmental/natural vulnerability to erosion was performed, it is observed that in the distribution of the weights there was the greatest consideration of the slope in relation to the other themes, with a weight of 0.33, due to this aspect having a strong influence on the erosive processes and landslides, while the lowest weight distributed was for geology of 0.14. With the realization of the AHP technique there is the assignment of the weights from highest to lowest importance in the following order: slope, pedology, coverage, use and occupation and geology. The Vulnerability Map (Figure 8) is the result of the overlapping of the raster base cards with the sum of the vulnerability values established by Crepani (1996; 2001) and AHP weights, resulting in the following classification in Table 8.

Table 8 – Values of the Stability/Vulnerability to erosive processes classes

Vulnerability Classes	Interval	Area km²	Area (%)
Very low	0 – 1.000	43.698.351	28%
Low	1.000 – 1.250	83.144.632	54%
Average	1.250 – 1.800	21.642.716	14%
Loud	1.800 – 2.000	5.566.955	4%
Very high	2.000 – 2.800	1.119.965	1%
	Total	155.172.619	100%

Source: Authors

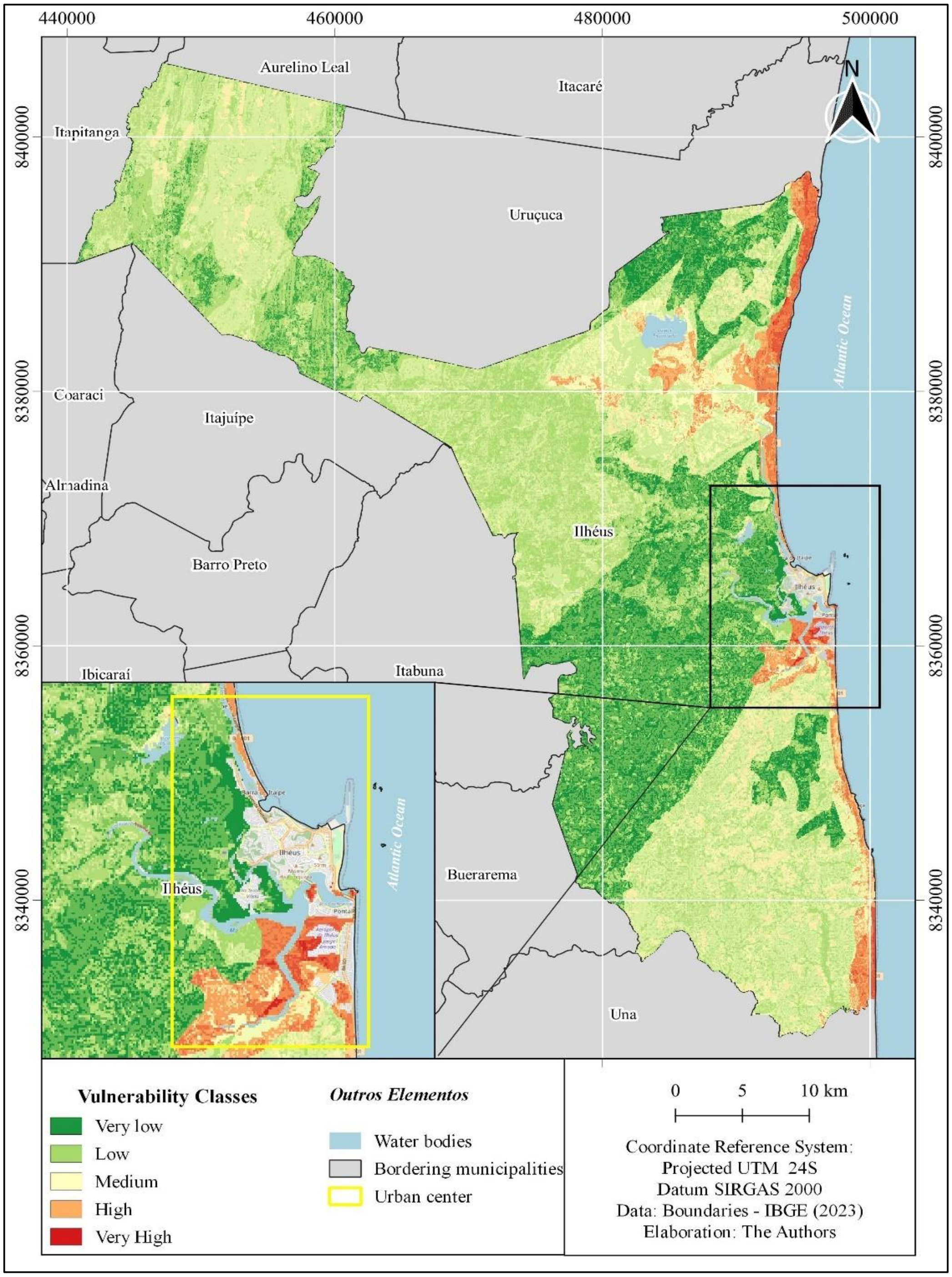

Figure 8 – Vulnerability Map to erosive processes in the municipality of Ilhéus
Source: IBGE (2023)

The Stability/vulnerability in the municipality of Ilhéus is distributed as follows: very low vulnerability, 1% of the area; low vulnerability, 27%; average vulnerability, 30%; high vulnerability, 35%; and very high vulnerability, 8%. It is verified that the highest percentages of the area of the municipality are classified as high and average, adding up to 65%, while very high only 8%. The total percentage of the municipality with low vulnerability is 28% (Figure 9).

The very low vulnerability class represents the geological covers of older formations, with lithological types metamonzonite, metasyenite, metagabronorite, metamonzodiorite, metamorphic rock class, of very undulating relief, soils of the argisol type, which despite being located in a sloping area, presents low vulnerability due to the vegetation cover and forms of land use and occupation that provide greater stability to the landscape. In the low vulnerability class are the slopes from gentle undulating to undulating, geological cover of average vulnerability, of the geological type Sandy argilite and conglomeratic argillite, class of sedimentary rock, soil class Latosol and density of vegetation cover and forms of use and occupation that make the landscape less vulnerable.

The determining factors for the average, high and very high vulnerability classes are the increase in slope, the most recent geological cover with clayey and sandy lithological types, sedimentary rock class and forms of cover, use and occupation of greater vulnerability, such as the presence of restinga and water bodies, pastures, non-vegetated areas and agricultural mosaics.

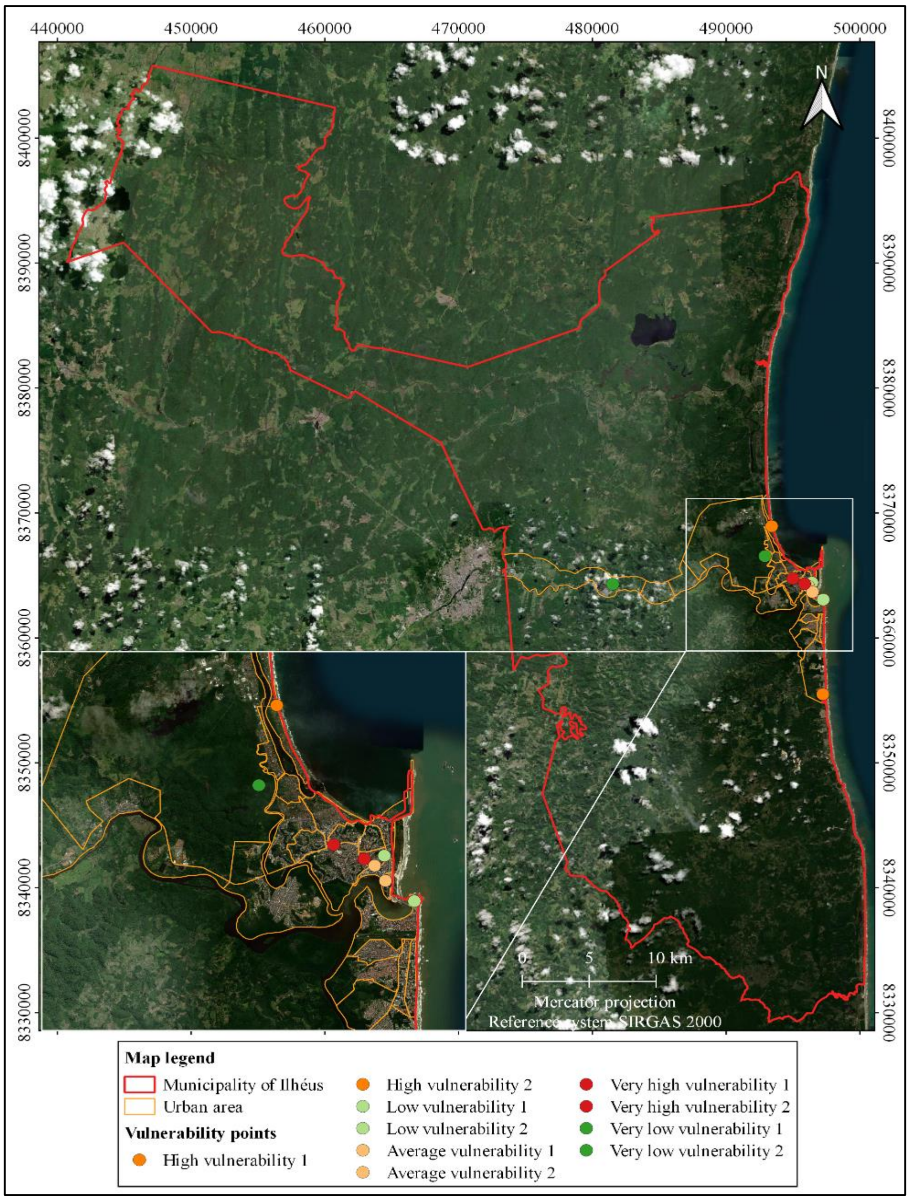

Figure 9 – Location of Vulnerability Points
Source: Google Earth, 2022

6.7 Very low vulnerability areas

The risk level class, very low vulnerability to the erosive process, was defined comprising the range of values in equal interval between the minimum 0 and 0.85000. Spatially, this class is represented by areas located in greater quantity of the eastern to southwestern range of the municipality. This region corresponds to environments in equilibrium, where morphogenetic stability prevails. They do not present major environmental problems for the development of socioeconomic activities, provided that standards and criteria for sanitation and soil infiltration are established, in order not to favor the occurrence of erosive processes

This sector presented, in totality, the lowest values in the map of vulnerability to erosive processes, even registering values of average altitude and slope. It is also observed the use and cover of land with a large percentage of dense vegetation, another characteristic to keep the level of conservation high and low vulnerability to erosive processes. The relief varies from gentle wavy to very wavy with slope from 15% to 30%.

The representative areas of the very low risk level class occupy 10% of the total area and are spatially distributed in the municipality according to Figure 10, as well as some photographic records of their aspects. The sites have altitudes of 36 meters and 34 meters respectively. It is observed in the first photograph the conservation of mangrove vegetation, in the foreground, and in the background hills with dense Atlantic Forest.

Point 1

Point 2

Figure 10 – Very Low Vulnerability Areas

6.8 Low Vulnerability Areas

The low vulnerability level class to the erosive process was defined comprising the range of values in equal interval between the minimum 0.85000 to 1.20437. Spatially, this class is represented by areas located in greater quantity of the northwest range of the municipality. The relief varies between flat and gently undulating, presents slopes between 0 and 15%, the localities photographed have altitudes of 8 meters and 49 meters respectively. It is also observed that the influence of degradation is practically minimal in these areas.

The areas corresponding to this class occupy 18% of the total area of the municipality, representing the largest extension among the 5 classes of vulnerability level. The spatial distribution of this class and photographic records of landscape aspects are shown in Figure 11. They correspond to environments in equilibrium, where morphogenetic stability prevails. They do not present serious environmental problems for the development of socioeconomic activities, provided that standards and criteria for sanitation and soil infiltration are established, in order not to favor the occurrence of floods and floods.

In the first photograph it is noted that the level of use and occupation is low, which keeps the environment in balance. In the second photograph it is possible to visualize the geomorphological process of deposition of marine sediments, in both localities the morphogenetic stability prevails. The Gleysols patches and mangrove ecosystem, in addition to the restinga vegetation, are located in the vicinity of the urban core of the municipality.

Point 1

Point 2

Figure 11 – Low Vulnerability Areas

6.9 Average vulnerability areas

For the representation of the average vulnerability level class to erosive processes, values from 1.20437 to 1.43495 were taken. This class, which covers the intermediate values of vulnerability levels, has the representative sectors occupying 5% of the total municipality, the locations occur in patches of pasture (or exposed soil).

The spatial distribution of this class and photographic records of aspects of its landscapes are shown in Figure 12. The region contemplates the areas of very varied relief, going from the flat to the very undulating, the localities represented in the figure have an altitude of 23 meters and 30 meters respectively.

They correspond to environmental systems with ecodynamics of transitional environments, where there is a fragile balance between the conditions of morphogenesis and pedogenesis. They are also susceptible to occurrences of erosive processes. These environments can be degraded by socioeconomic activities and also require specific criteria for land use and occupation.

Point 1

Point 2

Figure 12 – Areas of Average Vulnerability

In the first photograph, despite the presence of a vegetation that varies between large trees, shrubs and bamboo, it is noted the existence of slip scars. In the second photograph you have a panoramic view of the estuary of the Cachoeira and Santana rivers and fragments of mangroves. From the point photographed there is a very steep slope, without slip scars and little vegetation present, an aspect that allows a lower level of stability of the physical aspects.

6.10 Areas of High Vulnerability

To define the areas that comprise the high vulnerability level class to erosive processes, we took as a basis the equal interval range of the map generated in the linear combination of 1.43495 to 1.59938. It occupies practically the entire coastal strip, area of soils Podzols, Neosols and Ferralsols, restinga vegetation. In these sectors, the classes of flat and smooth wavy relief, of lower weights and altitude of 5 meters and 13 meters respectively represented in the photograph of Figure 13.

Point 1

Point 2

Figure 13 – High Vulnerability Areas

From these observations, it is inferred that the coastal strip of the municipality covers the areas that offer greater risks to erosive processes. The high vulnerability level class to erosive processes occupies 1% of the total area. The spatial distribution in the watershed of the representative sectors of this class and photographic records of landscapes of these sectors.

They correspond to environmental systems with unstable and strongly unstable ecodynamics. As in the previous definition, the classification of these areas considers the carrying capacity of the environment associated with inadequate processes of land use and occupation and limitations imposed by environmental legislation. They also have extreme situations of predisposition to occurrences of erosive processes.

The geomorphological processes caused by coastal erosion come from urban-environmental issues. Erosion is one of the geomorphological processes identified in loco, and one of the most modeling of the landscape, involving the exchange of matter and energy. In the case of this locality in Ilhéus, this phenomenon is constituted by the mechanical action of the waves and transport of marine sediments, responsible for the advance of the sea and destruction of the shore.

6.11 Areas of Very High Vulnerability

The last range of the map of values of equal interval has a variation of 1.59938 to 2.73905, corresponding to the sectors with the greatest potential of risk vulnerability to erosive processes by the high slope and altitude of 39 meters and 34 meters respectively. It is one of the main areas of risk of landslides. The first photograph shows a large work of hillside containment, it is also noticeable that the area is densely populated. The second image shows the inclination close to 90º degrees and the presence of slip scars, the proximity to urban occupations is evident and the risk to erosive processes is imminent.

These high values result from the higher weight attributed to areas of high slope, clay soils, areas of urban occupation and exposed soil, occupy less than less than 1% of the studied area. It is evidenced, in this observation, the potentiation of the negative effect offered by the occupation of areas with such characteristics for being of higher risk. It is also recorded that the predominant slopes are flat to smooth wavy relief, presenting little variation, whose weights are the lowest of the slope criterion. Figure 14 shows the spatial distribution of the representative sectors of this class and shows photographic records of landscapes.

Point 1 *Point 2*

Figure 14 – Very High Vulnerability Areas

They correspond to environmental systems with strongly unstable ecodynamics. The classification of these areas considers the carrying capacity of the environment associated with inadequate processes of land use and occupation and limitations imposed by environmental legislation. They have extreme situations of predisposition to occurrences of erosive processes.

7. Conclusions

The identification of the state of stability/vulnerability to erosive processes of the municipality of Ilhéus-BA permit and the integrated analysis of the landscape. Therefore, the indicators of geology, pedology, slope, land use and cover, and rainfall index are the variable environmental factors. The feasible methodology, on the other hand, uses few resources and provides tools for the principle of prevention, which facilitates its implementation by municipal governments.

The slope factor has a preponderant participation in the potential of erosive processes, with a weight of 0.29, higher than the Soil Type factor, with an importance of 0.21. The criterion Coverage and use received a weight of 0.13, rocks the weight of 0.23 while the factor rainfall intensity was attributed the least importance, with a weight of 0.14.

It is possible to use the AHP method (SAATY, 1991) and Crepani (2001) to analyze the environmental/natural vulnerability to erosive processes, reaching the conclusion that approximately 19% of the studied area has average to very high vulnerability. Being verified through the observation of the vulnerability map a greater concentration along the entire coast and points in the urban center. In these areas a plain relief prevails, with active erosive processes in the northern region of the municipality, undulating relief in the center, and in the urban area there are hills that exceed 30% of slope. In addition to the urban area and coastal region, the analysis returned as highly vulnerable areas near the estuary.

The vulnerability was distributed into five classes, with the final vulnerability map resulting in a high and average rating, totaling 18%, while very high only 1%. The total percentage of the municipality with very low vulnerability to low vulnerability adds up to 82%. It should be noted that these results essentially consider the stability of the landscape, and many of the areas considered low to very low vulnerability are degraded or deforested, but present low risk of erosion due to being located in areas of low slope and in older geological and pedological formations.

It is important to emphasize that although the methodology helps in the analysis of the phenomenon, it is still necessary that there is a deep discussion about which variable is more important than the other, considering that the method provides a simple means of relating such variables and still seeks to validate the degree of consistency of the relationships, not being able to exceed the 10% recommended by the methodology. The degree of consistency between the variables obtained the result of 2.7%, which does not replace the support of the literature and previous knowledge necessary to weigh the value of each variable, in addition, the equation presented here is only one of the tools for integrated analysis of the landscape, without the intention of replacing other existing analyses.

Acknowledgments

To the National Research Council (CNPQ), for granting financial aid via Universal Project - Process n.409304/2021-2.

To the Coordination for the Improvement of Higher Education Personnel (CAPES), for the granting of a postgraduate scholarship to one of the authors of the work.

To the Fluminense Federal University (UFF) for hosting and supporting the Graduate Program in Geography of the Institute of Sciences of Society and Regional Development (ESR).

To the Federal University of Southern Bahia (UFSB), for the granting of a scholarship to scientific initiation, for one of the authors of the work.

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