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GEOSPATIAL MODELING OF ENVIRONMENTAL SUSCEPTIBILITY TO WATER EROSION: A CASE STUDY OF ILHA DE ITAMARACÁ - PE.

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ABSTRACT

The use of geospatial modeling in the identification of vulnerability to water erosion is configured as a resource that enables the understanding in the recovery of degraded areas. The present work aimed to establish the vulnerability to water erosion of the Jaguaribe, Maceió and Paripe river basins, considering the relationship between slope, rainfall, pedology and water erosion, land use and occupation, through Geographic Information System (GIS) technology and the application of the AHP (Analytic Hierarchy Process). Thus, it appears that the area most susceptible to water erosion is the Maceió river basin, because it is in a highly urbanized river. Thus, the mapping of vulnerability to erosion can assist in public policies, enabling adequate environmental planning.

KEYWORDS: Degraded Areas, Analytic Hierarchy Process, Geographic Information System

MODELAGEM GEOESPACIAL DA SUSCETIBILIDADE AMBIENTAL À EROSÃO HÍDRICA: ESTUDO DE CASO DA ILHA DE ITAMARACÁ - PE

RESUMO

A utilização de modelagens geoespaciais na identificação da suscetibilidade à erosão hídrica se configura como um recurso que possibilita a compreensão na recuperação das áreas degradadas. O presente trabalho visou estabelecer a suscetibilidade da erosão hídrica das bacias dos rios Jaguaribe, Maceió e Paripe, considerando a relação entre os fatores declividade, precipitação pluvial, pedologia e uso e ocupação do solo, pela tecnologia de Sistema de Informações Geográficas (SIG) e a aplicação do AHP (Processo Analítico Hierárquico). Verificou-se que a área mais suscetível à erosão hídrica é a da bacia hidrográfica do Rio Maceió, por compreender uma região bastante urbanizada. Assim, o mapeamento da suscetibilidade à erosão hídrica pode auxiliar em políticas públicas, possibilitando um planejamento ambiental adequado.

PALAVRAS-CHAVE: Áreas Degradadas, **Processo Analítico Hierárquico, Sistema de Informações Geográficas**.

1. INTRODUTION

Erosion is a worrying phenomenon and a major threat to soil resources, agricultural productivity, biodiversity, and is still partly responsible for negative impacts on the food sector, water quality, river silting, ecosystem balance, because it affects the hydrological cycle, causing environmental degradation on a large scale, contributing to poverty in many parts of the world, (Chao et al., 2023; Oliveira et al., 2023).

This process arouses the great interest of many researchers with regard to the causes that lead to its origin, evolution and control, as it reaches and renders extensive areas of land unusable, causing various environmental impacts verified in space-time patterns (Francisco et al., 2023). Through land use and cover scenarios, it was found the removal of approximately 71 million ha of native vegetation in Brazil, being the agribusiness sector the main responsible, (Santos, 2020). In the cerrado, environmental consequences were verified, with the biome marked by agropastoral practices, due to deforestation of approximately 24.7 million ha., (Maciel et al., 2020; Alencar et al., 2020). This accelerated degradation of natural resources has severely interfered with changes to the Earth's surface (Chalise et al., 2019), so that exploration in some regions presents itself without control and awareness that part of natural resources are finite or arduous recovery (Riekhof et al., 2019).

For Sartori et al. (2019) erosion causes economic losses on the scale of 40 to 490 billion dollars depending on the country. Telles et al. (2011) add that in the United States the negative economic impact caused by soil erosion is around 44 billion dollars/year, while in the European Union countries it is around 45.4 billion dollars/year and in Brazil, in the state of Paraná alone, the loss accounts for 245 million dollars/year.

However, this information has never been integrated to understand the efforts in geospatial modeling in soil erosion, with mapping and identification of environmental vulnerability. For the implementation of environmental policies it would not be possible to consider soil erosion if there were no accessible tools for modeling and mapping on a large scale, since this scenario is associated with the conflict of political and economic interests with the form of exploitation, generally not sustainable (Alewel et al., 2019; Jian et al. 2022; Soares et al., 2023).

In this sense the geospatial technologies (Remote Sensing, Geographic Information System - GIS, geoprocessing techniques, satellite navigation system, among others), although seen as procedures that take time and costs to be performed (Martins et al., 2019; Pagan et al., 2020; Bohn et al., 2021), represent important resources for analyzing erosion processes, mapping the most vulnerable areas, in order to assist in the prevention and/or recovery process of degraded areas, (Alves et al., 2021), in addition to integrating the information in modeling processes to estimate soil losses, integrating qualitative information in modeling processes to estimate soil losses in watersheds, (Martinez et al., 2003; Arabameri et al., 2020; Pal et al., 2020).

The AHP method (Analytic Hierarchy Process) has been applied in different areas of knowledge, specifically when it comes to environmental issues, such as geotechnology, geomorphology, urban planning, for example, in the determination of areas of environmental vulnerability , social, mapping areas of soil susceptibility to erosion and landslides. Such a method tries to reduce the subjectivity of susceptibility and danger maps elaborated from heuristic methods, and also helps in the analysis and weighting of the most relevant parameters that can condition the occurrence of mass movements (Santana, 2020; Franco et al., 2021).

Orozco et al., (2020) describes that the term vulnerability can be used as an indicator, which analyzes the risks to the exposure and responsiveness of an area, when related to the socio-environmental and under the effects caused by anthropic and/or natural factors. Anthropogenic actions promote areas vulnerable to erosion processes, resulting in environmental fragility, leading to restrictions on land use, (Peixoto et al., 2018).

The municipality of Ilha de Itamaracá-PE, like other coastal municipalities in the Northeast region of Brazil, underwent disorganized urban interventions starting in the late 20th century, without proper oversight by the public authorities. This resulted in densely populated areas that are unsuitable for occupation (Pereira & Ferreira, 2013). Furthermore, the municipality has physical-natural characteristics that strongly predispose it to the occurrence of water erosion. In this context, this study aims to use GIS technology in conjunction with the AHP method to develop a susceptibility map that identifies areas most prone to water erosion in the watersheds of the municipality of Ilha de Itamaracá, Pernambuco.

2. CHARACTERIZATION OF THE STUDY AREA

The municipality of Ilha de Itamaracá is located in the Metropolitan Mesoregion and Itamaracá Microregion of the State of Pernambuco, restricted to the north with Goiana, to the south with Igarassu, to the east with Atlantic Ocean, and to the west with Itapissuma. The cyty is located on the northern coast of Pernambuco, 50 km from Recife, capital of the state, between latitudes 7° 35` S and 7° 55` S and longitudes 34° 48` W, 34° 52` W whose access is made by BR-101; PE-035 (França & Severi, 2022).

The climate is the same as that found along the coast, constantly influenced by the flow of "caallarian" air. The dominant rainfall occurs in winter, mainly by the emissions of the Arctic Polar Front-FPA, while the autumn supplies derive from the oscillations of the Intertropical Convergence - CIT. The evaporation rate is below precipitation, resulting in a positive annual balance and contributing to an intense decomposition of the rocks, generating arable soils (Bezerra, 2022). The geographical position of Ilha de Itamaracá guarantees a typical tropical climate, with high temperatures and constant humidity. According to Köppen's classification, the c climate is of the As` and Am's type: The average temperature is 27o C and the thermal amplitude around 5o C, 'being attenuated in the hottest months, September - November, by the southeast trade winds, a dry season in summer and frequent rains in autumn and winter (Noriega et al., 2022).

Geologically the Iha de Itamaracá city is inserted in the Borborema Province, formed by the lithotypes of the Salgadoinho Complex, Beberibe Formation, Itamaracá Formation, Gramane Formation, Maria Farinha Formation, Barreiras Group and Flúvio- marine Deposits (Bezerra, 2022). Its most striking characteristics at Ilha de Itamaracá are the light quartz-feldspathic sands, incoherent, fine to medium grained, interspersed with greenish-gray clays. From the base to the top of the city, the following are found: (a) conglomeratic sandstone with channeled cross stratification, yellow color; (b) greenish variegated clay filling the channel bottom; (c) massive red medium sandstone. Coroa do Avião.

The vegetation of the municipality is mainly related to soil conditions and climate and tidal action. On the coast the mangrove vegetation develops, which can also be found in the water courses (Moura et al., 2022). At the Sossego Beach and Dolphin Cove, a strip corresponding to the Pleistocene marine terraces, presents a very representative vegetation of restinga, although some areas are in degradation by anthropic action (Albuquerque, 2009). In the tableland areas of the Formação Barreiras, there are testimonies of the Atlantic Rainforest.

The hydrography of the region has two main rivers: Jaguaribe and Paripe (Figure 1). The main watersheds is that of the Jaguaribe River, with about 730 km², approximately 9 km in length and 212 ha of estuarine area. The river follows the Southwest-Northeast direction with a permanent flow throughout the year. The drainage pattern of the basin is dendritic and watercourses of reduced extension.

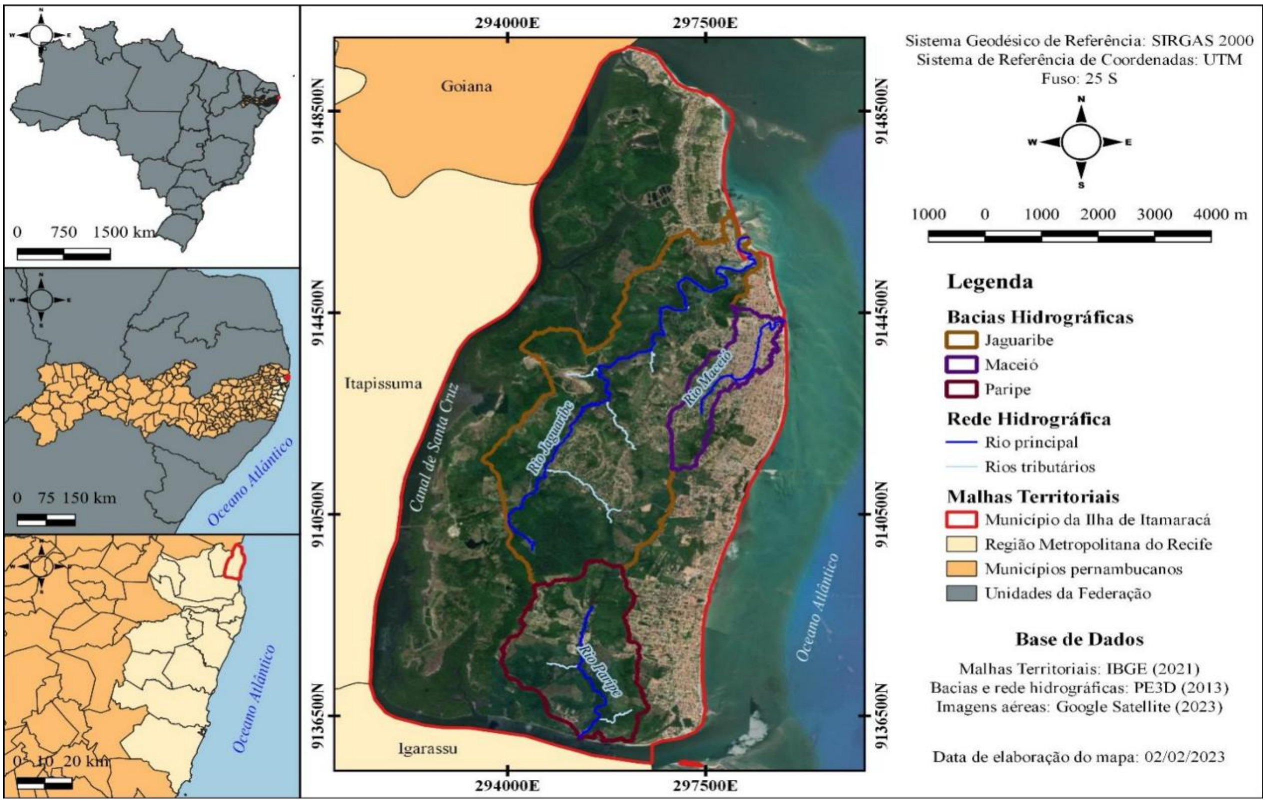

Figure 1: Location of the Jaguaribe, Maceió and Paripe river basins. Source: Prepared by the authors

The Paripe River is located to the south of the municipality, having 4 km of extension and an estuary covering an area of 37.3 ha, of which 79% correspond to an area of mangrove (Moura et al., 2022). The main body of accumulation is the Lagoa Pai Tomé. The river drainage network of the Ilha de Itamaracá city, in the winter, contributes with a total average discharge of 55.9 $m^3.s^{-1}$ and in the summer of 0.8 $m^3.s^{-1}$. The city is bathed in part of its surroundings by the Atlantic Ocean. And around the other part of the city, separating it from the mainland, is the Santa Cruz Channel, 22 km long sea arm, maximum width of 1.5 km and with an estuarine area of about 5.292 ha.

The hydrogeology of the region is composed by aquifers framed in the domains of the Paraíba Sedimentary Basin and the Crystalline Basement. The Paraíba Basin, in the state of Pernambuco, is located in the northern part of the coastal zone, extending from the municipality of Olinda towards the state of Paraíba (Maia, 2022). Its extension is in the order of 750 km^2.

3. MATERIALS AND METHODS

The methodology applied in the development of this study can be seen in Figure 2. The map of susceptibility to water erosion was prepared from the conditioning factors to this type of phenomenon, which were selected from the recurrence in similar studies. Then, scores were assigned to the factors, according to the level of susceptibility to water erosion, so that the AHP could be applied. Finally, the map algebra process was performed, resulting in the water erosion susceptibility map.

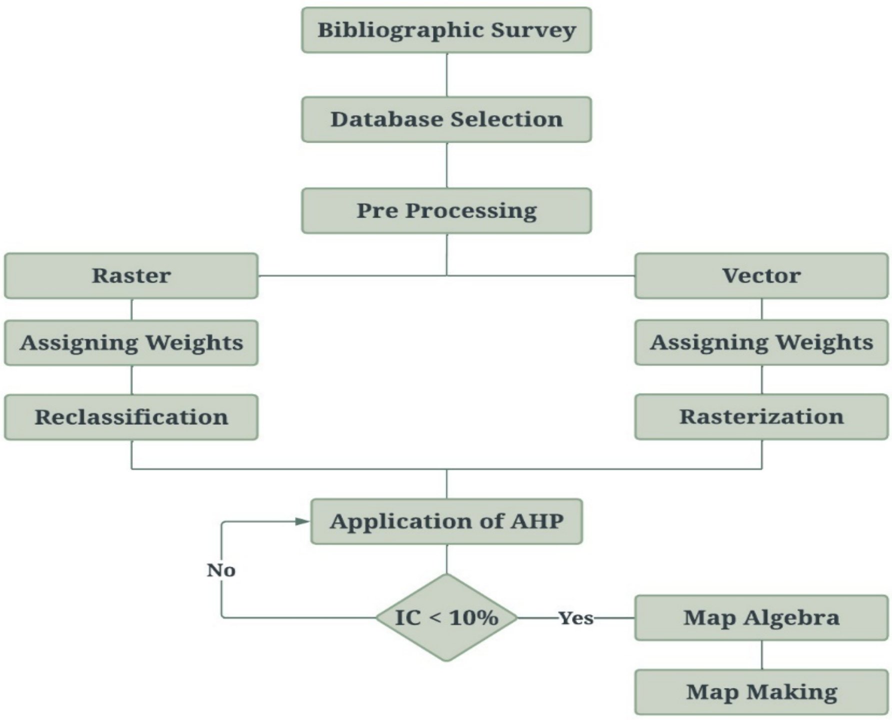

Figure 2: Summary of methodological procedure. Source: Prepared by the authors

3.1 Selection of conditioning factors to water erosion susceptibility

Seeking to achieve the objective proposed in this study, initially a selection of factors that condition a watershed to water erosion was carried out. This analysis took into account fifteen similar studies from the Journal Portal of the Coordination for the Improvement of Higher Education Personnel (CAPES) that used, above all, GIS technology to identify areas susceptible to this type of phenomenon. Table 1 presents the analyzed studies, relating the authors to the factors used.

table 1: Factors used in similar studies on mapping areas susceptible to water erosion

Authors	Factors										
	Slope	Goelogy	Geomorphology	Hipsometry	Vegetation Index (NDVI)	Lithology	Morphometric Parameters	Conservationist Practices	Rainfall	Pedology	Soil Use and Occupancy
Aoufa et al. (2022)	X							X	X	X	X
Bensekhria e Bouhata (2022)	X							X	X	X	X
Costa et al. (2022)	X					X				X	
Ferreira et al. (2022)	X								X	X	X
França e Silva Neto (2022)	X									X	X
Bolleli et al. (2021)	X									X	X
Gomes et al. (2021)	X								X	X	X
Martins et al. (2021)	X				X				X	X	X
Neji et al. (2021)	X				X	X			X		X
Arabameri et al. (2020)							X				
Nehai et al. (2020)	X				X	X			X		
Santos e Nascimento (2020)	X			X					X	X	
Soares Júnior (2020)		X	X						X	X	X
Bedoui (2019)	X							X	X	X	X
Caldas et al. (2019)	X		X						X	X	X
Total	**13**	**1**	**2**	**1**	**3**	**3**	**1**	**3**	**11**	**12**	**11**

Source: Prepared by the authors, based on a literature review

Through this analysis, it was found that the factors Slope, rainfall, pedology and land use and occupation were the most recurrent, used in several studies. Due to this recurrence, these factors were also employed in this work. Some other factors were also considered in the similar studies analyzed, but did not present a great recurrence, such as geology, geomorphology, hypsometry, NDVI, lithology, morphometric parameters, and the conservation practices. Therefore, these factors were not used in this study, because they did not present a insignificant relevance in the analysis.

3.2 Collection and treatment of spatial data for the elaboration of thematics maps

At this stage, the spatial data used in the elaboration of thematic maps of the conditioning factors to the susceptibility to water erosion were obtained in the virtual platforms of official bodies. The methods how these maps were produced are described in Table 2. All spatial data were processed in QGIS software (version 3.10.9), in UTM coordinates and in the Geocentric Reference System for the Americas (SIRGAS).

table 2: Sources for obtaining spatial data and methods for preparing thematic maps

Map	Source of data and methods
Slope	Prepared in matrix format (raster) from a Digital Elevation Model (DEM) with a spatial resolution of 1 meter from the Pernambuco Tridimensional program (PE3D), which was produced by airborne laser profiling (PE3D, 2013). The slopes presented in the map were represented as a percentage and grouped into six categories, namely: 0 - 3% (flat), 3% - 8% (gently wavy), 8% - 20% (wavy), 20% - 45% (strongly wavy), 45% - 75% (mountainous) and >75% (steep). These are in accordance with the classification proposed by the Brazilian Agricultural Research Company (EMBRAPA) (1979).
Spatial variability of precipitation	Produced from historical rainfall data from four rainfall stations available on the platform of the Pernambuco Water and Climate Agency (APAC). These data correspond to a historical series of 21 years, from January 1, 2002 to December 31, 2022 (APAC, 2023). In view of this information, it was found that some rainfall stations did not present complete data, that is, they had some gaps. To supplement the absence of this information, the simple linear regression method was adopted. In this method, rainfall data at the faulty station are statistically correlated with data from a neighboring station that is complete. After the treatment of rainfall data, the Arithmetic method was used to obtain the average annual precipitation of each season. Then, these stations were georeferenced in QSIG (version 3.10.9) and, soon after, the tool "Interpolation IDW" was used to map the spatial variability of precipitation in the study region.
Pedological	Acquired by EMBRAPA's virtual platform in vector format (shapefile) and scale 1:100,000 (EMBRAPA, 2018). Then, the cut was made in this layer, which represented the soil types of the state of Pernambuco, under the polygon of the study region.
Soil use and occupation	Obtained by the virtual platform of the Annual Mapping Project of Soil Use and Coverage in Brazil (MapBiomas) (2023), the file came from Collection 6, in matrix format and with spatial resolution of 30 meters.

Source: Prepared by the authors

3.3 Reclassification of water erosion susceptibility factors

For this stage, the spatial data related to the factors that condition water erosion were reclassified according to a process of attributing scores, which varied on a scale of values between 1 and 5, so that the value 1 is equivalent to the least susceptible criteria, or that is, exempt from water erosion and 5, those most susceptible.

The criteria (classes) of the reclassified factors regarding the scores attributed to the conditions of susceptibility to water erosion in the study region are presented in Table 3. To perform this reclassification, the tool "Reclassify by table" of the QSIG toolbox was used for the matrix files (version 3.10.9). The spatial data of vector representation, were converted to the matrix, so that it was possible to perform this type of procedure.

table 3: Reclassification of fator criteria according to susceptibility to water erosion

Map	Classes	Score	Map	Classes	Score
Slope (%)	0 - 3	1	Pedology	Soils mangrove	1
	3 - 8	2		argisols	2
	8 - 20	3		spodosols	2
	20 - 45	4		gleissols	3
	45 - 75	5		neosols	3
	> 75	5		Urban area	4
Rainfall (mm)	1650 - 1675	1		river	5
	1675 - 1700	2	Soil use and occupation	Vegetated area	1
	1700 - 1725	3		Farming	3
	1725 - 1750	4		Exposed soil	4
	1750 - 1775	5		Artificial area	4
				Water bodies	5

Source: Prepared by the authors

3.4 Application of AHP

The proposed method for identifying areas susceptible to water erosion was based on the application of the Analytic Hierarchy Process (AHP), which was developed in the mid-1970s by Thomas L. Saaty. This methodology covers a procedure aimed at making decisions about complex issues involving multiple criteria, which are hierarchized and organized in levels of detail, enabling the decision maker to establish priorities, achieving the best choice (Gómez Romero et al., 2020; Moreira-Franco, Ortega-Ordóñez, 2021; Rodríguez-Peral et al., 2022).

Applying the AHP, a scale of importance was established through the weights asGISned to the factors evaluated, since each factor represents a certain relevance with regard to susceptibility to water erosion. Thus, the factors were arranged in a Paired Comparison Matrix (Table 4), in which their weights were asGISned according to the criteria of importance of the Saaty Fundamental Scale, presented in Table 5, whose values vary from one to nine.

Table 4: Paired Comparison Matrix

Factor	**Factor 1**	**...**	**Factor p**	**...**	**Factor n**
Factor 1	1	...	a_{1p}	...	a_{1n}
...	...	...	...	...	...
Factor p	a_{p1}	...	1	...	a_{pn}
...	...	...	...	...	...
Factor n	a_{n1}	...	a_{np}	...	1

Source: Prepared by the authors, based on Saaty (1977)

Table 5: AHP Importance Judgement Scale

Values	Description of the importance	Justification
1	Equal	Both factors contribute equally.
3	Moderate	The comparative factor is a little more important than the other.
5	Essential or strong	Judgment strongly favoring one factor over the other.
7	Very strong	One factor is strongly favored, with demonstration in practice.
9	Extreme	The compared factor has a greater importance than the other at the highest possible level.
2, 4, 6 e 8	Intermediate Values	When there is an intermediate condition between two definitions.

Source: Prepared by the authors, based on Saaty (1977)

After the Paired Comparison Matrix was filled, the vector of weights related to this matrix was determined, according to Table 6, in which each element of the vector represents the relative importance of each factor, when compared to the others.

Table 6: Vector of weights associated to the paired comparison matrix

Fator	Fator 1	Fator p	Fator n	Autovetor	Pesos
Fator 1	1	a_{1p}	a_{1n}	$\overline{g_1} = \sqrt[n]{a_{11} \times \ldots \times a_{1p} \times \ldots \times a_{1n}}$	$\omega_1 = \frac{\bar{g}_1}{S}$
Fator p	a_{p1}	1	a_{pn}	$\overline{g_p} = \sqrt[n]{a_{p1} \times \ldots \times a_{pp} \times \ldots \times a_{pn}}$	$\omega_p = \frac{\bar{g}_p}{S}$
Fator n	a_{n1}	a_{np}	1	$\overline{g_n} = \sqrt[n]{a_{n1} \times \ldots \times a_{np} \times \ldots \times a_{nn}}$	$\omega_n = \frac{\bar{g}_n}{S}$
Soma (ωS)	$\sum_{p=1}^{n} a_{p1}$	$\sum_{p=1}^{n} a_{pp}$	$\sum_{p=1}^{n} a_{pn}$	$S = \sum_{p=1}^{n} \bar{g}_p$	1

Source: Prepared by the authors, based on Saaty (1977)

Subsequently, as determined by Saaty (1977), it was necessary to verify the consistency of the results generated. This procedure was performed by calculating the Consistency Index (CI) and the Consistency Ratio (CR). The CI was obtained through Equation 1.

$$IC = \frac{\lambda_{máx} - n}{n - 1} \quad (1)$$

Where n is the number of factors listed in the Paired Comparison Matrix and λmax is the maximum Eigenvalue, obtained through Equation 2.

$$\lambda_{máx} = \left(\frac{1}{n}\right) \sum_{p=1}^{n} \frac{\omega S_p}{\omega_p} \quad (2)$$

Where it $\sum_{p=1}^{n} \frac{\omega S_p}{\omega_p}$ represents the Coherence Vector (C), ω_p, the Weighting Coefficient (weight),and, ωS_p, o the Sum Vector, all obtained according to Table 6.

Then, the CR was calculated, according to Equation 3. To obtain this parameter, the values of the CI and the Random Index (RI) were related, which varies according to the number "n" of factors listed in the Paired Comparison Matrix Saaty (1987) proposed a table with the RI's of matrices of order 1 to 10, demonstrated in the laboratory, as shown in Table 7. For this study, which applied 4 factors, the value corresponding to the RI was 0.90.

$$RC = \frac{IC}{IR} \tag{3}$$

Where IC is the Consistency Index and IR is the Random Index.

Table 7: Random Index (IR)

m	1	2	3	4	5	6	7	8	9	10
IR	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1987).

According to Saaty (1987), if the CR results in a value less than or equal to 10%, the judgments obtained are consistent.

3.5 Application of map algebra and verification of the efficiency of the water erosion susceptibility map

The "Raster Calculator" function, found in QSIG (version 3.10.9), was used for the use of map algebra. For this, the reclassified spatial data of the factors conditioning susceptibility to water erosion were related to the weights defined by the AHP. As a subsidy for the use of this function, the mathematical model shown in Equation 4 was applied.

$$M = \omega_D \times D + \omega_P \times P + \omega_S \times S + \omega_U \times U \tag{4}$$

Where M represents the water erosion susceptibility map, D is Slope, P is spatial variability of precipitation, S is pedology, U is soil use and land cover, and ω is the weight of the respective factor (determined by AHP

Finally, the map produced by the map algebra was reclassified, so that the pixels that had values between zero and one, one and two, two and three, three and four and four and five represented, areas of susceptibility to water erosion considered as very low, low, medium, high and very high.

In order to verify the efficiency of the method employed, the water erosion susceptibility map was confronted with photographic records of episodes of this type of phenomenon that occurred in the region studied. These records were collected through on-site visits, in the period between February 25th and March 1st, 2023, and georeferenced, making it possible to verify whether the evidence is located in places of high to very high susceptibility to water erosion, according to the AHP.

4. RESULTS AND DISCUSSION

From the use of GIS, maps that configure the factors were established: Slope (A), rainfall indexes (B), pedology (C) and land use and occupation (D) that influence susceptibility to water erosion, and which were selected, in the watersheds of the Jaguaribe, Paripe and Maceió rivers, as shown in Figure 3 and Table 8.

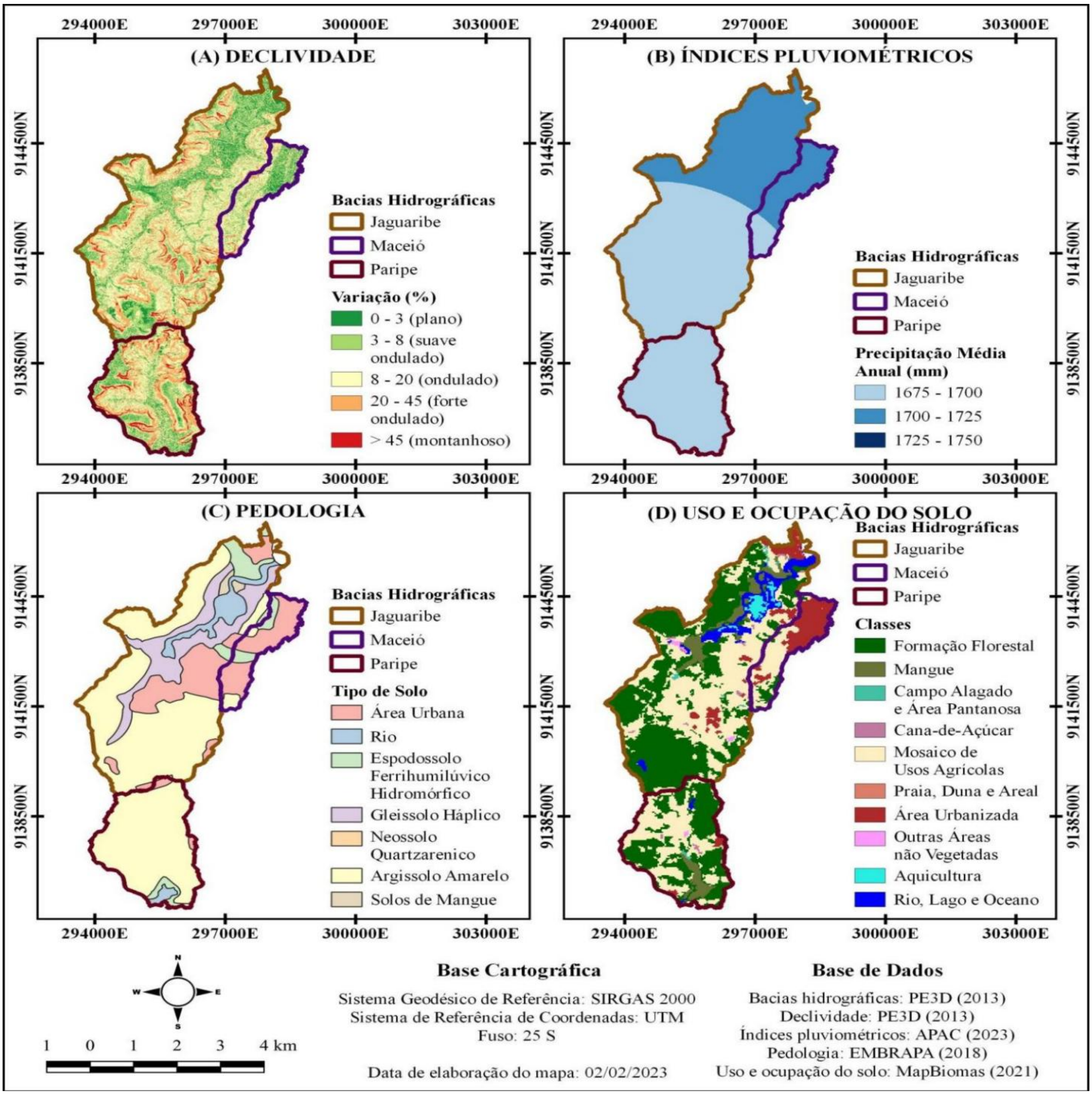

Figure 3: Representation of the factors that influence susceptibility to water erosion listed for this study. Source: Prepared by the authors

Table 8: Slopes rates of the Jaguaribe, Paripe and Maceió river basins

Variation (%)	Basin river Jaguaribe		Basin river Maceio		Basin river Paripe	
	Area (km²)	Rate (%)	Area (km²)	Taxa (%)	Area (km²)	Rate (%)
0 - 3	2.71	16.19	0.35	15.20	1.20	20.11
3 - 8	4.89	29.25	0.48	20.82	1.30	21.77
8 - 20	4.37	26.13	0.61	26.44	1.40	23.44
20 - 45	4.10	24.52	0.83	36.09	1.56	26.01
> 45	0.65	3.91	0.03	1.44	0.52	8.66
Total	**16.71**	**100.00**	**2.30**	**100.00**	**5.98**	**100.00**

Source: Prepared by the authors

Analyzing the information identified it is possible to verify that as for the topography, there is an equitable distribution between the slopes considered as low and high in the Maceió river basin, covering, respectively, 36.02% and 37.53% of its total area. For the Jaguaribe and Paripe river basins, there is a predominance of regions considered flat and gently undulating, that is, with slopes between zero and 8%, which when added to the areas of these regions, give 45.44% and 41.88% of their surfaces.

The slope factor significantly influences susceptibility to water erosion through various mechanisms, including particle displacement, soil erodibility, and hydrological dynamics (Beczek et al., 2024; Soniari et al., 2024). Steeper slopes tend to increase the speed of water runoff, which can lead to higher erosion rates (Jain et al., 2024).

Regarding the variability of the average annual precipitation, the range of rainfall rates between 1,675 mm and 1,700 mm is the most incident in the studied region, covering 61.64%, 24.35% and 100.00% of the areas of the Jaguaribe river basins, the Maceió river and the Paripe river, respectively (Table 9). The indexes between 1,700 mm and 1,725 mm, which give average susceptibility to water erosion, are present in a portion of 38.30% of the Jaguaribe river basin and 75.65% of the Maceió river basin.

Table 9: Rates of rainfall in the watersheds of the Jaguaribe, Paripe and Maceió rivers

Rainfall indexes (mm)	Basin river Jaguaribe		Basin river Maceio		Basin river Paripe	
	Area (km²)	Rate (%)	Area (km²)	Taxa (%)	Area (km²)	Rate (%)
1,675 - 1,700	10.30	61.64	0.56	24.35	5.98	100.00
1,700 - 1,725	6.40	38.30	1.74	75.65	0.00	0.00
1,725 - 1,750	0.01	0.06	0.00	0.00	0.00	0.00
Total	**16.71**	**100.00**	**2.30**	**100.00**	**5.98**	**100.00**

Source: Prepared by the authors

The intensity and availability of precipitation also influence the potential for erosion and river siltation. The greater the availability of rainfall, the higher the precipitation intensity, which accelerates the soil saturation process. Once the soil reaches its field capacity, runoff begins, reducing its resistance, increasing the transport of sediments, and nutrients from the soil (Panagos et al., 2015; Oliveira et al., 2020).

Regarding pedology, it can be seen in Table 10 that the urban area added to the rivers are identified in great quantity in the Maceió river basin, with 74.35% of its total area. However, in the basins of the Jaguaribe and Paripe rivers, these classes, which are highly susceptible to water erosion, do not have as much representation, covering 22.38% and 5.52% of their regions, respectively.

Table 10: Pedology rates of the watersheds of Jaguaribe, Paripe and Maceió rivers

Types of soil	Basin river Jaguaribe		Basin river Maceio		Basin river Paripe	
	Area (km²)	Rate (%)	Area (km²)	Taxa (%)	Area (km²)	Rate (%)
Urban Area	2.68	16.04	1.71	74.35	0.15	2.51
River	1.06	6.34	0.00	0.00	0.18	3.01
Ferrihumiluvic spodosol	0.79	4.73	0.34	14.78	0.24	4.01
Hydromorphic Haplic Gleissoil	2.92	17.47	0.01	0.43	0.00	0.00
Quartzarenic neosol	0.00	0.00	0.00	0.00	0.01	0.17
Yellow Argisol	9.08	54.34	0.24	10.43	5.40	90.30
Mangrove Soils	0.18	1.08	0.00	0.00	0.00	0.00
Total	**16.71**	**100.00**	**2.30**	**100.00**	**5.98**	**100.00**

Source: Prepared by the authors

The gleissolos and neosols, which are soils that confer average susceptibility to water erosion, cover a little insignificant area of the study region, corresponding to rates of 17.47%, 0.43% and 0.17%, respectively, related to the Jaguaribe, Maceió and Paripe river basins. Soils that contribute little or not to water erosion, that is, spodosols, argisols and mangrove soils, are the most recurrent in the Jaguaribe and Paripe river basins, representing 60.15% and 94.31% of these regions, respectively, while they occupy 25.21% of the area of the Maceió river basin.

Pedology significantly influences susceptibility to water erosion through various soil characteristics, including mineral composition, aggregate structure, and topographic stability. Sandy soils, characterized by larger particles and lower cohesion, are more prone to erosion because they allow rapid infiltration and runoff of water. In contrast, clayey soils, with their finer particles and higher cohesion, tend to retain water better, reducing surface runoff and the potential for erosion (Wu et al., 2024).

As for soil use and occupation, the regions studied presented different behaviors (Table 11). Urban occupation areas prevail in the Maceió river basin (48.26% of the total area), especially in the coastal region, while in the Paripe (1.84%) and Jaguaribe (4.67%) river basins this type of class is not very representative, for both are further away from the coastal portion. Also for this reason, forest vegetation can be found in most of the Paripe and Jaguaribe river basins, occupying areas respective to 48.33% and 45.30% of their regions, however, the Maceió river basin configures a rate of only 9.57% relative to this class.

Table 11: Soil use occupation rates in the watersheds of the Jaguaribe, Paripe and Maceió rivers

Classes	Basin river Jaguaribe		Basin river Maceio		Basin river Paripe	
	Area (km²)	Rate (%)	Area (km²)	Taxa (%)	Area (km²)	Rate (%)
Forest training	7.57	45.30	0.22	9.57	2.89	48.33
Mangrove	0.79	4.73	0.00	0.00	0.34	5.69
Flooded Field	0.08	0.48	0.00	0.00	0.02	0.33
Sugar cane	0.10	0.60	0.00	0.00	0.03	0.50
Mosaic of uses agrícolas	6.09	36.45	0.96	41.74	2.55	42.64
beach. dune and sand	0.02	0.12	0.01	0.43	0.00	0.00
urbanized area	0.72	4.31	1.11	48.26	0.10	1.67
Other non-vegetated areas	0.06	0.36	0.00	0.00	0.01	0.17
aquaculture	0.28	1.68	0.00	0.00	0.00	0.00
River, lake and ocean	1.00	5.98	0.00	0.00	0.04	0.67
Total	**16.71**	**100.00**	**2.30**	**100.00**	**5.98**	**100.00**

Source: Prepared by the authors

Agriculture and cattle-raising represent a class that covers the whole region of the study in a GISnificant way, mainly by pasture, sugarcane cultivation and subsistence agriculture, covering 37.05%, 41.74% and 43.14% of the Jaguaribe, Maceió and Paripe basins, respectively. The water bodies are represented by the hydrographic networks of the basins. The exposed soil makes up a small portion of the study region, and this class is largely represented by dunes and an emersed beach.

Intensive land use and improper management have been intensifying the erosion process and altering the physical, chemical, and biological properties of the soil, as these formations are involved in supporting root growth, water and nutrient storage and supply, gas exchanges, and biological activity (Souza et al., 2020). Changes in land use, such as deforestation, urbanization, or improper agricultural practices, reduce the natural protection of the soil, making it more susceptible to erosion (Oliveira et al., 2023).

The Paired Comparison Matrix elaborated for the mapping of the areas susceptible to water erosion in the watersheds of the Jaguaribe, Maceió and Paripe rivers was developed as shown in Table 12. When analyzing this matrix, it can be seen that, according to the values of the weights, the factor related to the use and occupation of the soil was considered as the most important and pedology as the least important. Land use and occupation is the most significant factor, as it directly influences soil impermeability and water runoff. Compared to the others, it is a more dynamic factor with a more immediate impact, as it can quickly modify land conditions and alter the behavior of precipitation, thereby intensifying the risk of erosion.

Table 12: Vector of weights associated with the paired comparison matrix of the factors that influence the susceptibility to water erosion listed for this study (factor)

Factor	A	B	C	D	Weights
Slope (A)	1	1	4	1	0,31
Rainfall indexes (B)	1	1	3	1/2	0,25
Pedology (C)	1/4	1/3	1	1/3	0,09
Soil use and occupation (D)	1	2	3	1	0,35

Source: Prepared by the authors, based on Borges et al. (2023).

After determining the weights of each factor in the Paired Comparison Matrix, it was necessary to verify the consistency of its values. Thus, a CI equal to 0.02 and a CR equal to 2.80% was obtained. Because the CR is less than 10%, the comparisons can be considered reliable, according to Saaty (1987).

Finally, the mathematical model M = 0.31D + 0.25P + 0.09S + 0.35U was developed to create the water erosion susceptibility map in the Jaguaribe, Maceió and Paripe river basins. This model was processed using map algebra, resulting in the map presented in Figure 4.

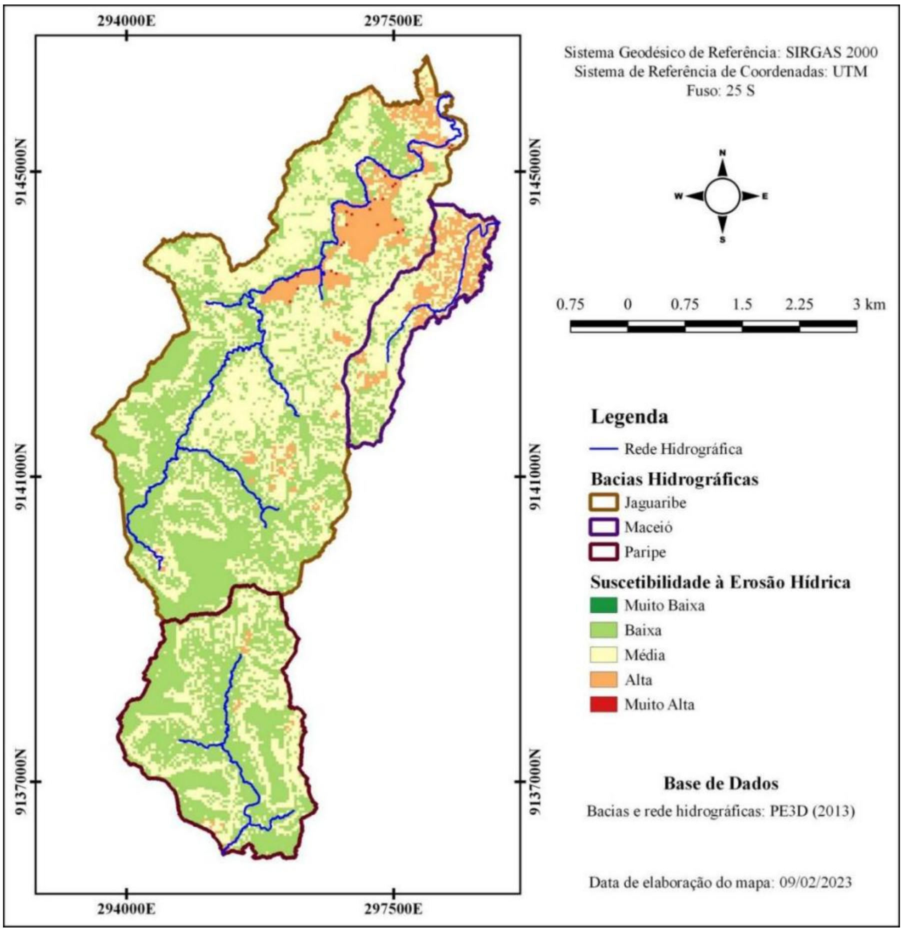

Figure 4: Map of water erosion susceptibility in the watersheds of the Jaguaribe, Maceió and Paripe. Source: Prepared by the authors

Through the GIS it was also possible to classify, in percentage rates, the proportion of areas susceptible to water erosion in the watersheds of the Jaguaribe, Maceió and Paripe rivers, presented in Table 13.

Table 13: Proportion of the areas susceptible to water erosion in the watersheds of the Jaguaribe, Paripe and Maceió rivers

Susceptibility	Basin river Jaguaribe		Basin river Maceio		Basin river Paripe	
	Area (km²)	Rate (%)	Area (km²)	Taxa (%)	Area (km²)	Rate (%)
Very low	0.00	0.00	0.00	0.00	0.00	0.00
low	7.35	44.01	0.32	13.92	3.76	62.83
average	7.76	46.41	1.25	54.31	2.15	35.96
high	1.57	9.38	0.73	31.77	0.07	1.21
Very tall	0.03	0.20	0.00	0.00	0.00	0.00
Total	**16.71**	**100.00**	**2.30**	**100.00**	**5.98**	**100.00**

Source: Prepared by the authors

When analyzing the mapped region, it is found that the areas most prone to water erosion make up 9.58%, 31.77% and 1.21% of the watersheds of the Jaguaribe, Maceió and Paripe rivers, respectively, manifesting in a large part of the urbanized areas, bodies and regions for aquaculture. It is also observed that the Maceió River basin presents an amount of area highly susceptible to water erosion greater than the other basins, because it is located in a region of expressive urban density.

It was also found that the areas of lower susceptibility to water erosion represent, respectively, 44.01%, 13.92% and 62.83% of the watersheds of the rivers Jaguaribe, Maceió and Paripe, and are located in the mainly in the portions constituted by forest formation and agricultural use. These areas are also characterized by a more clayey soil that, according to Silveira et al. (2014), has a high risk of landslide, but low risk of erosion.

The combination of steep slopes and land use, as observed in areas of the study region, significantly influences soil erosion susceptibility, as both factors affect soil properties and hydrological processes. Steep terrains increase gravitational forces on the soil, while different land uses alter soil structure and vegetation cover, further impacting erosion rates (Šiljeg et al., 2024).

In similar works it was possible to find similar results to those of this study, such as Santos and Nascimento (2020), who found that for the portion of the São Francisco river basin that covers the state of Sergipe there is a predominance of areas classified as very low to moderate risk to water erosion, especially in regions of low rainfall and slope, high altimetric quotas, and present soils with a clayey texture. Similarly, Basílio et al. (2019) found that the regions most prone to water erosion in the Claro river basin in São Paulo are those in urbanized areas, which are already consolidated on the site.

Seeking to endorse the findings verified in the mapping in this study, a survey of water erosion occurrences in the watersheds of the Jaguaribe, Maceió and Paripe rivers was carried out through on-site visits, carried out in the period between January 15 and 21, 2023. In all, six photographic records were collected, as shown in Figure 5, representing water erosion situations in the most prone areas, according to the mapping produced in this study. These checks ensure the level of accuracy of the AHP, demonstrating the effectiveness of the method.

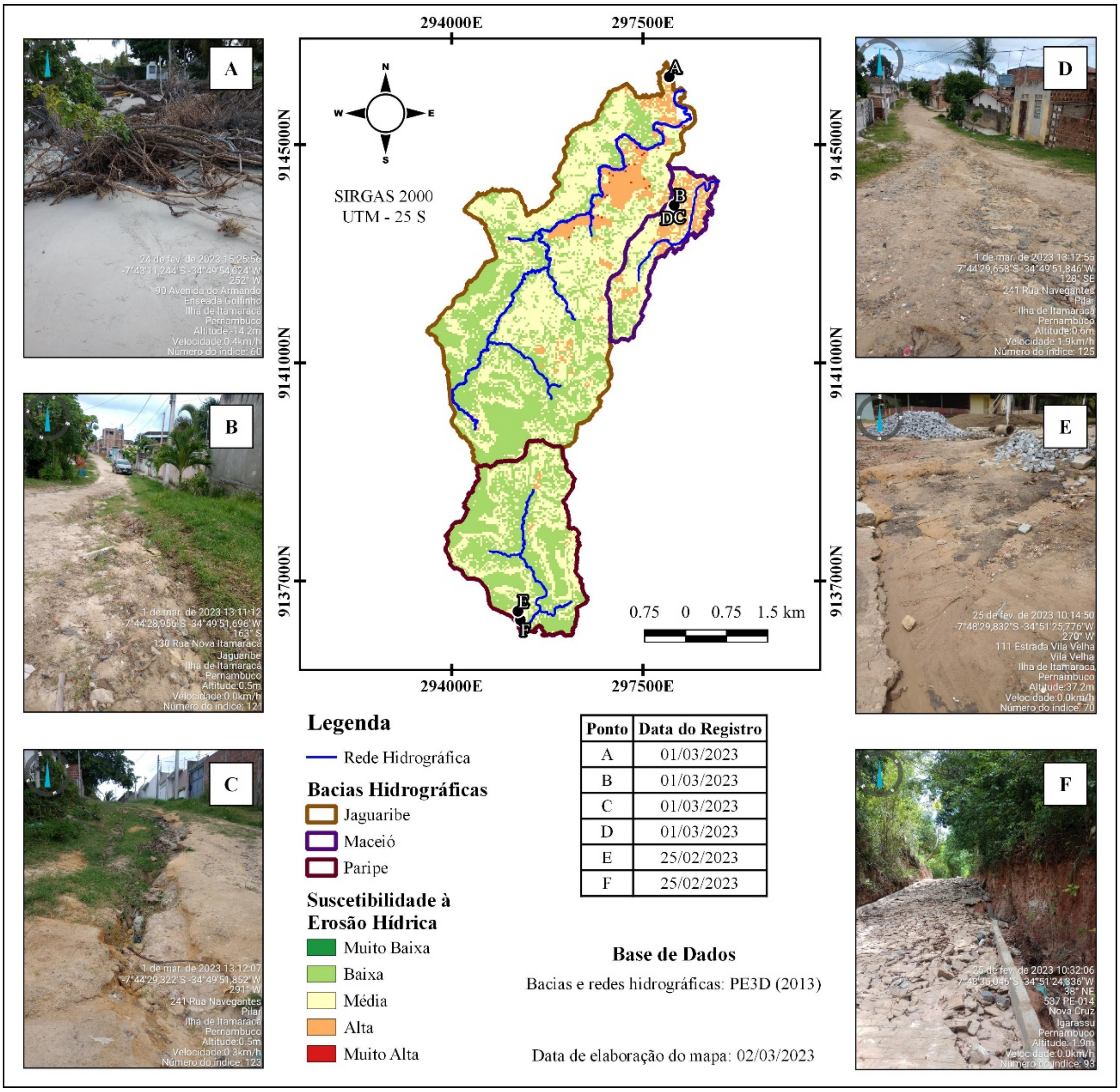

Figure 5: Photografic records of water erosion occurrences in the watersheds of the Jaguaribe, Maceió and Paripe rivers point. Source: Prepared by the authors.

According to Ferreira et al. (2020), another method that allows to validate a mapping of areas susceptible to water erosion is the Revised Universal Soil Loss Equation (RUSLE), which is based on the interaction between rainfall erosivity, soil erodibility, the influences of the relief and the use and occupation of the soil in a GIS environment. In this perspective, Thomas et al. (2018) identified the water erosion risk areas of the Muthirapuzha River watershed in India by the AHP and RUSLE model and by comparing the results, they found that the water erosion intensity in the region show significant agreement.

In general, mapping water erosion susceptibility in a region has significant practical implications for environmental management, as it allows for targeted interventions to mitigate erosion risks and improve land sustainability (Ou et al., 2024). By identifying the most vulnerable areas, relevant authorities can prioritize resources and implement effective management strategies (Nguyen et al., 2024).

5. CONCLUSIONS

The disorderly urban occupation bordering the watersheds of Ilha de Itamaracá has contributed to the region's insignificant susceptibility to water erosion in certain stretches. In the Maceió river basin, where urbanization includes 74.35% of its total area, the susceptibility to water erosion is high, which can signal problems for the inhabitants of the region. This susceptibility, which was endorsed by the high slope (37.53% of the total area), also comprising a rainfall index that ensures the basin a favorable environment for water erosions.

The Jaguaribe river basin also demonstrates a susceptibility to water erosion due to the urbanization process, even if not so expressive in relation to its area (susceptibility comprising 9.58% of the basin). At first, the data may be of minor representation, however, it indicates a potential degradation process in the area if there is no proper urban planning.

Of the main watersheds in the municipality, the Paripe River had the lowest susceptibility to water erosion in most of its area (62.83%), contrasting mainly because it has a larger forested area, contributing strongly to demonstrate that the increase in susceptibility is linked to urban occupation.

In view of this, it is clear that the lack of specific legislation, as well as the effective application of existing ones at the national and state level, can contribute to the aggravation of erosion processes in the municipality. Anthropic actions have been one of the main responsible for the degrading ways of using natural resources, therefore, it is up to the managers the responsibility of developing interventions in a sustainable way.

For this to occur, it is necessary to involve them in an environmental planning process that contributes to the establishment of effective preservation, conservation, and restoration measures, thus preventing these areas from being degraded due to unplanned urban expansion.

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