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Erosion Susceptibility of the Macumiri River Watershed - AM Based on Multi-Criteria Analysis and Map Algebra in a GIS Environment

Ivy de Araújo Alves¹, Rodrigo Couto Alves², Alex Martins Ramos³

¹ Bachelor's degree in Environmental and Sanitary Engineering. Federal University of Amazonas. ORCID: 0000-0003-1978-9462. E-mail: ivy.alves@ufam.edu.br

² Ph.D. in Environmental Sciences and Sustainability. Professor at the Federal University of Amazonas. ORCID: 0000-0002-7452-9455. E-mail: rcouto@ufam.edu.br

³ Ph.D. in Chemical Engineering. Professor at the Federal University of Amazonas. ORCID: 0009-0005-1464-6624. E-mail: alexmartins@ufam.edu.br

ABSTRACT

Soil erosion is a major environmental degradation process in tropical watersheds, strongly influenced by natural factors and land use dynamics. In this context, the present study aimed to identify areas susceptible to sheet erosion in the Macumiri Stream basin, located in Amazonas State, Brazil, through spatial modeling using a Geographic Information System. The methodology was structured in two main stages: environmental diagnosis of the watershed and application of a multi-criteria decision analysis integrating soil properties, slope, and land use/land cover variables. Data processing was conducted in QGIS using map algebra and geoprocessing techniques, with weighted criteria assigned according to their relative influence on erosion processes. The results revealed a predominance of moderate erosion susceptibility, mainly associated with intermediate slope gradients and forested areas, while high-susceptibility zones were spatially limited and linked to specific natural conditions such as sandy soils and steeper terrain. The analysis highlighted the critical role of vegetation cover in mitigating soil loss, even in inherently fragile environments. It is concluded that the integration of multicriteria analysis and map algebra within a GIS framework is an effective approach for identifying erosion-prone areas, providing robust technical support for environmental planning and sustainable watershed management in Amazonian regions.

Keywords: multicriteria analysis; soil erosion; geoprocessing; spatial modeling; environmental vulnerability.

Introduction

Soil erosion is one of the main processes of environmental degradation on a global scale, directly affecting the stability of ecosystems and the sustainability of productive systems. This process, especially in its laminar form, leads to the gradual removal of the soil's surface layers, compromising its physical, chemical, and biological properties. Recent studies indicate that the intensification of erosion is associated with changes in land use and climate variability, which increases its magnitude and spatial complexity (Borrelli et al. 2017; Hidalgo et al. 2025; Stefanuto et al. 2026). In this context, understanding the factors influencing erosion is essential for informing environmental management and conservation strategies (Mandal and Roy 2024).

In tropical environments, such as the Amazon, erosion processes exhibit unique characteristics resulting from the combination of high rainfall, highly weathered soils, and intense land-use dynamics. These conditions favor the occurrence of water erosion, especially in areas where vegetation cover has been removed (Bueno 2024; Colares et al. 2022; Lense et al. 2021). Furthermore, the spatiotemporal variability of rainfall erosivity plays a decisive role in intensifying these processes, as evidenced by Silva et al. (2020), who highlight the complexity of erosive patterns in the Amazon region. Thus, the analysis of erosion susceptibility in Amazonian watersheds requires integrated approaches that consider these specificities (Alves 2026; Baía et al. 2026; Colares et al. 2022; Lense et al. 2021).

Land use and land cover dynamics have been widely recognized as one of the main factors influencing soil erosion. Changes such as deforestation, agricultural expansion, and unplanned land use significantly alter soil structure and surface runoff patterns (Justino et al. 2025; MapBiomass 2024). These changes reduce water infiltration and increase runoff energy, intensifying soil loss through sheet erosion (Bueno 2024; Lense et al.



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2021; Yakhlefoune et al. 2025; Yin et al. 2025). In this regard, the integrated analysis of these variables is essential for understanding erosion processes in watersheds, especially in agricultural frontier regions.

Advances in geotechnologies have enabled a more precise and integrated analysis of environmental processes, particularly through the use of Geographic Information Systems (GIS). These tools allow for the integration and processing of multiple spatial variables, facilitating the modeling of erosion susceptibility at different scales (Longley et al. 2021; Viana et al. 2019). In this context, Fonseca and Filho (2023) highlight the relevance of GIS in applied geomorphological analysis, demonstrating its efficiency in the spatial representation of erosive processes. Thus, the use of GIS has established itself as an essential approach for environmental studies in watersheds (Wag and Manekar 2023).

Among the approaches used in modeling erosion susceptibility, multi-criteria analysis methods stand out, as they allow for the integration of different influencing factors based on their relative importance. Techniques such as the Analytical Hierarchy Process (AHP) and Paired Overlap have been widely applied, yielding consistent results in identifying vulnerable areas (Alharbi 2024; Lira et al. 2022; Riquetiti et al. 2023; Silva 2025; Yuan 2022). Studies conducted by Arabameri et al. (2018; 2019; 2020) demonstrate the effectiveness of these approaches in spatial erosion modeling, highlighting their ability to integrate variables such as slope, soil, and land use. Thus, multi-criteria analysis emerges as a robust tool for supporting decision-making in environmental planning (Islam et al. 2022).

Map algebra represents a fundamental step in integrating variables within a GIS environment, allowing for the mathematical combination of different thematic layers. This technique enables the generation of synthetic spatial models, based on the assignment of weights and values to the considered variables (Miranda 2019; Santos 2020). When combined with multi-criteria analysis, map algebra expands the capacity for spatial representation of erosion processes, making the models more consistent and applicable (Arabameri et al. 2020; Fonseca and Filho 2023). Thus, its application has established itself as one of the main methodological advances in contemporary environmental modeling through the application of geoprocessing techniques in a GIS environment (Wang et al. 2021).

Despite advances in erosion susceptibility modeling, significant gaps remain in the Amazonian context, particularly regarding the integrated application of multi-criteria methods and map algebra in smaller-scale watersheds. Many studies focus on other regions or use isolated approaches, without considering the complexity of local environmental factors (Costa et al. 2020; Neto et al. 2025). Furthermore, the scarcity of detailed data and the limited application of integrated models hinder the understanding of spatial erosion patterns in the Amazon (Colares et al. 2022; Silva et al. 2020; Justino et al. 2025). In this regard, there is a need for studies that advance methodological integration and spatial analysis of these processes.

Given this scenario, the present study aims to identify areas with potential for sheet erosion in the Macumiri Stream Watershed, located in the lower Solimões River channel in the state of Amazonas, by developing an erosion susceptibility map using GIS techniques. By integrating multi-criteria analysis and map algebra, this study seeks to contribute to methodological advances in the modeling of erosive processes in tropical environments, as well as to provide insights for environmental planning and the sustainable management of natural resources in the Amazon region (Arabameri et al. 2020; Fonseca and Filho 2023).

Methodology

The methodology proposed in this study was developed in two stages: i) Conducting an environmental assessment of the watershed; and ii) Application and modeling of the Multi-Criteria Decision Support Method.

Figure 1 presents a simplified flowchart of the proposed methodology.

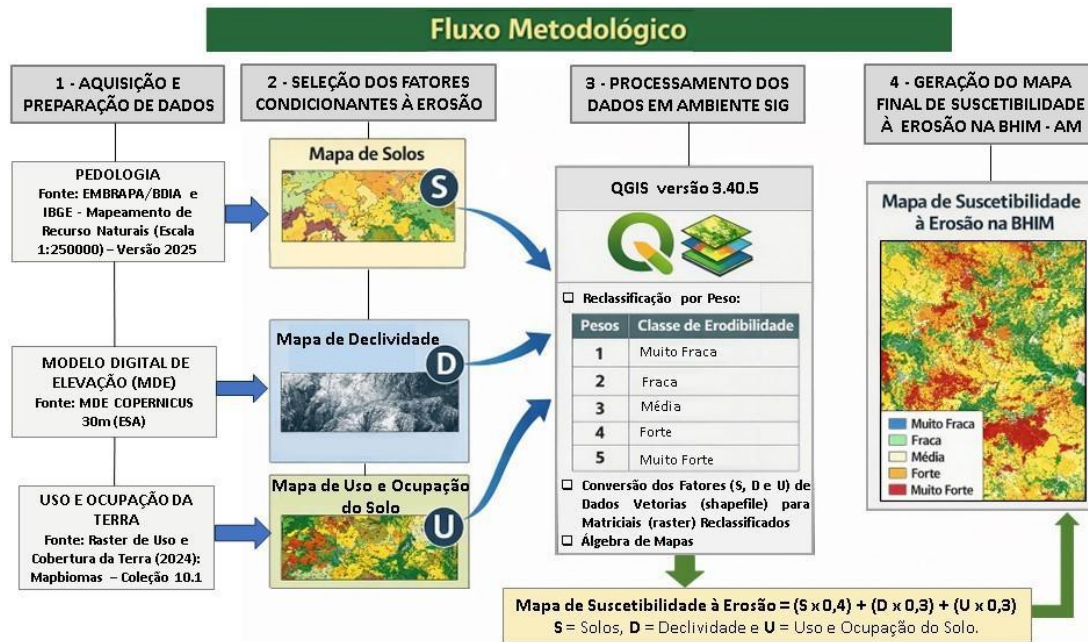


Figure 1: Simplified flowchart of the proposed methodology. Source: Authors

Study Area

The study area is the Macumiri Stream Watershed, located in the rural zone of the municipality of Manacapuru, Amazonas (Figure 2), which is situated in the 7th subregion of the middle Amazon River (ANA 2026). Its municipal seat is located on the left bank of the Solimões River, at the confluence with the mouth of the small river that gives the municipality its name, located at the coordinates 60° 36' 55.378" West and 3° 17' 23" South. The municipality of Manacapuru has a land area of approximately 7,336.58 km² (IBGE 2026). The BHIM is part of the lower Solimões River channel and has a total area calculated using QGIS version 3.40.5 Bratislava of approximately 562.94 km², which corresponds to 7.67% of the municipal territory; the basin's main river has an estimated length of approximately 42.50 km from the basin's outlet.

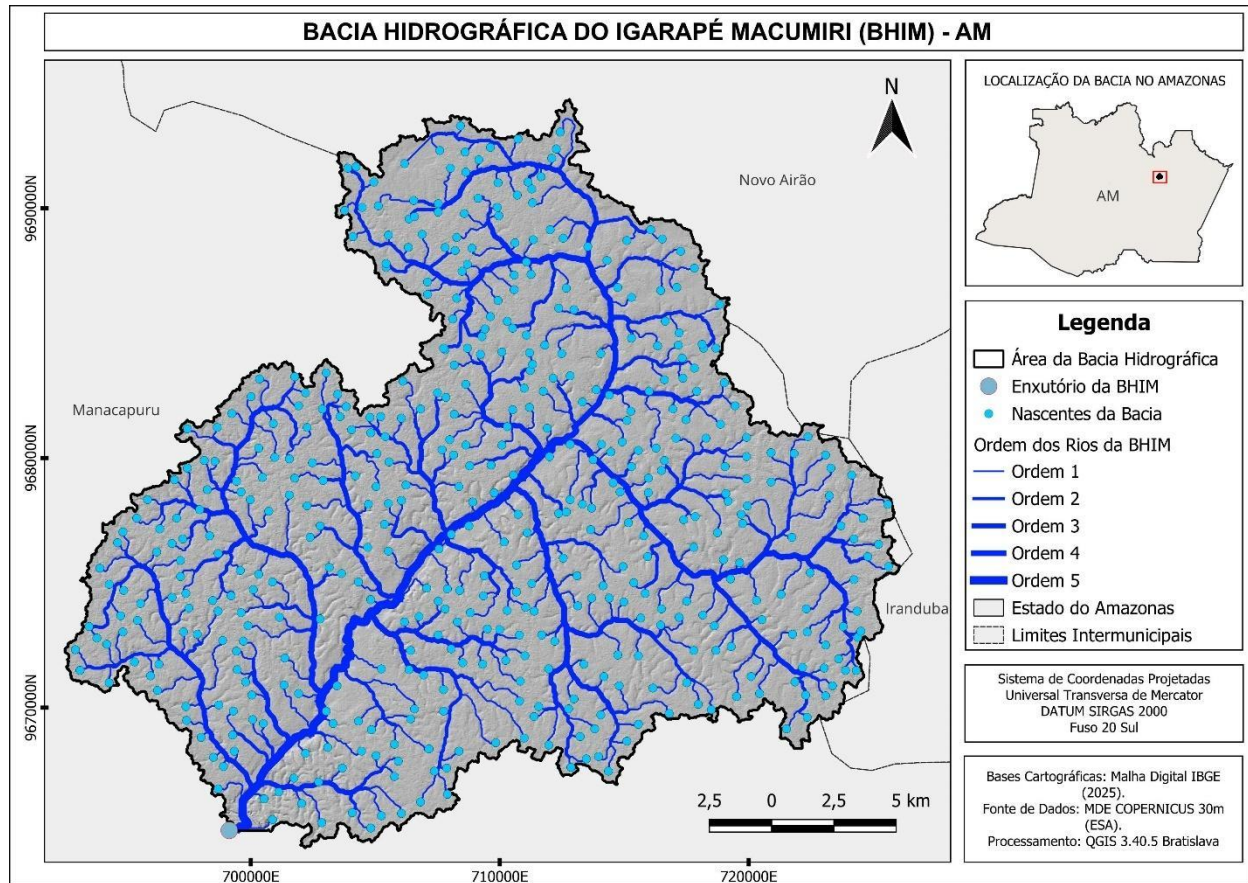


Figure 2: Location of the Igarapé Macumiri/AM watershed. Source: Authors.

Environmental assessment of the basin

The environmental assessment of the BHIM was conducted to identify the main environmental problems affecting water quality caused by land use and land cover in relation to the environmental fragility index. To this end, the main factors analyzed in the environmental fragility assessment regarding natural soil loss were: land use and land cover; slope; and pedology.

For the environmental assessment of the BHIM, each component of the method for generating areas with potential for sheet erosion was adopted through the calculation of environmental fragility in the basin. Given its empirical nature, the method for generating areas with potential for sheet erosion in this study served as a roadmap for identifying the interrelationships between the subcomponents and the environmental component (Figure 3). For each subcomponent, established scientific methodologies were applied (Crepani 2001; Guerra et al. 2007; Ross 2023; Xaviel et al. 2010; Silva and Machado 2014) were applied to each subcomponent in order to obtain consistent results in the identification of impacts on the surface water quality of the BHIM caused by natural vulnerability to soil loss.

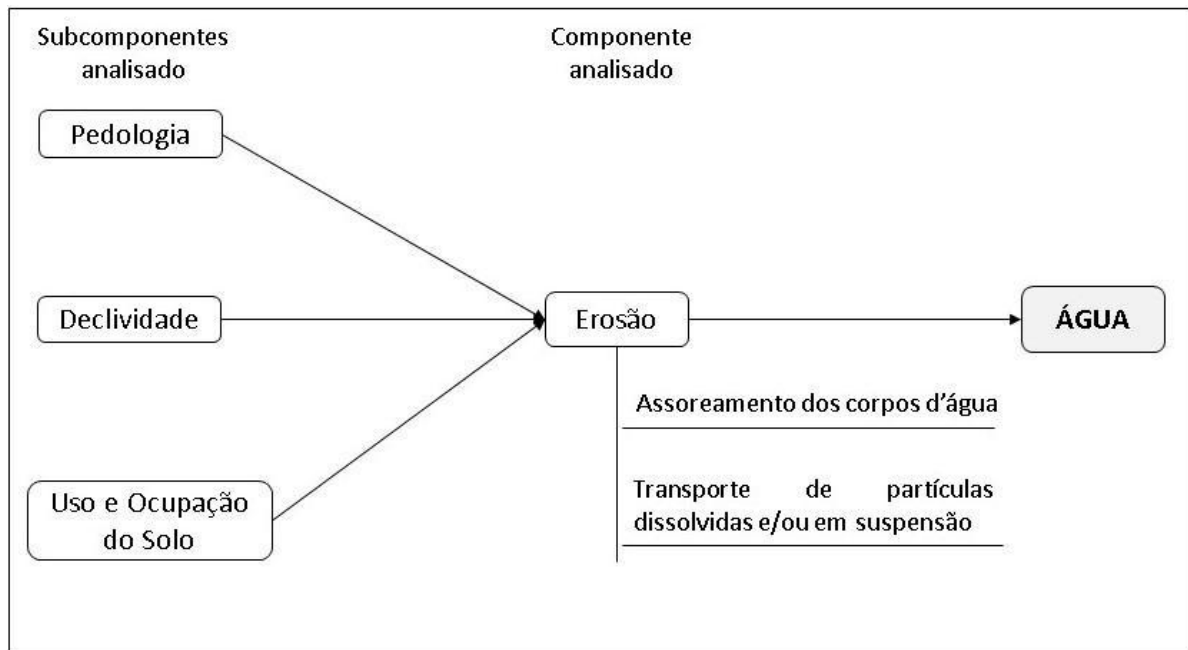


Figure 3: Cause-and-effect diagram of the subcomponents and components analyzed in the environmental assessment of the Igarapé Macumiri basin and their implications for water quality. Source: Authors.

Erosion

In this study, areas with potential for sheet erosion in the Igarapé Macumiri watershed—Amazonas—were identified by generating an erosion susceptibility map. To create this map, the methodology described by Silva and Machado (2014) was followed, which employs multi-criteria analysis. This type of analysis allows for the combined investigation of different variables to generate a summary map.

The variables adopted for this study were the subcomponents: slope, pedology, and land use and land cover. The maps were created and the data were cross-referenced using the QGIS software (, version 3.40.5 Bratislava (64-bit) Long-Term Release (LTR) (QGIS 2026)).

Using the multi-criteria method, weights (0–100%) were assigned to each analyzed subcomponent to differentiate the degree of importance and correlation with the component in question—erosion (erosion susceptibility)—and scores (1 to 5) were assigned to each legend component, such that the higher the score, the greater the erosion susceptibility (1: very low; 2: low; 3: medium; 4: high; 5: very high), as suggested by Silva and Machado (2014). The final erosion susceptibility map was developed by cross-referencing the parameters (map algebra) established for the subcomponents.

To this end, the first step was to generate the soil map of the watershed using the 1:25,000-scale soil map of Brazil available in the IBGE database (2026). Demarchi and Zimback (2014) emphasize that the soil map is very important in analyzing natural susceptibility to sheet erosion, as knowledge of soil types, their properties, and hydrological characteristics makes it possible to perform inferential analyses regarding erosion susceptibility.

According to Xavier et al. (2010), some soils are more susceptible to erosion than others, even when they share certain characteristics, such as slope, precipitation, vegetation cover, and the erosion control practices are the same. Differences in susceptibility are due to the intrinsic properties of the soil, referred to as the degree of soil erodibility. Guerra et al. (2007) and Ross (2023) note that each soil type is associated with a specific degree of erodibility, varying across 5 erodibility classes, as shown in Table 1.

Table 1: Erodibility classes, importance of soil types in the occurrence of erosive processes, and scores established for the components of pedological units.

Erodibility Class	Pedological Units	Weight (1 to 5)
I – Very Poor	Purple Latosols; Dark Red and Yellow-Red Latosols with Clay Texture; Hydromorphic Soils on Flat Terrain; Gleysols; Planosols; Organosols; Quartz-rich Neosols on Flat Terrain.	1



II – Weak	Yellow and Yellow-Red Latosols with Medium Clay Texture; Structured Purple Soil; Dark Red Latosol.	2
III – Medium	Yellow-Red Argissols and Dark Red Argissols; Clay Texture; Yellow-Red Latosols; Clay and Medium Texture; Yellow-Red Latosols; Brown Soil.	3
IV – Strong	Non-abrupt Red-Yellow Argisols; medium-clayey and medium texture; Cambisols; Red-Yellow Argisols with medium-sandy texture; Plintosols.	4
V – Very Strong	Cambisols; Lithic Neosols; Abrupt Red-Yellow and Dark Red Argisols, medium-sandy texture; Quartzarenic Neosols on gently undulating and undulating terrain.	5

Source: Adapted from Guerra et al. (2007), Ross (2023), Xavier et al. (2010).

Subsequently, a pedological characterization of the BHIM was conducted using data from the Environmental Information Database (BDIA, 2025) and the IBGE Natural Resources Map (2025), at a scale of 1:250,000. The original pedological map was reclassified based on erodibility indices specific to the soil classes identified in the basin region, allowing for the spatialization of the intrinsic erosive potential of each mapping unit.

After determining the soil erodibility classes of the study area, slope mapping was carried out. For this purpose, the Digital Elevation Model (DEM) from the Copernicus GLO-30 project, with a spatial resolution of 30 meters, obtained from the European Space Agency (ESA 2026), was used. The altimetric data were processed in the QGIS software environment, version 3.40.5 Bratislava, using the raster analysis algorithm (Raster > Analysis > Slope), which allowed the derivation of terrain slope in percentage values, essential for the subsequent modeling of soil loss.

Next, the slope was stratified into five class intervals, correlated with the respective degrees of erosion potential (Table 2). This reclassification step was performed in the QGIS GIS environment using the `r.reclass` algorithm integrated into the GRASS GIS module. The procedure followed the specific syntax for reclassification rules (Figure 4), allowing the conversion of continuous slope data into discrete categories of environmental vulnerability.

Table 2: Slope classes, degree of erodibility, and scores established for the slope intervals.

Slope	Degree of Erosion Potential	Weight (1 to 5)
0 – 3%	Very Low	1
3 – 8%	Weak	2
8–12%	Average	3
12–20%	Strong	4
>20%	Very Strong	5

Source: Adapted from Xavier et al. (2010).

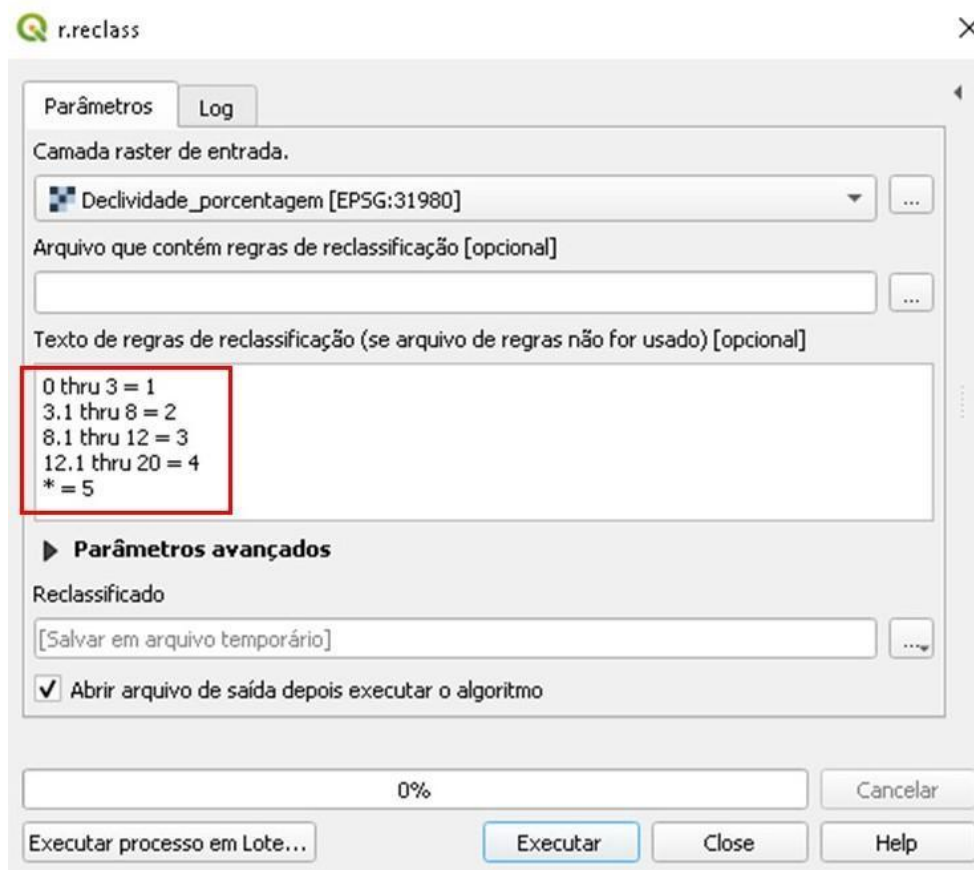


Figure 4: Text of reclassification rules executed in QGIS. Source: Authors.

Subsequently, a thematic map of land use and land cover for BHIM was created. To this end, raster data from Collection 10.1 of the MapBiomas project (referring to the year 2024) was used, with geospatial processing conducted in QGIS 3.40.5 Bratislava software (MAPBIOMAS 2026). The discretization of the classes allowed for the identification and spatialization of the different land uses in the study area. The analysis of vulnerability to erosion processes associated with land use was based on the criteria established by Ross (1994) and Guerra et al. (2007), as summarized in Table 3.

Table 3: Erodibility classes for land use and land cover and scores established for each class.

Classes	Land Use and Occupation	Weight (1 to 5)
1 – Very High	Deforested areas; exposed soil; non-conservationist agriculture; low-growing vegetation cover, with intense human activity.	5
2 – Strong	Long-cycle crops with low density; short-cycle crops; low- and medium-stature vegetation cover; with moderate human activity.	4
3 – Medium	Long-cycle crops; pastures with low livestock trampling; forestry; low- and medium-stature vegetation cover, with very limited human activity.	3
4 – Poor	Natural shrub formations; secondary forests; savannas and scrublands; tall to medium-sized vegetation cover, with very limited human activity.	2
5 – Very Weak	Natural forests and woodlands with biodiversity, bodies of water, and floodplains, whose erosion potential can be considered negligible.	1

Source: Adapted from Guerra et al. (2007), Ross (2023), Xavier et al. (2010).

After the thematic maps were prepared, weights were assigned to the variables and their respective analyzed subcomponents. The intra-variable weights, which distinguish the influence of each internal class, are detailed in Table 4. Additionally, Table 5 presents the weighted weights adopted for each analyzed factor, reflecting the relative importance of each variable in the composition of the final vulnerability model.



Table 4: Scores assigned to the variables of the analyzed subcomponents.

Subcomponent analyzed	Variables of the analyzed subcomponent	Weight (1 to 5)
Soil Science	, a sandy-textured, flat-relief Hydro-Hyperthick Humiluvic Espodossol	5
	Typical dystrophic Tb Haplic Gleissol with mixed texture on flat terrain	1
	Yellow Acric soil with a very clayey texture and a gently undulating surface	2
Slope	0-3%	1
	3-8%	2
	8-12%	3
	12-20%	4
	>20%	5
Land Use and Land Cover	Forest Formation - tall to medium-height vegetation cover, with very limited human activity	1
	Floodplain Forest	1
	Flooded Fields and Wetlands	1
	Open Grassland	1
	Pasture	2
	Non-vegetated areas	5
	Water Body	Mask (NoData)

Source: Authors.

Table 5: Analyzed subcomponents and their respective weights.

Subcomponent analyzed	Weight (0-100%)
Soil Science	40
Slope	30
Land Use and Land Cover	30

Source: Adapted from Silva and Machado (2014).

Once the weighted values assigned to each variable based on their relative importance in the erosion process were defined, the map algebra method (Equation 1) was applied using the QGIS raster calculator to generate the final erosion susceptibility map. This procedure is based on the processing of variables organized into matrix structures, which allow for the integration of multiple geographic criteria to model complex environmental phenomena (Santos et al. 2020). It also highlights that the effectiveness of this technique lies in the ability to associate quantitative values with each cell of the operational grid, aiming to facilitate decision-making in watershed management. As Ferreira and Bolfe (2022) point out, the integration of data within a Geographic Information System (GIS) environment provides researchers with the necessary autonomy to adjust the influence of each environmental factor according to the specific characteristics of the study area.

$$E = (S * 0,4) + (D * 0,3) + (U * 0,3) \quad (1)$$

Where:

E: Susceptibility to erosion (final product);*S*: Pedology subcomponent (Pedological Map);*D*: Relief subcomponent (Slope Map);

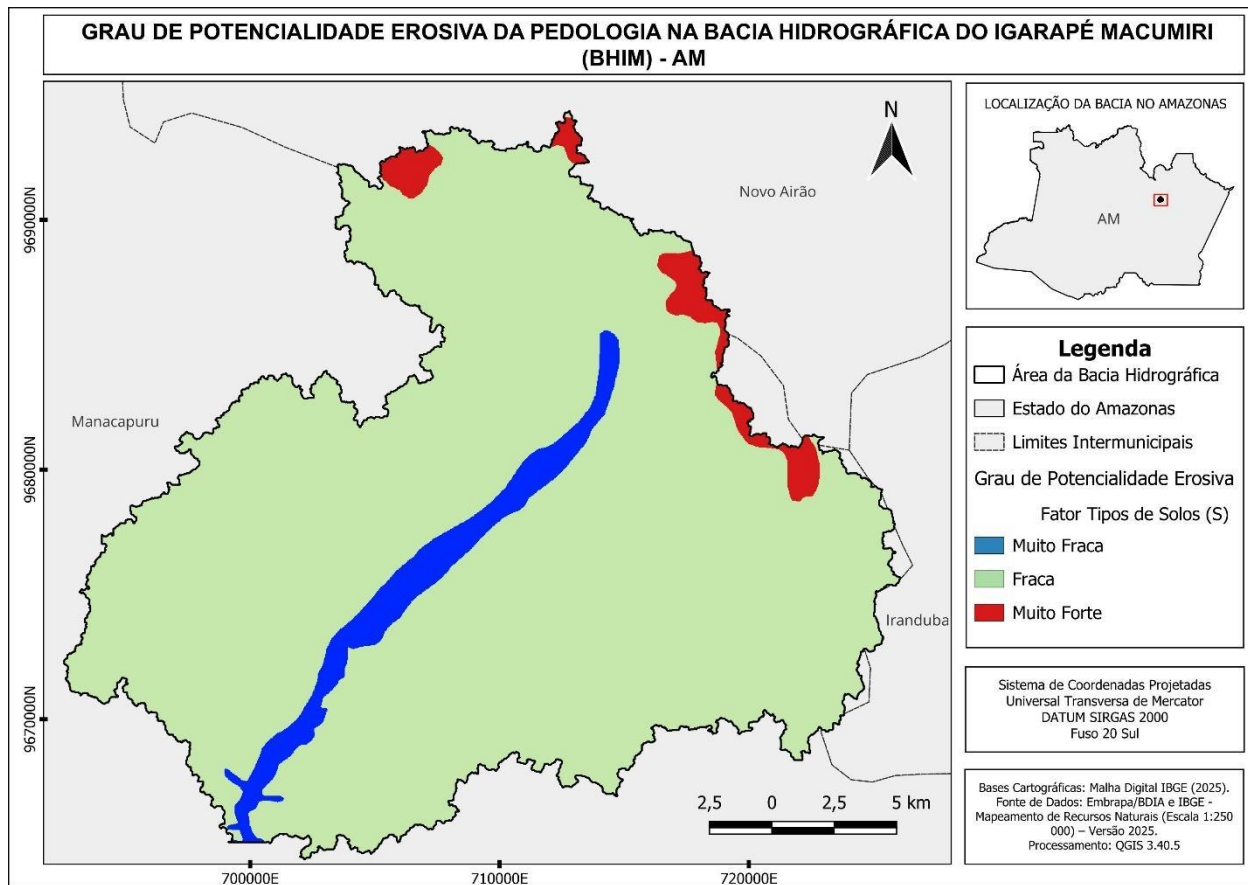


Figure 6: Map of the degree of erosive potential of the pedological factor in the BHIM. Source: Authors

Table 6: Percentages of areas by degree of erosion potential of the pedological factor in the BHIM.

Erodibility class (%)	Area (km ²)	Area (%)
Very Low	25.84	4.59
Poor	522.81	92.87
Average	-	-
Strong	-	-
Very Strong	14.29	2.54
Total Area	562.94	100

Source: Authors.

The Yellow Latosol (LA) is the dominant soil class in the basin, corresponding to the "Low" erosion potential class, which covers a significant 92.87% of the total area (522.81 km²). This predominance confers natural structural stability against sheet erosion across much of the basin. As noted by Santos et al. (2018), the Yellow Latosols of the Amazon region are deep and well-drained soils, which favor high rates of water infiltration into the profile. Scientifically, the low susceptibility observed corroborates the studies by Couto et al. (2021), which associate the stability of these soils with their mineralogy and the formation of microaggregates, which hinder the detachment of particles by the kinetic energy of rainfall (splash effect), provided that vegetation cover is maintained.

In contrast, the areas of greatest vulnerability are restricted to the portions where Humiluvic Espodosols (EK) occur. This unit was classified as having "Very High" potential, occupying 2.54% of the BHIM (14.29 km²). Although the area is geographically small, its environmental significance is critical. The extreme fragility of EK soils is associated with their sandy texture and low particle cohesion—properties that, according to Silva and Teixeira (2023), make these highly susceptible to water erosion and the formation of accelerated erosive processes when subjected to human interventions.



Finally, the “Very Weak” potentiality class, associated with Haplic Gleysols (GX) in floodplain zones, accounts for 4.59% of the area (25.84 km²). This stability is explained by the topographic position of flow convergence and the water saturation regime, which minimizes the kinetic energy of direct surface runoff. As discussed by Arantes et al. (2022), hydromorphic soils tend to act as retention zones, exhibiting low sediment export to sedimentary basins, making these pedological areas sediment recipients rather than sources, which justifies the low erodibility classification in the applied map algebra model (Silva and Ferreira 2022).

The pedological configuration of the BHIM indicates that, although more than 97% of the basin exhibits low to very low susceptibility, the management of the 2.54% (14.29 km²) of critical areas (Very High) is crucial for maintaining water quality and soil integrity in the region. This is because the removal of vegetation in these critical areas can trigger irreversible erosive processes, compromising the physical integrity of the basin and the quality of downstream water bodies.

The relief of the BHIM presents a predominantly gentle configuration, typical of the dryland and floodplain surfaces of the Lower Amazon, as observed in the Map of the Degree of Erosive Potential of the Slope Factor (Figure 7). The results obtained from the slope reclassified into percentage intervals of erosion potential indicate that the “Very Low” (0–3%) and “Low” (3–8%) erosion potential classes cover most of the area, with 16.08% (90.52 km²) and 50.06% (281.79 km²), respectively, according to the data summarized in Table 7.

Table 7: Percentage of area for each erosion potential class in the Igarapé Macumiri basin.

Slope (%)	Erodibility class (%)	Area (km ²)	Area (%)
0 – 3	Very Low	90.52	16.08
3 – 8	Weak	281.79	50.06
8 – 12	Average	104.53	18.57
12–20	Strong	69.02	12.26
>20	Very Strong	17.08	3.03
Total Area		562.94	100

Source: Authors.

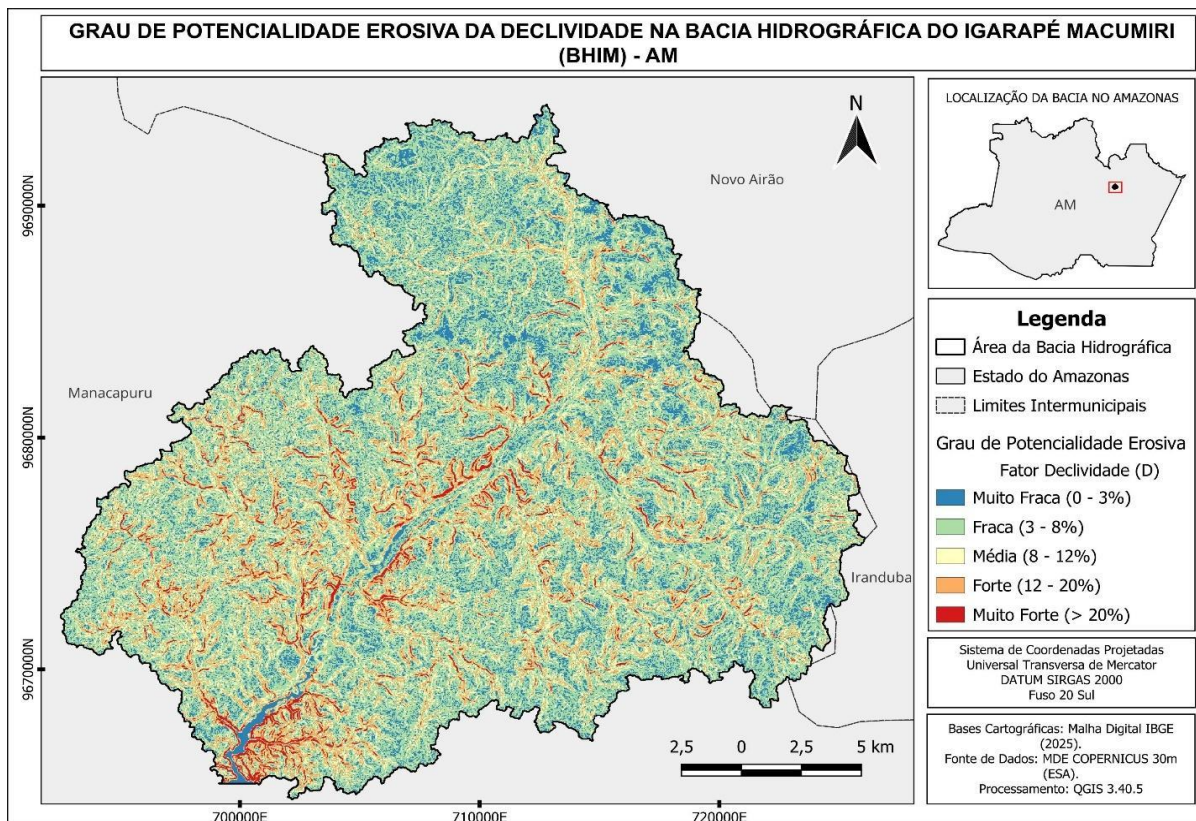


Figure 7: Map of the degree of erosion potential of the slope factor in the BHIM. Source: Authors.



From a hydrosedimentological perspective, the predominance of slopes less than 8% in the BHIM basin favors water infiltration into the soil rather than surface runoff. As highlighted by Colares et al. (2022) and Neto et al. (2025), in studies of the Amazon basin, areas with flat to gently undulating topography act as regulators of the hydrological cycle, minimizing the rate of sediment transport to water bodies. However, gentle relief does not eliminate the risk of erosion if deforestation occurs, since the kinetic energy of intense tropical rainfall can trigger surface runoff.

On the other hand, based on the analysis in Table 7, it is evident that areas with slopes greater than 12% (Steep and Very Steep classes) account for 15.29% of the basin (86.1 km²). Although geographically smaller, these zones of steeper slopes and more active inter-river valleys, shown in Figure 7, have critical implications for the aquatic ecosystem. According to Santos et al. (2023), an increase in terrain slope exponentially raises the water flow's transport capacity. During extreme rainfall events, which are common in the region, these slopes become the primary sources of sediment load for the Igarapé Macumiri.

The direct implication of this process on the water is increased turbidity and the influx of nutrients and pesticides (if agriculture is present) into the drainage channels. Similar studies conducted by Silva and Teixeira (2023) in the Western Amazon demonstrate that basins with steep slopes exhibit sedimentation peaks that can lead to the silting of low-order streams, altering the habitat of the fish fauna and the quality of water for consumption by riverside populations. The presence of structural relief and hills in the BHIM, even if only 3.03% of the area falls into the "Very Strong" class, requires special attention regarding Permanent Preservation Areas (APP), as these are the locations that determine the hydrosedimentological integrity of the downstream basin.

Land use and land cover dynamics in the BHIM reflect a high state of natural conservation, as shown on the Land Use and Occupation Map (Figure 8). The basin is characterized by the absolute dominance of Forest Formation—a tall-to-medium-stature phytophysionomy with reduced anthropogenic activity—as well as Flooded Forest and Flooded Field. According to Gomes et al. (2021), maintaining this dense forest matrix in Amazonian basins is vital for regulating the hydrological cycle, as the canopy acts to intercept precipitation, reducing the direct impact energy on the soil. Furthermore, Salomão (2015) emphasizes that the diversity of vegetation strata, such as the wetland areas identified in the BHIM, functions as natural erosion retention zones, preventing sediments and debris from reaching the main channel of the tributaries.

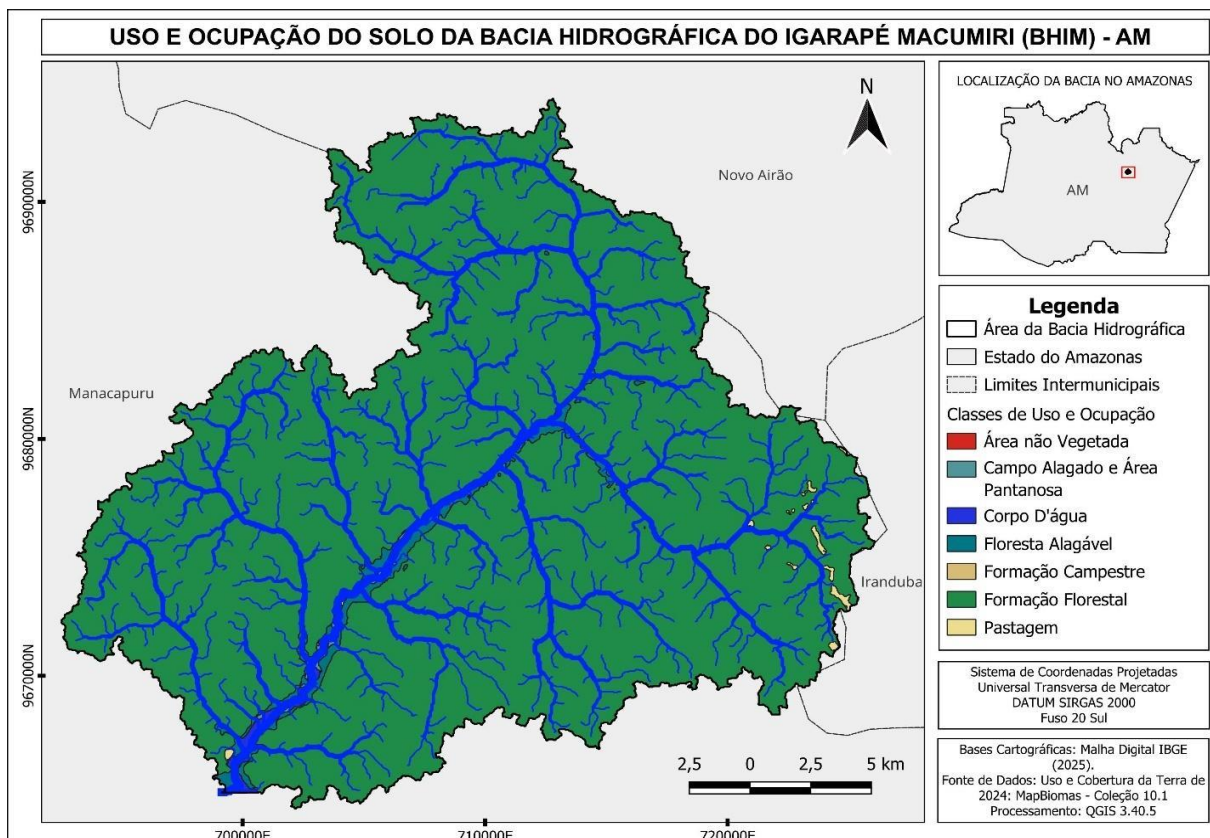


Figure 8: Land use and land cover of the Igarapé Macumiri watershed. Source: Authors.



The spatial distribution of the vulnerability inherent to these land uses is presented in the Map of the Degree of Erosive Potential of the Land Use Factor (Figure 9), where the integration of data demonstrates that the basin possesses robust mechanical protection. The results quantified in Table 9 confirm this condition, indicating that the “Very Low” potentiality class accounts for 99.75% of the total area (561.75 km²).

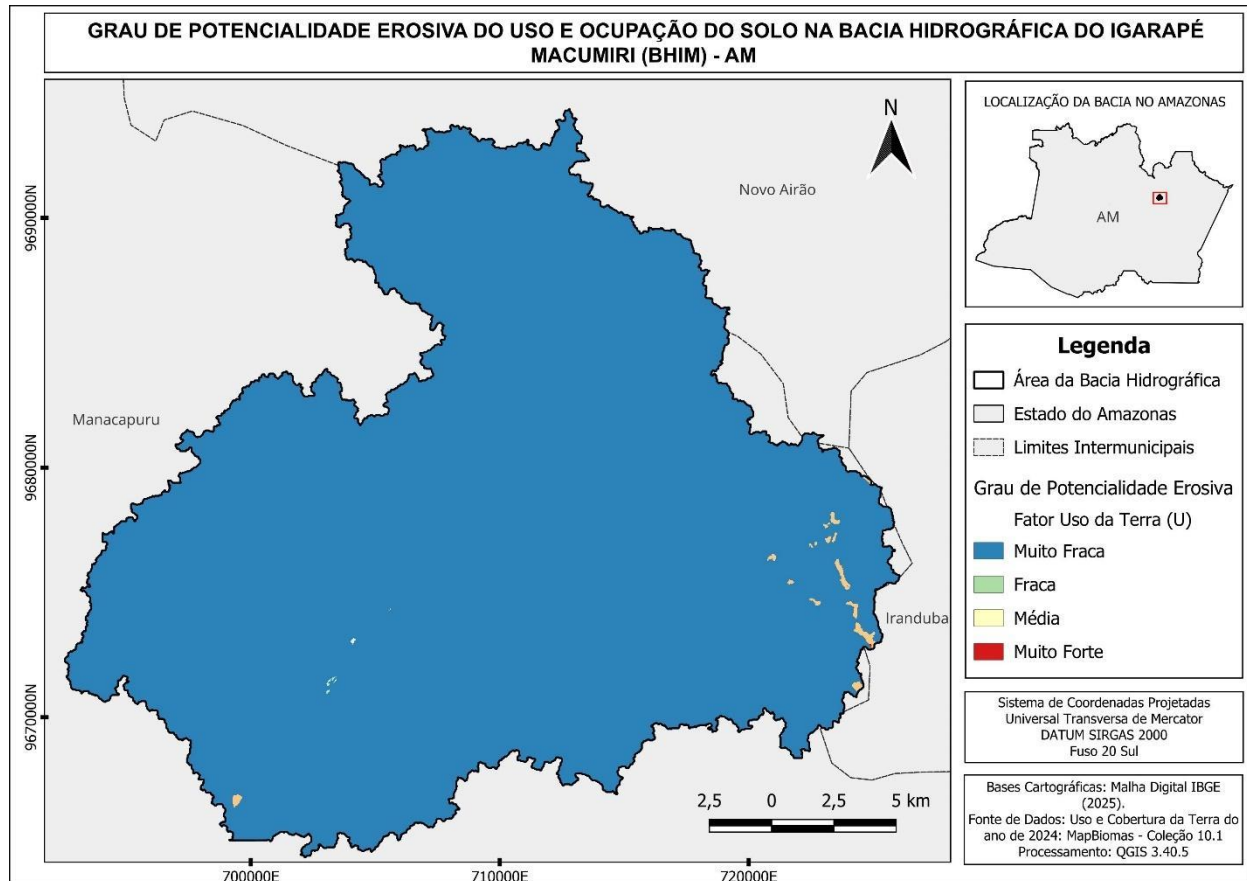


Figure 9: Map of the degree of erosion potential of the land use and land cover factor in the BHIM. Source: Authors.

Table 8: Area classes for the degree of erosion potential of the land use and land cover factor in the BHIM.

Land Use and Occupation	Erodibility Class (%)	Area (km ²)	Area (%)
Forest Formation; Flooded Forest; Flooded Field and Wetland Area.	Very Low	561.53	99.75
Countryside vegetation	Poor	0.05	0.01
Pasture	Medium	1.36	0.24
-	Strong	-	-
Areas without vegetation	Very Strong	0.01	0.0014
Total Area		562.94	100

Source: Authors.

According to Bueno (2024), watersheds with this profile of preserved vegetation cover act as natural regulators of solid load, minimizing sediment export. Santos et al. (2023) reinforce this analysis by emphasizing that the density of the root system of native vegetation in Amazon rainforest areas significantly increases soil cohesion, which ensures bank stability and maintains low levels of water turbidity, in addition to substantially reducing the volume and velocity of flash floods, dissipating runoff energy and slowing down erosive processes. This dynamic minimizes the transport of suspended sediments, ensuring that the Igarapé Macumiri maintains low turbidity levels and a stable chemical composition.

On the other hand, anthropogenic pressures, although territorially insignificant, are located at sensitive points in the basin. Pasture areas cover 1.36 km² (0.24%) and Non-Vegetated Areas only 0.01 km² (0.0014%),



classified as having Medium and Very High erosion potential, respectively. As discussed by Santos et al. (2023), the conversion of forest to pasture significantly alters the water balance, increasing surface runoff and the risk of nutrient input into the water system. The implications for water quality in these critical sectors are severe; Silva and Teixeira (2023) warn that even small patches of exposed soil can act as accelerators of degradation in low-order streams, promoting siltation and compromising water potability for riparian communities. Therefore, preserving the observed forest integrity is the main bulwark for the hydrosedimentological sustainability of the downstream basin.

The erosion susceptibility map generated using map algebra is presented in Figure 10.

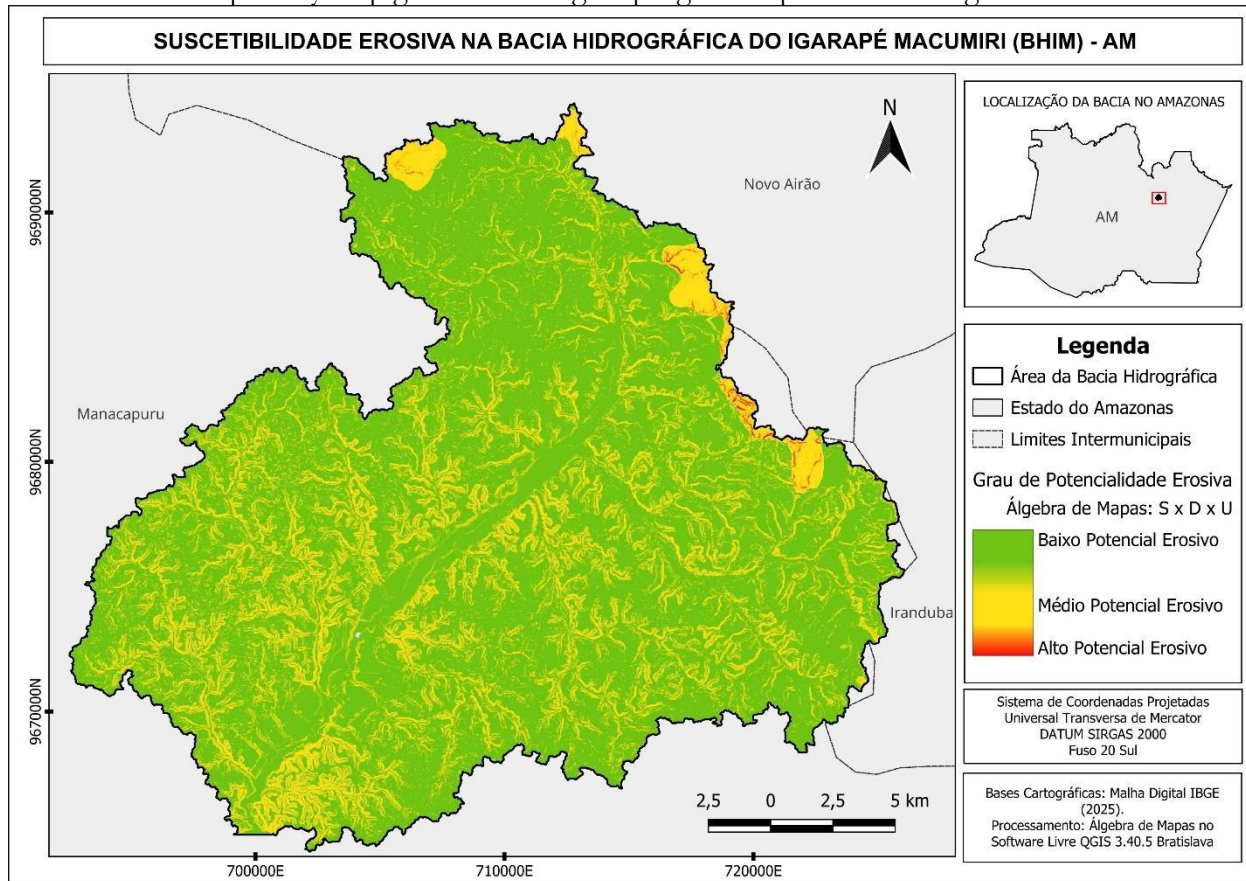


Figure 10. BHIM erosion susceptibility map. Source: Authors.

The final map (Figure 10) shows that a large part of the area can be classified as having low potential for erosion susceptibility. Approximately 65.06% (Table 9) of the total watershed area falls into this low-potential class, which can be explained by the fact that these areas coincide with the areas of moderate slopes identified and with forested areas. Next is an area of high erosion potential, which accounts for only 1.65% of the total area.

The area classified as having high erosion susceptibility is driven by natural factors, characterizing an area with natural soil loss erosion, which occurs because the watershed possesses characteristics that make it naturally susceptible to erosion, without anthropogenic influence. This type of erosion depends, among other factors, on surface runoff, the presence of vegetation, and the slope of the terrain, which directly affect the action of water on the surface of the Igarapé Macumiri basin.



Table 9: BHIM Erosion Susceptibility Area Classes.

Erosion susceptibility classes	Area (km ²)	Area (%)
Low Erosion Potential	366.25	65.06
Medium Erosion Potential	187.42	33.29
High Erosion Potential	9.27	1.65
Total	562.94	100

Source: Authors.

According to Stevaux and Latrubesse (2017), there are three main types of erosion, which differ according to the agent responsible: water, wind, and ice. These processes are known as hydrological, eolian, and glacial erosion. In Brazil, where the tropical climate predominates, water is the primary agent of erosion, making hydrological erosion the most common. The most frequent types of erosion caused by water include sheet erosion, rill erosion, gully erosion, and ravine erosion. In the study basin, the predominant types of erosion observed are sheet erosion and rill erosion.

According to Santos et al. (2015), sheet erosion refers to the process of relatively homogeneous removal of soil layers in a given area, without the formation of rills on the surface of the watershed. On the other hand, rill erosion involves the removal of soil through furrows and channels where surface water runoff is concentrated. Depending on the frequency and depth of these furrows, this type of erosion can be classified as gully or ravine erosion.

Furthermore, regarding the watershed's vulnerability to soil loss, it is found that areas with the highest erosion potential account for only 1.65% of its total area. These areas are concentrated mainly on vegetation-free land with slopes between 12% and 20% (or steeper), as well as sections with sandy-textured humiluvic spodosol on flat terrain.

Conclusion

The main objective of this study was to identify and spatially map areas susceptible to sheet erosion in the Igarapé Macumiri watershed through the integration of geoprocessing techniques, multi-criteria analysis, and map algebra in a GIS environment. The results showed that the basin's erosion dynamics are predominantly controlled by natural factors, particularly the interaction between slope, pedological characteristics, and vegetation cover.

The predominance of areas with low susceptibility to erosion (65.06%) reflects the combination of gently undulating terrain and relatively well-preserved forest cover, indicating a balance between natural fragility and soil protection mechanisms. On the other hand, areas of higher susceptibility, although spatially limited (1.65%), reveal high environmental sensitivity, especially in sectors with sandy soils and steeper slopes, constituting priority zones for monitoring and conservation.

From a methodological standpoint, the integrated application of multi-criteria analysis and map algebra in a GIS environment demonstrated high robustness and spatial synthesis capability, allowing for the incorporation of multiple environmental variables and the generation of consistent erosion vulnerability scenarios. This approach stands out for its flexibility in weight assignment and its ability to adapt to different scales and environmental contexts, although it depends on the quality of input data and the careful definition of parameters, which constitutes a significant limitation.

As a scientific contribution, the study advances the integrated application of spatial modeling techniques in medium-scale Amazonian watersheds, filling gaps related to the scarcity of systematic analyses in this region. Furthermore, the results provide technical insights applicable to environmental planning, especially regarding the identification of priority areas for conservation, land-use management, and the mitigation of erosion processes.

From a practical standpoint, the generated outputs can guide public policies focused on land management, water resource protection, and the maintenance of environmental quality in regions of high ecological sensitivity. For future research, it is recommended to incorporate climatic variables, such as rainfall erosivity, as well as to empirically validate the models using field data, with the aim of improving the accuracy of the analyses and expanding their applicability in different environmental contexts.



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