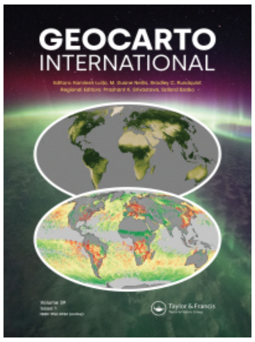

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‘Environmental vulnerability of a tropical river watershed, Eastern amazon’

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‘Environmental vulnerability of a tropical river watershed, Eastern amazon’

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ABSTRACT

The assessment of environmental vulnerability to soil erosion (EVSE) has been used to predict the probability of physical soil degradation. The aim of this study is to analyze the EVSE in the Itacaiúnas River Watershed (IRW) in eastern Amazonia. The methodological approach is based on Multicriteria Decision Analysis based on Geographic Information Systems (MCDA-GIS). It integrates geological, geomorphological, pedological, climatological and land cover characteristics to determine the EVSE. From the integrated map analysis, a final EVSE map was generated from arithmetic average of the five thematic maps. The results showed that the IRW is moderately stable/vulnerable (68% of the watershed), moderately stable (22%) and moderately vulnerable (10%). The land use in nonprotected areas promoted intense deforestation, generating areas of greater EVSE. The vulnerability maps represent effective products to assist in territorial planning, as they highlighted conflicts of use, enhancing areas with soil losses and their environmental impacts.

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KEYWORDS
Environmental vulnerability; soil erosion; geoprocessing; Itacaiúnas River Watershed

1. Introduction

To understand the environmental vulnerability of a tropical river watershed is crucial to use an integrated and multidisciplinary approach. Hence, the erosion vulnerability index has emerged as a practical approach for environmental management (Crepani et al. 2001). Building upon the foundational works of Ross (1994, 1996, 2012) and the ecodynamic concept introduced by Tricart (1977). The key factors influencing soil erosion include rainfall erosivity, soil physical properties, vegetation cover, and slope characteristics (Ramalho Filho and Beek 1995; Guerra et al. 1998). According to Rosa (2016), Lal (2001),

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and Pimentel et al. (1995), watershed degradation due to deforestation, urbanization, agricultural expansion and natural climatic phenomena disrupts the vegetation cover that stabilizes the soil. This leads to significant increases in soil erosion, sediment production, water siltation and pollution in the context of watersheds (Santos et al. 2012; Barbosa et al. 2015).

It is important to emphasize that watersheds represent a fundamental unit of analysis in environmental studies (Choudhari et al. 2018; Jothimani et al. 2020). The ecosystem services provided by watersheds are crucial for promoting sustainable water supplies, climate regulation, and biodiversity habitats (Millennium Ecosystem Assessment 2005). By integrating these perspectives, studies of watershed vulnerability can become more detailed by considering environmental aspects, including geology, geomorphology, relief, soil, climate and land cover and land use changes (Chauhan et al. 2022). Some paper have been published

Assessing the environmental vulnerability of watersheds from soil erosion analysis have been done in mountain region in subtropical climate, for example in the Indian Himalayan (Kumar Pradhan et al. 2020; Chauhan et al. 2022) and Mantiqueira Ridges in southeast Brazil (Campos et al. 2023). However, few studies have been done in tropical mountain region, such as Carajás Ridges in the Brazilian Amazon. This study assesses the environmental vulnerability in the context of a mountain tropical watershed, where land cover changes and soil erosion are among the most important problems observed in the tropics (Pontes et al. 2019; Browning and Sawyer 2021). In the Amazon watershed, deforestation intensifies soil erosion, especially after converting forested areas into agricultural and pasture areas (Souza-Filho et al. 2016; Borrelli et al. 2017). Although deforestation in the Amazon region is a relevant and recurring topic on the national and international environmental agenda (Tacconi et al. 2019), little is known about the influence of deforestation on soil erosion and degradation rates. Thus, evaluating the dynamics of the process of erosion due to deforestation and the consequent changes in land cover and land use in the region is essential for emphasizing the importance of soil conservation and helping in creating effective strategies for reducing erosion (Efthimiou et al. 2017).

By employing this methodology, we can explore the intricate dynamics of environmental vulnerability to soil erosion (EVSE) within a tropical watershed, paving the way for informed decision making in land management practices (Singh and Murai 1998; IPCC 2014). In this context, the geographic information system (GIS) tool has emerged as a highly efficient tool for integrated landscape analysis (Rêgo et al. 2020; Albuquerque et al. 2023; Campos et al. 2023), enabling the mapping and characterization of land use patterns and facilitating the collection of essential morphometric, climatic, and soil data within drainage basins (Silva et al. 2022). Hence, the integration of GIS and remote sensing technologies complements these methodologies, providing a comprehensive and detailed view of environmental dynamics, which is essential for adaptive management in the face of climate change and anthropogenic pressures.

This study aimed to assess the environmental vulnerability of a tropical watershed situated in the transitional area between the Brazilian Amazon and Cerrado biomes, e.g. the Itacaiúnas River Watershed (IRW). By integrating geological, geomorphological, pedological, land use, land cover, and climatological (pluviometric intensity) data, this paper presents the map showing the environmental vulnerability of the IRW to soil erosion *via* map algebra.

2. Materials and methods

2.1. Study area

The study area comprises the Itacaiúnas River Watershed (IRW), which is located in the State of Pará, southeast of the Amazon; the IRW is located in the context of the Carajás Mineral Province, one of the largest mineral provinces on Earth (Tolbert et al. 1971). From a socioeconomic–environmental point of view, the IRW is the most important watershed in the state, as it hosts several socioeconomic activities, including mining (the exploitation of iron, manganese, copper, nickel and gold minerals), livestock production and agriculture (IBGE 2017). The watershed occupies a drainage area of approximately 41,350 km^2 and is formed by the subbasins of the Itacaiúnas, Parauapebas, Vermelho, Sororó, Cateté, Aquiri, Cinzento, Tapirapé and Preto Rivers. Additionally, the watershed is marked by the presence of a mosaic of protected areas and the Xikrin do Cateté indigenous land, which occupies 10.6% of the watershed area (Figure 1).

The IRW is located in the Carajás Mineral Province and hosts various socioeconomic activities. These include the exploitation of iron, manganese, copper, and nickel ores, much of the exploitation occurs within protected areas (Souza-Filho et al. 2015, 2016, 2018, 2019; Nunes et al. 2019). The region encompasses extensive livestock and agricultural activities (IBGE 2017), the assets of which contribute to approximately 25% of the GDP of the state of Pará (Silva Júnior 2017) (Figure 1).

The IRW (Figure 3(a)) features northern Neoarchean to Paleoproterozoic units composed of high-grade metamorphic rocks and metavolcanic and metasedimentary rocks. The Carajás Province and southern part of the watershed are occupied by Archean domains predominantly consisting of Mesoarchean granitoid rocks of diverse composition and subordinate metamafic–ultramafic greenstone belts (Monteiro et al. 2008; Feio et al.

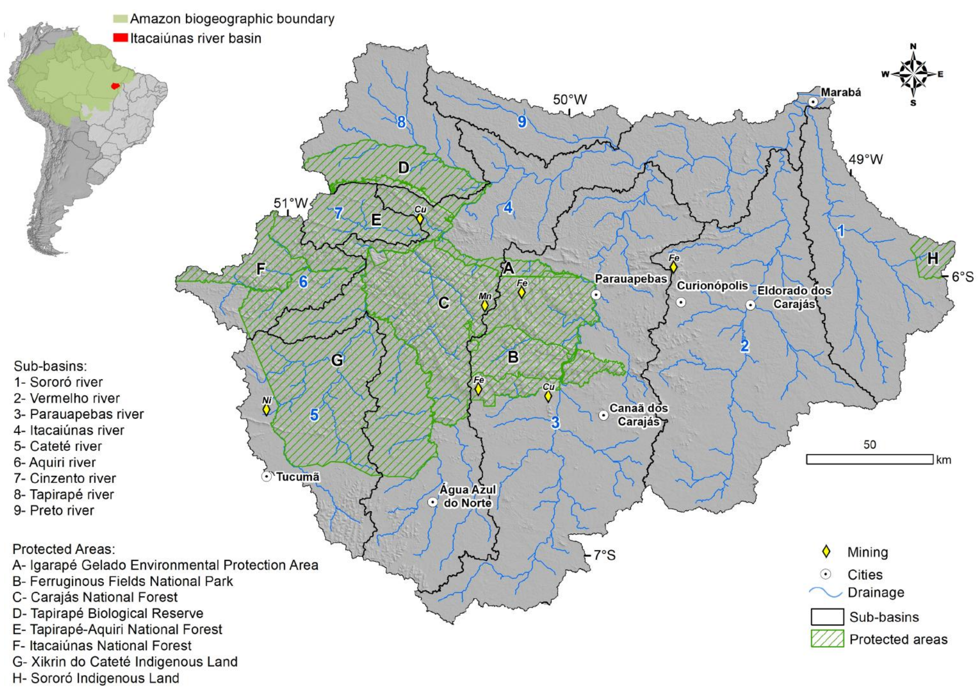

Figure 1. Area of the Itacaiúnas River watershed, showing subbasins, protected areas, and main mines and cities.

2013; Sousa et al. 2015; Dall'Agnol et al. 2017). According to these authors, the Sossego copper mine and several other copper deposits are located in this segment of the watershed. The centre of the IRW corresponds to the Serra de Carajás, which consists mainly of Neoarchean metavolcanic–sedimentary sequences dominated by mafic and intermediate metavolcanic rocks and banded iron formations in which large iron deposits are present. Neoarchean granites cut the metavolcanic–sedimentary and Archean units that are partially covered by Paleoproterozoic sedimentary rocks. The eastern portion is represented by the Araguaia Belt, which consists of sedimentary, metasedimentary, mafic–ultramafic and Quaternary deposits and lateritic covers.

The geomorphology of the area is marked by the occurrence of four morphostructural domains (IBGE 2021): Neoproterozoic cratons composed of the Serra dos Carajás, Serra de São Félix, Antonhão and Seringa geomorphological units and the Bacajá and Middle Xingu Depressions; Neoproterozoic mobile belts (the Middle and Lower Araguaia Depression); Phanerozoic sedimentary watersheds and covers (Patamar Dissecado Capim – Moju); and Quaternary sedimentary deposits formed by river plains and terraces (Figure 3(b)).

The soil classes defined for the IRW (CPRM - SERVIÇO GEOLÓGICO DO BRASIL 2021; IBGE 2021) are presented in Figure 3(c); the soils are diazotrophic red–yellow Ultisols, which occupy more than 60% of the area, followed by dystrophic red–yellow Oxisols, which occupy 23%. Finally, Neosols (litholic dystrophic and quartzarenic orthic) occupy approximately 11% of the area.

Land use and vegetation cover information in the IRW used in the assessment of the environmental vulnerability was published by Souza-Filho et al. (2015, 2018), which showed the evolution of these changes over the past four decades. Nunes et al. (2019) detailed the current uses and primary and secondary vegetation covers (Figure 3(d)).

2.2. Data source and processing

Environmental vulnerability to soil erosion is controlled by a variety of endogenous factors (e.g. original rock composition and geological structures) (e.g. rock weathering, erosion, and landslides) linked to geological, geomorphological and pedological processes, land use and land cover, and climate (Crepani et al. 2001; Oliveira-Andreoli et al. 2021).

In this study, secondary spatial databases at various scales were utilized that were obtained from federal and state public agencies, as well as primary data collected in laboratories and in the field. Table 1 presents the source and main characteristics of the data used in this study, highlighting the comparison between the years of acquisition and the spatial scale/resolution of the databases.

Based on spatial databases and through the use of geoprocessing techniques, the base maps were reclassified to obtain thematic maps of geology, geomorphology, pedology, land use and cover, elevation, and precipitation (Figure 3). Subsequently, among the reclassified maps, resulting in an environmental vulnerability map for each theme. Finally,

Table 1. Source and main characteristics of the data used in the study.

Source	Database	Scale/Spatial resolution
CPRM (2006)	Geological map	1:250.000
IBGE (2021)	Geomorphological map	1:250.000
Embrapa (2013), IBGE (2021)	Pedological map	1:250.000
Souza-Filho et al. (2015, 2018), Nunes et al. (2019)	Land cover and land use ITV DS 2019	12 m
JAXA (2023)	DEM Palsar	12,5 m
CHIRPS (2021)	CHIRPS (1981 to 2021)	5,55 km

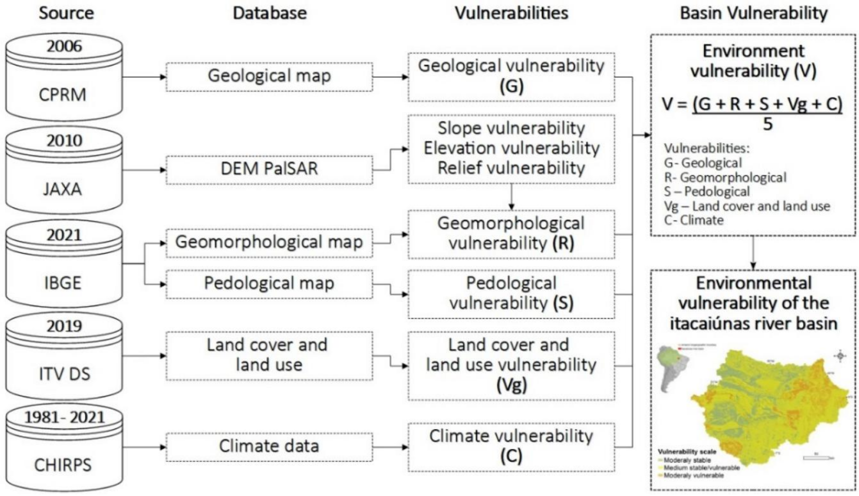

Figure 2. Flowchart of the research stages, data sources and methodologies used to obtain a map of environmental vulnerability to soil erosion in the IRW. See details in Table 1.

the map of environmental vulnerability to soil erosion was produced at a scale of 1:75,000 and georeferenced to DATUM WGS-84, UTM Zone 22S (EPSG:32722). Figure 2 shows the data processing flow used to generate the final map.

Climate-related data, based on average (monthly and annual) rainfall, were acquired from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) database (rainfall estimates from rain gauge and satellite observations), where rainfall information representing a 41-year time scale was obtained (from 1981 to 2021) and distributed throughout the watershed at a spatial resolution of 0.05° (approximately every 5.55 km). For each reference point (2977 points), the average annual precipitation was calculated for the analyzed period, and finally, from these values, it was possible to perform spatialization *via* the inverse distance weighted (IDW) method and prepare a map of precipitation, with an annual mean distribution (40 mm isohyets) along the IRW (Figure 3(e)).

Despite the spatial and temporal differences, the results achieved agreement above 70% over an extension of approximately 41350 km^2 (IRW area). However, after a decade of monitoring, some areas (< 30%) presented noncompliant results considering their tacit knowledge about the region.

2.3. Generation of vulnerability maps

The methodology adopted is based on the proposal of Crepani et al. (2001), who expressed susceptibility and vulnerability to soil erosion through a scale of values distributed from the predominance of pedogenetic processes vunerability degree = stable), intermediate situations (vunerability degree = medium stable/vunerable) and morphogenesis processes (vunerability degree = vunareble) (Table 2).

To determine the environmental vulnerability of soil erosion (EVSE) in the IRW, values were assigned to the soil loss processes for each thematic variable: geology, geomorphology, pedology, land use and land cover, and climate.

The methodology to assess the EVSE adopted in this study is founded on the proposal of Crepani et al. (2001). This approach is supported by Multicriteria Decision Analysis based on Geographic Information Systems (MCDA-GIS), a remote sensing and

Table 2. Vulnerability scale. Adapted from Crepani et al. (2001).

Vulnerability scale			Vulnerability degree	Colors	R/G/B color
	3		Vulnerable		255/0/0
↑	2,9				255/51/0
	2,8				255/102/0
	2,7				255/153/0
	2,6		Moderately Vulnerable		255/204/0
V	2,5				255/255/0
U	2,4				204/255/0
L	2,3				153/255/0
N	2,2	S	Medium stable/vulnerable		102/255/0
E	2,1	T			51/255/0
R	2	A			0/255/0
A	1,9	B			0/255/51
B	1,8	L			0/255/102
L	1,7	E	Moderately Stable		0/255/153
E	1,6				0/255/204
	1,5				0/255/255
	1,4				0/204/255
	1,3		Stable		0/153/255
	1,2				0/102/255
	1,1	↓			0/51/255
	1				0/0/255

geoprocessing advance applied to ecological-economic zoning and territorial planning of Brazil, widely used throughout the country (Rêgo et al. 2020; Gomes et al. 2021; Campos et al. 2023). Analogous approaches have been applied in other countries, such as India (Chauhan et al. 2022), China (Wei et al. 2020) and Vietnam (Nguyen et al. 2016). Therefore, the factors selected in this study were selected according to scientific literature.

Generation of the geological vulnerability map was established from the imputed values for each set of lithological units of the main rocks existing in the different geological units (Table S1). For loosely cohesive rocks, erosive processes (morphogenesis) prevail, for which values close to 3.0 are assigned, while for highly cohesive rocks where weathering and soil formation (pedogenesis) processes prevail, values close to 1.

In establishing the values of the vulnerability scale for the natural landscape units with respect to geomorphology, the following morphometric indices of the terrain were generated and analyzed: dissection of relief by drainage, altimetric amplitude and slope. These indices were obtained by applying the methodology (routine) of the geoprocessing proposals of Guimarães et al. (2017) and Lima (2018), and finally, the matrix was crossed to define the vulnerability of the relief (geomorphology) (Equation 1). The indices used in the procedures adopted are shown in Table S2.

$$R = (G + A + D)/3 \tag{1}$$

where

R = Geomorphological vulnerability.

G = Vulnerability attributed to the degree of dissection.

A = Vulnerability attributed to the altimetric range.

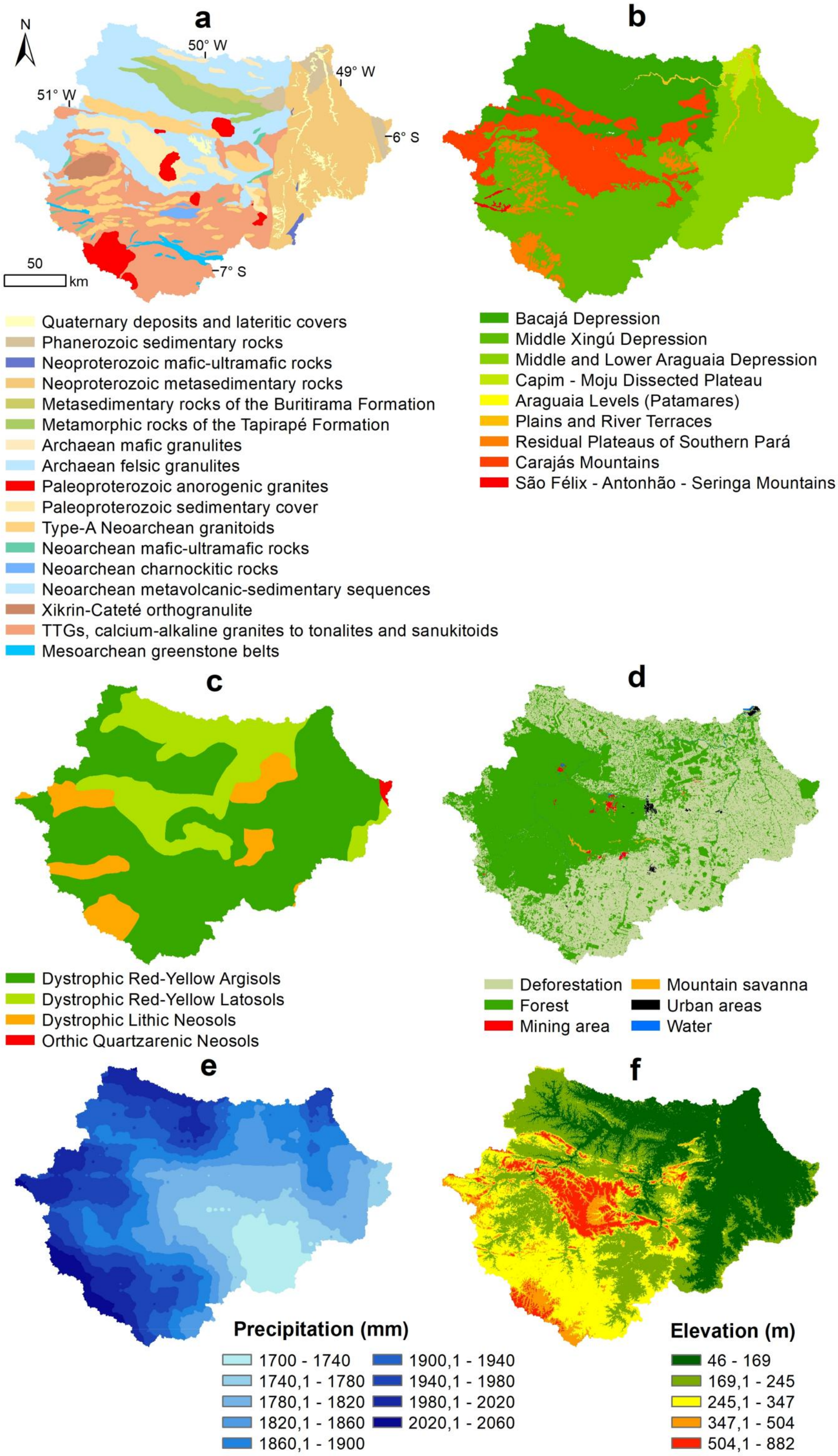

Figure 3. Itacaiúnas River watershed cartography: Geological map (a) (CPRM, 2006), geomorphological map (b) (IBGE, 2021), soil map (c) (EMBRAPA, 2013), land use and vegetation cover map (d) (Nunes et al. 2019), mean annual precipitation map (e) (CHIRPS, 1981-2021) and digital elevation model (f) (JAXA, 2010).

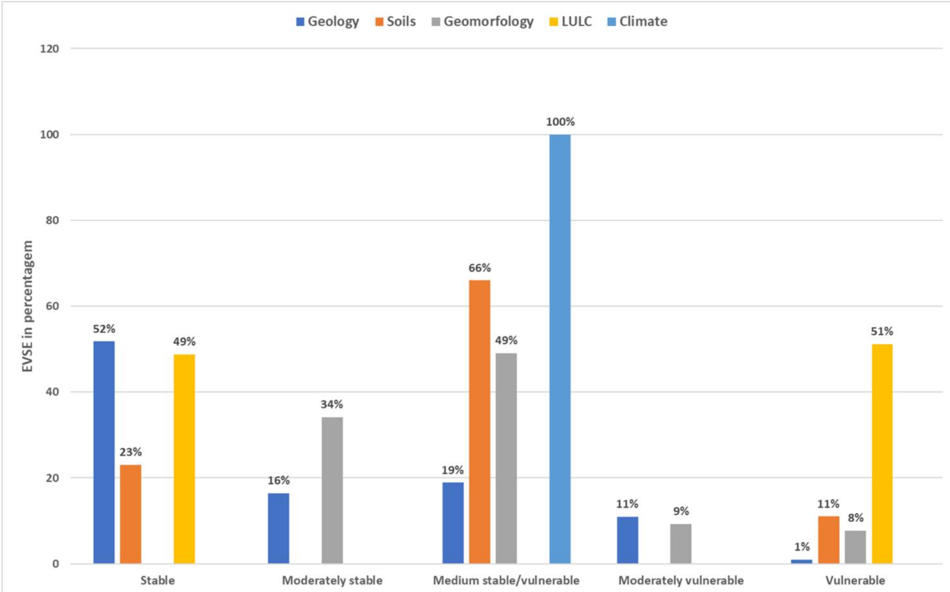

Figure 4. Thematic environmental vulnerability to soil erosion (EVSE) of the IRW.

D = Vulnerability attributed to declivity.

The IRW pedological vulnerability map is the result of the valuation attributed to the dominant soil types in the study area. These are Latosols, Argisols and Dystrophic Litholic and Orthic Quartzarenic Neosols, ranging from stable, medium stable/vulnerable to vulnerable respectively (Table S3).

The generation of the vulnerability map linked to land cover and use includes the vegetation cover density as the parameter to be obtained; i.e. it is the protection factor against erosive processes. Stability values (pristine forest) were assigned to high densities on the vulnerability scale, while intermediate densities and low densities (pasture, mining, and cities) were assigned values close to the vulnerability values (Table S4).

To construct the climate vulnerability map (Figure 3), rainfall intensity values were calculated, the average annual rainfall (in mm) was obtained for the duration of the rainy season (in months), which extends from November to May with an average annual rainfall of approximately 1,500 mm (Moraes et al. 2005; Silva Júnior et al. 2017); then, the corresponding value of the scale of erosive vulnerability was assigned to rain defined by the methodology of Crepani et al. (2001) (Table S4).

The environmental vulnerability index was calculated in a GIS environment using map algebra based on the methodology proposed by Ribeiro and Albuquerque (2021), which represents the combination of variables using the Boolean method of combining maps, where the information plane vector formats were converted to raster formats (matrices). Finally, each theme that composes each basic territorial unit (natural landscape) was applied individually, which receives a final value, resulting from the arithmetic mean of the individual values according to Equation 2:

$$\mathbf{V} = \frac{(\mathbf{G} + \mathbf{R} + \mathbf{S} + \mathbf{Vg} + \mathbf{C})}{\mathbf{5}} \tag{2}$$

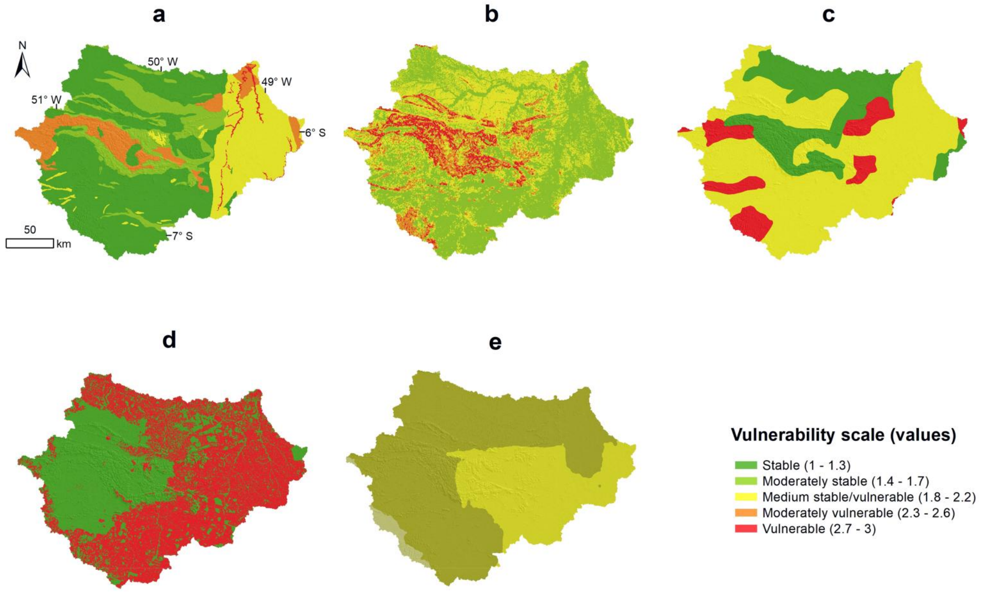

Figure 5. Thematic maps of vulnerabilities: Geological (a), geomorphological (b), pedological (c), land use and vegetation coverage (d) and climate (e) in of the Itacaiúnas River watershed (IRW).

where V = Environmental Vulnerability; G = Geological Vulnerability; R = Geomorphological Vulnerability; S = Pedological Vulnerability; Vg = Vulnerability to Land Use and Coverage; and C = Vulnerability to Climate.

Each of the variables has a degree of vulnerability followed by a range of values from 1 to 3 (Table 2).

3. Results

3.1. Thematic environmental vulnerability of the Itacaiúnas River watershed (IRW)

The environmental vulnerability map of the IRW is the result of thematic environmental maps quantified from cross-referencing data related to geology, geomorphology, soils, land use, land cover, and climate.

The geological vulnerability of the watershed to soil erosion was defined based on the characteristics of the outcropping rocks (mineralogy, texture and structure).

The IRW, with approximately 70% of its area consisting of plutonic igneous, volcanic and metavolcanic–sedimentary rocks, has very cohesive (resistant) rocks (Figure 3(a)). Geologically, the process of soil formation (pedogenesis) predominates, providing greater stability against erosive processes (morphogenesis). These areas cover the entire central–north–northwest and south–southwest portions of the IRW, whose degree of vulnerability varies from stable (52%) to moderately stable (16%) (Figures 4 and 5(a)).

Approximately 19% of the watershed area, particularly in the eastern portion, is moderately stable/vulnerable, mainly represented by the rocks of the Araguaia Belt, indicating a transition between stability and vulnerability. The areas with a moderate degree of vulnerability (11%) extend along the central portion of the study site, which is basically covered with more friable metasedimentary rocks (meta-sandstones, metaconglomerates and meta-siltstones) and has greater vulnerability to erosion (Figure 4 and 5a). The geologically vulnerable areas are restricted to unconsolidated sedimentary deposits represented by

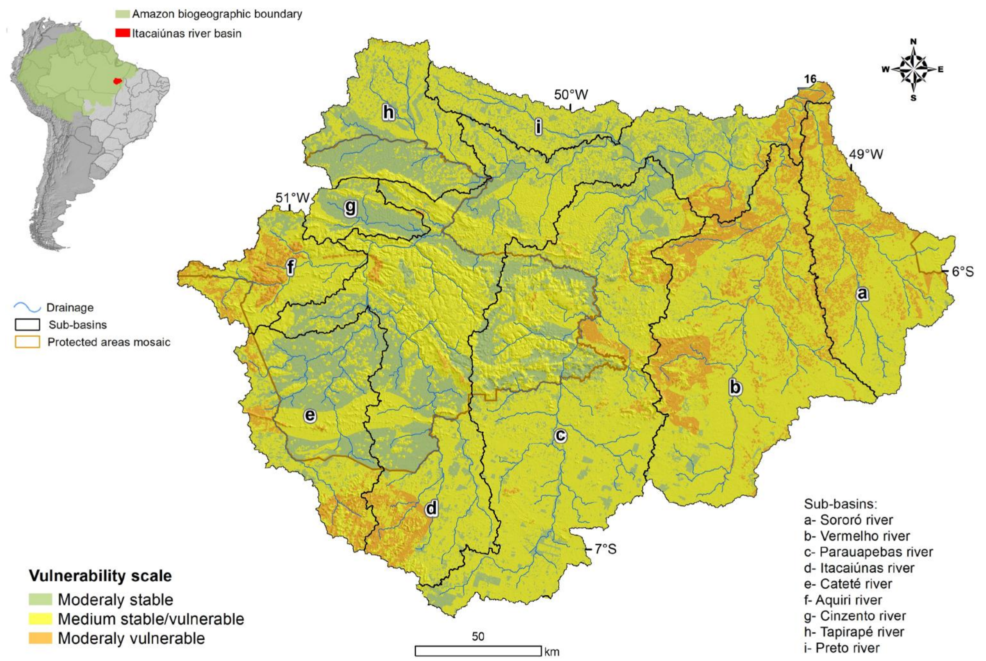

Figure 6. Mapping of environmental vulnerability to soil erosion (EVSE) in the Itacaiúnas River watershed (IRW).

alluvium and floodplains distributed along the main drainages corresponding to less than 1% of the watershed area (Table S1).

The geomorphological vulnerability of the IRW reflects the average interaction of the three morphometric indices: (i) the dissection of the relief, (ii) the altimetric range, and (iii) the slope (Table S2a). The analysis of geomorphological vulnerability (Figure 4, Figure 5(b), and Table S2b) revealed that the influence of high vulnerability of the relief dissection prevailed, and thus, no stable areas are identified. Moderately stable areas occupy 34% of the basin's area, dominating the flatter to gently undulating areas with very low to low slopes, encompassing the same geomorphological units that are stable in terms of the altimetric range and slope. Medium stable/vulnerable relief areas represent approximately 50% of the basin, dominating the northern portion but sparser in the eastern and central–southern sectors of the basin. The moderately vulnerable areas (9.2% of the area) to vulnerable areas (7.7%) are concentrated in the areas of the Carajás and residual plateaus.

The soil vulnerability of the IRW is dominantly stable/vulnerable (Figure 5(c) and Table S3). The areas of stable vulnerability have Latosols with a very clayey to clayey texture and cover an area of approximately 9,500 km^2 (approximately 23% of the watershed), occurring in the northern portion of the watershed in the interfluvial area the Parauapebas River; the very clayey to clayey soils cover much of the Serra dos Carajás, indicating good resistance to erosion and other degradation processes. In medium stable/vulnerable areas, the Argisols extend throughout the watershed in an area of 23,300 km^2 (66%), and the texture varies from very clayey to clayey and is present in all geological domains and in most of the flat reliefs, suggesting a balance between stability and vulnerability factors but with a tendency towards vulnerability. It is wavy, especially along the subbasins of the Vermelho and Sororó Rivers. The vulnerable soils are dispersed in the watershed, composing an area of approximately 4,600 km^2 (11%), and they are formed by litholic and quartzarenic Neosols, with indiscriminate to sandy textures, indicating that these areas are at risk of degradation; these areas cover Serra de São Félix and most of the residual plateaus of southern Pará.

Land cover and land use vulnerability present two distinct degrees: stable, linked to areas with forest cover that occupy 49% of the study area, indicating good management practices and sustainable use; and vulnerable, related to areas of pasture, canga vegetation, agriculture, mining and urban areas, which correspond to 51% of the IRW area; these areas are under pressure and at risk of degradation (Figure 4, Figure 5(d), and Table S4).

Climate vulnerability is strongly related to rainfall intensity in the IRW. The average annual precipitation varies from 1,700 to 2,060 mm in the IRW from east to west. The average precipitation is lower in the southeastern and eastern regions (1,700–1,750 mm) and greater in the southwestern and western regions (1,925–2,060 mm) of the basin (Table S5). The entire area presents a moderate degree of vulnerability, with variations from 1.8 to 2.0 at the analysed scale (Figure 4, Figure 5(e), and Table S5). In the central–southeastern portion, the lowest intensities (243-250 mm) are observed, followed by higher intensities (250-275 mm) in a large part of the watershed. The southwestern region presents the highest intensities (275-294 mm) of rainfall.

3.2. Environmental vulnerability of soil erosion (EVSE) of the Itacaiúnas River watershed (IRW)

The environmental vulnerability to soil erosion of the IRW was obtained from thematic map algebra, where three degrees of vulnerability were found: moderately stable, medium stable/vulnerable, and moderately vulnerable (Figure 6).

The moderately stable areas of the IRW cover 8,961 km^2 (22%), where stable geology and vegetation intersect with medium stable/vulnerable soils, geomorphology, and climate. These areas are characterized by resistant rocks, preserved forest vegetation, and flat to holling hill relief. These environmental characteristics are responsible for the transport of rainfall towards rivers through interception, infiltration, absorption, transpiration and percolation. This process minimizes erosive effects, the leaching of nutrients from the soil and the silting of water bodies, maintaining the stability of the soil.

The most extensive environmental vulnerability defined as a soil erosion category is the medium stable/vulnerable area. This area occupies 28,058 km^2 (68%) and includes regions with different types of rocks, soils, and vegetation, ranging from flat to mountainous reliefs. Notably, despite its high mountainous relief, the Serra dos Carajás region has dense pristine forest cover and resistant rock, indicating a critical balance between stability and vulnerability. In addition, flat to holling hills are formed by resistant rocks, but completely deforested areas present the same environmental vulnerability.

Moderately vulnerable areas are the least representative, covering 4,314 km^2 (10%) of the IRW. These areas include the Residual Plateau of southern Pará, the Carajás Mountains, and parts of the Araguaia Belt, marked by dissected terrain and dominated by pastures and susceptible soils. These moderately vulnerable areas are associated with lithic Neosols that developed over metavolcanic–sedimentary rocks that outcrop in a region of holling hills that is frequently deforested.

4. Discussion

Environmental vulnerability studies have been conducted from theoretical aspects of different thematic disciplines for management planning and decision-making with minimal subjectivity and maximum quantifiable information (Villa and McLeod 2002). Following this approach, we used a Multicriteria Decision Analysis based on Geographic Information Systems (MCDA-GIS) supported by regional, spatial and open access data to propose an environmental vulnerability soil erosion (EVSE) index at a detailed scale. The findings of this study demonstrate that the use of EVSE is an effective and cost-efficient method for the assessment of environmental vulnerability in tropical mountain regions located in the southeastern Amazon. As previously stated by Macedo et al. (2018), this quantifiable methodology has significant potential for application in the management, recovery, and conservation of tropical river basins.

The results show that the IRW is environmentally vulnerable to soil erosion (Figure 6), as observed in other tropical watersheds worldwide (Browning and Sawyer 2021). The IRW presents a median dominant vulnerability index, which represents an intermediate degree of propensity for erosion (Tricart 1977). Although the index reveals a degree of morphodynamic balance within the watershed, there are sectors in which morphogenetic processes are intensified. The analysis also reveals that the indices mapped in a large part of the basin are considered to favour pedogenetic processes. Thus, the natural stability has facilitated the spatial occupation of the basin and facilitated anthropogenic use (Souza-Filho et al. 2018).

This EVSE of the IRW is strictly related to chemical weathering of the rocks, rolling hills and mountainous relief, high and intense rainfall, which are strongly increased by deforestation processes. Studies addressing geological characteristics corroborate that regions underlain by crystalline rocks (igneous and metamorphic) located on the western side of the IRW tend to be more stable than those with sedimentary rocks located on the eastern side of the basin (Askaripour et al. 2022). The landscape developed over crystalline rocks at IRW is characterized by rock fragments that are responsible for a reduction in runoff. Consequently, the soil erosion decreases in comparison to muddy and sandy bare soils (Li et al. 2022).

According to Guerra et al. (2020), soil erosion protection has decreased over time across terrestrial biomes as result of vegetation cover loss, hydrological process, and changes in rainfall erosivity. These processes have been well described in the IRW by Souza-Filho et al. (2016, 2018), Pontes et al. (2019), and Cavalcante et al. (2019), respectively. These authors believe that deforestation was the main cause of the land cover and hydrological changes observed in the context of the IRW.

The degree of environmental vulnerability to soil erosion due to geomorphological characteristics is associated with mountain ranges, despite its importance as an active factor in affecting flow (Freitas 2021). However, we did not observe a significant influence on vulnerability because mountainous areas with steeper slopes are densely vegetated, protect the soils against erosion and are less subject to anthropogenic interference. As a result, this landscape in the IRW is classified as having a medium stable/vulnerable degree.

Land cover and land use changes have the greatest impact on environmental vulnerability to soil erosion in the IRW because they present two opposite and distinct classes: a stable class, with 49% represented by native forest cover, and a vulnerable class, with 51% of the area covered mainly by pasturelands. These percentages of vulnerable areas are directly related to the geographic position of the IRW, which is located in the 'Amazon Arc of Deforestation', where has been developed extensive pasturelands for livestock farming (Laurance et al. 2009). Conversely, stable areas are related to the existence of areas of sustainable use and conservation where industrial mining activities (Souza-Filho et al. 2019) and indigenous lands occur. This has led to the conservation of approximately 20,000 km^2

of native forest that composes multiple conservation units in the mosaic of Carajás protected areas, where forests and other vegetation physiognomies are preserved (Nunes et al. 2019).

The preservation of forests is crucial for preventing soil erosion due to the production and deposition of organic material, which promotes greater resistance to soil erosion (Gomes et al. 2021). The remaining occurrences of pristine tropical forests in the IRW are restricted to sectors related to protected areas and indigenous land, confirming the importance of these units for their stability in their vulnerability to soil erosion. This result highlights the importance of the role of vegetated areas in hydrological cycle dynamics by acting as natural barriers that delay the movement of rainwater towards rivers through interception, infiltration, absorption, transpiration, and percolation, thus minimizing erosive effects, the leaching of nutrients from the soil and the silting of water bodies (Lorenzon et al. 2013).

On the other hand, the conversion of more than 50% of the tropical forest to pasture in the IRW is responsible for the continued exposure of less resistant geological substrates and bare soil, resulting in permanent increases in streamflow, sediment transport by runoff and reduced rainfall infiltration (Souza-Filho et al. 2016, Silva et al. 2021, Lense et al. 2020). Hence, more vulnerable areas are associated with land uses that include pastures, mining, and urban areas, which are subjected to greater erosion and landscape instability (Silva et al. 2021).

5. Conclusions

We concluded that the IRW is environmentally vulnerable to soil erosion based on thematic vulnerability from the point of view of geological, geomorphological, pedological, climatological and land cover and land use characteristics. This research showed that the use of remote sensing data and geographical information system approaches to map the environmental vulnerability to soil erosion in a tropical watershed was effective and easy to apply. It enables an integrated analysis of physical aspects and thematic mapping to be carried out through geoprocessing tools, allowing the creation of a product with synthesized characteristics to highlight greater or lesser levels of environmental vulnerability in the studied area. This analysis has considerable relevance because it facilitates conservation at the regional scale, considers the potential of natural resources, and considers the potential of the environmental vulnerabilities.

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Data availability statement

The data needed to evaluate the conclusions are published and presented in the paper.

Any additional data/code related to this paper may be requested from the authors.

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