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Determination of areas vulnerable to erosion and priority areas for recovery in the watershed of Potengi River – RN

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Authors' notes'

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Abstract

Purpose: The study aims to identify areas vulnerable to soil loss in the Potengi River hydrographic basin (BHRP) in Rio Grande do Norte, through a multicriteria analysis involving various geo-environmental attributes, in order to guide efforts towards efficient actions for the Recovery of Degraded Areas (RAD).

Methodology: Data on geology, climate, geomorphology, pedology, hydrographic network, and interpretation of land cover and land use were collected. Through map algebra, it was possible to model the landscape of the basin and locate the areas most vulnerable to soil loss.

Originality/Relevance: After the investigation using geoprocessing, the results generated in the form of cartographic products were evaluated and validated through field inspections to verify all situations identified as critical and assess the accuracy of the method used. It is important to note that in other studies conducted in BHRP, there was no specific objective of evaluating and validating the reality.

Results: It was found that approximately 76% of the 4,170 km² area of the basin is moderately vulnerable to erosion, with nine critical areas of very high vulnerability identified, which need to reduce soil loss to avoid future effects such as drainage siltation and transport of soil nutrients.

Social/Managerial contributions: Mapping the current state of land cover, land use, and preservation areas is essential to develop protection and monitoring measures. This allows for the implementation of initiatives such as Payment for Environmental Services (PSA) and the creation of a bank of priority areas, aiming to preserve water resources, especially in the semiarid region of Northeast Brazil.

Keywords: multicriteria analysis, geoprocessing, water resources, Potengi River, Rio Grande do Norte

DETERMINAÇÃO DE ÁREAS VULNERÁVEIS À EROSÃO E PRIORITÁRIAS À RECUPERAÇÃO DA BACIA HIDROGRÁFICA DO RIO POTENGI – RN

Resumo

Objetivo: O estudo visa identificar áreas vulneráveis à perda de solo na Bacia hidrográfica do Rio Potengi (BHRP) no Rio Grande do Norte, por meio de análise multicritério envolvendo vários atributos geoambientais, a fim de orientar esforços para ações eficientes de Recuperação de Áreas Degradadas (RAD).

Metodologia: Foram levantados dados de geologia, do clima, da geomorfologia, pedologia, rede hidrográfica e foto interpretação da cobertura e uso da terra. Por meio da álgebra de mapas foi possível modelar a paisagem da bacia e localizar as áreas mais vulneráveis à perda de solo.

Originalidade/Relevância: Após a investigação com geoprocessamento, os resultados gerados na forma de produtos cartográficos foram avaliados e validados por meio de vistorias de campo, a fim de verificar todas as situações apontadas como críticas e avaliar a precisão do método utilizado. É importante ressaltar que, em outros trabalhos realizados na BHRP, não foi identificado um objetivo específico de avaliar e validar a realidade.

Resultados: Verificou-se que cerca de 76% da área de 4.170 km² da bacia encontra-se moderadamente vulnerável à erosão, sendo identificadas nove áreas críticas de vulnerabilidade muito alta, e que precisam reduzir a perda de solo para evitar efeitos futuros, como o assoreamento das drenagens e transporte de nutrientes do solo.

Contribuições Sociais/Gerenciais: Mapear o estado atual da cobertura e uso da terra e das áreas de preservação é essencial para desenvolver medidas de proteção e fiscalização. Isso permite a implementação de iniciativas como o Pagamento por Serviços Ambientais (PSA) e a criação de um banco de áreas prioritárias, visando preservar os recursos hídricos, especialmente no semiárido do Nordeste brasileiro.

*Palavras Chaves***:** análise multicritério, geoprocessamento, recursos hídricos, Rio Potengi, Rio Grande do Norte

DETERMINACIÓN DE ÁREAS VULNERABLES A LA EROSIÓN Y ÁREAS PRIORITARIAS PARA LA RECUPERACIÓN EN LA CUENCA DEL RÍO POTENGI - RN

Resumen

Objetivo: El estudio tiene como objetivo identificar áreas vulnerables a la pérdida de suelo en la cuenca hidrográfica del río Potengi (BHRP) en Rio Grande do Norte, a través de un análisis multicriterio que involucra varios atributos geoambientales, con el fin de orientar los esfuerzos hacia acciones eficientes de Recuperación de Áreas Degradadas (RAD).

Metodología: Se recopilaron datos de geología, clima, geomorfología, pedología, red hidrográfica e interpretación fotográfica de cobertura y uso de la tierra. Mediante álgebra de mapas, fue posible modelar el paisaje de la cuenca y localizar las áreas más vulnerables a la pérdida de suelo.

Originalidad/Relevancia: Después de la investigación con geoprocesamiento, los resultados generados en forma de productos cartográficos fueron evaluados y validados mediante inspecciones de campo para verificar todas las situaciones señaladas como críticas y evaluar la precisión del método utilizado. Es importante destacar que, en otros trabajos realizados en BHRP, no se identificó un objetivo específico de evaluar y validar la realidad.

Resultados: Se encontró que aproximadamente el 76% de la superficie de 4.170 km² de la cuenca es moderadamente vulnerable a la erosión, con nueve áreas críticas de alta vulnerabilidad identificadas, que necesitan reducir la pérdida de suelo para evitar futuros efectos, como el enarenamiento de los drenajes y el transporte de nutrientes del suelo.

Contribuciones Sociales/Gerenciales: Mapear el estado actual de la cobertura y uso de la tierra y las áreas de preservación es esencial para desarrollar medidas de protección y vigilancia. Esto permite la implementación de iniciativas como el Pago por Servicios Ambientales (PSA) y la creación de un banco de áreas prioritarias, con el objetivo de preservar los recursos hídricos, especialmente en el semiárido del noreste de Brasil.

Palabras clave: análisis multicriterio, geoprocesamiento, recursos hídricos, Río Potengi, Río Grande del Norte

Introduction

The terrestrial landscapes contribute directly and indirectly to human well-being (Costanza et al., 1997). Landscape units are constantly changing, both due to human activities and natural phenomena. Each agent modifying the landscape has a rhythm, with rapid transformations occurring (minutes to years) or slow ones (decades to millennia). Although soil formation is a slow process, its movement through erosion is fast and susceptible to acceleration through human activities. Each year, the Earth's surface loses about 0.90 to 0.95 mm of soil (Pham et al., 2018). Global soil loss increased by 20% between 2001 and 2012 (Borrelli et al., 2017) due to vegetation removal and the consequent change in land cover.

The inappropriate use of land, especially for food production, results in its exposure to erosive agents that leach, remove nutrients, decrease arable and pasture areas, leading to nutrient depletion, stream sedimentation, and potentially causing floods by increasing river peak flow (Guo et al., 2019). Soils in tropical climate regions are more susceptible to erosive processes due to their larger active zone with constant moisture variation (Almeida et al., 2015). Additionally, pastures, one of the main erosive agents, occupy a significant part of Brazil (Thomaz & Dias, 2009), potentially causing compaction of the soil cover with constant trampling by animals, reducing root penetration, and consequently, water storage (Guo et al., 2019).

The evolution of soil loss is accelerating worldwide, necessitating the establishment of threshold levels of erosion to mitigate economic losses (FAO, 2019). In the period from 2000 to 2019, there is a significant increase in global reforestation efforts. China leads these efforts with an additional 41 million hectares of recovered forest in this period. In 2020 alone, 42 million hectares were planted, and 34 million in 2021. However, Brazil is not following this path; from 2000 to 2019, the country topped the deforestation ranking with 53 million hectares of lost forests (FAO, 2021). The water crisis in the Brazilian semi-arid region between 2012 and 2018 is further evidence of the importance of addressing these processes.

The landscape assessment process presupposes knowledge of the environmental dynamics of the region, involving land use and occupation, urban expansion, soil characteristics, topography, vegetation, geology, and climate. These factors can favor erosive processes and their consequences on the quantity and quality of water (Paiva et al., 2022). Thus, new forms of territorial and water planning based on geomorphological, geological, pedological, climatological, land use, and land cover analyses gain relevance (Troleis & Silva, 2018).

With the advancement of geoprocessing, mathematical modeling can be developed in Geographic Information Systems (GIS), allowing the discrimination of landscapes to assist in decision-making. The Universal Soil Loss Equation (USLE), the Potential Erosion Method (EPM), and the Soil and Water Assessment Tool (SWAT) have been developed to quantitatively estimate the annual soil loss in a region for each point in watersheds (Pham et al., 2018), although they have some limitations. On the other hand, the ecological zoning methodology proposed by Crepani et al. (2001) is capable of determining the natural susceptibility to erosion through qualitative analysis of climate, geomorphology, geology, pedology, and land use and land cover. This may be sufficient to identify the priority of certain areas for erosion control actions, such as reforestation.

However, quantifying vulnerability is not a simple task as it is not reduced to a single metric and involves the quality of the data used, as well as the perceptions and preferences of decision-makers (Souza et al., 2019). Maps can vary in detail depending on the intensity of fieldwork and their scale. Exploratory maps, such as soil maps developed by the RADAMBRASIL Project between 1973 and 1987, are based on the interpretation of semi-controlled radar image mosaics and fieldwork. These products are useful for a preliminary assessment of soil potential and also serve for the planning of the development of pioneering regions. Thus, diagnostics enable the spatialization of regions susceptible to environmental damage under conditions that threaten public health and environmental quality. When addressing the occurrence of natural processes based on probability classes, they indicate natural susceptibility. Meanwhile, studies addressing environmental vulnerability indicate the fragility of the environment in the face of anthropogenic actions.

In the face of this scenario, environmental agencies linked to public administration in each country have already begun to take action, demanding mitigation of environmental damage caused by anthropogenic land uses, such as fencing off protected areas and reforestation. In this context, environmental management and planning are essential tools for controlling this imbalance. With the aim of mitigating the impact of these activities, various institutions have sought to establish models for land use and regional development. Therefore, this article results from research supported by the Ministry of Integration and Regional Development (MIDR) and aims to identify areas vulnerable to soil loss in the Potengi River Watershed, in order to direct efforts towards Recovery of Degraded Areas (RAD) and demonstrate the efficiency of the environmental modeling methodology. Despite the quantity of academic work related to this watershed, no research was identified with the perspective of identifying priority areas for recovery.

Methodology

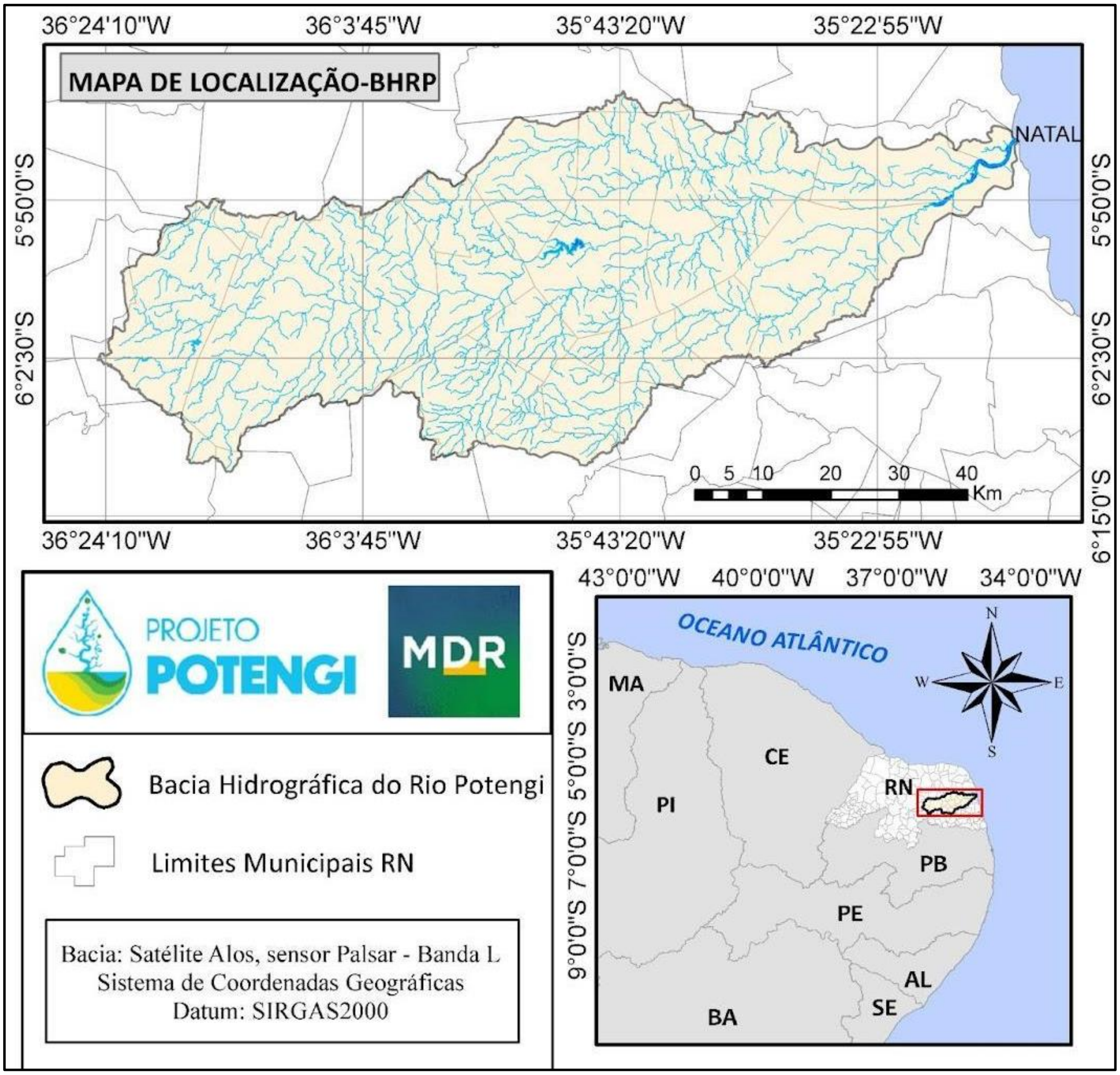
The Potengi River Watershed (BHRP) comprises 4,170 km^2, covering 25 municipalities in the state of Rio Grande do Norte. As one of the most important basins in the state, and with its main course, the Potengi River, intersecting the state capital and encompassing various significant activities (agriculture, livestock farming, extractivism, shrimp farming, fishing, commerce, transportation, industry, wind energy generation, tourism, religious events, the shipyard of the Brazilian Navy, and the Sewage Treatment Plant (ETE) of the Water and Sewer Company of RN (CAERN)), it is understood that there is a possibility of the existence of areas in the process of degradation. Therefore, these areas should be the focus of recovery actions to improve/maintain the socio-environmental condition of the watershed (Figure 1).

Among the rivers that make up the Potengi River Watershed (BHRP), only 144.81 km are perennial, while intermittent rivers total 2,559.23 km due to the semi-arid geological substrate and rainfall regime of the region. As for the sources of the Potengi River, they amount to 427, with its main source located in the municipality of Cerro-Corá, using the first-order channels mapped by the National Water Agency (ANA) as a reference. All these characteristics result in 323 ha designated as Permanent Preservation Area (APP) for springs, 3,546 ha of APP related to water bodies, and 19,329 ha of APP related to watercourses.

The Potengi River Watershed (BHRP) falls under a tropical climate, with irregular rainfall distribution to the west of the basin, ranging between 450 mm and 1,700 mm per year. The highest rainfall indices are located in municipalities along the coastal area, where maritime and terrestrial breezes influence a pronounced probability of rainfall. However, in the hot and semi-arid climate, where the Intertropical Convergence Zone (ITCZ) and upper-level cyclonic vortices (VCAN) are predominant, the western part of the basin experiences the lowest annual precipitation average, concentrated in three rainy months, resulting in increased rainfall intensity in the region.

Figure 1

Map of the location of the Potengi River watershed



Source: Produced by the authors.

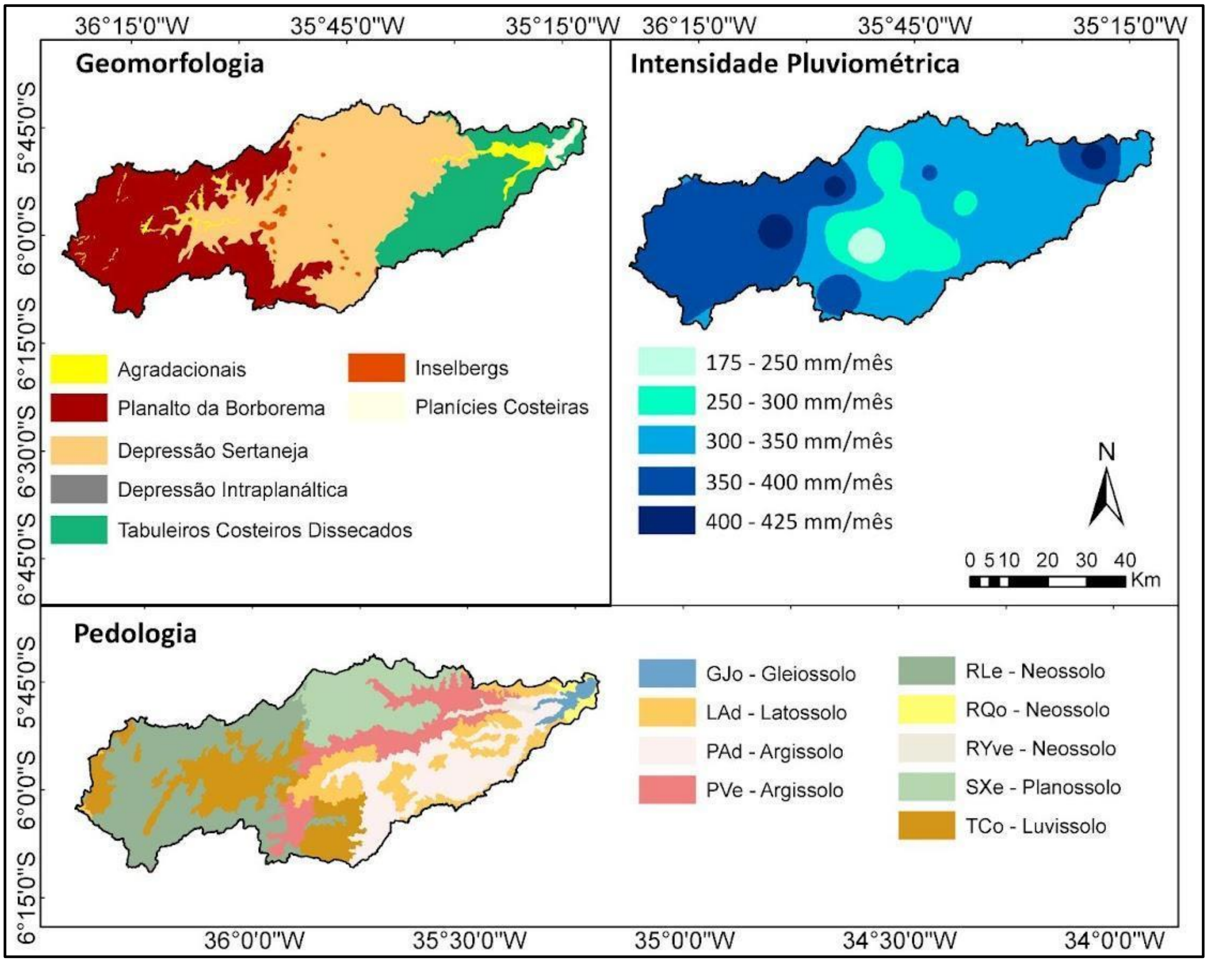
Rainfall data were collected from the EMPARN website (2022) for the 17 stations located in the municipalities within the watershed area, considering the period between 2001 and 2021. Based on this, it was possible to establish the number of rainy days, considering a rainy day as one with precipitation greater than 1 mm. Subsequently, data interpolation was performed to generate the thematic map. In Figure 2, rainfall intensity data are presented for a

20-year time scale (2001 – 2021), along with geomorphology and soil types that make up the study area.

The regional geomorphology comprises morpho-sculptural subunits of the territory of Rio Grande do Norte and reflects three evolution events: the Brasiliano Orogeny, the fragmentation of the Gondwana Megacontinent, and Cenozoic tectonic reactivations (Diniz et al., 2017). The Sertaneja Depression corresponds to the flattened areas of the Brasiliano Belt, marked by pronounced dissection processes. The Borborema Plateau consists of a set of highlands with rugged relief, intensely dissected (Corrêa et al., 2010). To the west of the watershed, the division between these two morpho-sculptures is observed. The coastal basins to the east of the basin were covered by sediment deposits derived from the relief dissection process of the inland crystalline terrains, and the Coastal Plateaus evolved overlying the sandstones of the Barreiras Formation, Açu Formation, and Jandaíra Formation with flattened reliefs. Finally, at the extreme east of the basin, there is the aggradational terrain of the Fluvial and Coastal Plains, composed of continental sediments formed by the direct action of coastal marine processes.

Figure 2

Spatialization of Geomorphology, Pedology, and Rainfall



Source: Produced by the authors.

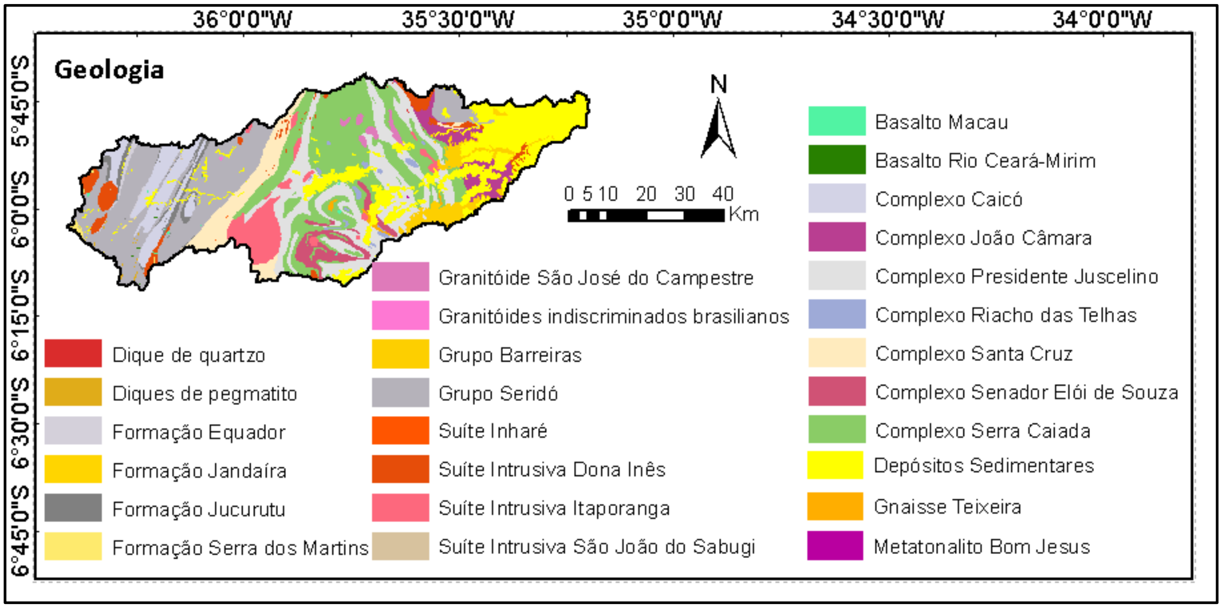
According to the methodology of Crepani et al. (2001), geomorphological characteristics were represented by the arithmetic mean of slope, interfluve width, and altimetric range. Based on the DEM (Digital Elevation Model), the Slope tool was applied to determine the slope of the Potengi River Watershed (BHRP). Next, using the automatic method (Guimarães et al., 2017), the interfluve width and altimetric range of each section of the study area were determined, and the representation of this information plane (PI) was obtained.

The Pedology of the Potengi River Watershed (BHRP) consists of nine soil types. Argisols are located in the central and eastern parts of the watershed, with sandy and clayey textures and drainage decreasing in their B horizon, possessing high natural fertility due to the dynamics of their composition. Gleissols are periodically saturated with water as they are located at the mouth of the Potengi River. To the west of the watershed, there are Latosols, clayey, and Luvisols, shallow and stony, in areas with water restrictions. Throughout the watershed, Neosols and Planosols are distributed; under semi-arid climate conditions, they remain shallow and are composed of clays. This information was georeferenced by the RADAMBRASIL project and made available by the Brazilian Institute of Geography and Statistics (IBGE).

To the west of the watershed are the complexes Presidente Juscelino Serra Caiada, Caicó, Santa Cruz, and intrusive suites Itaporanga, Dona Inês, São João do Sabugi, and Inharé, consisting of intensely fractured gneisses and migmatites. We can also find the Equador, Jucurutu, and Seridó formations to the west, consisting of biotites, amphiboles, and metamorphosed marbles from low to high grade (Figure 3). There are also undifferentiated Brasilian Granitoids, consisting of diorites, the Rio Ceará-Mirim and Macau Basalts, consisting of diabase and basalt, the Serra dos Martins formation, and, along with alluvial deposits, are composed of sandstone and unconsolidated sediments. To the east of the watershed, we observe the Jandaíra formation, composed of calcarenites. The Barreiras Group and alluvial deposits consist of quartz sediments. Therefore, near the coast to the east, sedimentary rocks predominate, while to the west, igneous rocks prevail.

Figure 3

Espacialização da Geologia da BHRP



Source: Produced by the authors.

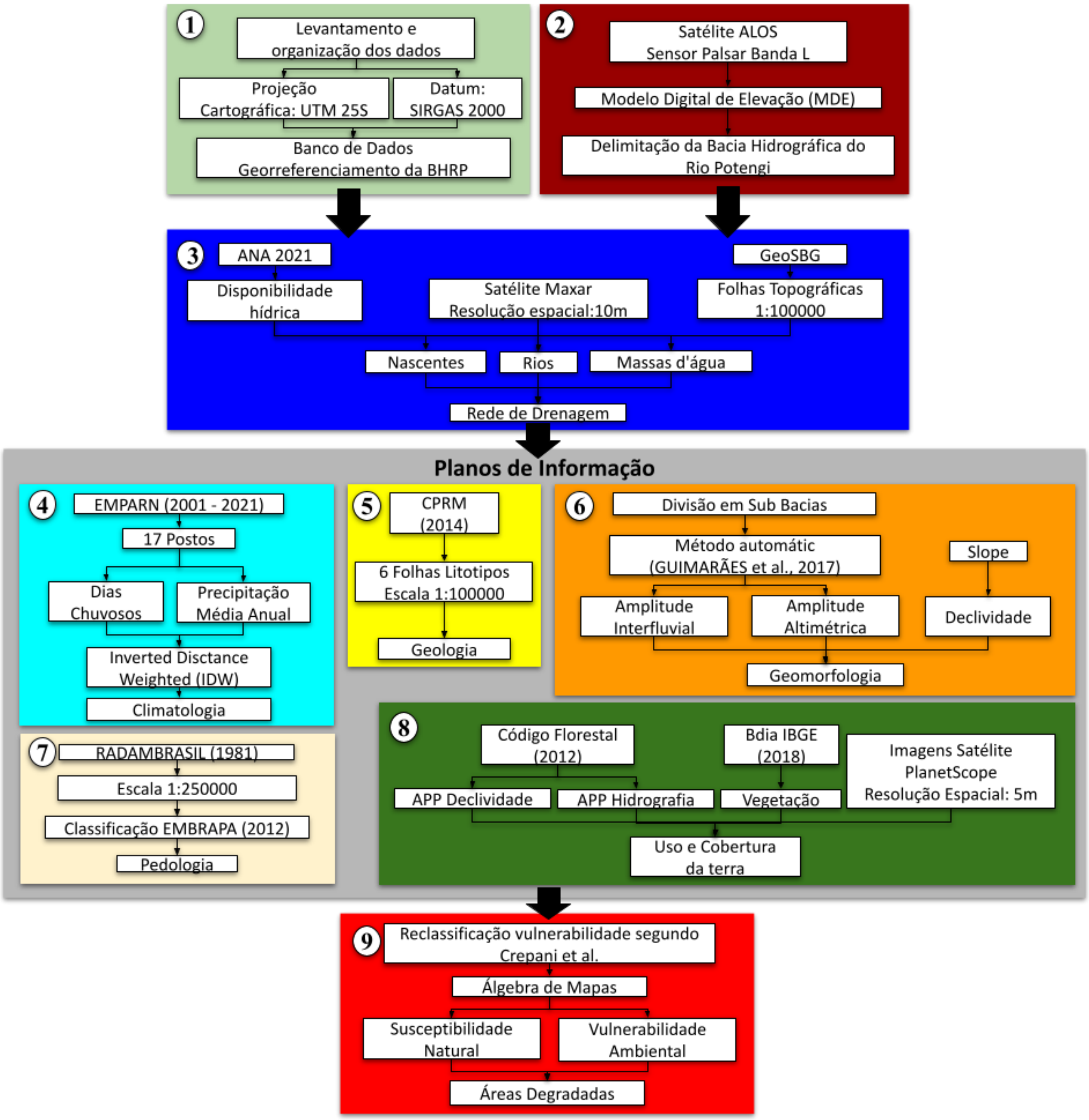
For the elaboration of the land cover and land use map, photointerpretation of Planet Scope satellite images from April 2022 was conducted. The images correspond to the PS2:SD sensor with a spatial resolution of 5 m and a scale of 1:25,000. A Red-Green-Blue (RGB - 123) color system composition was used to separate natural and anthropogenic interference regions. Through the photointerpretation of images and the Environmental Information Bank (BdiA) of the Brazilian Institute of Geography and Statistics (IBGE), it was possible to delineate four vegetation formations - wooded steppe-savanna, forested steppe-savanna, park-like steppe-savanna, and pioneer formation with fluvio-marine influence. Additionally, areas designated for cultivation, livestock farming, mining, and urbanized areas were distinguished.

After the collection and processing of georeferenced data, integration and modeling procedures were applied, following the flowchart in Figure 4, with the aim of identifying areas most vulnerable to erosion. The data were manipulated using the Sirgas 2000 Datum in UTM coordinates, zone 25S, and the watershed delineation was based on the Digital Elevation Model

(DEM) from the ALOS satellite, from the Japan Aerospace Exploration Agency (JAXA) - PALSAR sensor, which has a spatial resolution of 12.5 x 12.5 meters (ASF, 2015).

Figure 4

The methodology used for the environmental modeling of the BHRP



Source: Produced by the authors.

The environmental modeling of the watershed was carried out using multicriteria analysis based on map algebra and paired linear combination. In a GIS environment with the assistance of ARCMAP 10.8 software, an adaptation of Crepani et al.'s (2001) ecological zoning proposal was executed. Geodata used are presented in Table 1.

Table 1

Geographic database

Information	Description	Source	Spatial Resolution/ Scale
Digital Elevation Model (DEM)	Slope/ Basin Delineation	JAXA/METI (2010)	12,5m
Climatology	Rainfall Stations (Historical Series 2001-2021).	EMPARN(2022)	1:100.000
Geology	Union of six geological sheets	Geo SGB/CPRM(2014)	
Pedology	RADAMBRASIL Mapping	Adapted pelo IBGE (2017)	1:250.000
Geomorfology	Potiguar Morphostructures	DINIZ et al. (2017)	
Land Cover	Photointerpretation of satellite images from April 2022	Satellite: PlanetScope; Sensor PS2: SD; Bands: 1,2 e 3.	5m

Source: Produced by the authors.

Subsequently, they were weighted and classified according to the following criteria:

- **Pedology -** Classified based on the degree of soil maturation and stability, ranging from Latosols (1.0) to Neosols (3.0) in increasing order
- **Geology -** Classified based on the degree of rock cohesion, ranging from Quartzite and gneiss (1.0) to Sand and Clay (3.0) in increasing order

- **Climatology -** Classified based on rainfall intensity (mm/month), ranging from 175 mm/month (1.5) to 425 mm/month (2.6) in increasing order.
- **Geomorfology -** Classified based on the arithmetic mean of the values assigned to slope, altimetric range, and interfluve width. Vulnerability to soil loss is proportional to slope and altimetric range and inversely proportional to interfluve width..
- **Land Cover and Use -** Classified based on vegetation cover density for natural susceptibility and soil exposure for environmental vulnerability. Ranging from Woody steppe (1.0) to bare areas (3.0) in increasing order.

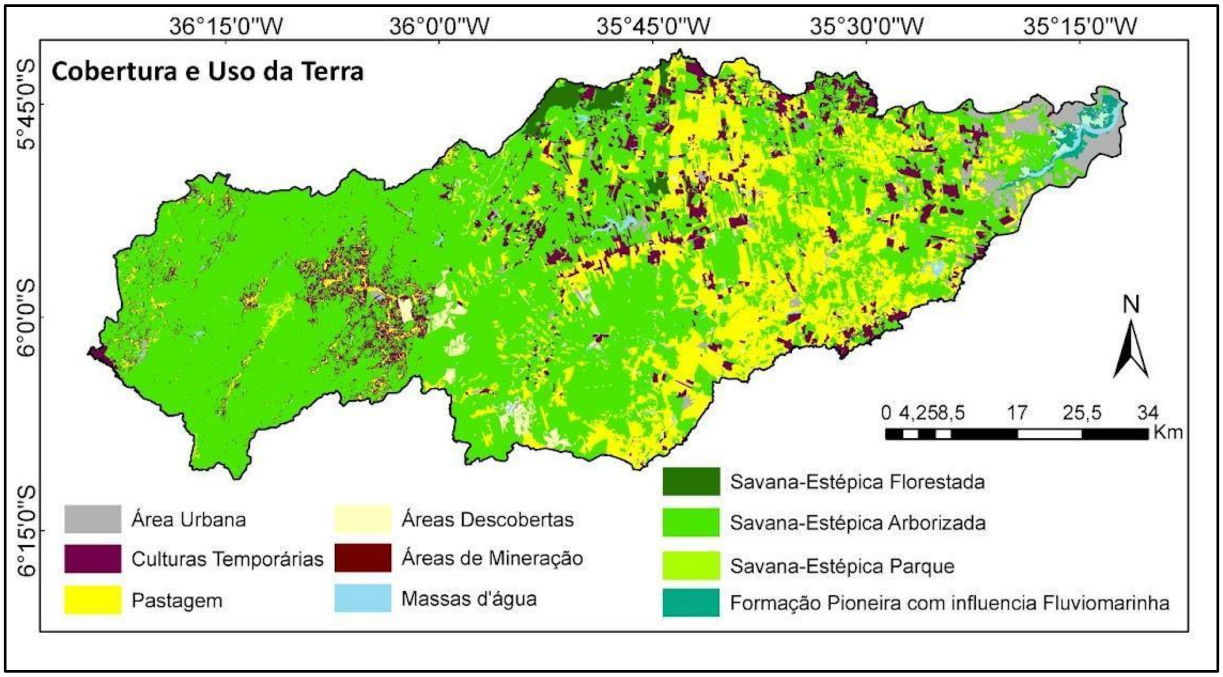
Results e Discussion

The land cover and use map (Figure 5) reveals that 2.74% of the area is occupied by urban zones, 20.81% by livestock farming, 8.45% by agriculture, and 0.03% by mineral extraction. Approximately 65.16% is covered by vegetation, predominantly composed of wooded steppe-savanna. This is a caatinga vegetation consisting of species with an average height of up to 2 meters, more or less dense, with thick trunks and branched branching, exhibiting specimens near the banks of rivers, with a forest-like character (Silva & Farias, 2019).

Another important factor to be considered in the watershed context relates to the agricultural sector, classified as the most significant in most municipalities within the watershed. Activities carried out by the agricultural sector can negatively impact the landscape, as they involve the use of large land and water expanses. It was observed that livestock farming is concentrated mainly in the Middle and Lower Courses of the BHRP, totaling approximately 86,800.68 hectares. The Upper Course region of the watershed presents more conserved areas. Additionally, there is a presence of both permanent (640.98 hectares) and temporary crops (34,586.66 hectares) along all courses of the watershed, along with bare areas, mainly located in the middle course. Although only 1.55% of the watershed area has exposed soil, this number represents 6,451.18 hectares of land susceptible to erosion.

Figure 5

Land Cover and Use Map of the BHRP



Source: Produced by the authors.

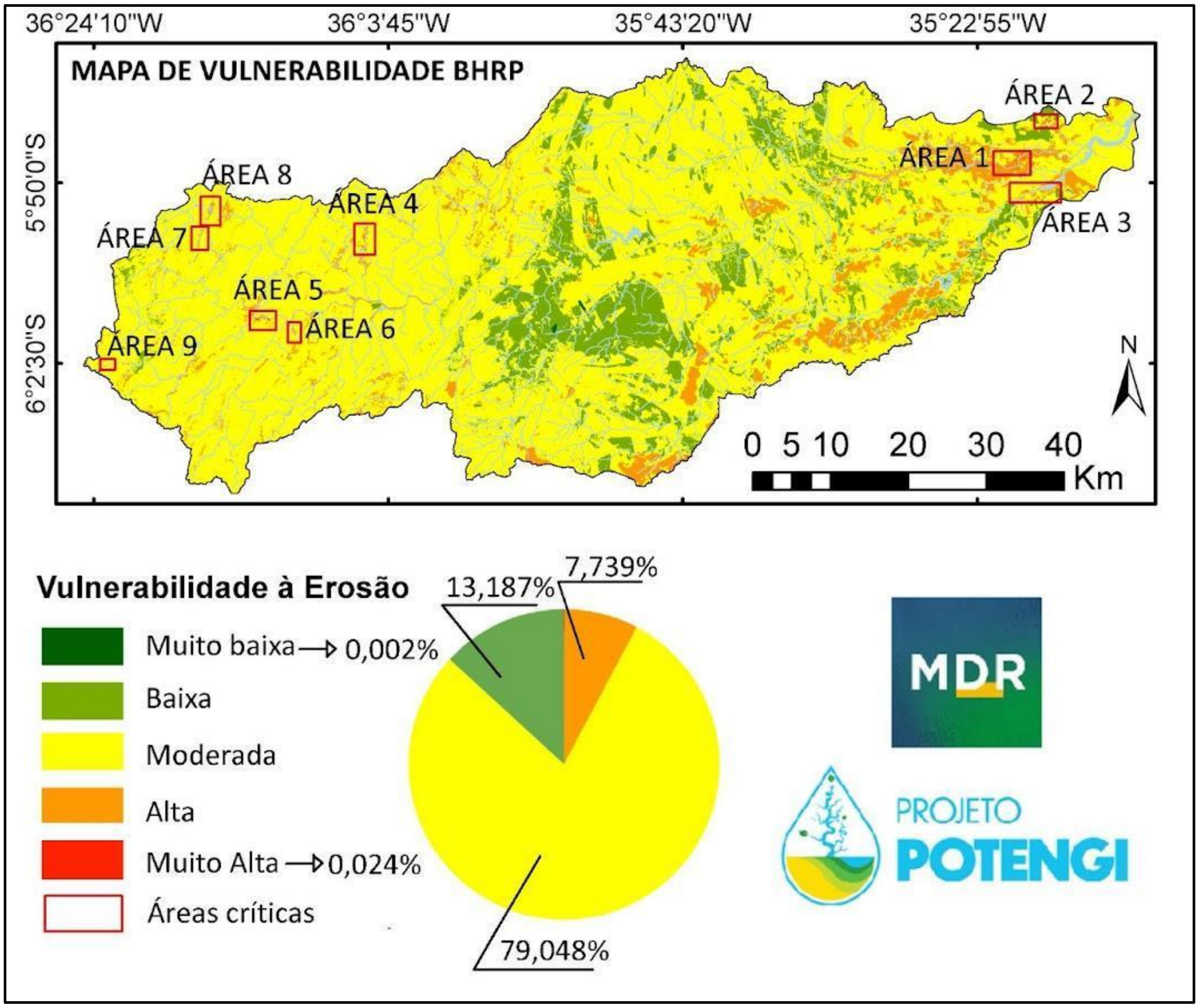
The multicriteria analysis resulted in the erosion vulnerability map represented in Figure 6, where vulnerability was considered very low in the range (1 to 1.3), low (1.4 to 1.7), moderate (1.8 to 2.3), high (2.4 to 2.6), and very high (2.7 to 3.0).

It was observed that areas classified with very low vulnerability, corresponding to 0.07 km² (0.002%), are located near the President Juscelino Complex, consisting of gneisses, Yellow Latosols, and always covered by wooded steppe-savanna, a factor that hinders erosion. Additionally, they are in a zone of low rainfall intensity, characteristics that contribute to the protection of the soil surface.

The class of moderate vulnerability was more representative, corresponding to 3,174.47 km² (79.05%) of the area. This is due to the predominance of Luvissols and Planosols under moderate rainfall intensities ranging between 300 mm/month and 400 mm/month. Even though these soils have high erodibility, they are predominantly covered by wooded steppe-savanna and have low slopes (<6%), factors that resist soil loss. These areas are extensively used for extensive livestock farming, involving the removal of natural vegetation to provide pasture for animals, resulting in increased soil exposure to erosive agents such as rain and wind. The soil compaction from animal trampling can also reduce the soil's water retention capacity and affect plant growth and vegetation diversity (Thomaz & Dias, 2009). Additionally, due to the watershed being under the influence of a semi-arid tropical climate, with short rainy periods, high intensities can have a significant erosive capacity on the dry soils of the semi-arid region (Almeida et al., 2015).

Figure 6

Erosion Vulnerability Map of the BHRP



Source: Produced by the authors.

The high and very high vulnerability classes (2.3 to 3.0) deserve greater attention. They are located in the eastern, southeastern, and western portions of the watershed, representing approximately 311.77 km² (7.76%). These areas experience high rainfall intensity (between 350 mm/month and 420 mm/month), high degrees of human impact from agriculture and pasture, combined with geology and pedology of sedimentary deposits and neosols. However, the erosive process tends to be delayed in the eastern part of the watershed due to the low slope typical of sedimentary terrains originating from the Barreiras Formation, even though they are composed of neosols that favor erosive processes.

The most critical regions are located in the northern part of Cerro Corá, north and west of São Tomé, central and northeast of São Gonçalo do Amarante, and northeast of Macaíba, as can be seen in Figure 7. In these locations, higher vulnerability values (2.7 - very high) prevail. A total of nine Critical Areas were identified, whose characteristics favor land degradation, making them potential areas for recovery.

Critical Area 1 is located in the center of the municipality of São Gonçalo do Amarante. It encompasses approximately 1,709 hectares of land classified as having high vulnerability and 45 hectares with very high vulnerability. This region is intersected by the RN-160 highway and the Potengi River. Geologically, the area is situated in alluvial deposits where soils of the types Fluvic Neosols and Thiomorphic Gleysols have developed. Critical Area 2 is also located in the same municipality and totals 72 hectares of land classified as having high vulnerability and 2 hectares with very high vulnerability. The geology is characterized by marine deposits and alluvial deposits, where Quartzarenic Neosols have developed. Both areas are used for extensive livestock farming (pasture), temporary crops, and sand and clay extraction from the river.

Critical Area 3 is located northeast of the municipality of Macaíba. It consists of an area of approximately 162 hectares with high vulnerability and 2 hectares with very high vulnerability, along the banks of the Jundiaí River and BR-226. The geology of the area is composed of fluvio-marine deposits and outcrops of the Barreiras Group. The soil is classified as Thiomorphic Gleysols. It was observed that the soil is used for pasture, but most of the vulnerable areas are in regions vegetated by Arboreal Steppe vegetation, which have some cleared areas for sand extraction in the municipality.

Critical Area 4 is located in the northern region of the municipality of São Tomé. It consists of an area of approximately 78 hectares classified as high vulnerability and 3 hectares considered to have very high vulnerability. In this locality, the mapped geology indicates the presence of alluvial deposits. The predominant soils are of the Litholic Neosol type. They are used for pasture and small subsistence crops.

Critical Areas 5 and 6 are located in the central-western part of the municipality of São Tomé, with the first being intercepted by RN-203, along the banks of the Potengi River, and the second near an unnamed river, southeast of Area 5. It consists of approximately 127 hectares classified as high vulnerability and 24 hectares as very high vulnerability. Geologically, there are alluvial deposits and the development of Litholic Neosols in greater proportion. In these locations, the soil is used for pasture.

Critical Areas 7 and 8 are located in the northern region of the municipality of Cerro Corá, being intersected by dirt roads, near RN-104, along the banks of Riacho Chapador, and close to the Santa Rosa Mundo Novo Wind Park. Together, they cover approximately 159 hectares categorized as high vulnerability and 16 hectares as very high vulnerability. Geologically, there are alluvial deposits, and the soils are classified as Litholic Neosols, being used for pasture.

Finally, Critical Area 9 is located in the region of the municipality of Cerro Corá, encompassing the source of the Potengi River. It is an area of approximately 1.08 hectares classified as high vulnerability, located in the Chã da Divisão Site.

Figure 7

Validation of critical areas. (a) Area 1: downtown São Gonçalo do Amarante municipality; (b) Area 2: north of São Gonçalo do Amarante municipality; (c) Area 3: downtown Macaíba municipality; (d) Area 4: north of São Tomé municipality; (e) Area 5: downtown São Tomé municipality; (f) Area 6: downtown São Tomé municipality; (g) Area 7: north of Cerro Corá municipality; (h) Area 8: north of Cerro Corá municipality; (i) Area 9: Potengi River source.io Potengi.

Source: Produced by the authors.

It has been observed that this area has been undergoing a pronounced degradation process, especially during the dry season when the perennial spring locations are invaded by cattle in search of water. The lack of control over cattle access leads to soil trampling, resulting in soil compaction and destruction of the vegetation cover in the Permanent Preservation Area (APP) of the spring, making it susceptible to degradation. In addition to being a tourist attraction (a geosite of the Seridó Geopark), the area is frequently visited without proper access control and time restrictions, making the spring region more vulnerable to degradation. The geology of the aforementioned locality is composed of fractured sandstones from the Serra dos Martins Formation, where Chromic Luvisols are developed, and it has a steep slope.

In light of the above, it is understood that in areas classified with a moderate or higher vulnerability class, preventive actions such as the implementation of conservation practices that do not significantly impact farmer production, and the conservationist management of crops, can reduce a considerable portion of erosion caused by surface runoff (Guerra & Jorge, 2013). Examples of such practices include herbaceous cover and legumes in rotation with crops, crops on contour lines, terracing, and no-till farming, which protects soils from the direct impact of raindrops.

As highlighted by Kim et al. (2018), forests provide ecosystem services and play an irreplaceable role in cultural services, hydrological regulation, and biodiversity conservation. Therefore, reforestation is the most efficient way to enhance key services of vegetation cover, reinforcing soil conservation (Xu et al., 2022). Planting native forests improves nutrient cycling, increases water infiltration into the soil, reduces surface runoff, alters land cover and use, restores soil, and regulates water (with gains in both quality and quantity) (Teng et al., 2019). Moreover, it generates employment and income in rural areas by providing products such as timber, fruits, oils, essences, and nuts, thus reducing the demand for extraction from native forests.

Reforestation includes the implementation of forest bans, that is, the isolation of the area to promote natural or accelerated regeneration of vegetation cover (Li et al., 2016). However, local families that interact directly with ecosystems and the sustainability of reforestation can be negatively affected due to differences in interests between decision-makers and families (Li et al., 2020).

In Figure 8b, there is an area of permanent preservation (APP) located in the upper course of the basin being used for agricultural practices. This situation was observed in various points of BHRP in more humid regions, directly in the riverbed and/or APP due to the lack of rainfall in the region. If these areas are designated for reforestation, the income of families decreases drastically unless some auxiliary measures, such as providing water for irrigation with a motor pump and piping, are implemented. Therefore, the involvement of local residents should be considered in the process of restoring and protecting forests, which can help promote sustainable development and spread environmental education.

In this sense, it is emphasized the need for the recovery of degraded areas in these environments, as they are essential for maintaining the environmental services provided and, consequently, for preserving the water quality of the watershed and recharging aquifers.

Isolating areas (fencing) from extensive livestock farming, combined with reforestation measures, should be implemented to reduce erosion, ensure soil stability, and decrease surface runoff. This can also filter water pollutants, improve water quality, and regulate water flow in watersheds, including during dry periods (Morgan, 2005). Additionally, creating ecological parks for tourism or agroforestry may provide habitat for local fauna and areas for recreation and tourism for the population, helping to preserve biodiversity and ecosystem services.

Therefore, it is recommended that restoration efforts focus on forest quality and habitat improvement, as well as the establishment of new reforestation when appropriate. Additionally, the government should provide sustainable and evidence-based ecological subsidies to assist residents in obtaining alternative livelihoods to activities contributing to poverty. Large-scale reforestation brings a disadvantage, the livelihoods of affected families (Xu et al., 2022). While there is an overall improvement in the quality of life for families, the existence of financial inequalities and imbalances in attitudes between residents and decision-makers can impact the sustainability of benefits. Because of this, the initial cost of easing subsistence activities and the loss of cultivated land may be higher than the ecological subsidies provided by the government, and participation in reforestation may not yield immediate net benefits for families.

Despite the qualitative nature of the methodology, the results are consistent with those found in other methodologies and previous research conducted in different locations (Santos et al., 2013; Xavier et al., 2018; Silva & Farias, 2019) and are reliable due to on-site validation. Field observations satisfied the accuracy of the environmental model developed. However, there are also deficiencies in the study. There is evidence that the neosols of alluvial deposits have largely been transported by water flow, and the areas identified as critical and vulnerable to soil loss have few pedological characteristics from the RADAMBRASIL Project survey, supporting the hypothesis that they are easily erodible and very shallow.

The methodology proved to be efficient in indicating degraded areas, as they are naturally susceptible to erosive processes, and due to anthropogenic presence with agricultural and livestock activities, the degradation process has already been initiated. Although the information plans used require periodic updates, the climatic and land cover/use information used appeared to be up-to-date. The process of geomorphological modification is slow, so the lack of updating of this information plan did not significantly impact the results. However, there was a need for more detailed information on Geology and Pedology to refine the obtained results, as these were the most decisive factors that increased the vulnerability value. Discrepancies were observed between the geological formations presented on the maps (1:100,000) and those observed in the field; this is mainly due to the regional scale of the geological maps.

Conclusion

The zoning of vulnerability to erosion and soil loss developed for BHRP identified nine critical areas that require immediate action. Only with a joint effort from government agencies, local communities, and organized civil society will it be possible to ensure the conservation of natural resources (soil and water) for future generations. Urgent mitigating measures are needed to reduce the annual soil loss exposure, especially since these areas are located in riparian zones and at the sources of the hydrographic network.

In this scenario, it is essential to implement effective measures to minimize the impacts of erosion and soil loss. Promoting environmental education among local communities is necessary, encouraging sustainable land use practices and the responsible utilization of natural resources. Additionally, investing in bioengineering techniques and appropriate infrastructure to protect riverbanks and control erosion is crucial. Therefore, it is suggested to restore the most critical areas through reforestation, accompanied by ongoing support for the families affected by these interventions. This aims to clarify the long-term impacts of reforestation on their livelihoods. Moreover, incorporating other quantitative methodologies within a GIS environment and in situ, considering the aspects of climate change, is necessary to estimate the potential soil loss in the basin, refining the environmental modeling process.

The integration of mapped information and in situ analyses was crucial for evaluating the efficiency of the modeling and guiding the recovery actions for degraded areas in the BHRP. However, the challenge of convincing owners of critical areas to adopt conservation practices persists due to the lack of immediate financial return and the significance of these lands for agriculture and pasture in the semi-arid region. In this context, the implementation of a Payment for Environmental Services (PES) program and the establishment of a bank of priority areas can incentivize the conservation of water resources and environmental protection, contributing to sustainable development in the region.

It is also noteworthy to integrate information identifying the most vulnerable areas through Geographic Information Systems (GIS) with in situ analyses confirming environmental degradation. While a more detailed survey is necessary to improve the accuracy of the modeling, the study managed to assess the efficiency of the model and guide actions for the recovery of degraded areas in the BHRP to mitigate the qualitatively identified erosive processes.

However, it is necessary to overcome the difficulty of persuading the owners of critical areas to protect and improve land management. Often, these areas are alluvial lands and represent the only suitable wetland for agriculture and pasture in the semi-arid region. Additionally, landowners do not see a financial return in protecting these areas.

A viable solution to address this issue is the implementation of Payment for Environmental Services (PSA). This mechanism aims to encourage rural landowners and local communities to adopt sustainable environmental conservation practices. Through PSA, those responsible for preserving and restoring degraded areas can receive financial compensation or benefits in exchange for the ecosystem services provided, such as the protection of water resources.

Additionally, the creation of a bank of available and priority areas for preservation can be an effective strategy. This bank would be responsible for identifying and cataloging suitable areas for vegetation compensation, which could be used by enterprises needing to offset the environmental impacts of their activities. This way, it is possible to direct these enterprises to specific areas, ensuring the conservation of ecosystems and the maintenance of environmental services.

These combined measures - the implementation of PSA and the creation of a bank of priority areas for preservation - can significantly contribute to the conservation of water resources, environmental protection, and sustainable development in the semi-arid region of Northeast Brazil.

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