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Environmental vulnerability in Permanent Preservation Areas (PPA) of the Potengi River Watershed, RN, Brazil

Vulnerabilidade ambiental em Áreas de Preservação Permanente (APP) da Bacia Hidrográfica do Rio Potengi, RN, Brasil

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Abstract: The Permanent Preservation Areas (PPA) are established by the Brazilian Forest Code, which sets the general rules for the exploitation of native vegetation and regulates the protection of certain land uses in recognized vulnerable areas. The purpose of this research is to evaluate the Environmental Vulnerability to soil loss in PPA areas in the Potengi River Watershed (PRW), Rio Grande do Norte (RN). In addition, it is intended to identify conflicts related to land use and occupation in order to validate three specific PPA in the field. The Environmental Vulnerability was classified in Geographic Information Systems (GIS) based on Multicriteria Analysis, using map algebra based on weighted linear combination. As a result, five vulnerability classes were obtained in the PPA: Very Low, Low, Moderate, High and Very High. The degrees of Moderate, High and Very High vulnerability added up to 83.73% of the total PPA areas. With regard to land use conflicts, the predominant activity found in areas of Very High vulnerability was pasture, representing 91.4% of these areas.

Keywords: Erosion; Water resources; Geotechnologies; Environmental Modeling.

Resumo: As Áreas de Preservação Permanente (APP) são estabelecidas pelo Código Florestal Brasileiro, que institui as regras gerais sobre a exploração da vegetação nativa e regulamenta a proteção a certos usos do solo em áreas de reconhecida vulnerabilidade. O objetivo desta pesquisa consiste em avaliar a Vulnerabilidade Ambiental à perda de solo em áreas de APP na Bacia Hidrográfica do Rio Potengi (BHRP), Rio Grande do Norte (RN). Além disso, pretende-se identificar os conflitos relacionados ao uso e ocupação do solo de forma a validar três áreas de APP específicas em campo. A Vulnerabilidade Ambiental foi classificada em Sistemas de Informação Geográfica (SIG) a partir de Análise Multicritério, sendo utilizada álgebra de mapas a partir de combinação linear ponderada. Como resultados, foram obtidas cinco classes de vulnerabilidade nas APP: Muito Baixa, Baixa, Moderada, Alta e Muito alta. Os graus de vulnerabilidade Moderada, Alta e Muito Alta somaram 83,73% do total de áreas de APP. Com relação aos conflitos de uso do solo, a atividade predominante encontrada nas áreas de vulnerabilidade Muito Alta foi a pastagem, representando 91,4% dessas áreas.

Palavras-chave: Erosão; Recursos Hídricos; Geotecnologias; Modelagem Ambiental.

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1. Introduction

Watersheds, for various reasons, play a significant role in providing ecosystem services essential for human development and survival. These services include the provision of food, water for human consumption, and animal hydration, as well as industrial use, irrigation, and other needs (LI *et al.*, 2021). Ecosystem services refer to the environment's ability to provide sufficient resources for a growing population (FEEN, 1996). Conversely, degraded areas compromise the delivery of these services. Understanding ecosystems from the perspective of humans as beneficiaries has enormous potential to protect environmentally sensitive areas and the services they provide (BRAUMAN *et al.*, 2007).

Changes in different environmental systems (soil, topography, climate, water resources, and geology) in conjunction with inefficient land use management in a watershed can lead to negative environmental effects, including erosive processes, desertification, and contamination of water resources, as well as stream sedimentation (SPORL; ROSS, 2004; ALEXANDRE *et al.*, 2016). A significant portion of environmental damage occurs in watersheds. Therefore, a thorough understanding of their formation, constitution, and dynamics in the face of constant urban/industrial and agricultural growth is essential. Territorial planning in these areas becomes crucial for monitoring potential negative impacts on water resources (GUERRA; JORGE, 2013; MORGAN, 2005).

To ensure the protection of water elements and control human activities/occupation, the new Brazilian Forest Code (CFB), Federal Law No. 12,261/2012 (BRASIL, 2012), is adopted as the main legal basis. It establishes concepts such as Legal Reserves (LR) and Permanent Preservation Areas (PPA), whether in springs, hilltops, areas with steep slopes, and other variants (HOENIG; CANDIOTTO, 2012). Thus, monitoring different land cover and land use forms in these areas is of utmost importance, as the soil is a non-renewable, constantly changing system susceptible to environmental impacts (SILVA; SILVA, A.J., 2017).

The PPA is defined as a protected area, covered or not by native vegetation, with the function of preserving water resources, landscape, genetic flow of fauna and flora, and protecting the soil. It is currently regulated by the New Brazilian Forest Code of 2012, which repeals Law No. 4,771/1965 (BRASIL, 2012; CASTRO; MAY; GARCIAS, 2018). It was initially conceptualized in Law No. 4,771/1965, although there were already traces of the importance of similar areas in what would become the first Brazilian Forest Code in Federal Decree No. 23,793, 1934 (GUIMARÃES; GUIMARÃES, R.B.; LEAL, 2015). The restriction strip is adjusted according to the size of water bodies or reservoirs, where the guidelines established by the Forest Code are of great environmental importance due to the disorderly growth of urbanized areas and unplanned changes in land use (CHIAVARI; LOPES, 2016; OLIVEIRA *et al.*, 2007).

The benefits of vegetative cover in PPA areas include erosion reduction, soil stability, decreased surface runoff, pollutant filtration, improved water quality, regulation of water flow in watersheds, including during dry periods, providing habitat, and social advantages for the population, such as recreational areas (MORGAN, 2005).

Despite all these importance, PPAs are sometimes not considered in territorial planning. This makes the watershed a fundamental territorial unit for defining strategies to establish protected areas around water bodies (SILVA *et al*., 2021; SCHULT *et al.*, 2013). Based on this assertion, watersheds can be approached as significant analytical units in environmental studies, enabling an understanding of the natural dynamics of their space on a large scale of complexity (GUERRA; JORGE, 2013; DICKEL; GODOY, 2016). Thus, the Potengi River Watershed (PRW), one of the main water sources in the state of Rio Grande do Norte (RN), emerges as a means to assess the vulnerability of PPAs, as such studies are essential for territorial planning to define guidelines and actions in physical-territorial spaces (SILVA; BACANI, 2017).

In assessing environmental vulnerability, erosion represents one of the most significant phenomena capable of contributing to the input of contaminants and sediments until reaching the estuary of its main river. The problems resulting from soil erosion include nutrient removal, reduced root penetration and consequent water storage, decreased agricultural and livestock areas, sedimentation of water bodies, floods by raising the peak flow of rivers, and pollution of water bodies, especially due to the transport of agrochemicals with eroded sediments (GUO *et al.*, 2019). Certain regions of the PRW, specifically in its western region, have soils more susceptible to water erosion, which is the main form of erosion responsible for the degradation of tropical soils (SANTOS; SCUDELARI, 2011; PINTO *et al.*, 2020).

Globally, the term environmental vulnerability can be understood as the susceptibility of a certain environmental system to undergo modifications (APS *et al.*, 2018; ZHAO *et al.*, 2018). Several authors have developed works on the theme of environmental vulnerability to soil loss (SOUZA *et al.*, 2020; SILVA; BACANI, 2017), either by adapting the proposal elaborated by Crepani *et al.* (2001) or by combining it with other methodologies for environmental fragility (ROSS, 1994; SPÖRL; ROSS, 2004) as used by Paiva *et al.*, 2022. The methodology adopted for this work was developed by Crepani *et al.* (2001), originally designed to support the Ecological Economic Zoning of the Amazon, by creating maps of natural vulnerability to soil loss through multicriteria analysis. It aims to highlight fragile and susceptible areas to erosive processes, serving as indicators of environmental fragility (ZAPAROLI; CREMON, 2010). The methodology is based on Tricart's Ecodynamic Theory (1997), which establishes ecodynamic units based on morphodynamics as a determining element and a gradation between pedogenesis and morphogenesis (TRICART, 1997; LIMA; SILVA, 2018).

Given this issue, geoprocessing, coupled with the use of remote sensing tools in Geographic Information Systems (GIS), becomes relevant for studying environmental vulnerability at the watershed level, with a focus on PPAs of the water bodies it comprises (GRIPP JUNIOR *et al.,* 2010; MACHADO *et al.,* 2017). In a GIS environment, multicriteria analysis combined with map algebra can aid in integrating geographical information and decision-makers' judgments, reducing the subjectivity of traditional methods and considering the effects of human action on land use (PIGA *et al.,* 2017; COSTA *et al.,* 2020). Considering that the current scenario in many Brazilian PPAs is one of intense degradation, multicriteria analysis has been used by various authors to assist in planning the restoration of these systems to their initial conditions, enabling them to fulfill their ecological function for which they were created (SARTORI; SILVA; ZIMBACK, 2012; URIBE; GENELETTI; CASTILLO, 2014; VALENTE; PETEAN; VETTORAZZI, 2017; SALOMÃO; PAULA; ELMIRO, 2020).

The present study aims to assess environmental vulnerability to soil loss in PPAs within the Potengi River Watershed (PRW), Rio Grande do Norte (RN), and identify conflicts related to land use and occupation in the watershed's PPAs. It is important to note that this work is the result of research conducted by the Federal University of Rio Grande do Norte (UFRN), funded by the Ministry of Integration and Regional Development (MIDR), with the goal of implementing actions to recover springs and degraded areas in the PRW, aiming to improve water availability.

2. Study Area

The PRW covers an area of 4,093 km², representing approximately 7.7% of the territory of Rio Grande do Norte (RN), and spans 25 municipalities in the state (SEMARH, 1998). The Potengi River, the water body that gives its name to the watershed, holds significant historical importance for the state, as it alludes to the "Rio Grande" in the state's name (TEIXEIRA, 2015). It is also crucial for various economic activities such as fishing, agriculture, and animal hydration. However, the river is in a state of vulnerability, exhibiting unpleasant organoleptic characteristics and undergoing various chemical and physical alterations in its natural attributes (TORRES *et al.*, 2019) (Figure 1).

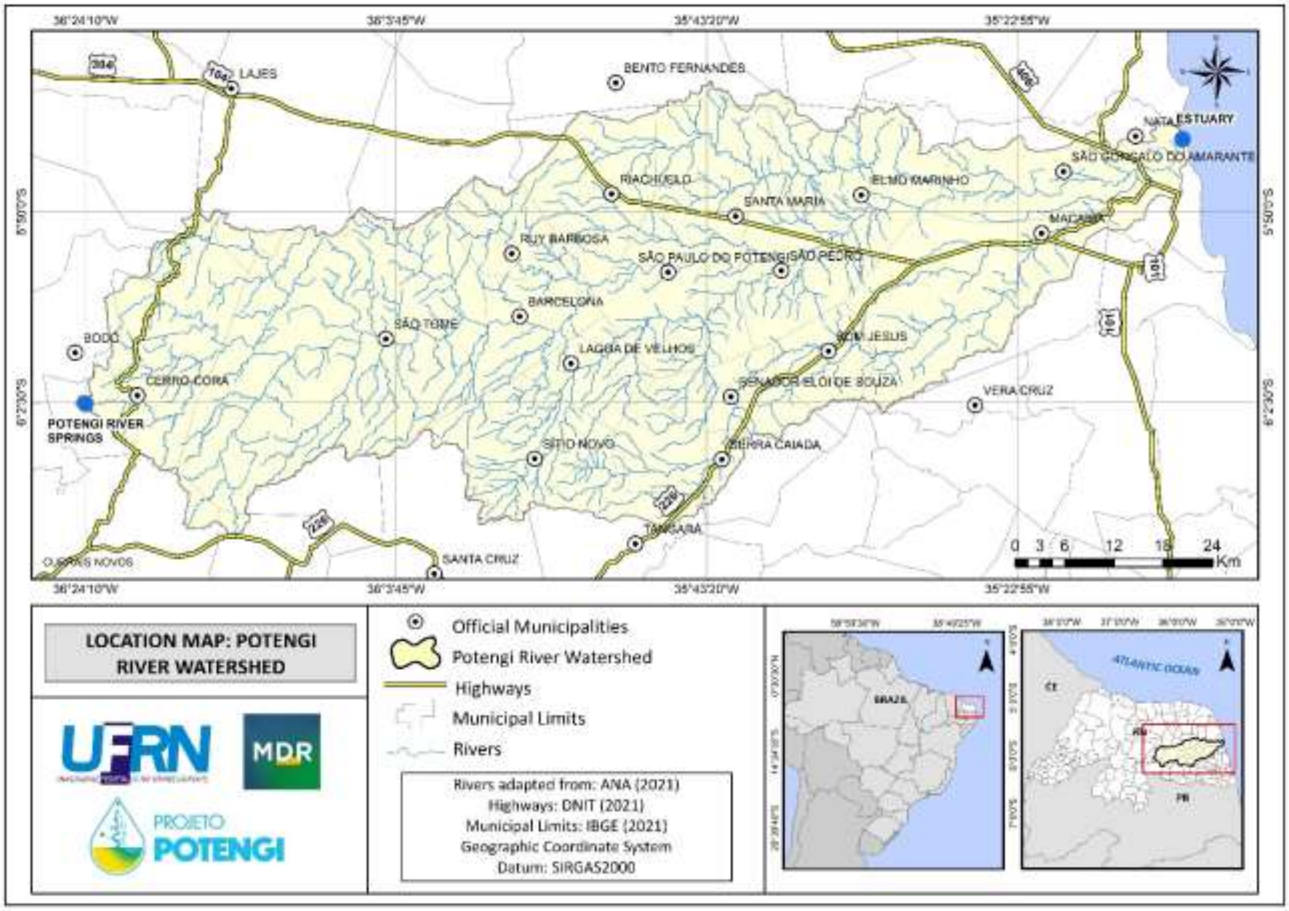

Figure 1 – Location map of the study area.
Source: Author (2022).

The Potengi River watershed is bordered to the north by the Ceará-Mirim River and Doce River watersheds, to the south by the Trairi River and Pirangi River watersheds, to the east by the Atlantic Ocean, and to the west by the Piranhas-Açu watershed. It exhibits a longitudinal characteristic, stretching from west to east for 135 km and from north to south for 50 km (SOUZA; AMORIM, 2022). The headwaters of the main river, the Potengi, are located in the central mountains of the state, in the municipality of Cerro Corá, with its mouth in the municipality of Natal (MIRANDA; FARIAS, 2021).

2.1 Climatology

Three climatic zones predominate in the PRW: tropical type As (with a dry summer) in the eastern portion of the study area, occurring mainly in the northeast of Brazil; predominantly semi-arid climate (zone B) type BSh in the middle course of the watershed, with an annual rainfall of less than 600 mm; and climate type BSw'h in the western portion of the watershed, with maximum precipitation in summer and a dry winter period (ÁLVARES *et al.*, 2014; KOPPEN, 1936). The Rainfall Intensity of the watershed (Figure 2 – A) was developed using data from 17 rainfall stations of the Agricultural and Livestock Research Company of Rio Grande do Norte (EMPARN) over a 21-year period (2001-2021).

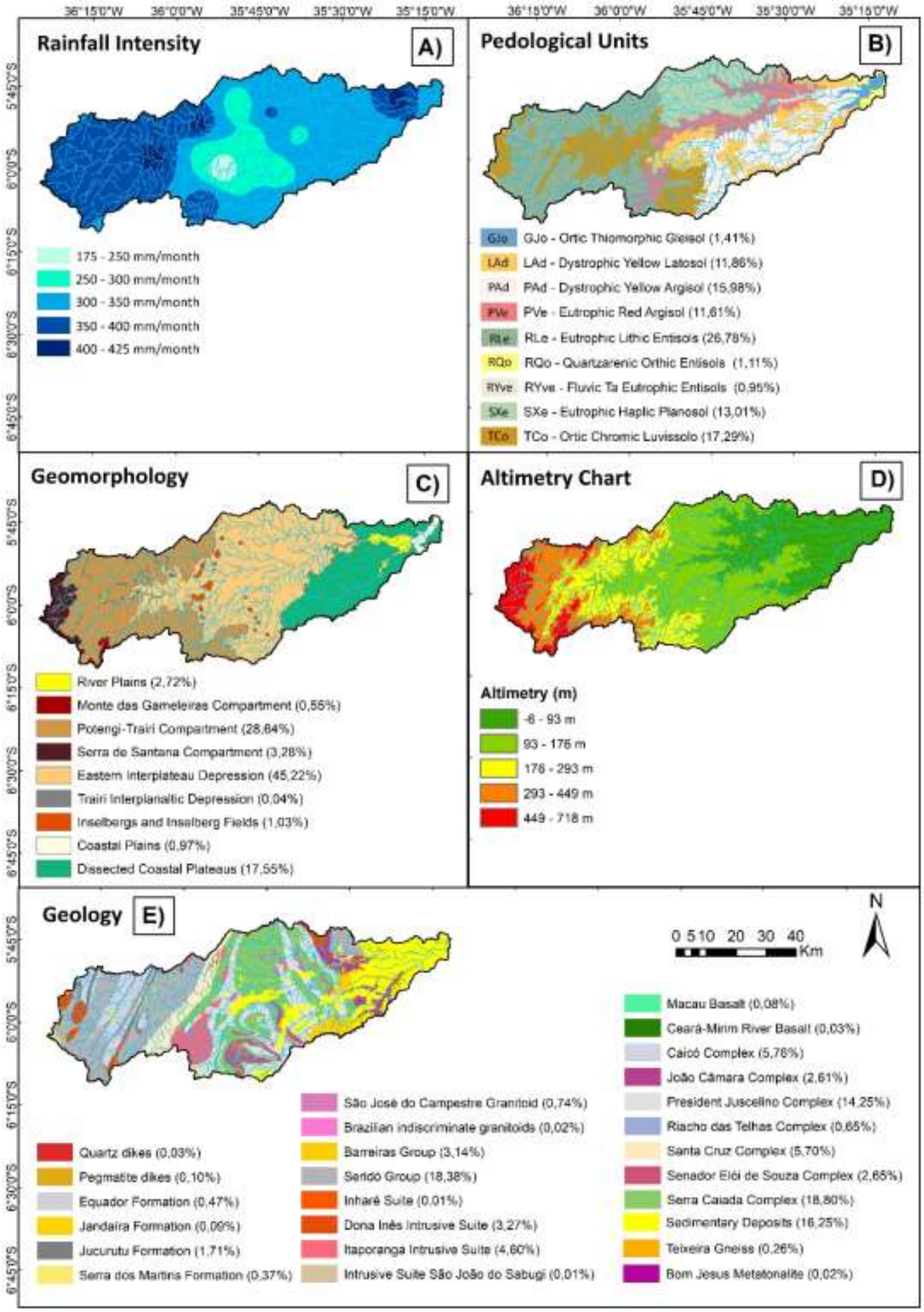

Figure 2 – Geo-environmental characteristics of the study area.
Source: Author (2022).

2.2 Pedology

Regarding Pedology (Figure 2-B), nine major soil groups were identified at the third categorical level, varying across four different orders: Gleissols, Oxisols, Ultisols, Entisols, Spodosols, and Alfisols (RADAMBRASIL, 1981). The PRW is predominantly composed of Entisols in its western and eastern portions, subdivided into Eutrophic Lithic Entisols (RLe), Quartzarenic Orthic Entisols (RQo), and Fluvic Ta Eutrophic Entisols (RYve), accounting for 26.78%, 1.11%, and 0.95% of the total area (4,093 km2), respectively. This order comprises soils characterized by a low intensity of pedogenetic processes and consists of minerals or organic material with less than 20 cm in thickness, a characteristic that significantly affects vegetation development and water flows in the profile (PEDRON *et al.*, 2010; EMBRAPA, 2018).

In the upper course of the PRW, along with the Eutrofic Lithic Entisols (RLe), the Chromic Orthic Luvisol (TCo) predominates, representing 17.29% of the total area. This major group has a textural B horizon, with high activity clay and high base saturation, typically shallow (no more than 1 meter of soil depth), characteristics justified by the scarcity of rainfall and climatic conditions (LIMA; SOUZA, 2016, EMBRAPA, 2018).

In the middle course of the watershed, the Eutrophic Haplic Planosol (SXe) stands out, occupying 13.01% of the PRW. The Planosol order is characterized by soils with mineral material in the A or E horizon, followed by a planic B horizon, with sandy/loamy and sandy/clayey textures (RADAMBRASIL, 1981; EMBRAPA, 2018). In the middle and lower course, there is the presence of the Dystrophic Yellow Latosol (LAd) (accounting for 11.86% of the total area). It is characterized by an advanced stage of weathering, with a latosolic B horizon and predominance of 1:1 clay minerals, typically poor in mineralogical composition and highly porous (RADAMBRASIL, 1981). Significantly, there is also the presence of the Eutrophic Red Argisol (PVe) and Dystrophic Yellow Argisol (PAd), representing 11.61% and 15.98% of the study area, respectively.

2.3 Relief and Altitude

For Geomorphology, regional taxonomic interpretations resulted in the geomorphological map (Figure 2-C) for the study area. In the PRW, three morphostructural units were identified: (i) the Brazilian Orogenic Belt, (ii) Marginal Sedimentary Basins, and (iii) Quaternary Sedimentary Covers, in addition to four morphosculptural units and nine morphosculptural subunits (DINIZ *et al.*, 2017). Nearly half of the total area of the watershed (46.25%), specifically in the middle course of the PRW, is formed by the Sertaneja Depression and its subunits: Eastern Interplateau Depression and Inselbergs. In Rio Grande do Norte, it is embedded in crystalline terrain (composed of igneous and metamorphic rocks), surrounding relief compartments and extending from the steep bases of plateaus (RADAMBRASIL, 1981; OLIVEIRA; CESTARO, 2016).

The lower course of the PRW is characterized by Dissected Coastal Plateaus, part of the Morphosculptural Unit Plateaus and Coastal Plateaus. Occupying 17.55% of the study area and surrounded in almost all quadrants by the Sertaneja Depression, it is considered one of the most significant orographic features in the Brazilian Northeast, directly influencing river distribution and regional climatic conditions (RADAMBRASIL, 1981; ALENCAR *et al.*, 2022). The remaining part of the watershed consists of the Eastern Interplateau Depression (middle course), Potengi-Trairi Compartment, and Serra de Santana (upper course). The altitude of the watershed (Figure 2-D) reaches a maximum peak of 718 m in regions of the upper course and a minimum of -6 m near the estuary of the basin.

2.4 Geology

The geology of the PRW (Figure 2-E) is, in general, composed of variations of crystalline rocks (igneous and metamorphic), sedimentary rocks, and sediment deposits. Different geological complexes, formations, and alluvial deposits can be identified, involving gneisses, migmatites, metamorphosed marbles, diorites, basalt, calcarenites, quartz sediments, among others. Among these elements, specific characteristics of sedimentation, metamorphism, intrusions, and extrusions can be identified, varying according to the nature of each geological formation (CPRM, 2006).

3. Methodology

The results for the PRW were generated using ArcGIS 10.8 and QGIS 3.22.7 (2022) software in the geographic coordinate system, SIRGAS2000 datum. The georeferenced geodata database used is presented in Table 1.

Table 1 – Geographic Database

<table>
<tr><th>Database</th><th>Descrição</th><th>Fonte</th><th>Escala/
resolução espacial</th></tr>
<tr><td>Topographic sheets</td><td>TIFF/SHP</td><td>SUDENE (1983)</td><td rowspan="3">1:100.000</td></tr>
<tr><td>Geology[1]</td><td>Geological sheets</td><td>CPRM (2012, 2013a, 2013b, 2016, 2018a, 2018b)</td></tr>
<tr><td rowspan="3">Hydrographic Network</td><td rowspan="3">Drainage network, water bodies</td><td>[1]Topographic sheets</td></tr>
<tr><td>ANA (2021)</td><td rowspan="3">-</td></tr>
<tr><td>Esri/Maxar (Basemap/ArcMap)</td></tr>
<tr><td>Pluviosity</td><td>Rainfall data from meteorological stations (2001-2021)</td><td>EMPARN (2022)</td></tr>
<tr><td>Geomorfology</td><td>Landforms</td><td>DINIZ et al. (2017)</td><td rowspan="2">1:250.000</td></tr>
<tr><td>[2]Pedology</td><td>Developed from sheets SB.24 and sheet SB.25</td><td>RADAMBrasil (1981)</td></tr>
<tr><td rowspan="3">Digital Elevation Model (MDE)</td><td>Hypsometry</td><td rowspan="3">Satellite ALOS - sensor PALSAR -JAXA/METI (2010)</td><td rowspan="3">12,5 x 12,5m</td></tr>
<tr><td>Slope</td></tr>
<tr><td>Watershed</td></tr>
<tr><td>Land use and land cover</td><td>Technical Manual of Land Use (IBGE, 2013)</td><td>Satellite: PlanetScope (PSL); Sensor PS2: SD; Bands: 1,2 e 3. Planet Labs PBC (2022)</td><td>5 x 5m</td></tr>
</table>

Source: Author (2022).

[1]João Câmara, Lajes, Natal, Santa Cruz, São João do Campestre and São José de Mipibu Sheets.

[2]Although printed at a 1:1,000,000 scale, the mapping was conducted at a 1:250,000 scale.

The watershed delineation was performed using the hydrological tools in ArcGIS 10.8, utilizing the Digital Elevation Model (DEM) from the Advanced Land Observing Satellite (ALOS), operated by the Japan Aerospace Exploration Agency (JAXA) – PALSAR (Phased Array type L-Band Synthetic Aperture Radar) sensor, operating in the L-band, with a spatial resolution of 12.5 x 12.5 meters. The delineation was further refined in a 3D environment using ArcScene software, and adjustments were made with the assistance of 1:100,000 topographic sheets available in the Brazilian Army Geographic Database (BDGEx).

3.1 Mapping of the Drainage Network and Delimitation of Permanent Preservation Areas (PPA)

The development of the drainage network involved a more refined approach due to its significance for generating Permanent Preservation Areas (PPA). Mapping was carried out based on vector hydrographic files from the National Water Agency (ANA) for the year 2021, information from topographic sheets in the Brazilian Army Geographic Database (BDGEx), and on-screen interpretation of remote sensing data such as the Digital Elevation Model (DEM) and satellite imagery (Table 1), including those provided by Google Earth Pro software. Using existing vectorization from the mentioned sources, the resulting drainage network was reconstructed to an approximate scale of 1:25,000.

The PPA for water elements were mapped based on the principles established by the Brazilian Forest Code (BRASIL, 2012). The study considered the definition outlined in Article 3, meeting the terms of Article 4, items I, III, IV, V, and IX. For intermittent and perennial river segments, width verification was conducted using the Measure tool in ArcGIS 10.8 software, measured from the edge of the regular riverbed, utilizing PlanetScope satellite images from April 2022 and multi-temporal images from Google Earth Pro. With the drainage network already vectorized, information on river width and the protected strip was added to the attribute table. A buffer was then applied to obtain a polygon with the river's width, and from that, another buffer was created to delineate the PPA, using the Geoprocessing -> Buffer tool (Figure 3).

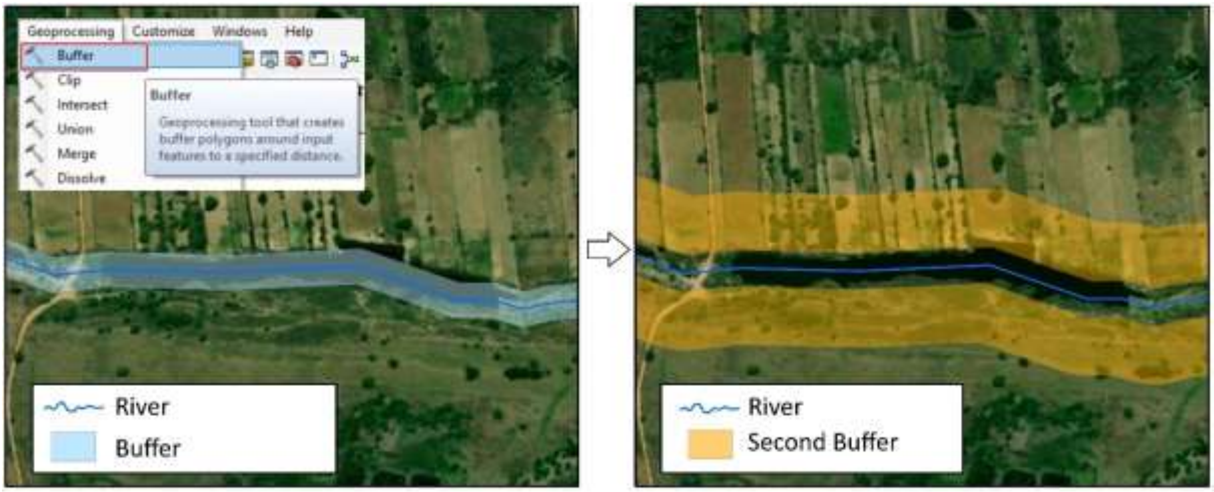

Figure 3 – Delimitation of Permanent Preservation Areas.
Source: Author (2022).

3.2 Environmental Vulnerability

To implement the erosion vulnerability methodology in PPA, the proposal by Crepani *et al.* (2001) was adapted. This involves the overlay and weighted sum of Georeferenced Information Plans: Geology (G), Geomorphology (R), Pedology (S), Rainfall Intensity (IP), and Land Use and Cover (U) (Equation 1). The latter was added in place of the Vegetation Information Plan in the original methodology. The same weight was assigned to all Information Plans used in the final formula for soil loss vulnerability. This includes Land Use and Cover, as most of the APP in PRW have areas that border on natural conditions. Therefore, it is considered prudent not to assign a high weight to occupation as a way to maintain what was observed during field visits.

$$V = \frac{(G + R + S + IP + U)}{5} \tag{1}$$

Where:
V = Vulnerability to Erosion;
G = Geology Information Plan;
R = Geomorphology Information Plan (Equation 2);
S = Pedology Information Plan;
IP = Rainfall Intensity Information Plan;
U = Land Use and Cover.

The formula for obtaining the Geomorphology Information Plan (R) is presented in Equation 2 below:

$$R = \frac{(DH + DV + D)}{3} \tag{2}$$

Where:
DH = Interfluve Amplitude (m);
DV = Altitudinal Amplitude (m);
D = Slope (%).

Individually, different weights were assigned to the variables that make up each Information Plan, classified between 1 (very low) and 3 (very high), as shown in Table 02. The above-mentioned geo-environmental variables were classified according to the values defined by Crepani *et al.* (2001) and by an interdisciplinary team composed of Environmental Engineers, Civil Engineers, and Geographers. In all matrix cartographic documents, the cell size was equalized (26m x 26m), equivalent to a scale of 1:100,000.

The methodological steps are described below:

- Rainfall Intensity (IP): Rainfall data from 17 stations in municipalities within the PRW were collected from the EMPARN website (2022). The historical series spanned 21 years (2001 to 2021), where the data provided information on the number of rainy days (during the month) for calculating rainfall intensity. Subsequently, spatial interpolation was performed in ArcGIS 10.8 using the Inverse Distance Weighted (IDW) tool.
- Geology (G): Geological information was obtained through surveys conducted by the Geological Survey of Brazil (CPRM). Six geological sheets at a 1:100,000 scale covering the PRW were used (Lajes, Natal, Santa Cruz, São José do Campestre, São José de Mipibu, and João Câmara).
- Soil Science (S): Obtained from data from the RADAMBRASIL project (1981) and made available by IBGE (2014). The soils found in the study area had their nomenclatures updated according to the Brazilian Soil Classification System (EMBRAPA, 2018).
- Land Cover and Use (U): Manual interpretation of PlanetScope satellite images, sensor PS2:SD with a spatial resolution of 5m, dated April 2022, was performed. The Red-Green-Blue (RGB-1-2-3) color composition was used to distinguish natural and anthropogenic interference regions. Despite the focus on PPA, mapping was conducted across the entire basin.
- Geomorphology (R): The variables composing Geomorphology were obtained by the arithmetic mean of Interfluve Amplitude, Altitudinal Amplitude, and Slope. Initially, the Slope tool in the MDE was used to determine the slope percentage of PRW. Then, using the method proposed by Guimarães *et al.* (2017), the interfluve and altitudinal amplitude of the study area were determined in ArcGIS and QGIS. Finally, the three variables were reclassified according to the methodology of Crepani *et al.* (2001), and an arithmetic mean was calculated to obtain the Geomorphology variable (Table 2).

Table 2 – Vulnerability classes for the variables IP, G, S, and U.

CLASSES OF VULNERABILITY FOUND IN PRW	
Vulnerability	**Variable (weight)**
	Rainfall Intensity (mm/month) - IP
Low (1,5 to 1,7)	150 -175mm (1,5); 175 - 200mm (1,6); 200 - 225mm (1,7)
Moderate (1,8 a 2,2)	225 -250mm (1,8); 250 - 275mm (1,9); 275 - 300mm (2,0); 300 - 325mm (2,1); 325 -350mm (2,2)
High (2,3 a 2,6)	350 - 375mm (2,3); 375 - 400mm (2,4); 400 - 425mm (2,5); 425 - 450mm (2,6)
	Geology - G
Very Low (1 a 1,3)	Quartz (1), Quartzite (1), Biotite (1,1), Monzogranite (1,1), Felsic Granulite (1,2), Biotite Gneiss (1,2), Migmatite (1,2), Orthogneiss (1,3), Gneiss (1,3), Granitic Orthogneiss (1,3)
Low (1,5 a 1,7)	Basalt (1,5), Aluminous Schist (1,7), Biotite Gneiss (1,7)
Moderate (1,8 a 2,0)	Gabbro (1,8), Amphibolite (1,8), pyroxenite (1,8), Hornblende (1,9), Calc-silicate Rock (2,0)
High (2,3 a 2,5)	Marble (2,3), Sandstone (2,4), Conglomeratic Sandstone (2,5)
Very High (2,9; 3,0)	Calcareous Limestones (2,9), Sand (3,0), Clay (3,0), Silt (3,0)
	Pedology - S
Very Low (1)	Latossolo Amarelo Distrófico
Moderate (2)	Eutrophic Haplic Planosol, Eutrophic Red Argisol, Dystrophic Yellow Argisol, Ortic Chromic Luvissolo
Very High (3)	Eutrophic Lithic Entisols, Ortic Thiomorphic Gleisol, Quartzarenic Orthic Erisols, Fluvic Ta Eutrophic
	Land Cover and Use - U
Very Low (1 a 1,3)	[3]Urbanized Areas (1); Water (1); Pioneer Formation with Fluvial-Marine Influence (1); Forested Savanna-Steppe (1,2); Wooded Savanna-Steppe (1,3)
Low (1,5)	Parked Savanna-Steppe (1,5)
Moderate (1,8)	Permanent Crops (1,8)
High (2,5)	Temporary Crops (2,5)
Very High (2,8; 3,0)	Pasture (2,8); Uncovered Areas (3,0); Mining Areas (3,0)
	Geomorphology - R
Low (1,7)	1,7
Moderate (1,8 a 2,2)	1,8; 1,9; 2,0; 2,1; 2,2
High (2,3 a 2,6)	2,3; 2,4; 2,5; 2,6
Very High (2,7 a 3,0)	2,7; 2,8; 2,9; 3,0

Source: Author (2022).

[3]The methodology of Crepani *et al.* (2001) does not indicate a degree of vulnerability for urbanized areas, considering that vulnerability is conditioned by the morphogenesis x pedogenesis relationship. According to Costa *et al.* (2015), the analysis in urban areas is challenging because such processes cannot be identified. This study assumes that in urban areas, the environment is stabilized due to the infrastructure of paving and construction. However, anthropized areas located in peri-urban regions were mapped as exposed areas and weighted according to the methodology.logia.

4. Results and Discussion

The PPA were mapped throughout the entire extent of PRW, including their dimensions from the regular riverbed, reservoir water surface, springs, and slopes, based on the Brazilian Forest Code (Law Nº. 12.651/2012). As shown in Figure 4, 45.18% of the mapped PPA had a protection strip of 30 meters, contributing to the preservation of rivers with a width less than 10 meters, while 28.62% of the areas have a protection strip of 50 meters, safeguarding rivers with a width greater than 10 meters and less than 50 meters. The results for water bodies were also significant, ranging from 50 to 100 meters of protection, depending on the location (urban or rural zone); these PPAs represented 14.33% of the protected areas. The PPA areas of springs received 50 meters of protection, corresponding to 1.39%. It is important to note that the width of the PPA for watercourses increases as the Potengi River approaches the estuary, as expected, since there is a higher concentration of tributaries in the estuarine region.

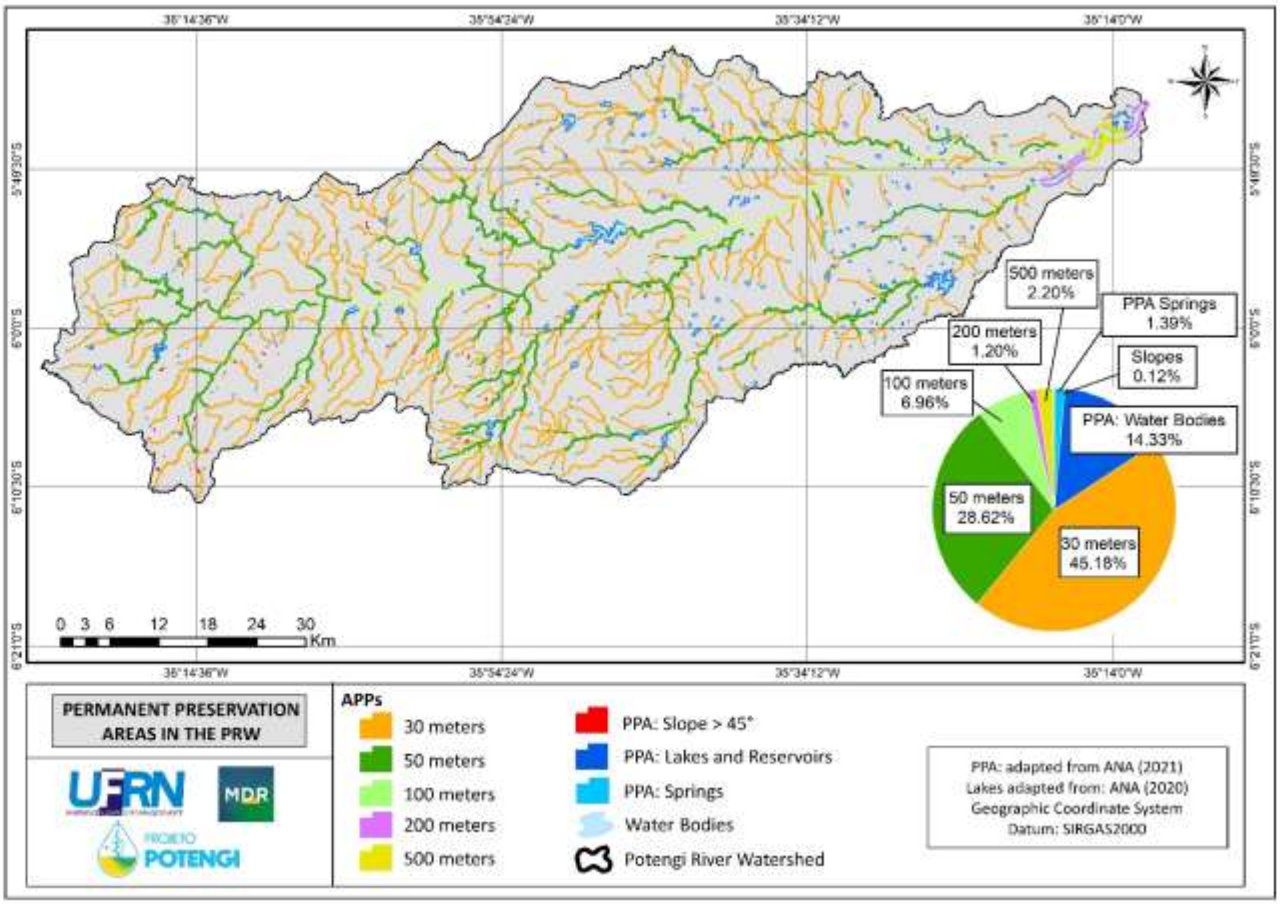

Figure 4 – Mapped PPA in PRW.
Source: author (2022).

Concerning land use (Figure 5), 10 distinct classes were identified on a watershed scale, which were later clipped to the APP. The identified classes were: Urbanized Areas, Temporary Crops, Water Bodies, Pasture, Mining Areas, Pioneer Formation with fluvial-marine influence, Permanent Crops, Wooded Savanna-Steppe, Parked Savanna-Steppe, and Forested Savanna-Steppe (IBGE, 2013).

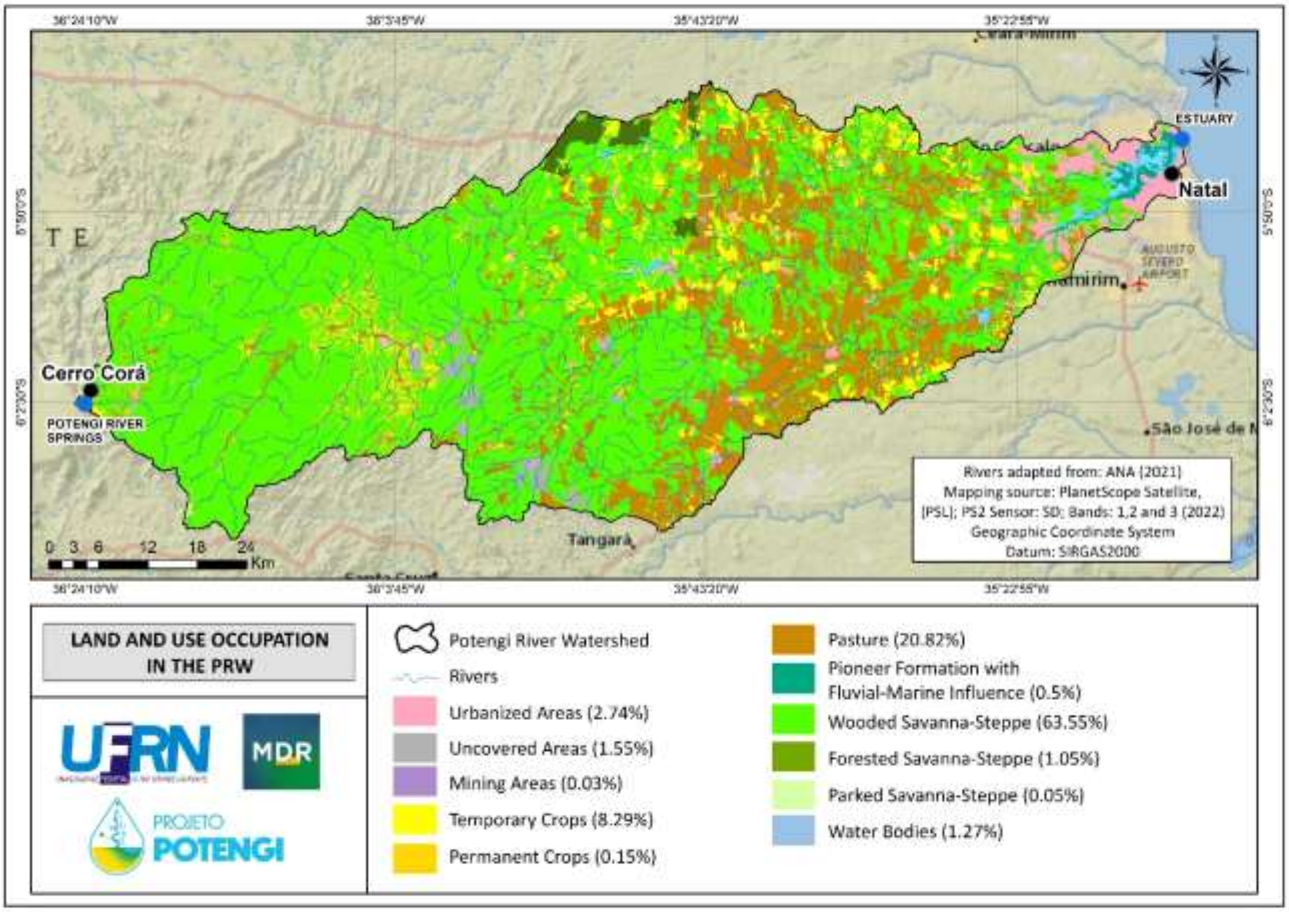

Figure 5 – Land Use and Occupation in PRW.
Source: Author (2022).

Analyzing the mapping, a significant presence of Forested Savanna-Steppe vegetation was observed in PRW, covering about 63.55% of its total area. Pasture activities, especially in the middle and lower course, and Temporary Crops are also significant in the watershed, accounting for 20.82% and 8.29%, respectively. Although in minimal quantity, there are records of mining areas and uncovered areas throughout the watershed.

4.1 Environmental vulnerability mapping in the Potengi River Watershed and in PPA.

The vulnerability mapping of the PRW resulted in five vulnerability classes, namely: Very Low, Low, Moderate, High, and Very High. The most significant values correspond to the Moderate vulnerability class, representing 79.58% of the watershed. Significant values were observed for the Low and High classes, accounting for 12.7% and 7.67% of the area, respectively (Figure 6).

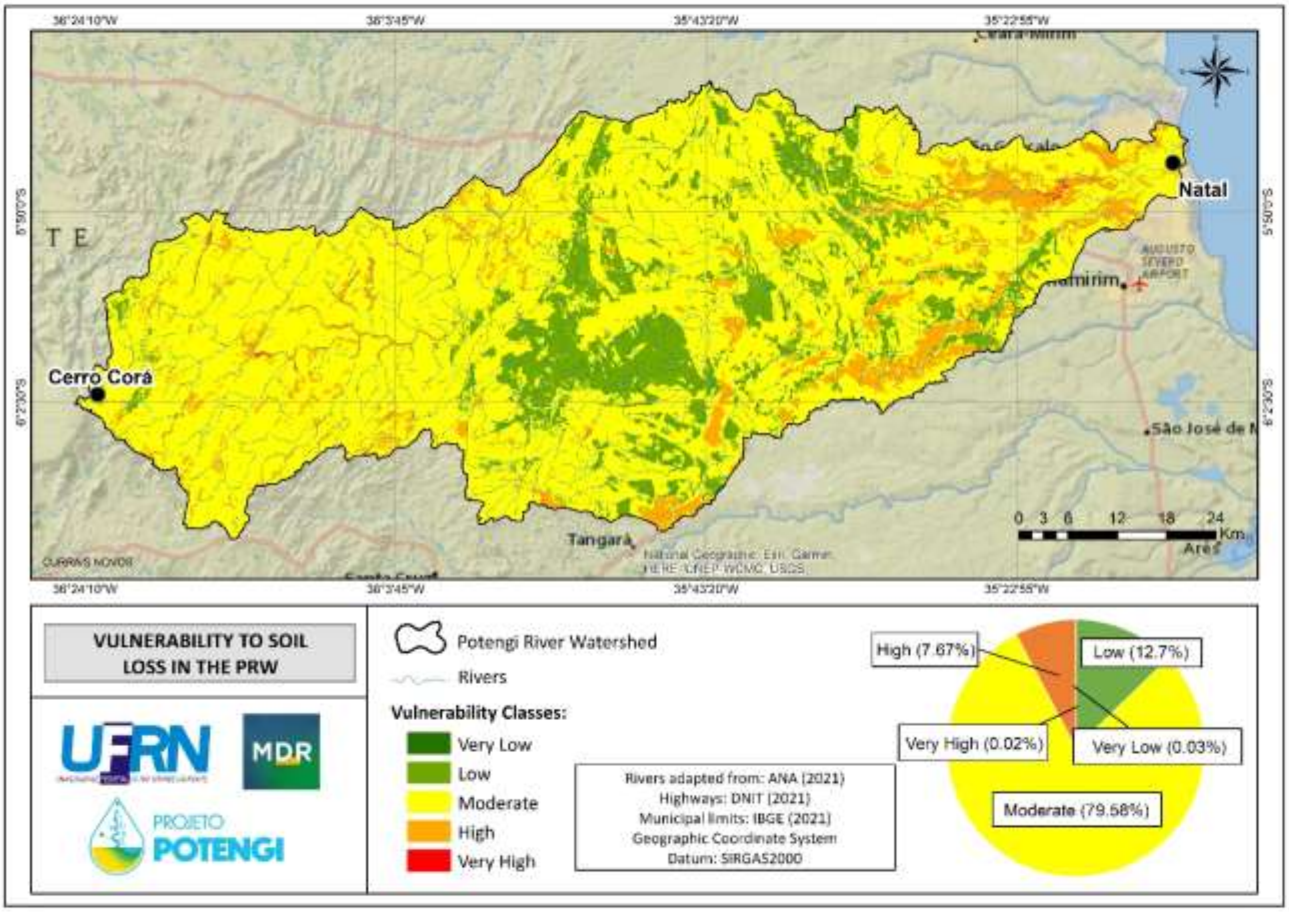

Figure 6 – Environmental vulnerability in PRW.
Source: author (2022).

In general, moderate vulnerability values in PRW are predominantly influenced by practices such as agriculture, resulting in the conversion of forested areas into anthropized lands. In addition to land use, it is important to note that soil erosion is also influenced by natural factors such as climatic conditions (rainfall intensity), pedological characteristics (thickness, texture, permeability), topographic aspects (such as slope, ramp length), as well as vegetation characteristics (such as type and density of vegetation cover) (SOARES *et al.*, 2018).

Based on the environmental vulnerability map of PRW, a clipping of the mapped PPA was carried out, revealing several critical regions concerning soil loss (Figure 7).

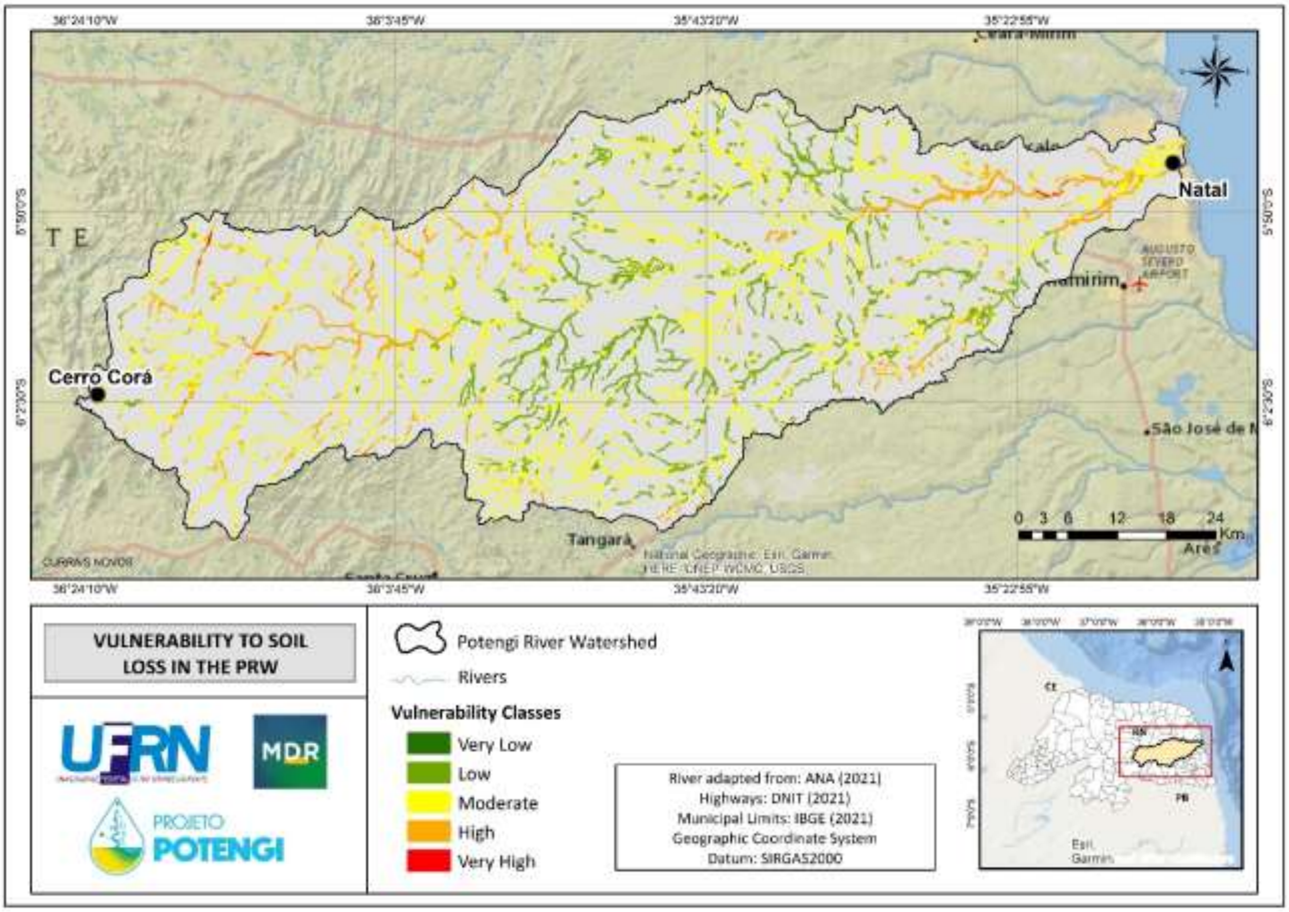

Figure 7 – Environmental vulnerability in APP of PRW.
Source: author (2022).

Approximately 16,837.98 hectares of PPA are classified as "Moderate" to soil loss, 2,350.66 hectares as "High," and 15.91 hectares as "Very High," corresponding to 72.66%, 10.14%, and 0.07% of the total PPA area, respectively. The predominance of areas classified as "Moderate" is due to the dominant presence of soils such as Luvissolo and Planossolo, which have high erodibility but are protected by wooded savanna-steppe vegetation cover. Additionally, they are located in regions with gently undulating to undulating relief and subjected to moderate rainfall intensities (EMBRAPA, 1979; CREPANI *et al.*, 2001).

The high vulnerability areas in PPA are located in the lower and upper courses of the study area. Analyzing Table 3, it is evident that these areas are mostly associated with pasture, wooded savanna-steppe, and temporary crops. On the other hand, the areas of very high vulnerability showed that 91.4% of their uses are related to pasture, 2.79% to temporary crops, and 5.18% to vegetation. The pasture areas mapped in PRW were mostly natural pastures intended for extensive livestock farming, far exceeding the planted pasture areas in the state of Rio Grande do Norte (EMBRAPA, 2014).

Table 3 – Classes of environmental vulnerability by land use and cover in PPA.

Land Use and Cover in PPA	**[4]Environmental Vulnerability in PPA (m)**							
	Very Low and Low		**Moderate**		**High**		**Very High**	
Classes	Hectares	%	Hectares	%	Hectares	%	Hectares	%
Urbanized Areas	33.27	0.84	191.11	1.13	20.63	0.88	-	-
Temporary Crops	16.39	0.41	1227.00	7.29	429.74	18.28	0.44	2.79
Water Bodies	91.59	2.31	353.23	2.10	3.18	0.14	-	-
Uncovered Areas	9.83	0.25	548.85	3.26	101.48	4.32	0.10	0.63
Pasture	53.59	1.35	3312.04	19.67	913.13	38.85	14.54	91.40
Mining Areas	0.07	0.00	3.98	0.02	-	-	-	-
Pioneer Formation with Fluvial-Marine Influence	1.43	0.04	663.76	3.94	122.34	5.20	-	-
Permanent Crops	4.02	0.10	19.56	0.12	-	-	-	-
Wooded Savanna-Steppe	3738.41	94.15	10406.90	61.81	759.99	32.33	0.82	5.18
Parked Savanna-Steppe	-	-	3.34	0.02	0.16	0.01	-	-
Forested Savanna-Steppe	21.95	0.55	108.20	0.64	-	-	-	-
Total	**3,970.55**	**100.00**	**16,837.98**	**100.00**	**2,350.66**	**100.00**	**15.91**	**100.00**

Source: author (2022).

[4]Considering the PPA of water bodies, water masses, and springs.

The areas of high vulnerability in PPA are located in the lower and upper reaches of the study area and are mostly associated with pasture, steppe savannas, and temporary crops. On the other hand, the areas of very high vulnerability show 91.4% of their uses associated with pasture, 2.79% with temporary crops, and 5.18% with vegetation. The mapped pasture areas in PRW were mostly natural pastures, surpassing the planted ones in the state of Rio Grande do Norte (EMBRAPA, 2014).

Regarding slope, the highest values were found in the PPA of springs in the upper course of the watershed (such as the Potengi River), with values ranging from 20 to 50% (high vulnerability) and exceeding 50% (very high vulnerability). These data confirm the high vulnerability to erosion found in these areas, mainly located in the Serra de Santana and Potengi-Trairi compartments, part of the Borborema Plateau. These regions have altitudes ranging from 480 to 718 meters and a high interfluve amplitude, directly influencing the Geomorphology Information Plan (PI Geomorfologia) in the Crepani methodology.

4.2 Field-validated PPAs

From the environmental vulnerability map, three critical areas of PPA were field-validated (Figure 8 - A, B, and C). These three areas were chosen because they represent high/very high vulnerability and have land use activities that are inconsistent with the Brazilian Forest Code. In general, geology and land use emerged as the predominant factors contributing to the increased vulnerability of the study area.

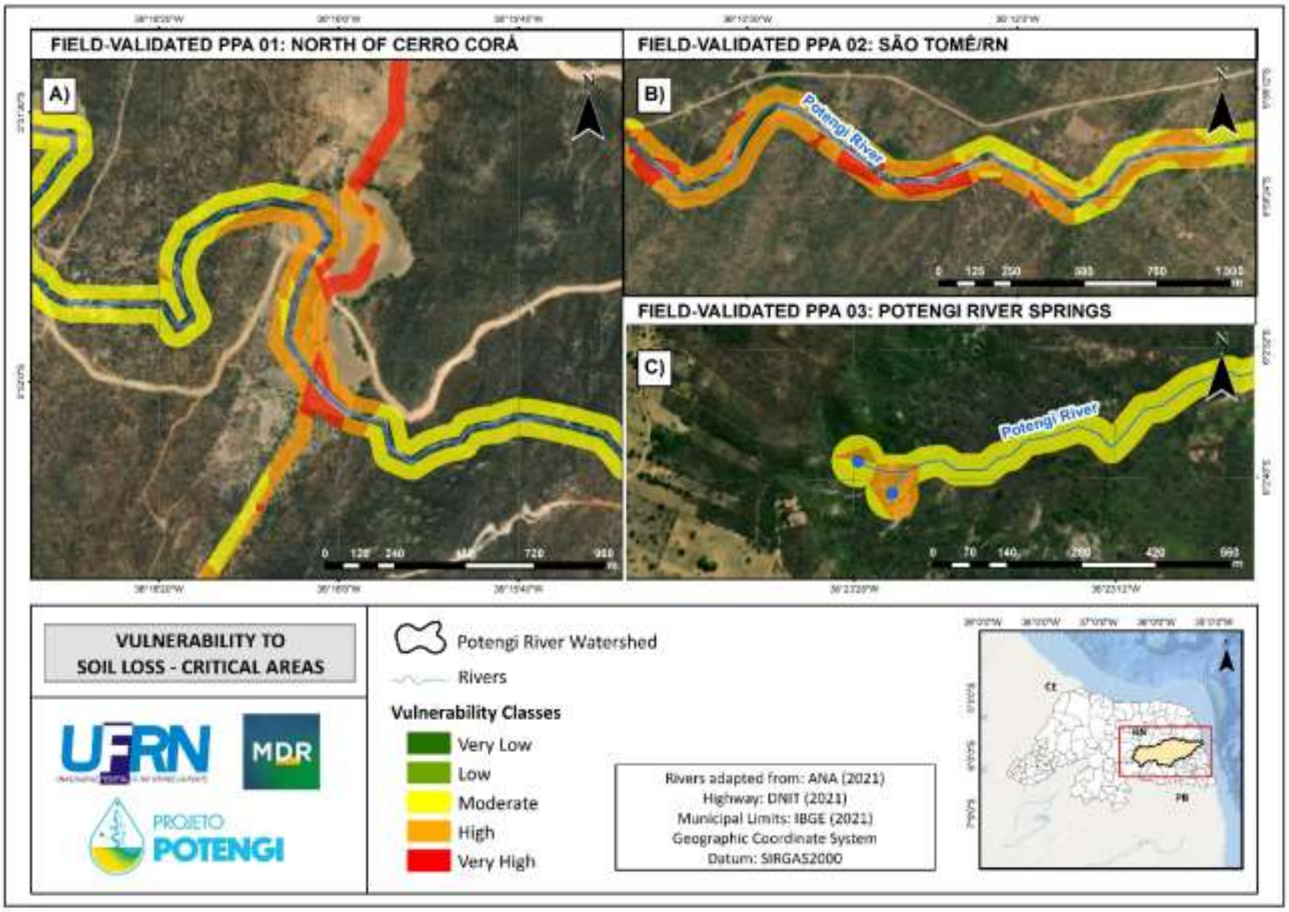

Figure 8 – Erosion Vulnerability in Field-Validated Permanent Preservation Areas (PPA). Source: Author (2022).

Area 01 (Figure 8-A), located north of the municipality of Cerro Corá/RN and adjacent to RN-104, corresponds to the intermittent stream's PPA named "Chapador" (ANA, 2021). It was observed that in this region, near the Santa Rosa Mundo Novo Wind Farm, the mapped classes were classified as "High" and "Very High." These values are largely attributed to the impacts of wind farm construction, especially earthmoving activities involving embankments and the opening of borrowing areas. The geology in this locality consists of Alluvial Deposits (Q2a), predominantly composed of unconsolidated sandy sediments, often exposed along watercourses such as rivers and streams (LIMA; DANTAS, 2016; COSTA; DANTAS, 2018). Because these materials are loose and poorly consolidated, they are more vulnerable to water erosion, naturally indicating high susceptibility to soil loss (CREPANI *et al.*, 2001). In conjunction with geology, the soil identified in the area was Eutrophic Litholic Neosol (RLe), with shallow depth and sandy to very sandy texture, conferring high erodibility, which can be intensified by a decrease in vegetation cover (THOMA *et al.*, 2022).

In addition to these factors, and in disagreement with the provisions of the Brazilian Forest Code, it is possible to observe that the area in question is predominantly composed of pastures intended for extensive livestock farming, exposed soils, and subsistence temporary crops along the watercourse margins (Figure 9-A, B, and Figure 10). Through drone aerial survey, it was possible to observe plantations along the riverbanks due to increased moisture, even in the absence of water due to its intermittent nature.

Figure 9 – Area 01: Livestock grazing in PPA (A); Aerial survey of a region with temporary crops in the intermittent stream "Chapador" in Cerro Corá/RN (B).
Source: Author (2022).

Figure 10 – Area 01: "Chapador" stream dry, evidenced by crops and exposed soil.
Source: Author (2022).

The Area 02 (Figure 8-B) is located in the municipality of São Tomé/RN, intercepted by RN-203, and is divided into two areas close to each other (Figure 11-A and Figure 11-B). Characterized by classes of high and very high vulnerability, the geology of the area is formed by Alluvial Deposits (Q2a), and the soils present are classified as Litholic Eutrophic Neosols (Rle). It is an Area of Permanent Preservation with naturally high vulnerability, where pastures and areas being prepared for cultivation were observed (Figure 11-A).

To the south of the area being prepared for cultivation, there is an intermittent tributary of the Potengi River, along with two consecutive dams. Advanced erosion in the PPA was observed in the field (Figure 11-B), leading to the subsequent deposition of sediments in the riverbed.

Figure 11 – Land preparation along the Potengi River banks in São Tomé/RN (A); Significant erosion in the PPA of a tributary of the Potengi River (B).
Source: Author (2022).

Area 03 (Figure 8-C and Figure 12) is located in the municipality of Cerro Corá/RN and displays classes of Moderate and High vulnerability. This area corresponds to the source of the Potengi River, recognized as a tourist spot of great importance to the PRW, also standing out as a Geosite of the Seridó Geopark.

The geology of the region in question consists of sandstones belonging to the Serra dos Martins Formation, which naturally exhibit high vulnerability to erosion. Additionally, the soils present are classified as Chromic Orthic Luvisols, characterized by an abrupt textural change to the B horizon (EMBRAPA, 2018; CPRM, 2018). The combination of these factors, along with the high rainfall intensity in the region (360 mm/month), results in significant vulnerability to erosion.

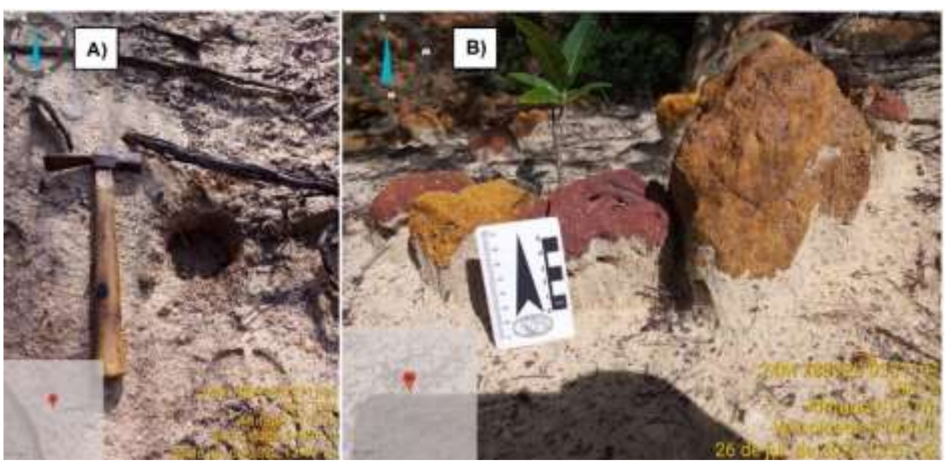

Figure 12 – Trampling by cattle in PPA of the Potengi River sources (A); Pinnacles highlighting centimetric erosion of the soil's A horizon (B).
Source: Author (2022).

In addition to the mentioned factors, it is observed that land use is the most predominant factor for the high vulnerability in the region in question. Through mapping analysis, areas without vegetation cover and pastures in PPA were identified. During an on-site visit, cattle trampling was observed in spring areas (Figure 12-A), resulting in soil compaction and, consequently, increased surface runoff from rainfall and accelerated erosive processes (Figure 12-B). The aerial survey validates the occurrence of degradation processes in the analyzed area, evidenced by intense erosive processes and reduced vegetation cover (Figure 13).

Figure 13 – Degradation process in the PPA of the source of the Potengi River in the municipality of Cerro Corá/RN. Source: Author (2022).

The factors influencing erosion in this area can be diverse and are directly related to the Potengi River being characterized as an urban river. It has undergone significant modifications in its form, dynamics, and geo-environmental components throughout its urbanization process (ALMEIDA, 2010). The region of Cerro Corá, being located in the northeastern hinterlands and within the semi-arid domain of the Brazilian caatingas, exhibits ecological instability and experiences more intensively the surface morphodynamic processes, such as erosion. Although erosion is a natural phenomenon, it can be accelerated due to the steep slope of the region, soil characteristics, and, especially, human land uses (NETO; FERNANDES, 2015; RABELO; ARAÚJO, 2019).

However, these processes in the region are largely attributed to cattle trampling, considered a significant agent of geomorphological change, favoring surface runoff and the formation of gullies and ravines (TRIMBLE; MENDEL, 1995; COSTA *et al.*, 2018).

The lack of access control to the region and proper fencing contributes to the expansion of these impacts, including the vulnerability of the springs.

5. Final considerations

The assessment of vulnerability to soil loss in PPA in the PRW allowed the identification of the predominance of the Moderate class, representing 72.66%, which, together with the High (10.14%) and Very High (0.07%) classes, accounts for a significant 82.87% of the watershed. Among the natural factors influencing this are the combination of crystalline/sedimentary geology, responsible for Neosols Litolics/Quartzarenic soils, being the main contributors. In the anthropic environment, various land uses were identified in watercourse PPAs, with a notable presence of pasture activities (livestock), temporary crops, and exposed soils in areas of higher vulnerability. Areas with Very Low and Low vulnerability (17.13%) represent less environmentally impactful situations for water elements.

In the watershed, three PPAs were validated, and during on-site visits, erosive processes and various irregularities in land use and occupation were observed, highlighting inconsistencies with the Brazilian Forest Code. It was noted that livestock practices without proper fencing in spring areas contributed to the degradation of the mapped areas with "High" and "Very High" vulnerability.

Considering that the PRW is one of the most important in Rio Grande do Norte, encompassing various economic and social activities, the conducted mapping can serve as a basis for the territorial planning of the municipalities within the watershed and for its yet-to-be-established committee. Actions for the recovery of degraded areas can be initiated in PPA with higher vulnerabilities. It is worth emphasizing the region of the springs farthest from the mouth of the Potengi River (Cerro Corá) as a priority in these actions, as it is an area with a high degree of environmental vulnerability and is located on the western edge of the Serra de Santana, composed of friable sandstones of the Serra do Martins Formation. Adverse events in this area, such as vegetation suppression, cattle trampling, and spring siltation, can trigger negative effects on the quantity and quality of water with cascading effects downstream. Thus, the importance of conservation actions in this region, which plays a vital role in preserving the environmental balance of the watershed, is further emphasized.

As a complement, the obligation present in the Brazilian Forest Code regarding the revegetation of PPA should be emphasized for the proper reduction of the watershed's environmental vulnerability. It is also suggested to continue validating other PPA, as well as conducting surveys by municipality and implementing measures to mitigate the main processes causing degradation in each region.

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References

ALEXANDRE, F. da S; RAMOS, P. S.; DEUS, R. A. S. G.; GOMES, D.D.M.; SILVA, S. A. Mapeamento do Uso do Solo no município de Palmeirina-PE. Revista de Geociências do Nordeste, [S. l.], v. 2, p. 1160–1167, 2016. DOI: https://doi.org/10.21680/2447-3359.2016v2n0ID10579.

ALENCAR, J. B. R.; BRITO, C. H. de; BACCARO, F. B.; BICHO, C. de L.. Beetle assemblage composition (coleoptera) across the borborema plateau in northeastern brazil. Revista Caatinga, [S.L.], v. 35, n. 1, p. 148-159, mar. 2022. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/1983-21252022v35n115rc.

ÁLVARES, Clayton Alcarde; STAPE, José Luiz; SENTELHAS, Paulo Cesar; GONÇALVES, José Leonardo de Moraes; SPAROVEK, Gerd. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, [S.L.], v. 22, n. 6, p. 711-728, 1 dez. 2013. Schweizerbart. DOI: http://dx.doi.org/10.1127/0941-2948/2013/0507.

ALMEIDA, Lutiane Queiroz de. Vulnerabilidades socioambientais de rios urbanos. 2010. 310 f. Tese (Doutorado) - Curso de Geografia, Universidade Estadual Paulista, Rio Claro, 2010. Disponível em: <https://repositorio.unesp.br/items/1e1617a7-1a33-47e9-982a-eb880da92d21>. Acesso em: 25 set. 2023.

ANA. Agência Nacional de Águas e Saneamento Básico. Disponibilidade Hídrica Superficial: Conjuntura dos Recursos Hídricos no Brasil, 2021. Disponível em: <https://metadados.snirh.gov.br/geonetwork/srv/api/records/7ac42372-3605-44a4-bae4-4dee7af1a2f8>.

APS, R; HERKÜL, K; KOTTA, J; CORMIER, R; KOSTAMO, K; LAAMANEN, L; LAPPLAINEN, J; LOKKO, K; PETERSON, A; VARJOPURO, R. Marine environmental vulnerability and cumulative risk profiles to support ecosystem-based adaptive maritime spatial planning. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 75 (7), 2488–2500. 2018. DOI: https://doi.org/10.1093/icesjms/fsy101.

BRASIL. Lei 12.651, de 25 de maio de 2012. Brasília, Diário Oficial da União, 2012. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm>. Acesso em: 01. set. 2022.

BRAUMAN, K. A., DAILY, G. C., DUARTE, T. K. E., MOONEY, H. A. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. Annu. Rev. Env. Resour. 32, 67–98, 2007. DOI: https://doi.org/10.1146/annurev.energy.32.031306.102758.

CASTRO, S. L. I; MAY, L. R.; GARCIAS, C. M.. Meio ambiente e cidades – áreas de preservação permanente (app) marginais urbanas na lei federal N. 12.651/12. Ciência Florestal, [S.L.], v. 28, n. 3, p. 1340-1349, 1 out. 2018. Universidade Federal de Santa Maria. DOI: http://dx.doi.org/10.5902/1980509833353.

CHIAVARI, J; LOPES, C. L. Os caminhos para a regularização ambiental: decifrando o novo código florestal. In: SILVA, A. P. M. da; MARQUES, H. R.; SAMBUICHI, R. H. S. (org.). Mudanças no Código Florestal Brasileiro: desafios para a implementação da nova lei. Rio de Janeiro: Ipea, 2016. p. 21-44. Disponível em: <https://repositorio.ipea.gov.br/handle/11058/6912>.

COSTA, C. W.; LORANDI, R.; LOLLO, J. A. di; SERIKAWA, V. de S.. Combinação de atributos naturais e antrópicos na definição do potencial de contaminação de aquíferos, sudeste do Brasil. Sociedade & Natureza, [S.L.], v. 32, p. 657-673, 11 set. 2020. EDUFU - Editora da Universidade Federal de Uberlandia. DOI: http://dx.doi.org/10.14393/sn-v32-2020-56221.

COSTA, C. W.; LORANDI, R.; LOLLO, J. A. de; IMANI, M.; DUPAS, F. A. Surface runoff and accelerated erosion in a peri-urban wellhead area in southeastern Brazil. Environmental Earth Sciences, [S.L.], v. 77, n. 5, 23 fev. 2018. Springer Science and Business Media LLC. DOI: http://dx.doi.org/10.1007/s12665-018-7366-x.

COSTA, A. P. da; DANTAS, A. R.. Geologia e recursos minerais da Folha Lajes SB. 24-X-D-VI: Estado do Rio Grande do Norte. Recife: CPRM, 2018. Programa Geologia do Brasil. Disponível em: <https://rigeo.cprm.gov.br/handle/doc/20238?mode=full>.

COSTA, Carlos; PIGA, Fabiola; MORAES, Mayra; DORICI, Mariana; SANGUINETTO, Evandro; LOLLO, Jose; MOSCHINI, Luiz; LORANDI, Reinaldo; OLIVEIRA, Leandro. Fragilidade ambiental e escassez hídrica em bacias hidrográficas: manancial do rio das araras - araras, sp./ environmental fragility and water scarcity in catchment basins. Revista Brasileira de Recursos Hídricos, [S.L.], v. 20, n. 4, p. 946-958, out. 2015. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.21168/rbrh.v20n4.p946-958.

CPRM. Companhia de Pesquisa de Recursos Minerais. Geologia e recursos minerais do estado do Rio Grande do Norte: texto explicativo dos mapas geológico e de recursos minerais do estado do Rio Grande do Norte. Recife: CPRM; FAPERN, 2006. Escala 1:500.000. Programa Geologia do Brasil (PGB). Disponível em: <https://rigeo.cprm.gov.br/xmlui/handle/doc/10234?show=full>.

CREPANI, E.; MEDEIROS, J. D.; HERNANDEZ FILHO, P.; FLORENZANO, T. G.; DUARTE, V. e BARBOSA, C. C. F. Sensoriamento Remoto e Geoprocessamento Aplicados ao Zoneamento Ecológico-Econômico e ao Ordenamento Territorial. São José dos Campos: Instituto Nacional de Pesquisas Espaciais, 2001. 124 p.

DICKEL, M. E. G.; GODOY, M. B. R. B. Desastres ambientais e impactos socioambientais: inundações no município de Itaóca- SP: Bacia Hidrográfica como unidade de planejamento e gestão de riscos. Caderno de Geografia, [S.L.], v. 26, n. 47, p. 737-759, 20 set. 2016. Pontificia Universidade Católica de Minas Gerais. DOI: https://doi.org/10.5752/p.2318-2962.2016v26n47p737.

DINIZ, M. T. M.; OLIVEIRA, G. P. de; MAIA, R. P.; FERREIRA, B. Mapeamento geomorfológico do estado do Rio Grande do Norte. Revista Brasileira de Geomorfologia, v. 18, n.4, 2017. DOI: https://doi.org/10.20502/rbg.v18i4.1255.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos. 5. ed. Brasília, DF. 2018. 355 p. Disponível em: <https://www.embrapa.br/en/solos/busca-de-publicacoes/-/publicacao/1094003/sistema-brasileiro-de-classificacao-de-solos>. Acesso em: 10 março 2023.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária. Diagnóstico das Paisagens no Brasil. 5. ed. Brasília, DF. 2014. 38 p. Disponível em: https://www.infoteca.cnptia.embrapa.br/bitstream/doc/986147/1/DOC402.pdf.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária. Súmula da X Reunião técnica de levantamento de solos, Rio de Janeiro. 1979. 87 p. Disponível em: <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/327212/1/SNLCSMiscelania11979.pdf>.

FEEN, R. H. Keeping the balance: Ancient Greek philosophical concerns with population and environment. Population and Environment, v. 17, p. 447–458, 1996. DOI: https://doi.org/10.1007/BF02208335.

GRIPP JUNIOR, Joel; SOARES, Vicente Paulo; RIBEIRO, Carlos Antonio Álvares Soares; SOUZA, Agostinho Lopes de; GLERIANI, José Marinaldo. Aplicação da geotecnologia no estudo de cadastro técnico rural e no mapeamento de áreas de preservação permanente e reservas legais. Revista Ceres, [S.L.], v. 57, n. 4, p. 459-468, ago. 2010. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/s0034-737x2010000400004.

GUERRA, A. J. T.; JORGE, M. do C. O. Processos erosivos e recuperação de áreas degradadas. 1. Ed. São Paulo: Oficina de Textos, 2013. 192 p. ISBN 978-85-7975-079-3.

GUIMARÃES, B. B.; GUIMARÃES, R. B.; LEAL, A. C. Código Florestal brasileiro: análise do conceito de área de preservação permanente e sua aplicação na bacia hidrográfica do córrego são pedro - anhumas, são paulo. Boletim Campineiro de Geografia, [S.L.], v. 5, n. 1, p. 157-173, 30 jun. 2015. Boletim Campineiro de Geografia. DOI: http://dx.doi.org/10.54446/bcg.v5i1.192.

GUIMARÃES, Felipe Silva; CORDEIRO, Claudia Mendes; BUENO, Guilherme Taitson; CARVALHO, Vilma Lúcia Macagnan; NERO, Marcelo Antônio. UMA PROPOSTA PARA AUTOMATIZAÇÃO DO ÍNDICE DE DISSECAÇÃO DO RELEVO. Revista Brasileira de Geomorfologia, [S.L.], v. 18, n. 1, p. 1-13, 31 mar. 2017. Revista Brasileira de Geomorfologia. DOI: http://dx.doi.org/10.20502/rbg.v18i1.1163.

GUO, M., WANG, W., SHI, Q., CHEN, T., KANG, H., LI, J. An experimental study on the effects of grass root density on gully headcut erosion in the gully region of China's Loess Plateau. Land Degrad Dev. v. 30, p. 2107– 2125, 2019. DOI: https://doi.org/10.1002/ldr.3404.

HOENIG, L. R.; CANDIOTTO, L. Z. P. ANÁLISE DO USO DO SOLO EM ÁREAS DE PRESERVAÇÃO PERMANENTE NO ALTO CURSO DA BACIA DO RIO COTEGIPE, FRANCISCO BELTRÃO - PR. XXI Encontro Nacional de Geografia Agrária. Universidade Federal de Uberlândia. 2012. Disponível em: <http://www.lagea.ig.ufu.br/xx1enga/anais_enga_2012/eixos/1388_1.pdf>

IBGE. Instituto Brasileiro de Geografia e Estatística. Coordenação de Recursos Naturais e Estudos Ambientais: Manual Técnico de Uso da Terra. Rio de Janeiro, 2013, 170 p. 3 ed. ISBM 978-85-2404-307-9.

JAXA/METI. ALOS PALSAR: MDE – Banda L. 2011. Disponível em: https://asf.alaska.edu/. Acesso em 05/11/2020.

KOPPEN, W; 1936: Das geographische System der Klimate – KOPPEN, W., R. GEIGER (Eds.): Handbuch der Klimatologie. – Gebrüder Borntraeger, Berlin, 1, 1–44, part C. Disponível em: <https://koeppen-geiger.vu-wien.ac.at/pdf/Koppen_1936.pdf>.

KLAIS, Halita Beatriz Antunes; DALMAS, Fabricio Bau; MORAIS, Renata Porto; ATIQUE, Gabriela; LASTORIA, Giancarlo; PARANHOS FILHO, Antonio Conceicao. Vulnerabilidade natural e ambiental do municipio de Ponta Pora, Mato Grosso do Sul, Brasil. Ambiente e Agua - An Interdisciplinary Journal Of Applied Science, [S.L.], v. 7, n. 2, p. 277-290, 31 ago. 2012. Instituto de Pesquisas Ambientais em Bacias Hidrograficas (IPABHi). DOI: http://dx.doi.org/10.4136/ambi-agua.786.

LI, X.; SUN, W.; ZHANG, D.; HUANG, J.; LI, D.; DING, N.; ZHU, J.; XIE, Y.; WANG, X. Evaluating water provision service at the sub-watershed scale by combining supply, demand, and spatial flow. Ecological Indicators, v. 127, p. 107745, 2021. DOI: https://doi.org/10.1016/j.ecolind.2021.107745.

LIMA, M. M. P.; SILVA, L. da. Análise da vulnerabilidade natural da bacia hidrográfica do Rio Banabuiú, com apoio de geotecnologia. Revista Brasileira de Geografia Física, [S.L.], v. 11, n. 4, p. 1442-1457, 2018. Revista Brasileira de Geografia Fisica. DOI: http://dx.doi.org/10.26848/rbgf.v11.4.p1442-1457.

LIMA, S. M.; SOUZA, J. Detalhamento das classes solos da bacia hidrográfica do riacho do tigre. Revista de Geociências do Nordeste, [S.L.], v. 2, p. 103-112, 27 out. 2016. Universidade Federal do Rio Grande do Norte - UFRN. DOI: http://dx.doi.org/10.21680/2447-3359.2016v2n0id10429.

LIMA, M. da G.; DANTAS, E. P. Geologia e recursos minerais da folha São José de Mipibu, SB.25-A-Y-II e III. Recife: CPRM, 2016. Disponível em: <https://rigeo.cprm.gov.br/xmlui/handle/doc/17627?show=full>.

MACHADO, T. C. E.; CAMPOS, M. C. C.; PAGANI, C. H. P.; CUNHA, J. M.; SOARES, M. D. R. AVALIAÇÃO DO USO E OCUPAÇÃO DAS ÁREAS DE PRESERVAÇÃO PERMANENTE NOS ANOS DE 2008 E 2013 NA ZONA URBANA DE HUMAITÁ, AMAZONAS. Revista da Universidade Vale do Rio Verde, [S.L.], v. 15, n. 2. 2017. Universidade Vale do Rio Verde (UninCor). DOI: http://dx.doi.org/10.5892/ruvrd.v15i2.3017.

MIRANDA, M. S. A.; FARIAS, J. F. UNIDADES GEOECOLÓGICAS DO MÉDIO CURSO DA BACIA HIDROGRÁFICA DO RIO POTENGI-RN: APONTAMENTOS PARA UM FUTURO SUSTENTÁVEL. REDE - Revista Eletrônica do PRODEMA, Fotaleza, Brasil, v.15, n.1, p.9 4 - 104. 2021. ISSN: 1982-5528.

MORGAN, R., P., C. Soil Erosion and Conservation. 3ª edição. Blackwell Publishing, Oxford, 2005. 304P. ISBN 1-4051-1781-8. DOI: https://doi.org/10.1111/j.1365-2389.2005.0756f.x.

NETO, Manoel Cirício Pereira; FERNANDES, Ermínio. Fragilidade ambiental da bacia hidrográfica do rio Seridó (rn/pb – Brasil). Revista Brasileira de Geomorfologia, [S.L.], v. 16, n. 3, p. 1-10, 30 set. 2015. Revista Brasileira de Geomorfologia. DOI: http://dx.doi.org/10.20502/rbg.v16i3.603.

OLIVEIRA, M. Z. de; VERONEZ, M. R.; THUM, A. B.; REINHARDT, A. O.; BARETTA, L; VALLES, T. H. A.; ZARDO, D.; SILVEIRA, L. K. da. Delimitação de Áreas de Preservação Permanente: Um estudo de caso através de imagem de satélite de alta resolução associada a um sistema de informação geográfica (SIG). Anais XIII Simpósio Brasileiro de Sensoriamento Remoto, Florianópolis, p. 4119-4128, abr. 2007. ISBN 978-85-17-00031-7.

OLIVEIRA, A. V. L. C. de; CESTARO, L. A. Caracterização dos sistemas ambientais do Rio Grande do Norte: um enfoque na depressão sertaneja. Revista de Geociências do Nordeste, [S.L.], v. 2, p. 221-231, 27 out. 2016. Universidade Federal do Rio Grande do Norte - UFRN. http://dx.doi.org/10.21680/2447-3359.2016v2n0id10444.

PAIVA, A. M. L. de; AMARO, V. E.; LOLLO, J. A. di; COSTA, C. W. Fragilidade Ambiental aplicada em área de manancial no Nordeste brasileiro. Revista de Geociências do Nordeste, [S.L.], v. 8, n. 1, p. 128-147, 14 abr. 2022. Universidade Federal do Rio Grande do Norte - UFRN. DOI: http://dx.doi.org/10.21680/2447-3359.2022v8n1id24368.

PEDRON, F. de A.; FINK, J. R.; DALMOLIN, R. S. D.; AZEVEDO, A. C. de. Morfologia dos contatos entre solo-saprolito-rocha em neossolos derivados de arenitos da formação caturrita no Rio Grande do Sul. Revista Brasileira de Ciência do Solo, [S.L.], v. 34, n. 6, p. 1941-1950, dez. 2010. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/s0100-06832010000600019.

PIGA, F. G.; TÃO, N. G. R.; RUGGIERO, M. H.; MARQUEZOLA, D. de S.; BOINA, W. L. de O.; COSTA, C. W.; LOLLO, J. A. de; LORANDI, R; MELANDA, E. A.; MOSCHINI, L. E. Multi-criteria potential groundwater contamination and human activities: araras watershed, brazil. Rbrh, [S.L.], v. 22, p. 1-13, 23 out. 2017. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/2318-0331.0217170052.

PINTO, G. S.; SERVIDONI, L. E.; LENSE, G. H. E.; MOREIRA, R. S.; MINCATO, R. L. Estimativa das perdas de solo por erosão hídrica utilizando o Método de Erosão Potencial. Geography Department University Of Sao Paulo, [S.L.], v. 39, p. 62-71, 23 jun. 2020. Universidade de Sao Paulo, Agencia USP de Gestão da Informação Acadêmica (AGUIA). DOI: https://doi.org/10.11606/rdg.v39i0.160233.

RABELO, Davi Rodrigues; ARAðJO, José Carlos de. Estimativa e mapeamento da erosão bruta na bacia hidrográfica do rio Seridó, Brasil. Revista Brasileira de Geomorfologia, [S.L.], v. 20, n. 2, 31 mar. 2019. Revista Brasileira de Geomorfologia. DOI: http://dx.doi.org/10.20502/rbg.v20i2.1414.

RADAMBRASIL. Secretaria Geral. Ministério das Minas e Energia. Projeto RADAMBRASIL: Folhas SB.24/25 Jaguaribe/Natal; geologia, geomorfologia, pedologia, vegetação e uso potencial da terra (Levantamento de Recursos Naturais). Rio de Janeiro, 1981. 745 p. 23 v.

ROSS, J. L. S. Análise empírica da fragilidade dos ambientes naturais e antropizados. Revista do Departamento de Geografia, 8, São Paulo, 1994. p. 63-74.

SALOMÃO, C. de S. C.; PAULA, L. G. de S.; ELMIRO, M. A. T. Use of multicriteria analysis to define priority areas for reforestation in the Piranga River Basin, MG, Brazil. Sustentabilidade em Debate, [S.L.], v. 11, n. 2, p. 95-120, 31 ago. 2020. Editora de Livros IABS. DOI: http://dx.doi.org/10.18472/sustdeb.v11n2.2020.30468.

SANTOS, R. de O.; SCUDELARI, A. C. AVALIAÇÃO DA SUSCETIBILIDADE À EROSÃO HÍDRICA NA BACIA HIDROGRÁFICA DO RIO POTENGI, RN. In: XIX SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 2011, Maceió. Anais [...]. Disponível em: < https://abrh.s3.sa-east-1.amazonaws.com/Sumarios/81/ccc229564e86f00a6440260d46034c6d_c5be99c4f4832ccc2b66cd52132839dc.pdf>.

SARTORI, A. A. da C.; SILVA, R. F. B. da; ZIMBACK, C. R. L. Combinação linear ponderada na definição de áreas prioritárias à conectividade entre fragmentos florestais em ambiente SIG. Revista Árvore, [S.L.], v. 36, n. 6, p. 1079-1090, dez. 2012. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/s0100-67622012000600009.

SCHULT, S. I. M.; GHODDOSI, S. M.; NOLL, J. F.; BACK, C. C.; KONDLATSCH, K. M. de S. Planejamento territorial e recursos hídricos: as áreas protegidas no entorno de corpos de água na Bacia Hidrográfica do Rio Itajaí (sc). In: XX SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICO, 2013, Bento Gonçalves/RS. Disponível em: <https://abrh.s3.sa-east-1.amazonaws.com/Sumarios/155/667ae3e73abb03e48193c9b52efe7410_122c05c530100303d14b87f1311c86ad.pdf>

SEMARH, Secretaria de Estado de Recursos Hídricos. Plano Estadual de Recursos Hídricos. 1998. Disponível em: <http://adcon.rn.gov.br/ACERVO/IGARN/DOC/DOC000000000150878.PDF>.

SILVA, I. A. A.; DUPAS, F. A.; COSTA, C. W.; SOUZA, A. R.; MEDEIROS, G. O. R. Spatiotemporal changes in land cover land use in protected areas of Serra da Mantiqueira, Southeastern Brazil. Environmental Challenges, p. 100195, 2021. DOI: https://doi.org/10.1016/j.envc.2021.100195

SILVA, P. L. F. da; SILVA, A. J. da. Avaliação do uso e ocupação do solo no município de Pilõezinhos-PB, de 1984-2016 utilizando o geoprocessamento. Revista de Geociências do Nordeste, [S. l.], v. 3, n. 1, p. 48–63, 2017. DOI: https://doi.org/10.21680/2447-3359.2017v3n1ID10982.

SILVA, L. F. da; BACANI, V. M. Análise da Fragilidade Ambiental e das Áreas de Preservação Permanente da Bacia Hidrográfica do Córrego Fundo, Município de Aquidauana-MS. Caderno de Geografia, [S.L.], v. 27, n. 49, p. 264-284, 2 maio 2017. Pontificia Universidade Católica de Minas Gerais. DOI: https://doi.org/10.5752/P.2318-2962.2017v27n49p264.

SOUZA, A. R. de; DUPAS, F. A.; DRUMMOND, I. N.; COSTA, C. W. ZONEAMENTOS DA VULNERABILIDADE AMBIENTAL E EXPECTATIVA DE PERDA DE SOLO: é possível usar a usle na determinação de vulnerabilidade ambiental?. Geociências, [S.L.], v. 38, n. 4, p. 1105-1119, 7 abr. 2020. UNESP - Universidade Estadual Paulista. DOI: http://dx.doi.org/10.5016/geociencias.v38i4.14083.

SOUZA, J. A.; AMORIM, R. F. de. Comportamento espaço-temporal da precipitação na bacia hidrográfica do Rio Potengi-RN. Revista de Geociências do Nordeste, [S.L.], v. 8, n. 1, p. 77-86, 14 mar. 2022. Universidade Federal do Rio Grande do Norte - UFRN. http://dx.doi.org/10.21680/2447-3359.2022v8n1id22006.

SOARES, D.L.; POLIVANOV, H.; BARROSO, E.V.; MOTTA, L.M.G.; SOUZA, C.C.. Soil Erodibility on Cutting Slopes of Unpaved Roads. Anuário do Instituto de Geociências - Ufrj, [S.L.], v. 41, n. 1, p. 179-193, 16 maio 2018. Instituto de Geociencias - UFRJ. DOI: : http://dx.doi.org/10.11137/2018_1_179_193.

SPÖRL, C; ROSS, J. L. S. ANÁLISE COMPARATIVA DA FRAGILIDADE AMBIENTAL COM APLICAÇÃO DE TRÊS MODELOS. Espaço e Tempo, São Paulo, n. 15, p. 39-49, 2004.

TEIXEIRA, R. B. O rio Potengi e a cidade do Natal em cinco tempos históricos. Aproximações e distanciamentos, Confins [Online] 2015, posto online no dia 12 Março 2015. DOI: https://doi.org/10.4000/confins.10114.

THOMA, A. C.; TASSINARI, D.; PRAT, B. V.; FERNANDES, J. S. C.; SILVA, A. C. Erodibilidade de Neossolo Litólico pelo ensaio de Inderbitzen modificado e eficiência de blocos de solo-cimento para controle da erosão hídrica. Engenharia Sanitaria e Ambiental, [S.L.], v. 27, n. 3, p. 511-522, jun. 2022. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/s1413-415220210099.

TORRES, D. M.; GOMES, M.D.B.; ANDRADE, E.K.F.; SILVA, R.D.R. ESTUDO DE CASO SOBRE A QUALIDADE DA ÁGUA DO RIO POTENGI NA CIDADE DE SÃO PAULO DO POTENGI, RIO GRANDE DO NORTE, BRASIL. Holos, [S.L.], v. 8, p. 1-15, 24 dez. 2019. Instituto Federal de Educacao, Ciencia e Tecnologia do Rio Grande do Norte (IFRN). DOI: https://doi.org/10.15628/holos.2019.9193.

TRICART, J. Ecodinâmica. Rio de Janeiro, IBGE, Diretoria Técnica, SUPREN, 1977. Disponível em: <https://biblioteca.ibge.gov.br/visualizacao/monografias/GEBIS%20- %20RJ/ecodinamica.pdf>.

TRIMBLE, S. W.; MENDEL, A. C. The cow as a geomorphic agent — A critical review. Geomorphology, [S.L.], v. 13, n. 1-4, p. 233-253, set. 1995. Elsevier BV. DOI: http://dx.doi.org/10.1016/0169-555x(95)00028-4.

URIBE, D; GENELETTI, D; CASTILLO, R. F. del; ORSI, F. Integrating Stakeholder Preferences and GIS-Based Multicriteria Analysis to Identify Forest Landscape Restoration Priorities. Sustainability, [S.L.], v. 6, n. 2, p. 935-951, 21 fev. 2014. MDPI AG. DOI: http://dx.doi.org/10.3390/su6020935.

VALENTE, R. A.; PETEAN, F. C. de S.; VETTORAZZI, C. A. MULTICRITERIA DECISION ANALYSIS FOR PRIORITIZING AREAS FOR FOREST RESTORATION. Cerne, [S.L.], v. 23, n. 1, p. 53-60, mar. 2017. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/01047760201723012258.

ZAPAROLI, F. C. M.; CREMON, E. H. Análise Comparativa entre Quatro Metodologias de Fragilidade Ambiental na Bacia Hidrográfica do Ribeirão Jangada, Noroeste Paulista. In: VIII SIMPÓSIO NACIONAL DE GEOMORFOLOGIA, 2010. Florianópolis. Anais [...] . 2010. Disponível em: <http://lsie.unb.br/ugb/sinageo/8/10/6.pdf>

ZHAO, J., JI, G., TIAN, Y., CHEN, Y., WANG, Z. Environmental vulnerability assessment for mainland China based on entropy method. Ecol. Indicat. 91, 410–422, 2018. DOI: https://doi.org/10.1016/j.ecolind.2018.04.016.