ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 9, nº 1 (2023)

https://doi.org/10.21680/2447-3359.2023v9n1ID31583

Environmental Vulnerability Mapping of the Bodó river sub-basin, in the region of Serra de Santana, Rio Grande do Norte State, Brazil

Mapeamento de Vulnerabilidade Ambiental da Sub-bacia do Rio Bodó, na região da Serra de Santana, estado do Rio Grande do Norte, Brasil

Raquel Cardoso Araújo[1]; Daniel Dantas Moreira Gomes[2]; José Yure Gomes dos Santos[3]; Marcelo Martins de Moura-Fé[4].

[1] Federal University of Rio Grande do Norte. Postgraduate Program in Geography (GEOCERES)/Caicó/RN, Brasil. Email: raquel.araujo.081@ufrn.edu.br
ORCID: https://orcid.org/0000-0002-6990-1021

[2] University of Pernambuco - UPE. Garanhuns/PE, Brasil. Email: daniel.gomes@upe.br.
ORCID: https://orcid.org/0000-0001-6868-040X

[3] Federal University of Rio Grande do Norte. Department of Geography at CERES/Caicó, RN, Brasil. Email: jose.yure.santos@ufrn.br.
ORCID: https://orcid.org/0000-0001-9840-8132

[4] Universidade Regional do Cariri. Departamento de Geociencias - Crato/Ceará, Brasil. Email: marcelo.mourafe@urca.br
ORCID: https://orcid.org/0000-0002-0336-557X

Abstract: The watersheds constitute a balanced natural system and are important planning units of water resources that make up the environmental systems. Considering the relevance of planning and environmental management today, this article aims to perform the mapping of the environmental vulnerability of the Bodó River sub-basin, in the region of Serra de Santana, RN, with the application of algebra of maps and integrated analysis of its physical and environmental variables. For this, maps of the slope, dissection index, geology, pedology, and vegetation were made. These maps were weighted according to their morphodynamic stability/vulnerability and then combined in map algebra. The map generated with the combination of these factors presented five vulnerability classes for the sub-basin in question: very weak, weak, moderate, strong and very strong. It is important to emphasize the need for studies aimed at quantifying with greater accuracy the environmental vulnerability in sub-basin areas and, in this way, to dictate the planning and environmental management of its resources with the sustainable management of its territory.

Palavras-chave: Map Algebra; Hydrographic Basin; Water resources. Geoprocessing.

Resumo: As bacias hidrográficas constituem um sistema natural equilibrado e são importantes unidades de planejamento dos recursos hídricos que compõem os sistemas ambientais. Considerando a relevância do planejamento e gestão ambiental na atualidade este artigo tem por objetivo realizar o mapeamento de vulnerabilidade ambiental da sub-bacia do Rio Bodó, na região da Serra de Santana, RN, com a aplicação de álgebra de mapas e análise integrada de suas variáveis físicas e ambientais. Para isso, foram confeccionados mapas de declividade, índice de dissecação, geologia, pedologia e vegetação. Esses mapas receberam pesos, conforme sua estabilidade/vulnerabilidade morfodinâmica e, posteriormente, combinados em álgebra de mapas. A carta gerada com a combinação desses fatores apresentou cinco classes de vulnerabilidade para a sub-bacia em questão: muito fraca, fraca, moderada, forte e muito forte. É importante destacar a necessidade de estudos com vistas a quantificar com maior acurácia a vulnerabilidade ambiental em áreas de sub-bacias e, desse modo, dirimir o planejamento e a gestão ambiental dos seus recursos com o manejo sustentável do seu território.

Keywords: Álgebra de Mapas; Bacia Hidrográfica; Recursos Hídricos; Geoprocessamento.

Received: 23/02/2023; Accepted:16/05/2023; Published: 10/06/2023.

1. Introduction

Environmental vulnerability studies include the mapping, analysis and knowledge of the potentialities and fragilities of a given study area. These researches show their importance in identifying what compromises the environmental balance of the place based on the degree of stability/vulnerability of the morphodynamic categories of landscape analysis (TRICART, 1977).

The hydrographic basins constitute a balanced natural system, where alterations to their physical environment can compromise their functionality, as the removal of vegetation cover can affect the temperature, the water regime and the resistance of the soil (LIRA; FRANCISCO; FEIDEN, 2022). According to Fistarol and Santos (2020), areas with inadequate soil cover can have high erosion rates that potentially compromise the natural stability of the hydrographic basins, causing serious environmental damage, such as the reduction of the productive capacity of soils, the erosion of watercourses and reservoirs, as well as the pollution of water sources (SANTOS et al., 2012). Ceconi et al. (2018) emphasize that the catchment basins for public supply deserve special attention by managers, since the quantity and quality of water depend on them, an indispensable element for the sustainability of life and a fundamental resource for various human activities. Moreover, the quality of the water of a spring, in addition to its uses, depends on the activities that take place in its basin, therefore, environmental planning of these units is of utmost importance, taking into consideration the interaction and integration of the systems that make up the environment (SILVA; SANTOS; LEAL, 2016).

Considering these assumptions, several studies have already been used for the analysis of environmental vulnerability and map algebra applied to hydrographic basins or sub-basins, highlighting those of Nicolau (2018); Rocha and Magri (2022); Lira and Feiden (2022); Zanella et al. (2013), among others that advocate the importance of these analyses, considering that several authors point to the hydrographic basin as an environmental unit that makes it possible to deal with the elements and dynamics necessary for the planning and management of environmental systems (SOUZA; VALE; NASCIMENTO, 2013).

The planning and management of environmental resources in the present century are relevant issues, especially considering the increasing climatic changes and the degradation of soils in fragile environments with high risks of desertification, as occurs in semiarid climate regions, such as the Seridó Potiguar. In this perspective, the studies of environmental vulnerability have the essential objective of indicating the potentialities and limitations of human use and occupation, with a view to contributing to the understanding of the spatial reality and possible interventions in it (SANTOS et al., 2006). According to Nicolau (2018, p. 294) the preparation of the environmental vulnerability map is an important resource that provides the understanding of the anthropic processes that directly affect the natural physical processes of a given basin, with the perspective of understanding which areas are potential or restricted to a certain type of use. For that reason, this instrument is so necessary, because the identification of the ideal areas can result in decision making, as well as in conservation measures and sustainable use of the territory.

It is important to highlight that land use/occupation is one of the factors that most aggravates environmental degradation and leads to the loss of soils. As well as the presence of limiting factors, such as slope, terrain roughness and the natural fragility of soils, when subjected to inefficient environmental management of natural resources, can increase the vulnerability of environmental systems.

Considering the above, the use of this environmental analysis methodology is justified for the Rio Bodó sub-basin, in the state of Rio Grande do Norte, considering that this unit covers the area of at least four municipalities of the Serra de Santana micro-region, which is an altitude region, sheltering important sites of geodiversity, natural-ecological resources and the sources of rivers of the important hydrographic basins of the state. In addition, the Rio Bodó sub-basin also has some tributaries that bathe this region and some water reservoirs and small barramentos along the basin that serve for animal provisioning and dessedentação for the local communities that make use of this water resource. It should be emphasized that the sub-basin in question presents a high index of anthropic pressure on the environmental systems, highlighting the use of the land for agriculture, extensive farming, urban occupation and, recently, for the installation of wind turbines in the areas of wind potential of the Serra de Santana. This pressure on environmental systems can lead to soil degradation, which involves the reduction of potential renewable resources, leading to land abandonment or "desertification" (ALMEIDA; ARAÚJO; GUERRA, 2010), especially if this degradation occurs in environments susceptible to desertification processes, such as semi-arid environments.

Thus, the environmental vulnerability chart constitutes an important analysis tool to support environmental planning and management for this important sub-basin of the state, considering the integration of the physical-environmental factors that compose it in the analysis of its potentialities and fragilities in relation to the use/occupation of the land and its water resources. Thus, this article aimed to map environmental vulnerability for the Rio Bodó Sub-basin, in the state of Rio

Grande do Norte/RN, with the application of map algebra and multicriteria analysis from the use of Geoprocessing and GIS techniques for the elaboration of the environmental vulnerability chart. With this, it is intended to analyze in an integrated way the physical-environmental aspects, which imply the potential fragility of the natural and anthropized environments, and to classify them, according to the degrees of morphodynamic stability/vulnerability of the landscape.

2. Characterization of the study area

The study area in question is the Bodó River Sub-basin (Figure 1), which is located in the state of Rio Grande do Norte, Northeast Brazil, between the municipalities of Santana do Matos, Bodó, Lagoa Nova and Cerro Corá, in the Serra de Santana microregion. Its main tributaries are the Piató, Diogo, Onça, Carnaúba, and Maria Francisca streams (to the north); the Cafuca river and the Dois Rios stream (to the south); the Poço dos Cavalos river (to the east); the Cafuca river, the Curralinho stream and the Grota da Fervedeira (to the west). All these watercourses have an intermittent regime and a dendritic drainage pattern (CPRM, 2005). According to the new IBGE (2017) division, the studied area is inserted between the limits of the immediate regions of Currais Novos and Açu, respectively, in the intermediate regions of Caicó and Mossoró.

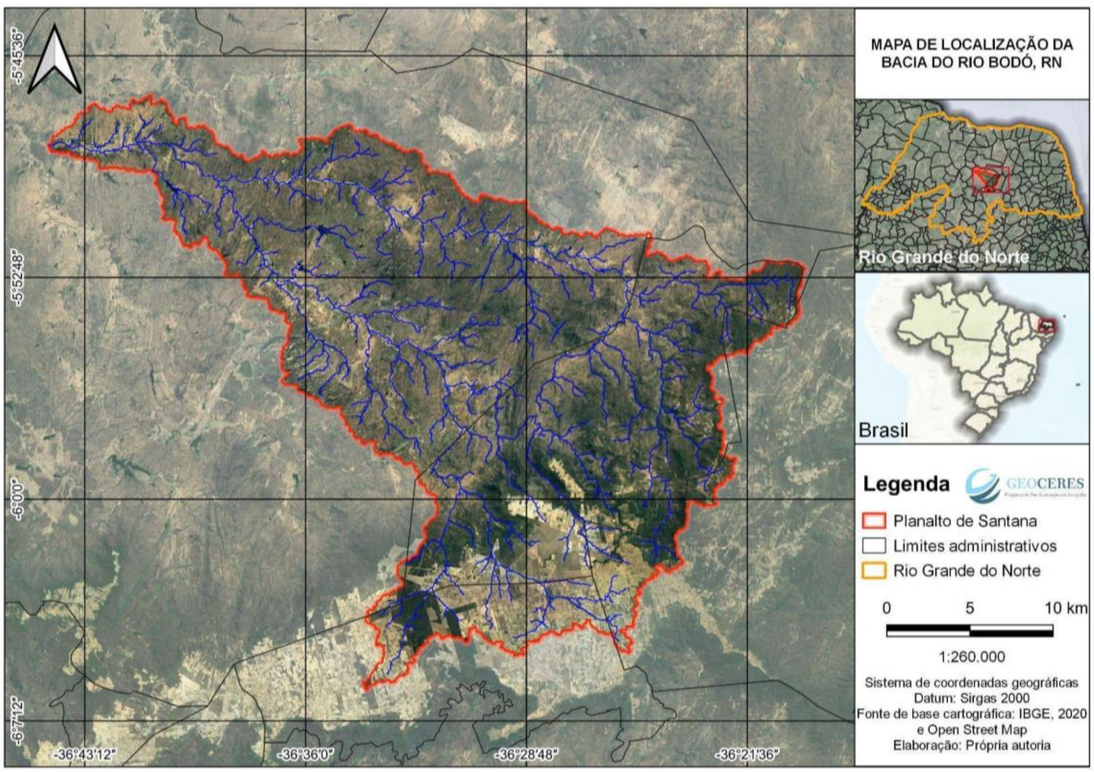

Figure 1 - Location Map of the Rio Bodó Sub-basin, RN.
Source: IBGE (2020); Open Street Maps. Prepared by: authors (2022).

In regional terms, the Bodó River sub-basin is inserted in the Piranhas-Açu River hydrographic basin. Its basin extension area is 665.9 km^2 , its perimeter is 258.659 and the KC of the basin is 2.81, which means that this basin is not subject to large hydrological processes of floods and floods. The relief of the study area is characterized by the following geomorphological units: Serras de Santana and Cuité; Depressão Sertaneja Setentrional; Encostas Orientais do Planalto da Borborema and Serras Ocidentais do Planalto da Borborema (IBGE, 2023). The average altitude of the basin varies from 63 to 723 meters, and the declivities vary from 0 to 55° (SRTM, 2000).

The geology of the study area is constituted by the lithotypes of the Caicó Complex; rocks of the Seridó Group, represented by the Seridó and Jucurutu formations; by the granitoid of the Poço da Cruz, Itaporanga and Brazilian Indiscriminate Granitoids suites; by the sediments of the Serra dos Martins Formation, as well as, Alluvial Deposits; Old

Alluvial Deposits and by the São João do Sabugi intrusive suite (CPRM, 2019). The soil classes found in this area are: LAd - Latossolo Amarelo Distrófico; RLe - Neossolo Litólico Eutrófico; SNo - Planossolo Nátrico Órtico and TCo - Luvissolo Crômico Órtico (IBGE, 2023). Finally, the climate of the region is characteristic of areas of high altitude humid heaths, occurring the climate Aw' (hot and humid tropical, with summer showers and dry winter) according to the Köppen classification, with average annual rainfall of 800 mm (FARIAS, 2016).

3. Methodology

3.1. Mapping stages

For the mapping of potential environmental vulnerability, the following stages were subdivided: I) mapping of the potential vulnerability variables; II) weighting of the factors, in which the situations in which there is a predominance of pedogenesis receive values close to 1, passing through intermediate situations (to which values close to 2 are attributed) and situations of predominance of morphogenesis processes (to which values close to 3 are attributed); III) multicriteria analysis and map algebra.

For the composition of the cartographic base for the creation of the maps, the Digital Elevation Model (DEM), from the *Shuttle Radar Topography Mission* (SRTM), with a spatial resolution of 30m, and Sentinel-2 satellite imagery, dated October 12, 2021, were used. The images and the DEM were acquired from the *United States Geological Survey* (USGS). For the composition of the cartographic base, we used the historical archives of the Instituto Brasileiro de Geografia e Estatística (IBGE), of the Programa Nacional de Levantamento e Interpretação de Solos do Brasil (PRONASSOLOS) and the geological historical archives of the geological-geophysical charts of the CPRM, at a scale of 1:100.000.

Regarding the delimitation of the basin, the SRTM 30 m DEM was used, which had the pre-filled depressions from the tool "r.fill.dir", being necessary the extraction of meias-basins, flow direction and drainage, from the use of the tool "r.watershed". After this stage, the basin was delimited from the outlet point, using the tool "r.water.outlet". The "water.outlet" tool generates a hydrographic basin from a drainage direction map and a set of coordinates, which represents the outlet point of the basin (QGIS, 2022).

After the delimitation of the basin, the raster file generated was converted into a vector file, from which the basin geometry calculations were extracted, such as area, perimeter, and the Compatibility Coefficient (KC), which was calculated from **Equation 1**, using the values of area and perimeter.

$$Kc = 0{,}28 \cdot \frac{A}{P} \tag{1}$$

Where Kc is compactness coefficient (dimensionless); P bay perimeter (m); A drainage area (m²).

A priori, the morphometric variables of declivity and geomorphology (Relief Dissection Index) were combined in order to generate the vulnerability factor for geomorphology. Then, this morphometric factor of the basin was combined with physical-environmental factors, such as: Pedology, Vegetation, Geology and Climate. This mapping was adapted according to the methodologies used by Crepani et al. (2001) and Ross (1994), which derive from Tricart's (1977) concept of Ecodynamics. Crepani (2001), in turn, used the variables of the dissection index of the relief, rock, soil and vegetation cover and established equal importance for the environmental variables in the study of environmental vulnerability for the ecological-economic zoning.

To generate the declivity map, the SRTM 30 m DEM was used, which had the pre-filled depressions from the "r.fill.dir" tool of the Qgis 3.22 *software*. From the previously treated DEM, the slope of the basin was extracted using the "slope" tool. After this step, the raster was reclassified according to the slope intervals recommended by Ross (1994).

For the Relief Dissection Index (RDI) mapping, the methodology of Ross (1994) and Guimarães et al. (2017) was used, where the latter subdivided this mapping into four main stages: the treatment of the digital elevation model, the mapping of the degree of channel filling, the mapping of the average interfluvial dimension for each basin, and the integration of these last two products. For this research, the same methodological procedures described by Guimarães et al. (2017) for automating the IDR were adopted, however, it is highlighted that different from the referred research, the processing stages were performed using the Qgis 3.22 *software* with the 30 m DEM. Thus, the procedures for the generation of the IDR consisted of the following stages: I) treatment and preparation of the DEM, using the "r.fill.dir"; II) generation of an inverted DEM; III) generation of the meander-baffles and flow direction, from the "watershed" tool; IV) vectorization of the meander-baffles; V) application of the statistics to the vectorized file from the use of the tool "zone statistics"; VI) calculation of geometries, vertical and horizontal dissection in the attribute table, later, calculation of the dissection index of the relief; VII) rasterization of the vector file and classification of the dissection classes.

For the classification of the intervals of the generated raster file, the classification proposal 3 of Guimarães et al. (2017) was used, in which the intervals were divided into: very weak, weak, moderate, high and very high relief dissection. In the confection of the other variables, the historical data of soils, vegetation and geology were used, the latter from the mosaic of the geological-geophysical charts of the CPRM, using the Açu, Lajes, Currais Novos and Santa Cruz sheets.

3.2. Multicriterial analysis and map algebra

For the diagnosis of environmental vulnerability, the degrees of fragility and instability resulting from the product of the combination of all factors were considered, as observed in pre-existing methodologies, such as those of Nicolau (2018); Tavares, Romão and Oliveira (2020) and Crepani et al. (2001), which, based on the principles advocated by Tricart (1977), established the evaluation according to the stability of morphodynamic categories.

In this sense, we used the methodology of Crepani et al (2001) in which the factors received the weights according to the morphodynamic categories of each analyzed factor, thus, when there is prevalence of pedogenesis, it presupposes the stability of the factors; when there is prevalence of morphogenesis, it presupposes that the variables present instability, as can be observed in Table 1. Thus, this stage was divided into: weighting of the vector information planes; reclassification of the rasters according to the weights attributed; conversion of the weighted vectors to raster; the combination of the factors in the raster calculator of Qgis 3.22 and, finally, the classification of the vulnerability values in the raster file properties.

Table 1 - Morphodynamic categories for vulnerability values.

Morphodynamic category	Pedo/Morfogênese ratio	Value
Stable	Pedogênese prevails	1,0
Intermediary	Balance Pedogenesis/Morphogenesis	2,0
Unstable	Prevalence of Morfogênese	3,0

Source: Adapted from Crepani et al (2001). Elaboration: Authors (2022).

In turn, the vulnerability scale of the basic territorial units, recommended by Crepani et al. (2001), is based on criteria developed from the principles of Tricart's Ecodynamics (1977), which establishes the following morphodynamic categories (Table 2). Based on these parameters, it was possible to weight the factors, considering the stage of morphodynamic evolution and the vulnerability attributed to each factor, applying the weights individually to the themes Geomorphology (IDR and Declivity), Geology, Soils and Vegetation.

Table 2 - Morphodynamic categories of vulnerability based on Tricart (1977).

Stable Means	Meios intergrades	Strongly unstable means
Dense vegetation cover; moderate dissection; and absence of volcanic manifestations.	Balance between the morphogenetic and pedogenetic interference.	Agressive bioclimatic conditions; vigorous soil dissection; presence of bare soils; lack of dense vegetation cover; plains and valley floors subject to flooding; and intense internal geodynamics.

Source: Adapted from Crepani et al (2001). Elaboration: Authors (2022).

For the weighting of morphometric factors, we used the standard recommended by Ross (1994), Becker and Egler (1996); Crepani et al. (2001) and Nicolau (2018), who proposed that values close to 1.0 of the vulnerability scale are associated with small slope angles of the hillsides, a situation in which the solo-forming processes of pedogenesis prevail. Meanwhile, values closer to 3.0 are associated with situations of the greater declivity, strongly undulating to steep or dissected reliefs in ridges, where the erosive processes of morphogenesis prevail (Table 3).

Table 3 - Vulnerability to declivity classes.

Morphometric classes	Declivity (%)	Vulnerability
Muito Baixa	< 6	1,0
Baixa	6 - 12	1,5
Media	12 - 20	2,0
High	20 - 30	2,5
Very High	> 30	3,0

Source: Adapted from Ross (1994) and Crepani et al (2001). Elaboration: authors (2022).

According to Ross (1994), the criteria used for the pedology variable include the characteristics of texture, structure, plasticity, degree of particle cohesion and depth/thickness of the surface and subsurface horizons. Therefore, they are directly related to the relief, lithology, climate, driving elements of pedogenesis and determining factors of the physical and chemical characteristics of the soils. Thus, the more developed the soil classes are, the more porous, well-drained and deep they are, the less vulnerable they will be and the more they will receive weights according to their stability. The less developed they are, i.e., shallow, young and susceptible to erosion, with morphogenesis prevailing, they will receive values according to the degree of their instability (Table 4).

Table 4 - Vulnerability/Stability values for the Pedology variable.

Soil classes	Legenda	Vuln./ estab.
Latossolo Amarelo Distrófico	LAd	1,0
Optical Planossolo Nátrico Órtico	SNo	2,0
Luvissolo Chronic Optical	TCo	2,0
Eutrophic Litholithic Neossolus	RLe	3,0

Source: Adapted from Crepani et al. (2001). Elaboration: authors (2022).

Similarly, for the other factors, the instability criteria were considered for each variable, attributing relative weights to vulnerability/stability and, subsequently, converting each theme from *shapefile* format to raster format.

Subsequently, in the Qgis 3.22 raster calculator, the map algebra was performed, which corresponds to the combination of the analyzed variables, resulting in the landscape vulnerability map, based on an empirical equation (Equation 2):

$$V = \left(\frac{G+R+S+V_g+C}{5}\right) \quad (2)$$

Where: V is vulnerability; G vulnerability for the Geology theme; R vulnerability for the Geomorphology theme; S vulnerability for the Solos theme; Vg vulnerability for the Vegetation theme; C vulnerability for the Climate theme.

Then, the generated raster was recoded to extract the areas of each class using the "r.report" tool of Qgis 3.22. Finally, the area information in km² was exported to an Excel table in order to quantify the percentage for each vulnerability class attributed to the Rio Bodó sub-basin.

3. Results and discussion

For this research, base-maps for the composition of the map algebra were elaborated. Among these maps we highlight the morphometric variables of the relief, which correspond to the geomorphological factor, being these: Declivity and Relief Dissection Index (ROSS, 1994).

The declivity is an important morphometric variable of the relief to be used in terrain vulnerability analysis, because the higher the terrain declivity, the higher the speed and transport capacity of rainwater, contributing to the erosive process of the soil (LIRA; FRANCISCO; FEIDEN, 2022). For Ross (1994) the analysis of relief fragility involving medium or small scales should be based on the shape standards with topographic roughness or the Relief Dissection Index Matrix, considering that relief dissection is greater in areas where deep, V-shaped, channeled valleys predominate, with small inter-fluvial dimension, characterized by high slopes (GUIMARÃES et al., 2017).

Considering these assumptions, the first slope map (**Figure 2**) presents six slope classes for the Rio Bodó sub-basin. It can be observed that gentle to undulating slopes (between 0 to 12) predominate in the areas surrounding the exutório and also in the south-southwestern part of the basin, where part of the Serra de Santana plateau is located. The most accentuated declivities correspond to the erosive escarpments of the Serra de Santana and Inselbergues of the geomorphological units Serras Ocidentais do Planalto da Borborema, which present a dissected morphology. These slopes are found in the middle and lower part of the basin (south-southeast) of the Slope Map, corresponding to about 23.13% of the basin. The gentle and gently undulating slopes correspond to 76.9% of the total surveyed area.

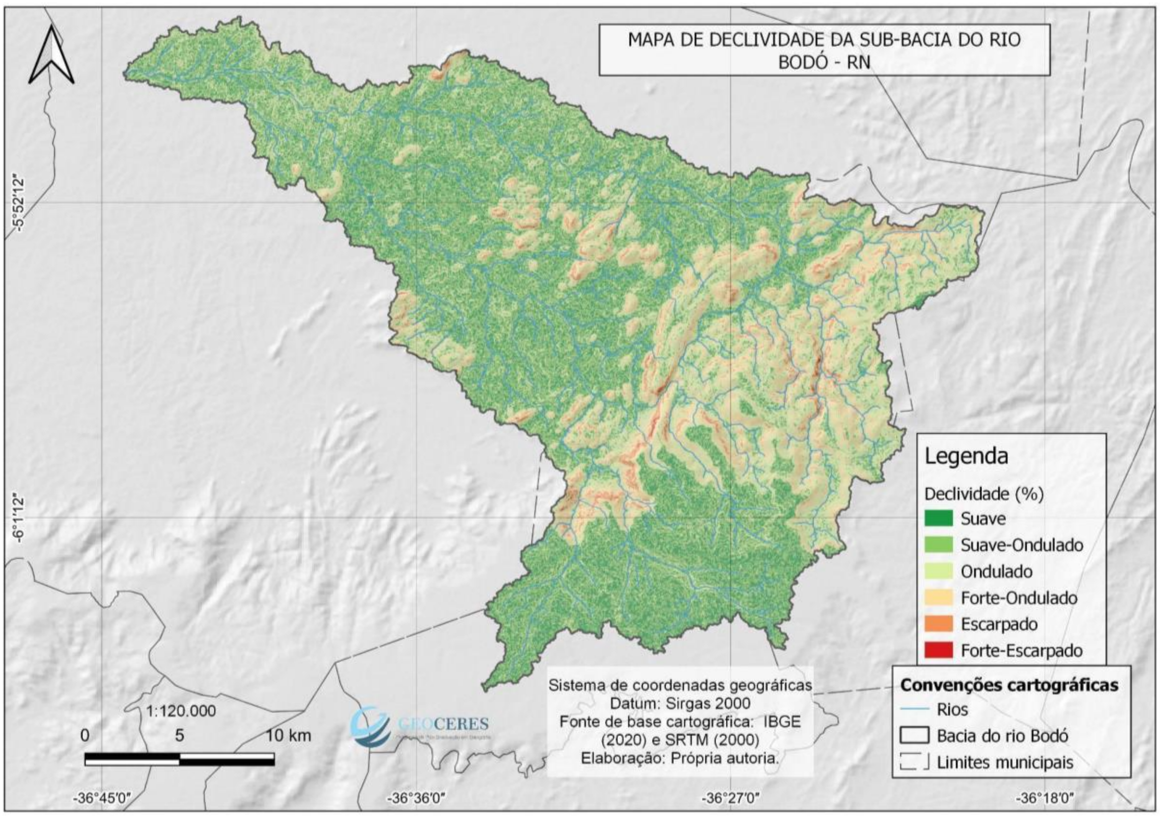

Figure 2 - Declivity Map of the Rio Bodó Sub-basin, RN.
Source: SRTM (2000); IBGE (2022). Prepared by: authors (2023).

The Relief Dissection Index (RDI) map, in turn, presented four dissection classes for the study area, being: weak, moderate, strong and very strong index. It is important to highlight that the dissection matrix of the relief presents very high values for the areas with "V" vales, extremely steep and declining, common in environments of high energy and high altimetric gradient. According to Crepani et al. (2001) the larger the interfluves (or the lower the intensity of dissection) the lower the values attributed to the natural landscape units in the vulnerability scale; Likewise, the natural landscape units with the lowest interfluves (or the highest dissection intensities) receive higher values on the vulnerability scale, considering that morphogenesis processes predominate, in general, to the detriment of pedogenesis.

For this research, the dissection matrix of the relay presented values varying between 14 and 55 that, according to the proposed automation of the IDR, according to Guimarães et al. (2017), correspond respectively to the low and very high dissection classes. Thus, the areas of the basin with very high and high dissection corresponded to 33.4% of the total; the areas with moderate dissection corresponded to about 0.6% and the areas with low dissection corresponded to 66% of the total area of the basin. It should be noted that the high and very high dissectional classes were obtained in the steep areas of the basin, which have steep, fairly dissected vales and a corresponding high altitudinal amplitude (above 600 m). Meanwhile, the weak dissection class corresponded to the areas with flat tops and weak declivity (Figure 3), related to the Santana mountain range and its lateritic cover planned on the top.

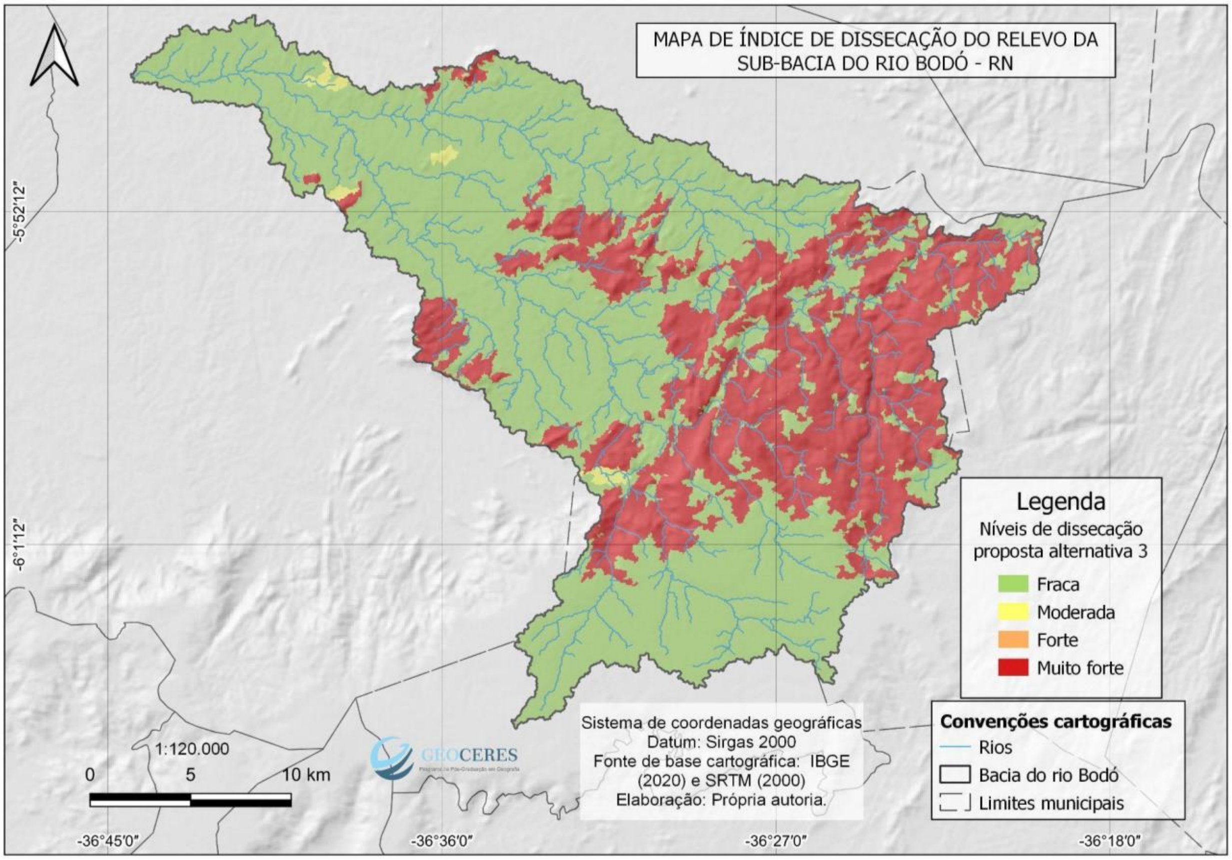

Figure 3 - Relay Dissection Index Map – IDR.
Fonte: Ross (1994), adapted from Guimarães et al (2017).: Prepared by: authors (2023).

For the other variables that made up this analysis, we considered the degree of vulnerability of each factor in relation to the morphodynamic categories of relay stability (TRICART, 1977).

Vegetation is an important variable to be applied to studies of environmental vulnerability, considering that the density of vegetation cover is a protective factor of the beds and the soil against erosive processes, especially for the capacity of interception of precipitation by the canopy of the trees, reducing the capacity of the "splash" and consequent breakage of the aggregates. Thus, the areas with a density of native vegetation species and of more arboreal size, receive weight 1.0, considering the protective factor of the vegetation cover on the soil. However, the areas occupied by agricultural activities, farming and urbanized areas receive higher weights, considering that the bare soil presents greater susceptibility to erosion processes, and activities such as agriculture and livestock farming promote soil compaction and consequent susceptibility to rain erosion processes, which lead to the loss of soil and accentuate the desertification processes in these areas.

Regarding the vegetation classes found, the class Savannah-Tree Forest (68.1%) received the lowest weights, taking into account the stability conferred by vegetation in relation to morphogenetic processes. Meanwhile, the classes Agriculture with Permanent Cultures (14.0%), Agriculture (14.7%) and Urban Influence (0.4%) had the highest weights in terms of the use of their potential and anthropization of the area, which leads to deforestation, accentuation of erosion processes, environmental degradation and scarcity of water resources. For the vegetation cover considered moderately vulnerable, values between 2.3 and 2.6 on the vulnerability scale were reserved, highlighting the vegetation class Savannah-Sepic Park, as weighted in the methodology of Crepani et al. (2001).

It is important to highlight the role of vegetation in the analysis of environmental vulnerability of the landscape, since vegetation plays the role of delaying the entry of water from rainfall into drainage currents by increasing the infiltration capacity of the soil (FLORENZANO, 2008). Thus, vegetation cover is, therefore, directly linked to the protection capacity of the soil against erosive processes, as well as a denser vegetation cover allows the development of pedogenesis, favoring the development and maturity of the soils.

For the study area, six vegetation classes (Figure 4) were identified in the study area according to IBGE (2021), being: Continental Water Body, Savana Estépica Arborizada, Savana Estépica Parque, Agriculturas com Culturas Permanentes, Agropecuária and Influência Urbana.

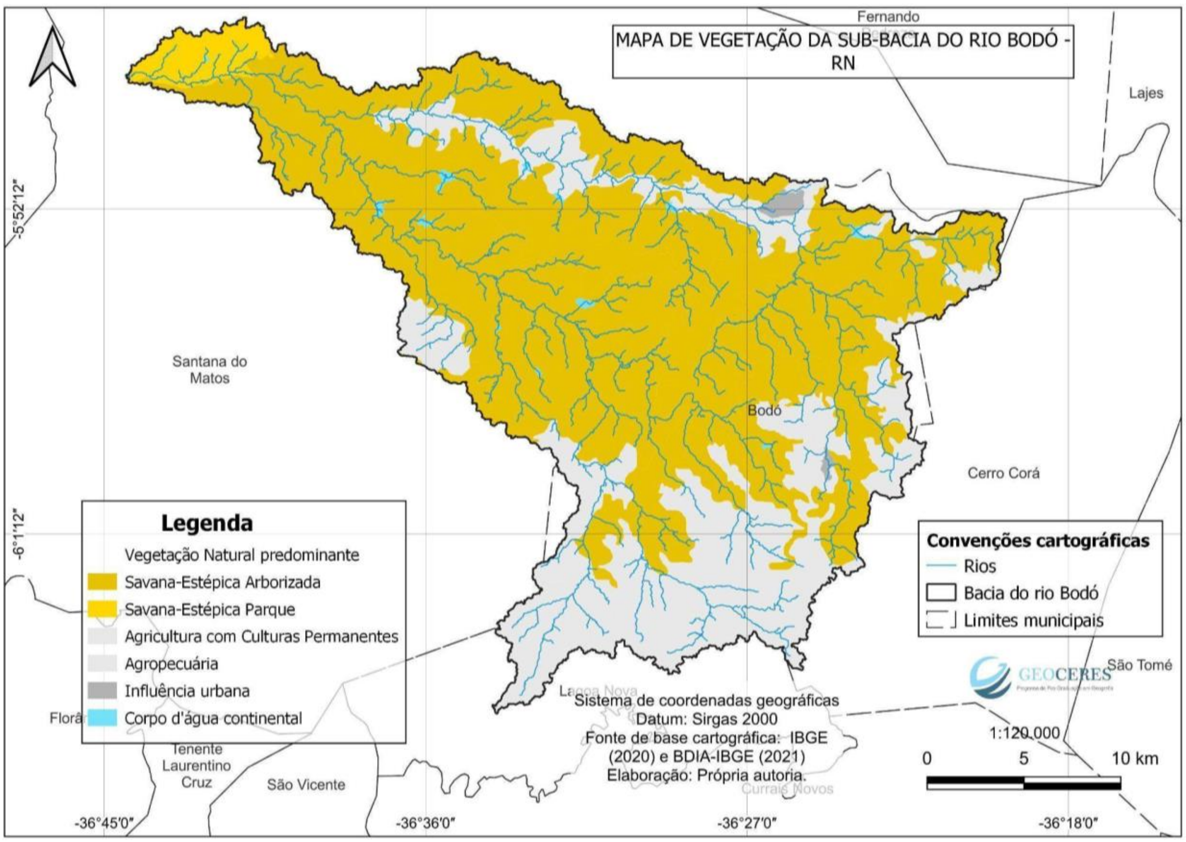

Figure 4 - Vegetation Map of the study area
Source: IBGE (2021); IBGE (2021). Prepared by: authors, 2023.

The vegetation class with the largest territorial extension is the Savana Estépica Arborizada with about 453.65 km²; Agricultura com Culturas Permanentes, with about 93.17 km²; Agropecuária with 97.7 km² and Savana-Estépica Parque with an area of 15.6 km². The classes that received the highest weights according to their morphodynamic instability were: Agropecuária and Urban influence. The classes considered moderately instability or intergrades were: Savanna Estépica Parque and Agriculturas con Culturas Permanentes, due to the anthropization of native vegetation to make room for permanent cultures. The classes considered stable, which received lower weights according to the prevalence of pedogenesis over morphogenesis, were: Savana Estépica Arborizada and Corpo de Água continental.

For the solo variable (Figure 5), it is highlighted that the classes of solos found in the study area are: LAd - Latossolo Amarelo Distrófico (18%); RLe - Neossolo Litólico Eutrófico (33.5%); SNo - Planossolo Nátrico Órtico (33.2%) and TCo - Luvissolo Crômico Órtico (15.3%).

The Latossolos are found predominantly in flat reliefs, in the Santana mountain range plateau, which is located in the south-southeast portion of the sub-basin and which presents vulnerability classes classified as stable, because, in general, pedogenesis predominates to the detriment of morphogenesis. According to Tavares, Romão and Oliveira (2020) the Latossolos are well-developed, deep and well-structured soils, with a predominance of aggregations, being considered more mature soils, with high porosity. In addition, this type of soil is in flat relief, although the predatory use of this pedological resource for agricultural practices and anthropic occupation can lead to its degradation and accentuate the erosive processes on the land.

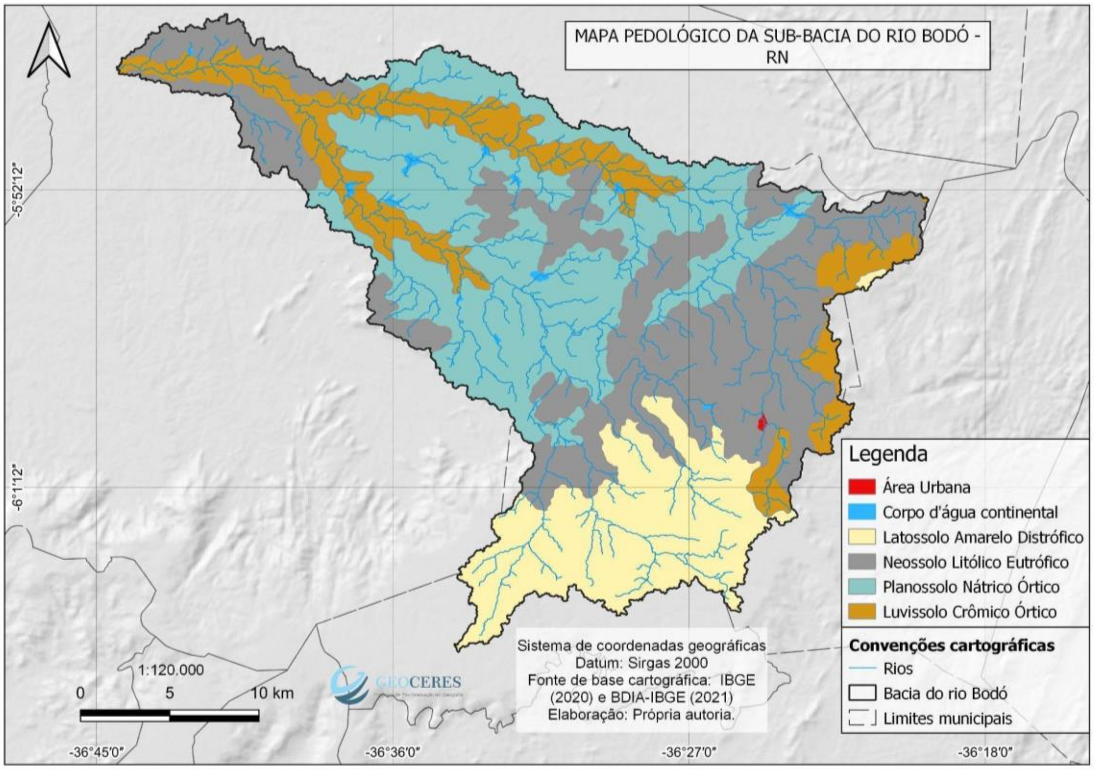

Figure 5 - Pedological Map of the Rio Bodó sub-basin, RN.
Source: Adapted from IBGE (2021). Prepared by: authors (2023).

The class Neossolo Litólico Eutrófico, in turn, is characterized as a class of young and sandy soils with low water retention capacity, being interpreted as very vulnerable to erosion and with low agricultural suitability (TAVARES, ROMÃO; OLIVEIRA, 2020). Thus, this type of soil presented greater instability, especially considering that they generally occur on steep slopes with a high percentage of declivity, with a predominance of morphogenesis, and erosive processes prevailing in this area of the sub-basin.

As explained by Saraiva et al. (2021), the Nátricos plains in a semiarid environment have a contrasting differentiation between the surface and subsurface horizons (flat B). On the surface the horizons are more sandy and permeable, which abruptly change to a compacted and more silty horizon with very restricted permeability, sometimes constituting a horizon that is responsible for the detention of the suspended water lenol. Therefore, this soil class presents intermediate vulnerability, considering that the abrupt differentiation of the horizons and its fragmented sandy and stony texture can make it susceptible to erosive processes, especially in a context where there is inadequate management of this pedological resource. In the same way, the classes of the chronic mudstones received intermediate weights in relation to their morphodynamic stability, since they present abrupt textural changes of the horizons and, generally, are only medium/argillaceous and stony textured soils, being susceptible to processes of laminar erosion, mainly considering that they are found in alluvial plains subject to flooding.

For the geology factor (Figure 6**),** the analysis of the morphodynamics category considers information related to the history of the geological evolution of the environment and the degree of cohesion of the rocks that compose it (FLORENZANO, 2008). The degree of cohesion of the rocks is the basic geological information to be integrated from the Ecodynamics, since the cohesive rocks prevail over the modifying processes of the relief supported by these lithologies.

Thus, for the present research, it was considered that the igneous rock classes are more stable in relation to the vulnerability of the landscape, since they present greater resistance to mining weathering, as Crepani et al. (2001) pondered.

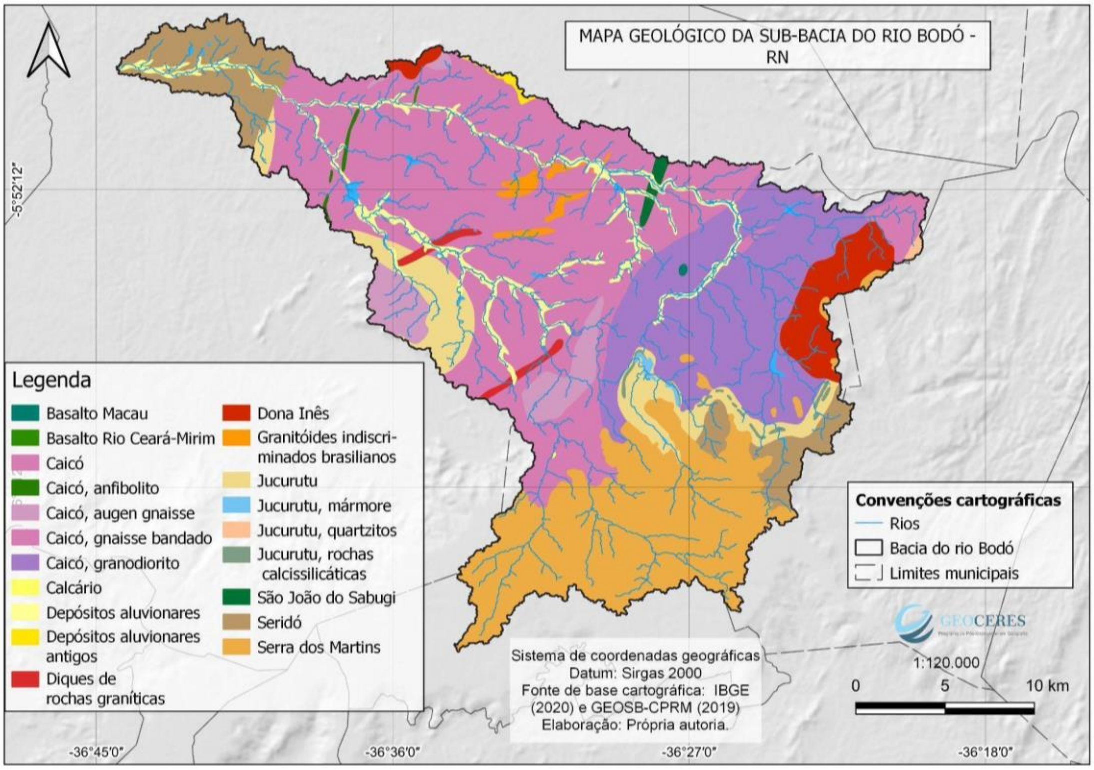

Figure 6 - Map of geological units of the study area.
Source - CPRM (2019). Prepared by: authors, 2023.

The metamorphic rocks, in turn, showed moderate stability for the sub-basin, considering the prevalence in the study area of rocks resistant to weathering processes, such as quartzites and gneisses; and others with lower resistance, such as marmore and granulites. It should be emphasized that the lithological differences between these units accentuate processes of relief instability, sometimes as a function of topographic and altimetric ruptures, such as the occurrence of diaclases, fracture planes associated with fractures and lineaments, as well as the formation of massifs and blocks in beds with a high percentage of the declivity, which can lead to severe erosive processes and mass movements.

Regarding the sedimentary rocks and related deposits, in general terms and considering the spatial scale of the research, these received greater weights, highlighting the unconsolidated limestones, argillites and other materials found in recent deposits, as well as polymitic conglomerates and sandstones, which occur mainly in Cenozoic alluvial plains of clastic composition and unconsolidated sedimentary rocks, because although the clastic sedimentary rocks present stability ensured by the diagenesis of the mostly homogeneous materials that compose them, fundamental for their resistance to weathering and erosion processes, the same cannot be guaranteed in relation to the aggregate that they form and many of them are cold or fissile (CREPANI et al., 2001).

Climate, in turn, is an important variable to be considered in environmental vulnerability analysis, especially the rainfall variable that directly interferes with the water erodibility capacity of a given area. For the study area in question, the Rainfall Map (Figure 7) presents rainfall intervals that vary from 752 to 882 mm, distributed in four intervals that vary from 752 to 782 mm; 782 to 797 mm; 797 to 818 mm e 818 to 882 mm.

It is observed in the referred map that the areas of higher pluviometric density correspond to the most dissected terrains, that is to say, the vertical temperature gradient and the humidity of the slopes to the west directly influence the amount of precipitation that the area receives and, consequently, also the climate. In addition, the north and east-facing slopes receive more humidity than the opposite slopes, which are located to the leeward. However, it should be noted that the sub-basin area is inserted in a semi-arid region, although the more dissected and high altitude areas have different characteristics from their surroundings, mainly, in the hypsometric intervals between 680 and 740 m, which confers a small decrease in the average rates of temperature and evapotranspiration and an increase in precipitation and fog in relation to its surroundings (MEDEIROS, 2019).

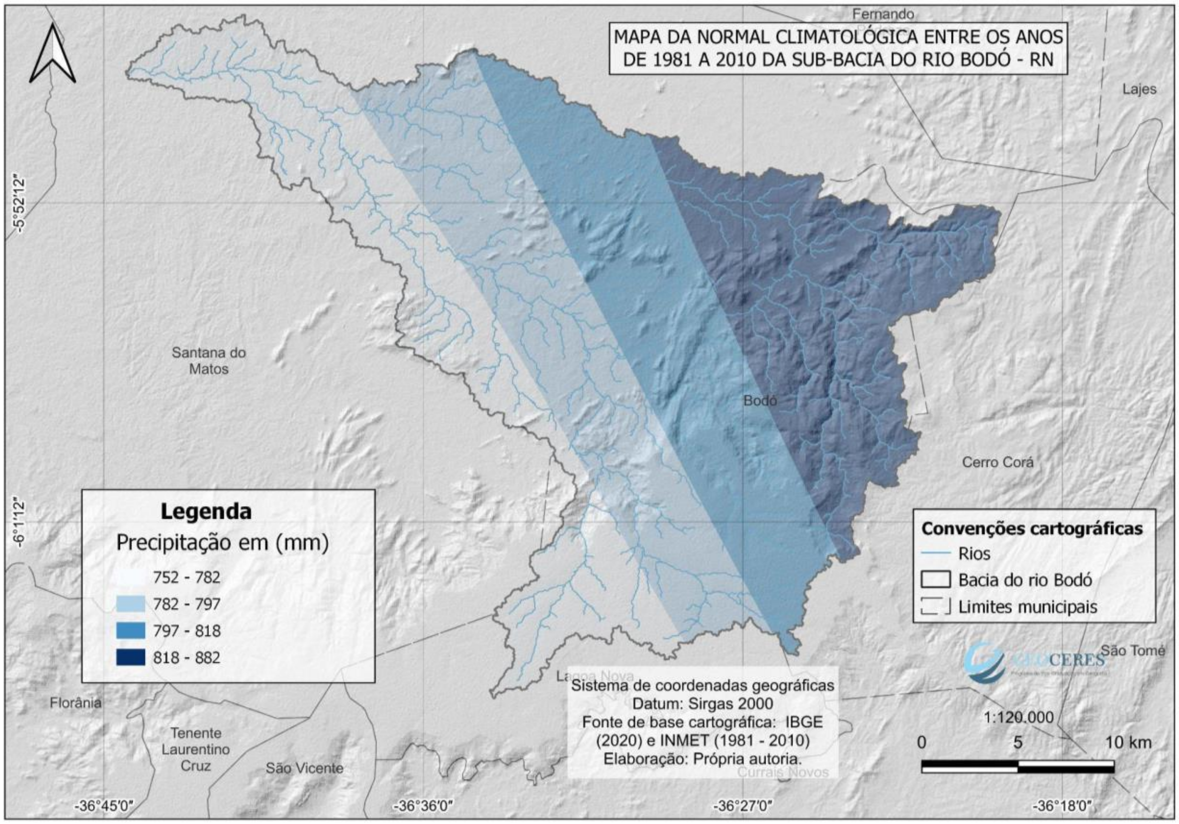

Figure 7 - Pluviometry Map.
Source: IBGE (2020); INMET (1981-2010). Prepared by: authors, 2023.

For the analysis of vulnerability based on the rainfall variable, Crepani et al. (2001) were considered in relation to the capacity of water erodibility, based on rainfall intensity, considering that areas with higher rainfall indices receive higher weights, since the higher the values of rainfall intensity, the greater the erosivity of the grape. Thus, the values from 818 to 882 mm received weights of 3.0, mainly considering that these rainfall indices occur predominantly in the wet areas of the slopes of the basin, where a higher percentage of humidity naturally occurs than in the surrounding area. On the other hand, areas with lower precipitation rates received lower weights.

All these factors combined resulted in the Environmental Vulnerability Chart applied to the Rio Bodó sub-basin, in the state of Rio Grande do Norte (Figure 8), which presented five vulnerability classes distributed for the area of the referred basin: very weak, weak, moderate, strong and very strong vulnerability.

Analyzing the referred map, it is perceptible that the very weak and weak vulnerability classes are distributed, above all, in the areas of occurrence of flat to gently undulating relief, with low relief dissection, as well as where the water reservoirs occur, due to the protection factor of the river margins and the influence of the ciliary vegetation. Likewise, it coincides with lands occupied by more stable soil classes, such as the Yellow Dystrophic Latossolos Amarelos and areas of preserved vegetation cover.

For the moderate vulnerability class, it was observed that they occur in the border areas between the stable and unstable classes of the sub-basin, which is configured as a moderately stable/vulnerable environment. In the adopted scale, they correspond to terrains that present undulating to strongly undulating relief; geologically instáveis areas (sedimentary); medium stable/vulnerable solo classes, such as the Luvissolos and Neossolos, and anthropized areas, such as those occupied for agricultural practices.

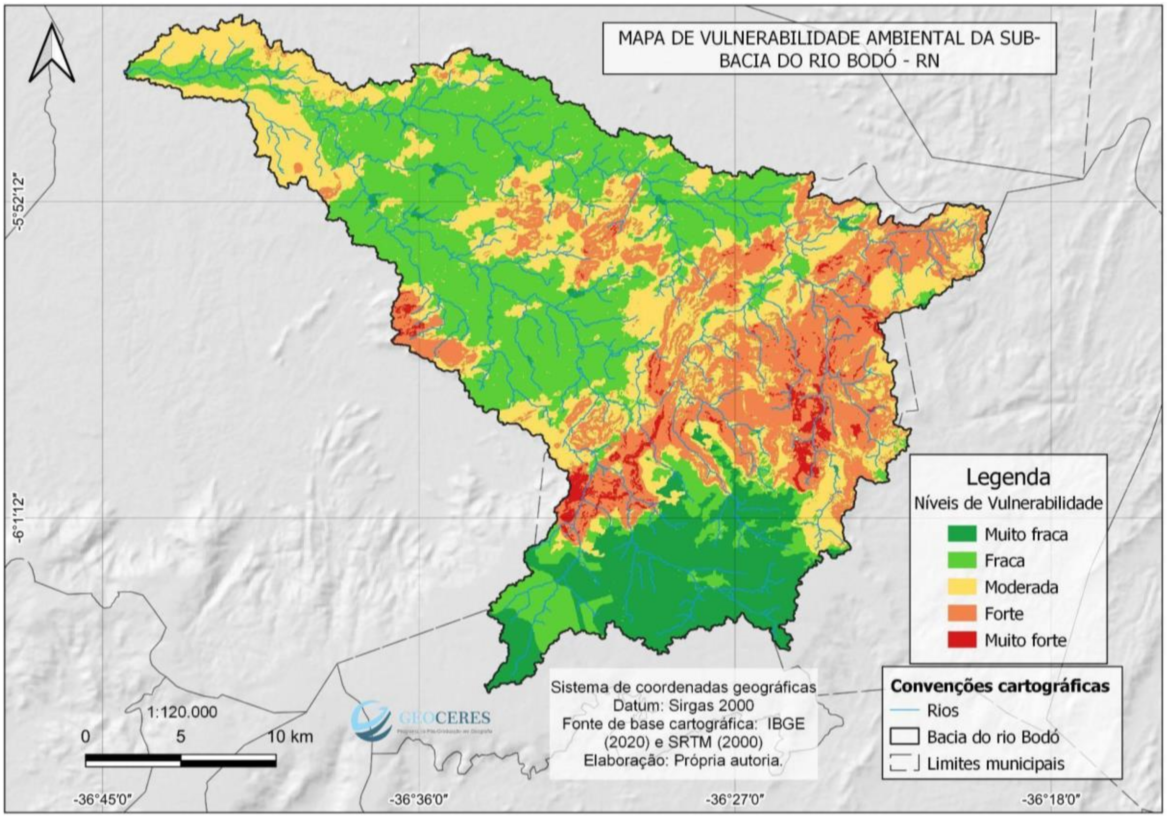

Figure 8 - Environmental Vulnerability Chart applied to the Rio Bodó sub-basin, RN.
Source: IBGE (2020); SRTM (2000); data from previously elaborated maps. Prepared from: authors, 2023.

Regarding the high and very high vulnerability classes, in turn, it was observed that they are distributed in areas of steep relief, strongly dissected, where the young and poorly developed soil classes occur, such as the Neossolo Litólico class. In these areas, there is an intense rugosity, where the highest humidity and rainfall indices prevail, due to the vertical temperature gradient and morphometric aspects, such as the orientation of the slopes. In this class, the predominance of morphogenesis over pedogenesis is accentuated, being strongly susceptible to relief-forming processes, weathering and erosive processes, and mass movements in slopes of the accentuated declivity. Likewise, in addition, it coincides with areas occupied by agricultural practices and lithologic contacts.

Considering the morphodynamic classes of landscape vulnerability analysis obtained for the sub-basin in question, it was found that 12.5% of the area studied corresponds to the very low vulnerability classes; 36.19% to the low class; 28.02% corresponds to the moderate class; 21.24% to the high vulnerability class and about 2.08% corresponds to the very high vulnerability class of the landscape (Figure 9). Thus, it can be observed that in the study area, there is greater stability of the landscape to morphodynamic processes, such as erosion, mass movements, among others, for the flatter areas of the relief, with a predominance of more developed soils, however, the importance of studies on a larger scale of detail to corroborate these data and quantify possible errors or discrepant data for analysis is emphasized.

Regarding the landscape units that presented greater instability/vulnerability, it was observed that they occur in areas of the accentuated gradient of the declivity, presenting strongly dissected relief, with the predominance of poorly developed soils, with a general prevalence of morphogenesis processes to the detriment of pedogenesis. The same was verified in areas that are occupied for agricultural practices, agriculture, and low density of vegetation formation. These areas, it is worth mentioning, naturally have unstable conditions, but the anthropic factor tends to accentuate this natural fragility, leading to their degradation and potential loss of soils and their dynamic equilibrium.

It should be noted that the areas of steep relief (those with slopes > 45%) are protected by the current Brazilian Forest Code (BRAZIL, 2012), as they are considered Permanent Preservation Areas (PPAs), as well as the edges of the plains, as is the case of the flat relief included in the limits of the basin in question (BRAZIL, 2012). Similarly, the margins of perennial or intermittent watercourses are also included in this protection factor, therefore, it is of utmost importance that the management and use of land in hydrographic basins take into consideration the fragility of the land in relation to the pressures exerted and its capacity for regeneration and dynamic equilibrium.

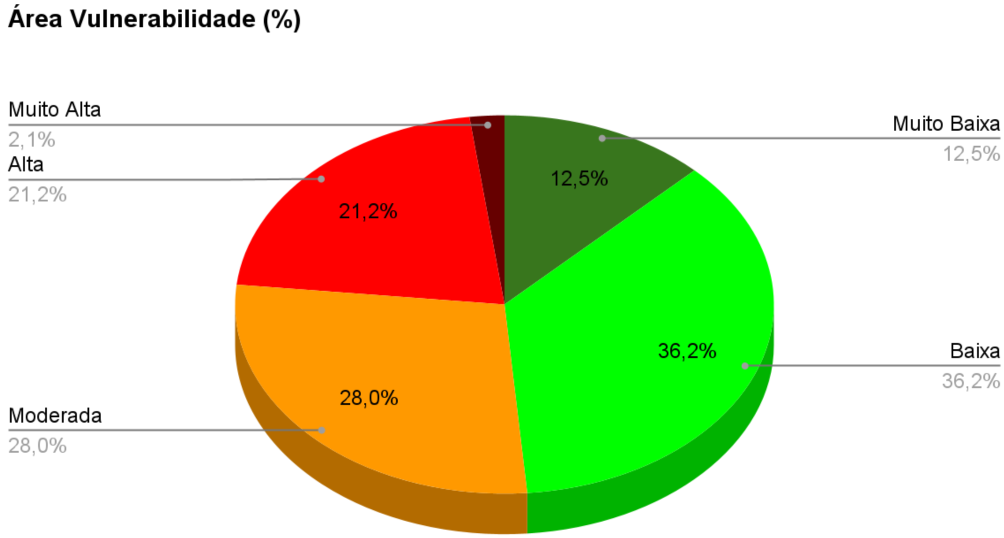

Figure 9 - Graph of environmental vulnerability areas for the Rio Bodó sub-basin, RN. Source: research results. Prepared by: authors (2022).

5. Final considerations

The results of this research pointed to the association between the high environmental vulnerability factor and the morphogenetic processes, mainly in the steep slopes of the relief that delimit this basin. It is important to emphasize that the predominant morphogenetic processes in the high altitude areas that delimit the basin can lead to a greater loss of soil and, consequently, to the deposition of these sediments in the watercourses, causing the accumulation of water bodies. This can accentuate the risks of flooding and inundation processes in the plains areas, which is aggravated by agricultural practices, the clearing of the rainforest, and the exploration of mineral resources, causing the degradation of the land and the loss of its natural fertility.

In this sense, the environmental vulnerability chart is an extremely important instrument for the planning and environmental management of natural resources in the territory and it can help in the decision making process based on the zoning of the installation areas, assisting in the identification of the environmental liability. Thus, the Environmental Vulnerability Chart for the Rio Bodó sub-basin can be used to contribute to the discussion of the decision-making processes for this planning unit and, consequently, subsidize the environmental protection of environmental resources in these systems.

In spite of the results achieved, it is also important to highlight the need for new studies, as well as the use of other methodologies and field research in more detailed spatial clusters, which can more accurately quantify the potential fragility of the sub-basin and direct the correct environmental management of its resources and potential, prioritizing the sustainable management of the territory.

References

ALMEIDA, J. R.; ARAÚJO, G. H. DE S.; GUERRA, A. J. T. *Environmental Management of Degraded Areas.* 6. ed. Rio de Janeiro: Bertrand Brasil, 2010. 322 p.

BATISTA, J. P. G.; DA SILVA, F. M. Evaluation of the environmental fragility of the Cajazeiras creek watershed in the semi-arid region of Potiguar. *Boletim Goiano de Geografia*, v. 33, n. 1, p. 53-72, 2013.

BECKER, B. K.; EGLER, C. A. *Detailing of the methodology for the execution of the ecological and economic zoning by the States of the Legal Amazon.* Brasília: SAE/MMA, 1996, 43p.

BRAZIL. *Law 12651 of 25 May 2012*. Provides for the protection of native vegetation. National Congress. Available at: http://www.jusbrasil.com.br/legislacao/1032082/lei-12651-12. Accessed on: 06 Dec. 2014.

Ceconi, D. E., Piccilli, D. G. A., Bernardi, F., & Fensterseifer, P. (2018). Analysis of vulnerability for environmental planning of a water supply basin. *Ambiente e Sociedade*, *21*. https://doi.org/10.1590/1809-4422asoc0078r2vu18l1ao.

CREPANI, E., et al. Remote Sensing and Geoprocessing Applied to Ecological-Economic Zoning and Land Use Planning. São José dos Campos, SP: *INPE,* Jun. 2001, 113 p.

CPRM - Geological Survey of Brazil. *Project cadastre of subway water supply sources.* Diagnosis of the municipality of Bodó, state of Rio Grande do Norte. Organized [by] João de Castro Mascarenhas, Breno Augusto Beltrão, Luiz Carlos de Souza Junior, Saulo de Tarso Monteiro Pires, Dunaldson Eliezer Guedes Alcoforado da Rocha, Valdecílio Galvão Duarte de Carvalho. Recife: CPRM/PRODEEM, 2005.

CPRM. - Serviço Geológico do Brasil. 2019. Project: Crustal evolution and metallogeny of the Mineral Province of Seridó. Vector files (shp) Geological chart of the sheet Currais Novos - SB.24-Z-B-II; Açu - SB.24-X-D-V; Santa Cruz- SB-24-Z-B-III e Lajes - SB-24-X-D-VI. Geographic Coordinates System, SIRGAS-2000. Scale 1:100.000.

FARIAS, P. K. P. *Genesis and soil survey of Serra de Santana in the Seridó Potiguar.* Mossoró, RN. f. 82, 2016. Dissertation (Master in Soil and Water Management). Universidade Federal Rural do Semiárido. Pró-reitoria de Pesquisa e Pós-graduação, Mossoró, 2016.

FISTAROL, P. H. B.; DOS SANTOS, J. Y. G. Implications of changes in the use and occupation of the solo in the solo losses of the Bacia do Rio de Ondas, Bahia State. *Revista OKARA: Geografia em debate***,** v. 14, n. 1, p. 81-103, 2020. João Pessoa, PB, ISSN: 1982-3878.

FLORENZANO, T. G. *Geomorphology: concepts and current technologies.* São Paulo: Oficina de Textos, 2008.

GOMES, R. L. Assessment of environmental fragility and natural vulnerability to soil loss in the Almada River watershed. *Boletim de Geografia*, v. 31, n. 3, p. 41-53, 2013.

GOUVEIA, I.C.M. C.; ROSS, J.L.S. Environmental Fragility: a Proposed Application of Geomorphons to the Relief Variable. *Revista do Departamento de Geografia-USP*, v. 37, p. 123-136, 2019. Available at: https://10.11606/rdg.v37i0.151030. Acesso em: 20 jun. 2021.

GUIMARÃES, F. S. et al. A Proposal for the Automation of the Index of Relief Dissection. *Brazilian Journal of Geomorphology,* v. 18, n. 1, 2017.

IBGE. Brazilian Institute of Geography and Statistics. *Environmental Information Database* - BDIA. 2023. Available from: https://bdiaweb.ibge.gov.br/. Acesso em: jan. 2023.

IBGE. Brazilian Institute of Geography and Statistics. *Database by municipalities of the Immediate and Intermediate Geographic Regions of Brazil.* Rio de Janeiro: IBGE, 2017.

IBGE. *Technical Manual of Brazilian Vegetation.* 2 ed. Rio de Janeiro, 2012.

LIRA, K. C. S.; FRANCISCO, H. R.; FEIDEN, A. Classification of environmental fragility in a watershed using fuzzy logic and AHP method. *Sociedade & Natureza.* Uberlândia, MG, v. 34, e62872, 2022, ISSN 1982-4513.

LUCENA, C. Y., LEAL DE SOUZA, J., QUEIROZ DA SILVA, B., SANTIAGO REIS, J., & LUNA LUCENA, R. (2022). The Serra de Santana in the Northeastern semi-arid region: geographic aspects and possibility of sustainable practices. *Revista Geográfica De América Central, 1*(70), 449 - 476. Available from https://www.revistas.una.ac.cr/index.php/geografica/article/view/16549. Accessed on: 10 Jan. 2023.

MARWELL, D. T. B. *Environmental vulnerability assessment in the Area of Direct Influence of the Agreste Branch and in the intermittent and ephemeral watercourses intercepted by this project using the AHP method and geoprocessing techniques*. Brasília - DF, 2015. 34 p. Monograph (Specialization course in environmental geoprocessing) - Universidade de Brasília, Brasília - DF, 2015.

MEDEIROS, D. B. S. *Mapping and integrated analysis of the landscape units (geofacies) of the Seridó Potiguar.* 2019. 200f. Dissertação (Mestrado em Geografia) - Centro de Ciências Humanas, Letras e Artes, Universidade Federal do Rio Grande do Norte, Natal, 2019.

MEDEIROS et al. Evaluation of environmental vulnerability in the area of the São Joaquim settlement, Selvíria/MS. *Caminhos de Geografia.* Uberlândia, MG. v. 15, n. 49, p. 126-137, 2014.

NICOLAU, R. F. Landscape vulnerability to soil loss in the Rio do Peixe watershed - Goias. *Caminhos de Geografia*, Uberlândia - MG, v. 19, n. 66, p. 285-296, 2018.

PRONASSOLOS. *National Program for Surveying and Interpreting the Brazilian Soils* - PronaSolos. Geoportal - Embrapa solo. Available at: Pronasolos (cprm.gov.br). Accessed on: 1 Jun. 2022.

RAMALHO FILHO, A.; BEEK, K. J. *System for assessing the agricultural aptitude of land.* Rio de Janeiro: EMBRAPA-CNPS, 1995. 65 p.

ROSS, J. L. S. Empirical analysis of the fragility of anthropized natural environments. *Geography Department Journal*, v. 8, p. 63-74, 1994.

ROCHA, L. B. de O.; MAGRI, R. A. F. Prediction of soil loss by laminar erosion in the hydrographic basin of Ribeirão Bocaina, Passos - MG. *Revista Caminhos de Geografia.* Uberlândia-MG, v. 23, n. 87, p. 153-174, 2022.

SAATY, T.L. A scaling method for priorities in hierarchical structures. *J. Math. Psychol.*, v.15, p.234-281, 1977. https://doi.org/10.1016/0022-2496(77)90033-5

SAATY, T. L. The Analytic Hierarchy Process. McGraw Hill, New York, 1980. How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48: p. 9-26, 1990.

SANTOS, J. Y. G.; SANTOS, C. A. G.; SILVA, R. M. Water and soil losses using simulated rainfall on different surface covers and moisture conditions in the semi-arid Paraíba state. *Revista Brasileira de Recursos Hídricos*, 17(4): 217-228, 2012.

SANTOS, P. A. F.; et al. Fragilidade Ambiental da bacia do Rio Ipiranga - PR. *VI Simpósio Nacional de Geomorfologia/Regional.* Conference on Geomorphology. Goiânia, 2006.

SARAIVA, S. M. FRAGA, V. S.; ARAUJO FILHO, J. C.; SANTOS, R. F.; FELIX, E. S.; CAMPOS, M. C.; DIAS, B. S.; CARNEIRO, K. A. A. A. Characterization of Natric Planosols in a rainfall gradient in the Brazilian semiarid region. In: RIBEIRO, J. C. (org.). *Education in soils and the environment.* Ponta Grossa: Atena Editora, 2021. chap. 1, p. 1-13.

SILVA, M. P; SANTOS, F. M.; LEAL, A. C. Environmental Planning of the Olga Stream Hydrographic Basin, UGRHI Pontal do Paranapanema. São Paulo. *Soc. & Nat.* Uberlândia, 28 (3): 409-428, set/dez/2016. DOI: http://dx.doi.org/10.1590/1982-451320160307.

SOUZA, S. O.; VALE, C. C.; NASCIMENTO, F. H. Peruípe River Basin (BA): morphometric classification test using SRTM data. *Revista Caminhos de Geografia.* Uberlândia, v. 14, n. 47 Set. 2013 p. 208-222. ISSN 1678-6343.

SPORL C. Analysis of soil-relief environmental fragility with the application of three alternative models in the upper basins of the Jaguari-Mirim, Quartel and Prata rivers. *GEOUSP - Espaço e Tempo*, 2001.

SPÖRL, C.; ROSS, J. L. S. Comparative analysis of environmental fragility with application of three models. Geousp - *Space and Time*, São Paulo, n. 15, p. 39-49, 2004.

TAVARES, K. S. R.; ROMÃO, P. A.; OLIVEIRA, I. J. Environmental Vulnerability in the Municipality of São Domingos (GO). *Brazilian Journal of Physical Geography*. v. 13, n. 05, p. 2212-2232, 2020.

TRICART, J. *Ecodynamics.* Rio de Janeiro: IBGE/SUPREN, 1977, 91p.

ZANELLA, M. A.; OLÍMPIO, J. L.; COSTA, M. C. L.; DANTAS, E. W. C. Socioenvironmental Vulnerability of the Lower Cocó River Basin, Fortaleza-CE. *Soc. & Nat***.,** Uberlândia**,** 25 (2): 317-332, 2013.