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Papers

Environmental Vulnerability of the Buriticupu River Watershed, Maranhão State – Brazil: Relief as a Key Element

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Abstract
Studying a watershed in the Amazon region requires understanding that this region has national and global relevance. The fact that the study area is located in the so-called arc of deforestation raises the need to understand its context, its vulnerabilities, and its physical, environmental, and anthropic components. This research assesses the environmental vulnerability of the Buriticupu River Watershed in Maranhão State, Brazil. The aim is to foster improvements that may contribute to environmental planning and, specifically, to water resource management. For this purpose, the authors used the Geographic Information System environment to work with Map Algebra, interrelating primary and secondary data on geology, relief, pedology, and land use and land cover to generate synthesis cartography. The results pointed to areas with predominantly medium vulnerability. However, the analyses highlight alluvial plains, which became the most fragile areas from an environmental point of view. This is mainly because these areas comprise water-saturated soils (gleysols), unconsolidated deposits of sand and silt (alluvial deposits), and extensive humid vegetation, characteristics of igapó and floodplain forests. This research generated a document that applies is applicable to the study area. It also provided, in a systemic and integrated way, a product that will help in planning, which is very important for the creation of a watershed committee, something necessary and still embryonic in Maranhão State, Brazil.

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INTRODUCTION

Articles discussing environmental vulnerability draw the attention of the scientific community. These articles include several applications in the most varied scales of analysis and different areas. The study by Crepani *et al*. (2001), perhaps one of the most cited, is fundamental for those who address vulnerability in assessing propensity to soil loss based on morphogenesis and pedogenesis processes. Due to the importance of that study in the context of ecological-economic zoning in the Amazon, its authors began to be widely mentioned in the academic/scientific community. This is because they created a concrete and coherent methodology, providing thematic mapping and synthesis cartography.

The vulnerability study methodology underwent many adaptations over the years in light of the technological advances in map generation and the ability to overlap and interrelate landscape elements. In addition, its theoretical variations have helped researchers reach certain specific objectives. Vulnerability, fragility, and susceptibility – each with its own specificities – were all fundamental to build methodologies that can be applied to the current and complex reality of the study areas.

In these processes, several authors used methodologies already established for analyzing environmental vulnerability (CREPANI *et al*., 2001) and environmental fragility (ROSS, 1990; 1994) in areas that underwent substantial adaptations. Some authors even used simplifications of these methodologies in their studies. This has placed the variable relief – a fundamental element in the entry and exit of matter and energy in the environmental system – in the background. Relief is the element capable of redistributing such endogenous and exogenous forces. Therefore, understanding it is fundamental to this methodological puzzle.

Gouveia and Ross also highlighted this situation (2019, p. 124), stating that such problems occurred due to “technical difficulties and difficulties concerning the time spent to prepare intermediate cartographic products”. In this sense, the possibility of obtaining vector and raster data in the most varied scales and available for free brought two situations. On the one hand, positive aspects emerged due to the ease and speed in obtaining and generating maps. On the other hand, distortions emerged from the scalar point of view (detailing), being very common.

Guirra *et al*. (2016), Ross and Fierz (2017), and Gouveia and Ross (2019) explored variable relief in their studies. This is one of the variables that most suffer from simplifications, mainly due to the lack of geomorphological detail and identification of relief units, devaluing the importance of river plains. These latter are commonly classified as low vulnerability classes because they have a flat slope, which, in reality, does not express the actual vulnerability of such areas. These are places with dynamics linked to soil erosion and flooding episodes. The use of such cartographic documents in planning ends up masking environmental and legal restrictions and propitiating an inappropriate use.

Bringing this discussion to the vulnerability bias is fully applicable. According to the United Nations Development Program, vulnerability is a process resulting from physical, social, economic, and environmental factors that determine the probability and scale of damage from some type of impact and/or certain hazard (UNDP, 2004). Plain areas will appear in this bias due to the probability of occurrence of land instabilities and episodes of periodic flooding.

Environmental vulnerability is a valuable tool for understanding the relief-soil relationship in face of the disorderly intervention of society on natural resources (BRUGNOLLI *et al*., 2014). This system presents little resistance to maintain itself in continuous balance (ARGENTO, 1979), and this balance can be broken whenever there is anthropic interference (SPÖRL, 2007). The consequences will depend on the greater or lesser vulnerability of these areas, whatever the scale of analysis.

The applied scale and study area of this research consists of an important watershed in Maranhão State, Brazil: the Buriticupu River Watershed (BHRB). This watershed is located in eastern Maranhão State, already in the Amazon region, and faces massive environmental problems. These include landscape fragmentation, removal of native vegetation, socioenvironmental conflicts, indigenous lands, agriculture, pastures, mining activities, among other various uses and conflicts that intertwine in this complex watershed region.

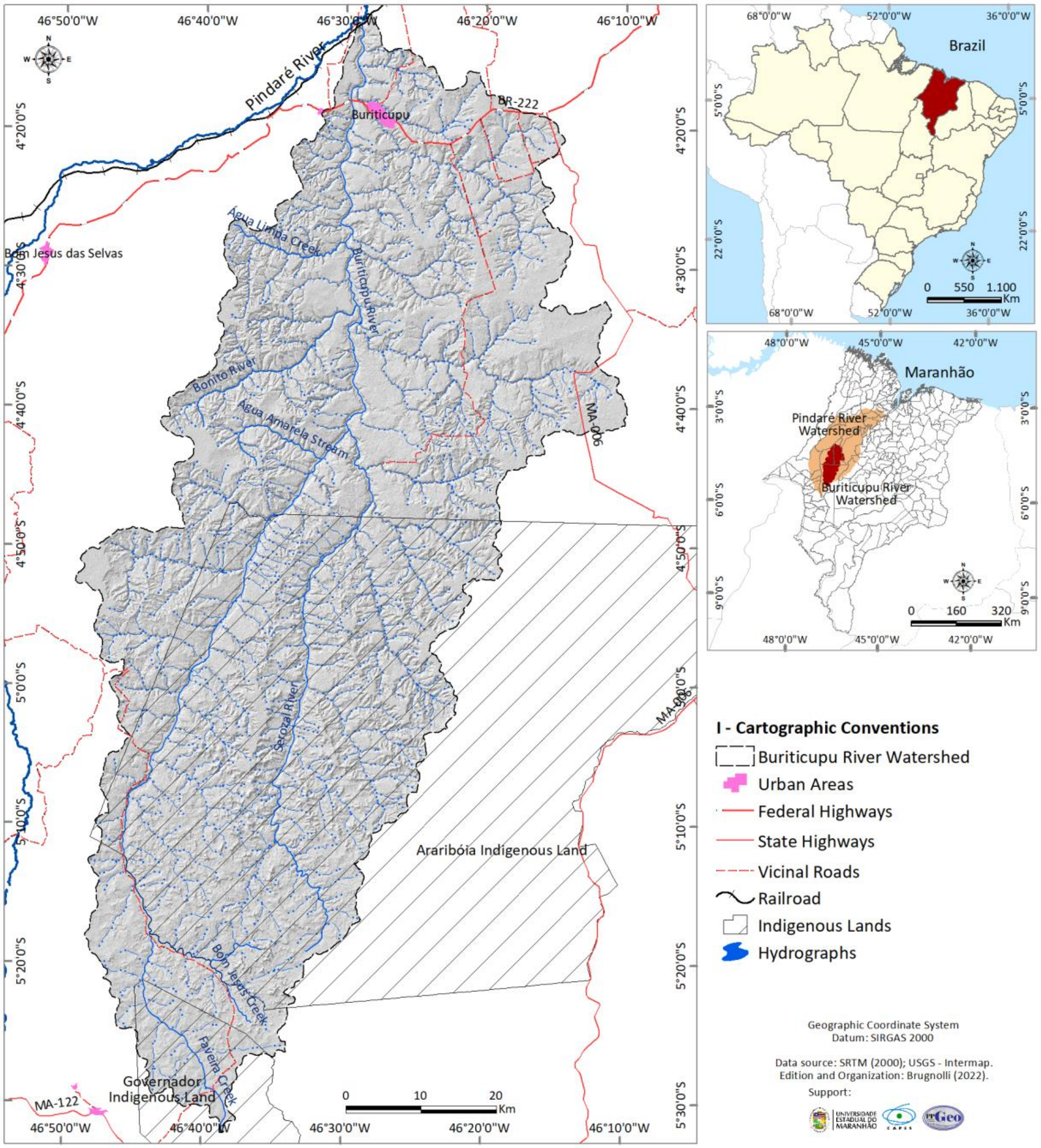
It is a region with a predominance of two indigenous lands in the high and middle courses: Araribóia and Governador. Both these lands are preserved, contrasting with the increase of anthropic use, especially pastures and agriculture that advance to the edges of indigenous lands. This situation has been causing conflicts, imposing the need to study this watershed from the point of view of vulnerability. Not to mention the fact that the watershed covers the Gurupi Mosaic, which, according to Celentano *et al*. (2018), encompasses six Indigenous Lands (Alto Turiaçu, Awá, Caru, Arariboia, Rio Pindaré, and Alto Rio Guamá) and one Conservation Unit (Gurupi Biological Reserve).

Therefore, understanding this watershed from an environmental point of view is fundamental to remedy and/or minimize its problems and provide information that helps in the production of an effective database. This is an important step for fostering a committee for the watershed in which the BHRB is inserted, namely the Pindaré River Watershed. This type of tool helps to make better use of geographic space as it indicates which areas are most vulnerable not only to natural processes, but mainly to anthropic actions. It thus allows to point out the potential of environments in a systemic way, indicating the restrictions of use in these watersheds.

In view of the above, the present study assesses, in an analytical-synthetic way, the environmental vulnerability of the BHRB. For that, the authors surveyed data on rocks, relief (declivity, hypsometry, and geomorphological compartments), soils, land use and land cover. Considering the methodology employed, the delimitation of geomorphological units stands out due to its importance in relation to hydrosedimentological processes.

The Buriticupu Watershed (BHRB) covers 5,342.27 km² and is a tributary of the right bank of the Pindaré river. The latter is one of the most important and most degraded rivers in the Maranhão Amazon, making up the eastern edge of the Legal Amazon. The Buriticupu river has its sources in the highest areas of the Araribóia Indigenous Land, which is preserved and has large embedded valleys and steep slopes. From its source to its mouth, the Buriticupu river runs 169.07 km (Figure 1).

Figure 1 – Location of the Buriticupu River Watershed, Maranhão State, Brazil



Source: The authors (2022)

METHODOLOGY

The first step of the methodology of this study consists of a geological analysis. For that, the authors used data made available in the GeoBank portal of the Companhia de Pesquisa de Recursos Minerais (CPRM, 2013), public company linked to the Mines and Energy Ministry with the attributions. The data was also linked to Instituto Maranhense de Estudos Socioeconômicos e Cartográficos (IMESC, 2020), state agency responsable for mapping and social, economic, and environmental analysis in Maranhão; and the Instituto Brasileiro de Geografia e Estatística (IBGE), the main agency that makes available geographic and statistical information in Brazil. All these mappings have different scales of detail, thus requiring a field trip to analyze the veracity of information and correct the polygons that proved to be wrong/inaccurate. For the latter purpose, the authors used the Geographic Information System environment through QGIS Desktop 3.22.5.

The field trip lasted five days and covered the BHRB (Figure 2) area during the dry period of 2021 (September). The equipment used consisted of a Portable GPS Garmin eTrex 22x SA, a camera, and a DJI Mavic Drone. Even with Geoprocessing being the main focus of this step, the authors highlight that the field trip is fundamental to promote an actual panorama and validate the information contained in official state and national bodies. Silva and Berezuk (2021) mention that the field can never be replaced in the face of the cognitive and sensory experiences it brings with it, essential in helping to build geographic knowledge.

Figure 2 – Photographs taken in the field trip.

Source: The authors (2021).

The field trip was fundamental in all methodological steps. From this articulation, field work has always been one of the most important instruments in the development of the geographical perspective. More than describing and interpreting in detail the physical-natural features of a given area, it includes formulating methods and concepts. These should lead to an integrated, systemic, and organic understanding amenable to application in Physical Geography.

Pedological analysis included data from IMESC and IBGE that also went through long processes of correction of the mapping polygons. The field trip was essential for this conference. The products used for mapping soil polygons were the following: road profiles, retention boxes on unpaved roads, Digital Terrain Model (DTM Alos Palsar), and satellite images (Sentinel 2B).

Relief mapping had three basic steps in which the authors used DTM Alos Palsar resampled to a 12.5-meter pixel, available at the Alaska Satellite Facility. This model underwent preprocessing in order to eliminate noise and spurious pixels (influence of vegetation on pixels). With regard to hypsometry, the authors used contour lines and altitudes from the BHRB. For slope, the authors considered data from the Sistema Brasileiro de Classificação de Solos (SIBCS), which is a soil taxonomic system, with the purpose of classifying all existing soils in Brazil, as well as data from Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA, 2018), a public company that provides agricultural data from Brazil; data used to link relief to slope classes. The last mapping consisted of the generation of an unpublished document of the BHRB relief based on information from IMESC and IBGE. At this step, the authors determined nomenclatures identified and described in the field with the aid of a DJI Mavic Drone (mapping through aerial photogrammetry), DTM Alos Palsar (to identify existing features), satellite images, and shaded relief (hillshade).

For land use and land cover, collection 6 from MapBiomas (2020) was used that consists of a mapping using the Landsat 8 – OLI sensor image. As MapBiomas (2020) emphasizes, the classification methodology is dynamic and procedural to improve the classification of each typology. In order to seek greater detail, the authors compared these data with images from the Satellite Sentinel 2B (USGS, 2020), in addition to carrying out the aforementioned field trip.

Finally, in generating the environmental vulnerability map, the authors grouped cartographies using a Raster Calculator in QGIS Desktop 3.22.5, applying the method called Map Algebra. This step corresponds to a cartographic superimposition in which each element will have a weight over the other, a pixel-by-pixel combination that will result in synthesis cartography. The procedures can be subtraction, addition, and multiplication. In this case, equation 1 was used:

Equation 1 – Environmental Vulnerability:

$$\mathbf{EV} = Gu + \left(\frac{ge + sl + so + lulc}{4}\right)$$

In which:
EV: Environmental Vulnerability
Gu: Geomorphological Unit
ge: Geology
sl: Slope
so: Soil
lulc: Land Use and Land Cover

The relief variable stands out in this proposal for the reasons already mentioned in the introduction. All elements pointed to a hierarchy in vulnerability classes: Very Low (1), Low (2), Medium (3), High (4), and Very High (5). To achieve these weights in each variable, the authors adopted pre-established criteria (Chart 1).

It is noteworthy that the adopted criteria did not take place only from the methodologies discussed in the introduction. The present study considered field trips and the knowledge of its researchers, which can be replicated in other areas. These facts allowed the generated mapping not only to be really applicable to the area and to contribute to the (re)ordering of land use in a more rational use, but also to provide relevant data for water resource management and for the creation of a committee of the Pindaré River Watershed.

Chart 1 – Methodology for defining the weights of environmental indicators

Indicator	Element	Criteria weight			Weight	Criteria
		● Geological time	● Mineral stability	● Resistance of rocks		
Rocks	Itapecuru Formation	2	2	2	2	Time refers to more or less recent formations. More recent rocks tend to be more vulnerable to pedo- and morphogenetic processes. Stability and resistance deal with minerals and rocks and their vulnerability to weathering.
	Mature Lateritic Covers	2	2	2	2	
	Ipixuna Formation	2	2	2	2	
	Alluvial Deposits	5	5	5	5	
		● Topography (position on the slope)	● Slope inclination	● Shaded relief (amplitude)		
Relief Unit	Low Plateaus	1	1	1	1	The relief classification will discuss altimetric levels, altimetric amplitudes, relief dissections, geographic position on the slope and, consequently, the greater or lesser propensity for erosion. *In this methodology a plain relief receives a weight of 5 since it consists of a priority area for preservation.
	Dissected Plateaus	2	2	1	2	
	Surfaces With Undulating Hills	3	2	2	2	
	Tabular Plateaus	4	1	2	2	
	Surfaces With Big Hills and Little Hills	3	3	3	3	
	Mesas and Mesetas	5	4	4	4	
	Embedded Valleys	4	5	5	5	
	Hills and Mountains	5	5	5	5	
	River Plains	1	1	1	5*	
		● Slope inclination				
Slope	0.00% to 3.00%	1			1	Indicates how much the relief is steep or flat within the SIBCS classifications.
	3.01% to 8.00%	2			2	
	8.01% to 20.00%	3			3	
	20.01% to 45.00%	4			4	
	45.01% to 75.00%	5			5	
	> 75%	5			5	
		● Waterproof	● Texture	● Depth and Maturity		
Soil	Dystrocohesive Yellow Latosol	1	2	1	2	Porosity indicates whether a soil is more or less permeable (drainage capacity). Higher values mean more impermeable soils (favoring runoff over infiltration). Depth and maturity correlate with the formation factor "time", which has to do with the degree of pedogenetic stability. Higher values mean shallow and little-evolved soils. Texture discusses the granulometry: sandy, clayey to silty, etc. Higher values mean more silty (more fragile) soils.
	Dystrophic Yellow Latosol	1	2	1	2	
	Dystrophic Red-Yellow Latosol	1	2	1	2	
	Dystrophic Yellow Argisol	3	3	2	3	
	Dystrophic Red-Yellow Argisol	3	3	2	3	
	Orthic Quartzarenic Neosol	5	5	5	5	
	Dystrophic Haplic Gleysol (Tb)	5	3	5	5	
		● Size of the vegetation cover	● Soil protection	● Vegetation density		
Land Use and Land Cover	Forest	1	1	1	1	Soil protection concerns the greater or lesser protection given by the vegetative canopy. Smaller values mean greater protection and less vulnerability. Size refers to the height of this vegetation, which also influences protection. Density corresponds to the distance between the vegetation, minimizing the direct penetration of rain droplets into the soil.
	Savannah	3	2	2	2	
	Forestry	2	2	2	2	
	Field	4	2	2	2	
	Pasture	4	3	3	3	
	Temporary Crops	4	4	5	4	
	Urban Area	5	5	5	5	
	Exposed Soil	5	5	5	5	
	Flooded Field and Swampy Area	4	5	5	5	

Source: The authors (2022)

BHRB COMPONENTS INVENTORY

From relief compartmentalization, which underlies the methodology of this research, the authors propose the description and inventory of the physical components of the Buriticupu River Watershed (BHRB). This inventory is fundamental within the vulnerability scope process. Another important issue in this study is the climatic issue. The climate of the region is equatorial hot and humid, a subdivision of the tropical climate. It has two well-defined seasons: a rainy season, from December to June, and a dry season, from July to November. Total rainfall ranges between 1,800 mm and 2,000 mm. The average annual temperature varies from 25 ºC to 27 ºC and relative humidity is on average 80% (CAJAIBA *et al*., 2019). This study comprised a systemic relationship including rocks, relief, soils, land use and land cover (Figure 3).

The relief of the region consists mostly of plateau formations separated into strips by drains and grottoes, located at an altitude of 200 m above sea level (LIMA *et al*., 2018). The mouth of the Buriticupu river is only 89 meters above sea level. More specifically, a geomorphological compartmentalization took place at the BHRB that made clear its relationship with the regional geological context. In the plains, one can notice the presence of alluvial deposits, which are unconsolidated deposits of sand, silt, and clay. According to CPRM (2013), these sediments have been transported and deposited by rivers and streams since the last 10 thousand years, covering the Quaternary period. These areas are seasonally or permanently flooded with water, presenting reduced slopes (which do not reach more than 3%). Due to this seasonality, the soils are water-saturated (*e.g*. gleysols).

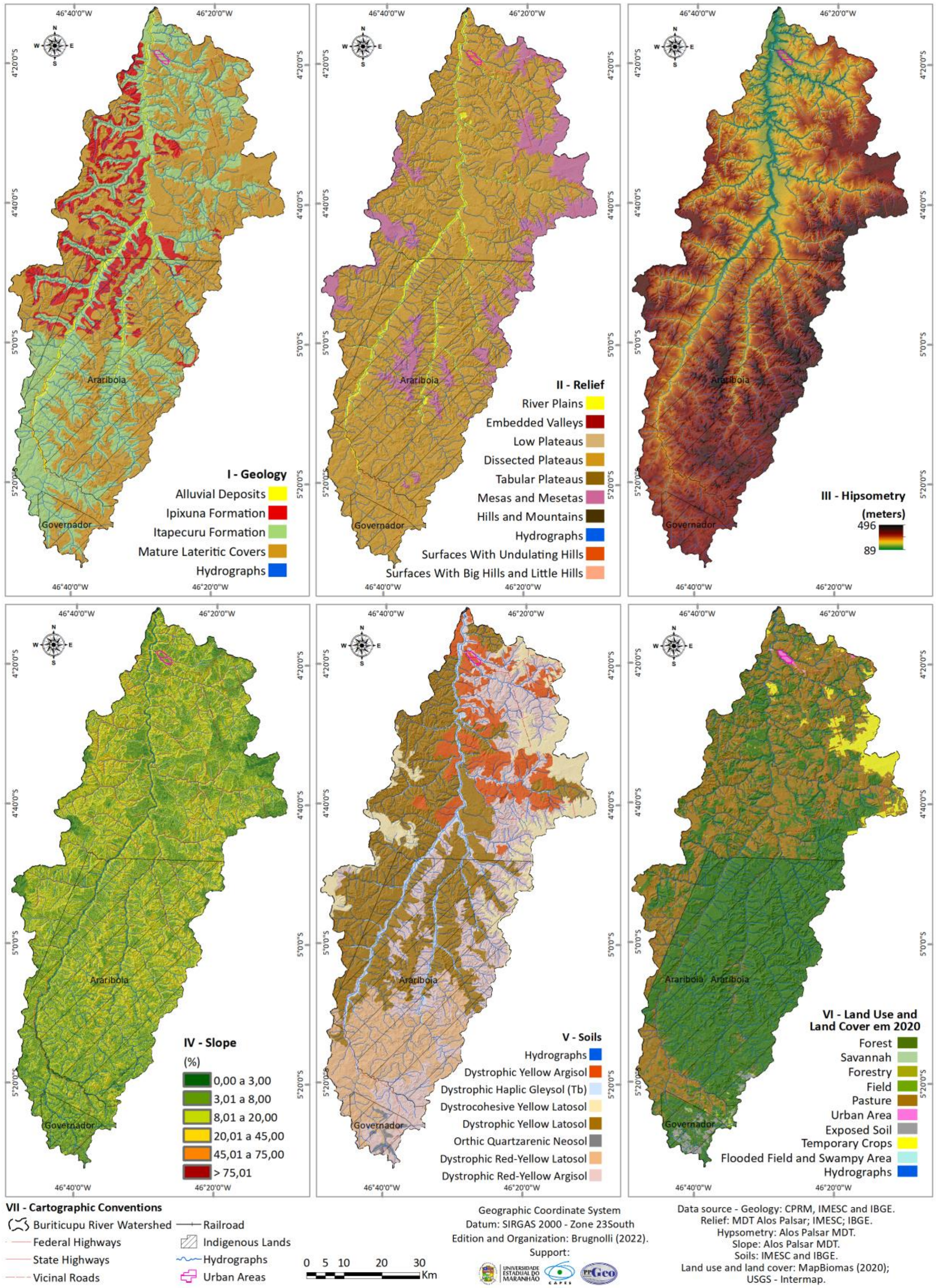
Moving to a higher hypsometric level, we have the low plateaus and the dissected plateaus. According to CPRM (2013), these areas present large extensions referring to the Itapecuru and Ipixuna formations, both formed by sandstones, claystones, siltstones, and shales interspersed with sandstones. What differs one formation from the other is the geological period (with Itapecuru being older) and the process of conglomerates of sandstones with pelites presented by the Ipixuna formation. Another fact concerning the BHRB is that the Ipixuna formation occurs in higher areas, and the Itapecuru formation occurs in lower slopes of the middle and lower courses (except for the valley bottoms, which are alluvial deposits).

These places show a predominance of pastures with extensive deforested areas. According to MapBiomas (n.d.), the continuous removal of native vegetation in these areas is remarkable. Furthermore, according to IBGE (2010) and NICASIO *et al*. (2019), the main economic activities in the city are plant extraction, livestock, and fruit growing. However, activities such as eucalyptus and soybean monocropping have recently expanded throughout the city. According to Cajaiba *et al*. (2019), Buriticupu city has already lost 97% of its native vegetation cover.

These soybean and eucalyptus areas occur in tabular plateaus, flat areas that have deep soils such as latosols and in which mature lateritic covers stand out. According to CPRM (2013), these lateritic covers are resistant to weathering and erosion and support tabular reliefs at different elevation levels, represented by plateaus. These lateritic profiles occur under flattened tops at elevations that in the BHRB vary between 300 m and 450 m. The profiles link to the interfluves between the rivers in the region, including the Pindaré and Buriticupu rivers.

Another compartmentalization that stands out in the region are the embedded valleys, which have steep slopes, some even exceeding 45%. These areas are protected by the forest code (BRASIL, 2012), which is a Brazilian federal legislation responsible for protecting native vegetation and water resources. In the lower course, however, pastures predominate in valley areas. On the other hand, forest vegetation is present in the middle and upper courses, mainly because these valleys are located within the Araribóia Indigenous Land.

Figure 3 – Physical and anthropic components of the BHRB



Source: The authors (2022).

This indigenous land even covers mesas and mesetas along with hills and mountains. These are the highest points of the BHRB, reaching up to 489 meters. Argisols and latosols are characteristic of these places, having large and steep slopes that reach more than 75%. A craggy relief thus takes place, especially on the edges of mesas and mesetas. These areas have an active relief characterized by frank dissection of extensive plateau surfaces (CPRM, 2013). Heavily carved surrounding slopes stand out in this scenario, which have been destroying low plateau surfaces due to the progressive retreat of the steep erosive ridges. This locally rugged relief is characterized by dissected hills and mountains with steep slopes, carved by incised valleys with high drainage density, which denotes expressive structural control in the sculpting process of the regional relief.

ENVIRONMENTAL VULNERABILITY OF THE BURITICUPU RIVER WATERSHED: PROPOSALS FOR LAND USE AND LAND COVER

The assessment of environmental vulnerability was possible thanks to the interaction between physical and anthropic components. These components provide information to define restrictions and to outline suggestions for improving land use and land cover. In short, anthropic actions affect the environmental system to a greater or lesser extent, and vulnerability assessment aims to identify precisely how fragile natural environments are in the face of anthropic interventions (Figure 4).

Areas of very low vulnerability were restricted to the Governador Indigenous Land, where forest vegetation stood out covering only 64.59 km² (1.21% of the total). Among the factors that reduce vulnerability are the presence of forest remnants linked to the Amazon Forest (dense and open ombrophilous forest), the sandstones of the Itapecuru formation, a relief of dissected plateaus that reach a maximum of 20% slope, and deep and well-drained soils such as the Dystrophic Red-Yellow Latosol. These are stable environments from a geological, geomorphological, and pedological point of view.

For these areas, the authors suggest that forest remnants be maintained and inspection be conducted to protect biodiversity and prevent anthropic occupation. This Indigenous Land is legally protected by Law No. 5,371 of 1967, which guarantees compliance with the policy of respect for indigenous peoples, making them owners of the lands they occupy (BRASIL, 1967).

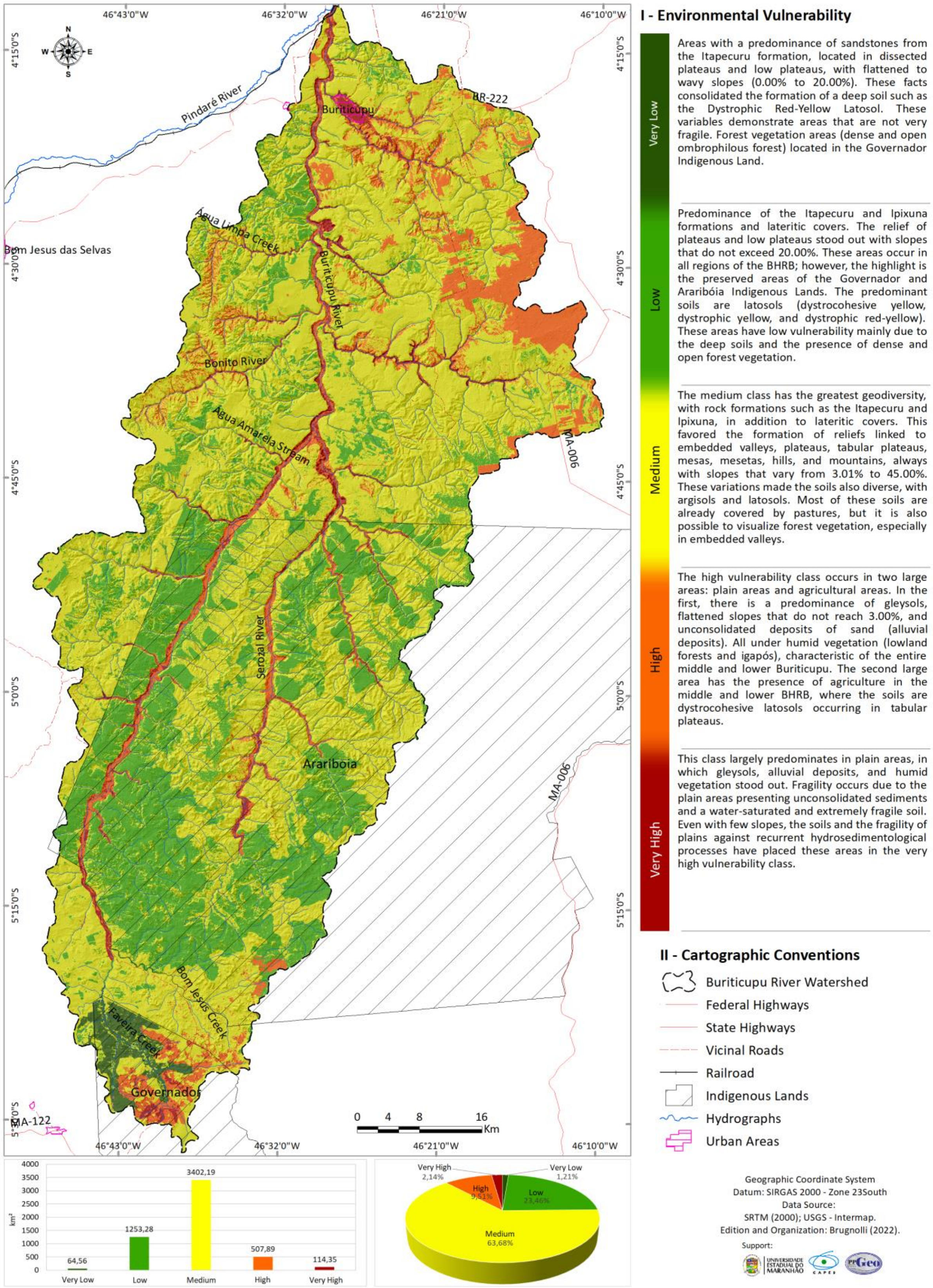
The low vulnerability class presents a predominance of sandstones from mature lateritic covers, as well as conglomerates of sandstones and pelites deposited from the Ipixuna formation. In these places, one can notice the formation of a flat to gently undulating relief, characteristic of low plateaus. Moreover, even because these are higher and flatter areas, well-developed soils predominate such as Dystrocohesive Yellow Latosol, Dystrophic Yellow Latosol, and Dystrophic Red-yellow Latosol.

The Buriticupu Watershed covers two large patches of forest vegetation, which are the Indigenous Lands. This evidences the importance of maintaining the remnants not only for the balance of the watershed, but also because of the important sources of the Buriticupu River and its main tributary, the Serozal River. It is also noteworthy that protection is essential to ensure the maintenance of ecosystem services and the hydrological regime. Despite being an extensive river, the Buriticupu River does not have a large water flow.

Regarding the low vulnerability class, forest remnants must be maintained and the springs preserved, including those located in wetlands. Therefore, inspection must be conducted for biodiversity protection and prevention against human occupation. In pasture areas, management practices must be incorporated to minimize possible negative impacts, especially because some of these areas are located in undulating terrain (close to 20% slope).

The medium class presents greater geodiversity, in which pastures stand out in flattened lands that have more fragile soils such as argisol. Moreover, forest formations occur in strongly undulating to mountainous terrains, as in the Araribóia Indigenous Land. Geological aspects end up not being preponderant in the medium class, which presents the Itapecuru and Ipixuna formations and mature lateritic covers.

Figure 4 – Environmental Vulnerability of the BHRB, Maranhão State, Brazil



Source: The authors (2022)

Especially in pastures, these territorial portions must display land management, which enhances and favors soil protection. Since these areas have medium environmental vulnerability, they consist of an integrated environment, that is, one in which morpho- and pedogenetic processes are equal. Notwithstanding, care must be taken with the anthropic advance on forest remnants, mainly because it is already possible to visualize landscape fragmentation. In addition, anthropic advance is reaching the margins of the springs, in many cases with the removal of the riparian forest.

The high vulnerability class begins a process of instability, with soybean and eucalyptus crops entering fragile areas. Here we have Dystrocohesive Yellow Latosols in tabular plateaus and plateaus with soft wavy relief. This high vulnerability is due to the fact that land use exerts a strong influence on the processes that cause instability. The other territorial portion is located in plain areas, which despite presenting flattened relief have fragile soils (gleysols). In addition to the vulnerability of plain areas, sediment deposition processes occur along with floods, justifying such a classification.

There are also important areas of high vulnerability in the Governador Indigenous Land that over time (Figure 4) have been undergoing deforestation processes due to logging. According to Cealentano *et al*. (2018), this region lives under constant threats of deforestation and degradation due to illegal logging and arson. Indigenous peoples and community leaders in the region are victims of the violence associated with such crimes.

It is under discussion the possibility of creating the "Ecological Corridor of the Maranhão Amazon", which will connect the main forest remnants in the region through the restoration of riparian forests along the Buriticupu, Pindaré, and Zutiua rivers (CELENTANO *et al*., 2018, p. 336). This proposal would bring about environmental protection and restore balance to the watersheds. Furthermore, it would strengthen cultural aspects and indigenous peoples, enhancing the natural heritage of the region. Although recognized as potentially rich, this heritage is still little studied by the scientific community.

The fact that this is one of the most impacted areas of the Maranhão Amazon brings up the debate and the need to create an ecological corridor. This is because areas such as the Governador and Araribóia Indigenous Lands, both parts of the BHRB, and the others that represent the Gurupi Mosaic are fundamental for the conservation of water resources and the connectivity of remnants.

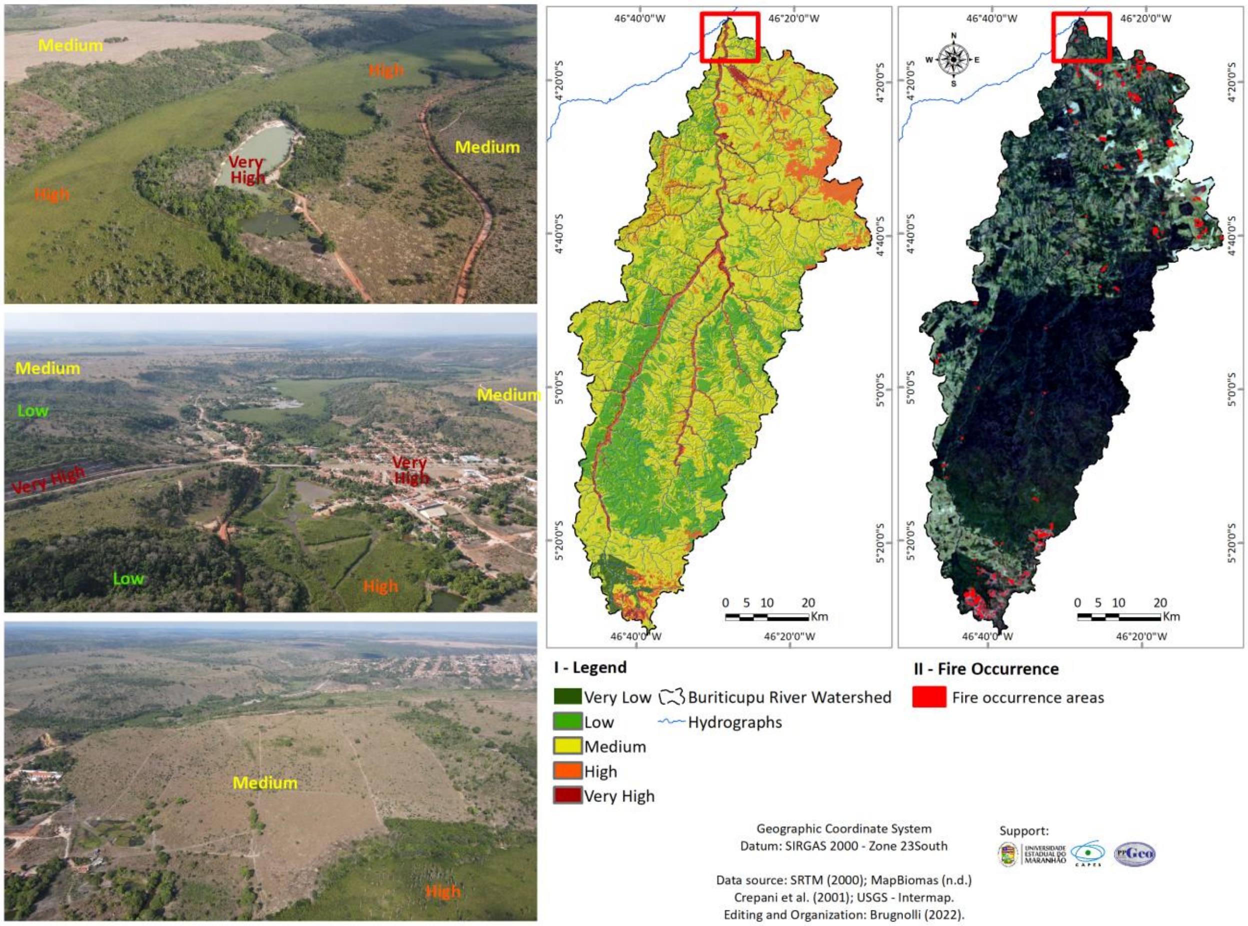
These facts would greatly contribute to the still embryonic proposal for the creation of the Pindaré Watershed Committee. The institutional implementation of the committee following the Política Nacional de Recursos Hídricos(BRASIL, 1997), which is the brazilian federal law that proposes the management of water resources through a water resources management system. and the initiative on the part of the public power would enable the realization of the aforementioned improvements and the implementation of the ecological corridor. Thus the need to maintain forest remnants, with inspection to protect biodiversity and prevent human occupation in these legally restricted areas.

According to data from MapBiomas (n.d.), since the 1980s the BHRB has been through continuous processes of environmental degradation, especially the removal of native vegetation (Amazon Forest) at first for the establishment of pastures and later for agriculture. These alterations put pressure on water resources and transform the watershed into a place of intense hydrosedimentological processes. At harvest time, the removal of extensive soybean areas leaves the soil unprotected against rainfall, favoring the carriage of sediments that will reach the plains.

Santos and Soares (2020) also confirmed these highlights in another watershed in northeastern Maranhão State, where soybean and eucalyptus cropping (something that also occurs in the BHRB) is responsible for leaving areas susceptible to the acceleration of erosion processes. The same authors still advance in the discussion, identifying that fires clean up agricultural areas and pastures, raising watershed degradation levels. These variables were also applied in the BHRB, as data collected from MapBiomas (n.d.) point to a large number of fires in the last twelve years (2010 to 2022).

Finally, the very high vulnerability class predominantly covered plains, which despite having native vegetation, are deposition sites and may suffer recurrent floods and erosion processes. For these locations, the authors recommend that the vegetation be maintained, as well as plain areas with pastures and/or mining activities be reforested (Figure 5).

Figure 5 – Most of the fires occur in areas of very high environmental vulnerability in the BHRB, Maranhão State, Brazil



Source: The authors (2022)

These plains have strong restrictions on urban occupation and on the implementation of buildings that may present problems of cracking and frequent collapses (CPRM, 2013). However, what happens in the BHRB is the occupation of the district on the margins of the plains or even in the plains, which periodically suffer from floods. This is also why it is essential to completely change the current uses of these areas while seeking to re-establish and restore a high environmental value through the recomposition of forest vegetation.

Understanding such dynamics is fundamental to propose, in the short, medium, and long term, changes in the current form of occupation and in landscape management strategies (RITTERS *et al.*, 1995; STEFFEN *et al.*, 2004; TREVISAN *et al.*, 2018; LEAL *et al.*, 2019).

FINAL CONSIDERATIONS

Proposing changes to the classic and initial methodology is not something new or unprecedented. However, the idea of working with the relief as a component capable of redistributing system energies and thus controlling the other elements of the landscape is something important that was highlighted in the present study. Assessing vulnerable areas is an important planning tool that, in addition to the proposal for the adoption of geomorphological units, made each unit controlled, conditioned, or dependent on slope and compartments. This not only promotes the identification of units, but allows them to have relatively homogeneous characteristics, facilitating decision-making.

The objectives were thus achieved and the results made it possible to identify vulnerability. In addition to changes in land use, the authors propose making occupation impossible – respecting the actual vulnerability of plains – or at least indicating a way to adapt these processes to the propensity for sediment loss, balancing these territorial portions.

Making use of these indicators made it possible to identify that the most fragile areas from an environmental point of view are located in three prominent locations. The first are the plains; the second are the areas of soybean crops and eucalyptus plantations in the middle course; and the third are fire occurrence areas, as these events left marks/scars on the landscape and brought about high environmental vulnerability, especially in the Governador Indigenous Land.

A fundamental point of this study, and one that may contribute to others to come in this important region of the Maranhão Amazon, is the protection exerted by indigenous peoples. With this protection, more than 50% of native vegetation remained resistant to anthropic actions, thus becoming an important refuge for biodiversity. Also noteworthy is the possibility of creating the Gurupi Ecological Corridor, something necessary and fundamental for the watersheds in the region. Indeed, this will positively affect the BHRB to some extent. The current challenge lies precisely in the application of such a measure. The authors of the present study thus hope to be a guide for improvement actions in view of the advance of agriculture and pastures over native vegetation.

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AUTHORS' CONTRIBUTION

Rafael Brugnolli Medeiros conceived the study, collected and analyzed the data, prepared the mappings, wrote and revised the text. Luiz Carlos Araujo dos Santos wrote, supervised and revised the text. José Fernando Rodrigues Bezerra collected, wrote and revised the text. Quesia Duarte da Silva eagerly revised the text. Silas Nogueira de Melo revised and waited for the text.