

GEOENVIRONMENTAL CHARACTERIZATION OF THE NEGRO RIVER WATERSHED (MA) UNDER THE PERSPECTIVE OF GEOSYSTEMS

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Abstract: Watersheds are fundamental units for territorial planning and environmental management, as they integrate physical, biotic, and anthropogenic components that shape environmental dynamics. In this context, this study aims to conduct a geoenvironmental characterization of the Rio Negro Watershed, located in the state of Maranhão, Brazil, within the surroundings of the Lençóis Maranhenses National Park, an area known for its high

environmental fragility. The research is grounded in the geosystem approach and landscape geoecology, integrating official cartographic data, spatial analysis in a Geographic Information System (GIS) environment, and field validation conducted during different hydrological periods. The analysis focused on relief, slope, soils, vegetation cover, and hydrological dynamics, with special emphasis on water connectivity in an intermittent river system. The results reveal the predominance of dune environments, sandy soils with high permeability, and vegetation adapted to extreme climatic and edaphic conditions, which together contribute to the area's high natural fragility. Mapping the seasonal course of the Rio Negro River highlights its essential role in maintaining connectivity between interdune lagoons and groundwater systems, even under a non-perennial flow regime. The study concludes that integrating geoenvironmental analysis with field observations provides valuable technical support for territorial planning, environmental conservation, and management strategies in fragile coastal landscapes.

Keywords: Environmental fragility; Geosystems; Watershed.

CARACTERIZAÇÃO GEOAMBIENTAL DA BACIA HIDROGRÁFICA DO RIO NEGRO (MA) SOB A PERSPECTIVA DOS GEOSSISTEMAS

Resumo: As bacias hidrográficas constituem unidades fundamentais para o planejamento e a gestão territorial, por integrarem componentes físicos, biológicos e antrópicos que condicionam a dinâmica ambiental. Nesse contexto, este estudo tem como objetivo realizar a caracterização geoambiental da Bacia Hidrográfica do Rio Negro, localizada no estado do Maranhão, inserida no entorno do Parque Nacional dos Lençóis Maranhenses, área reconhecida por sua elevada fragilidade ambiental. A pesquisa fundamenta-se na abordagem dos geossistemas e na geoecologia da paisagem, integrando dados cartográficos oficiais, análise espacial em ambiente de Sistema de Informações Geográficas (SIG) e validação por meio de trabalhos de campo realizados em diferentes períodos hidrológicos. Foram analisados aspectos relacionados ao relevo, declividade, solos, cobertura vegetal e dinâmica hidrológica, com ênfase na conectividade hídrica do rio, caracterizado por regime intermitente. Os resultados evidenciam a predominância de ambientes dunares, solos arenosos de alta permeabilidade e vegetação adaptada a condições extremas, fatores que contribuem para a elevada fragilidade natural da área. A análise do curso sazonal do Rio Negro confirma seu papel essencial na conexão entre lagoas interdunares e aquíferos, mesmo sob regime não perene. Conclui-se que a integração entre análise geoambiental e validação em campo fornece subsídios técnicos relevantes para o ordenamento territorial, conservação ambiental e gestão de áreas sensíveis no litoral maranhense.

Palavras-chave: Fragilidade ambiental; Geossistemas; Bacia hidrográfica.

CARACTERIZACIÓN GEOAMBIENTAL DE LA CUENCA HIDROGRÁFICA DEL RÍO NEGRO (MA) DESDE LA PERSPECTIVA DE LOS GEOSISTEMAS

Resumen: Las cuencas hidrográficas constituyen unidades esenciales para la planificación territorial y la gestión ambiental, ya que integran componentes físicos, biológicos y antrópicos que determinan la dinámica del paisaje. En este contexto, el presente estudio tiene como objetivo realizar la caracterización geoambiental de la Cuenca del Río Negro, ubicada en el estado de Maranhão, Brasil, en el entorno del Parque Nacional de los Lençóis Maranhenses, una región reconocida por su elevada fragilidad ambiental. La investigación se fundamenta en

el enfoque de los geosistemas y la geoecología del paisaje, integrando datos cartográficos oficiales, análisis espacial en un entorno de Sistemas de Información Geográfica (SIG) y validación mediante trabajo de campo en distintos períodos hidrológicos. Se analizaron variables relacionadas con el relieve, la pendiente, los suelos, la cobertura vegetal y la dinámica hidrológica, con especial énfasis en la conectividad hídrica de un río de régimen intermitente. Los resultados muestran el predominio de ambientes dunares, suelos arenosos de alta permeabilidad y vegetación adaptada a condiciones extremas, factores que contribuyen a la elevada fragilidad natural del área. La delimitación del curso estacional del Río Negro confirma su papel fundamental en la conexión entre lagunas interdunares y acuíferos. Se concluye que la integración entre análisis geoambiental y validación de campo es esencial para apoyar la gestión ambiental y el ordenamiento territorial en paisajes costeros frágiles.

Palabras clave: Fragilidad ambiental; Geosistemas; Cuenca hidrográfica.

INTRODUCTION

In the context of territorial planning and management, watersheds play a central role in assessing potential vulnerabilities, as they encompass physical, biotic, and socioeconomic components that imply unique dynamics for the relationships that exist there. Therefore, understanding the territory from this scale of analysis brings to light the integration of processes ranging from physical components such as relief, soils, and vegetation to processes of use and occupation and their evolution over time. This approach provides important insights to decision-makers to guide conservation or impact mitigation measures.

In this sense, it is worth noting that the Northeast region faces several challenges in relation to the conservation and management of water resources, as well as the preservation of coastal ecosystems, a location that is home to the largest population concentration according to data from the 2022 Demographic Census, with approximately 54.8% of the Brazilian population residing in the country's coastal regions (IBGE, 2024) and consequently aggravating the situation of environmental sensitivity. This fact alone implies attention to the pressures generated by population density in sensitive ecosystems such as mangroves, dunes, and fluvial-marine plains.

Thus, with the current occupation scenario, measures to mitigate the damage that occurs because of this occupation process must be observed, since the impacts extend from the irregular occupation of dune areas, removal and contamination of mangrove areas, as well as activities related to agriculture and tourism. Hass *et al.* (2021) highlight the importance of strengthening governance processes for the coastal region as a major challenge given the emergence of the observed impacts, thus seeking participatory strategies that involve the conservation and development of an area that is so rich and at the same time so sensitive.

It is in this scenario that the Lençóis Maranhenses National Park is located, a conservation unit that covers the municipalities of Barreirinhas, Santo Amaro do Maranhão, and Primeira Cruz in the state of Maranhão, a region that was recently awarded the title of Natural Heritage of Humanity by UNESCO and has a total area of 155,000 hectares of intermittent lagoons, as well as river systems with unique hydrodynamics compared to other systems on the Brazilian coast. The dynamics of the site are entirely conditioned by the rainfall regime, as well as by the action of the winds that shape the positioning of the dunes throughout the park. This fact reveals the inherent fragility that is mainly associated with the instability of this system, given its characteristics.

This scenario is even more evident when analyzing the Rio Negro Watershed, the subject of this research, since the region is highly vulnerable due to its characteristics. It is located within the Lençóis Maranhenses National Park and has specific hydrogeomorphological characteristics, such as the intermittent drainage pattern of its hydrography, the sandy nature of the soils with the presence of dunes, and dependence on the climate regime given the low retention capacity of the region's soils. Although it is an intermittent watercourse, the Rio Negro plays a fundamental role in the dynamics and maintenance of the balance of the PNLM, since its course connects the lagoons between the dunes, keeping the region in balance, even though it is extremely fragile.

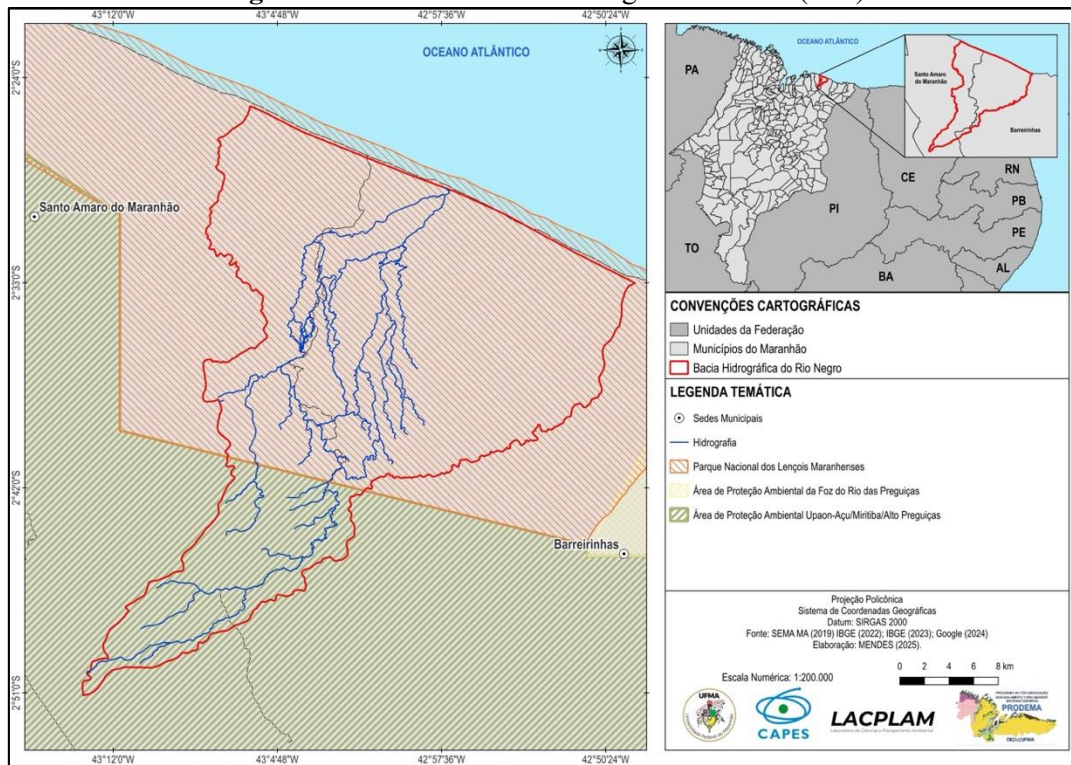
Therefore, this article seeks to perform a geo-environmental characterization of the Rio Negro Basin by applying concepts based on the theory of geosystems and the approach of landscape geocology, integrating the analysis of spatial data with field observations. In this sense, cartographic products made available in official databases such as IBGE and independent projects such as Mapbiomas will be used to ultimately understand the geocological dynamics of this important unit to support territorial management in an area of high fragility.

MATERIALS AND METHODS

Study Area

The Rio Negro River Basin is located between the municipalities of Barreirinhas and Santo Amaro do Maranhão, bordering the Lençóis Maranhenses National Park in the state of Maranhão. The drainage area is marked by intermittent watercourses and water connectivity, especially during the rainy season, when its main course is more clearly defined. The boundaries of the basin region are highlighted in Figure 1.

Figure 1 - Location of the Rio Negro Watershed (MA)



Source: Own work.

Methodological Procedures

The methodology adopted is based on an integrated approach to geo-environmental parameters and was structured in three stages:

Collection of cartographic data for the preparation of thematic maps

In this stage, cartographic bases were obtained from official agency platforms, with emphasis on environmental data produced by the Brazilian Institute of Geography and Statistics (IBGE), where data on relief, soils, vegetation, and territorial boundaries were collected. The entire cartographic base was processed in a GIS environment using the open-source software QGIS 3.34.

Analysis of the cartographic data produced

Based on the organization of the database, the data was cross-referenced and classified to generate thematic maps for the environmental diagnosis of the region, so that integrated analysis was indeed possible. Finally, the objective of this stage was to integrate the

cartographic products to understand the dynamics of the landscape elements and verify associations between the physical characteristics and the dynamics of the hydrographic basin.

Fieldwork for validation

Finally, fieldwork was carried out in March and November 2025 to validate the course of the Rio Negro during its flood season in the rainy period (March) and during the dry season (November). Thus, trails were made with local guides authorized by the Chico Mendes Institute for Biodiversity Conservation (ICMBIO), in addition to monitoring with residents of the communities surrounding the PNLM in order to identify the mouth of the river during the rainy season, since it undergoes changes over the years and constantly changes location, as well as to validate the location of the mouth during the dry season, which, according to locals, is in the Esperança lagoon. This identification was necessary for the mapping of the Rio Negro hydrography to be validated. Through partnerships, the activity obtained logistical support from the Santo Amaro do Maranhão City Hall, reinforcing an important partnership for the completion of future stages of the research.

THEORETICAL FRAMEWORK

Geosystems and Geoecological Analysis of the Landscape

The geoecological analysis of the landscape is based on the concept of geosystem developed by Georges Bertrand (1971), which proposes an integrative approach between natural elements (relief, soil, vegetation, climate, and hydrology) and anthropic dynamics. From this perspective, the landscape is understood as a set of interrelationships organized at different levels of integration, where energy and matter flows condition the spatial structuring of environments.

Bertrand (1971) establishes the geosystem as a unit of analysis capable of grasping the complex relationships between nature and society. For Tricart (1977), geosystems are “higher-order systems” in which natural forces interact with land use, defining relatively homogeneous compartments that are susceptible to transformation. This dynamic conception allows for the integration of biophysical and anthropic aspects under a functional logic, favoring a systemic understanding of landscapes such as coastal dunes.

Monteiro (2001) expands on this proposal by proposing the concept of the environmental system as a concrete territorial unit, resulting from the interrelationships

between physical substrate, vegetation cover, and human use. From this perspective, landscape analysis requires consideration of the spatial and temporal relationships that modulate the stability or instability of systems. Landscape geoecology, as conceptualized by Bertrand and updated by Rodrigues *et al.* (2021), allows for the integrated analysis of spatial dynamics based on functional divisions of the territory. This approach has been widely used in the analysis of river basins and coastal zones, as it considers the interactions between geo-environmental units, natural vulnerabilities, and anthropogenic pressures (SILVA *et al.*, 2024).

In the context of the Rio Negro Basin, the geosystem model allows for the interpretation of environmental processes on a local scale, without losing sight of the ecological structure of the Lençóis Maranhenses as a whole. The use of this approach is strategic for delimiting homogeneous areas of fragility and guiding environmental planning.

Environmental Fragility in Coastal and Interdune Environments

The discussion on environmental fragility gains prominence in coastal landscapes and dunes, characterized by geomorphological instability, friable soils, and discontinuous vegetation. According to Ross (1994), environmental fragility can be classified as natural, potential, or emerging, according to the interaction between physical factors and anthropic use. This conceptual approach has been used to delimit risk areas and assess environmental impacts in different Brazilian biomes.

Crepani *et al.* (2001) propose an integrated analysis methodology based on variables such as slope, soils, vegetation, and land use, applied to the delimitation of priority areas for conservation. In interdune environments, these factors overlap with seasonal dynamics that accentuate vulnerability to erosion, compaction, and loss of ecosystem functions (Gonçalves *et al.*, 2011).

Recent research, such as Oliveira *et al.* (2023), points out that fragility analysis should incorporate indicators of tourist pressure and landscape fragmentation, especially in protected areas with intense seasonal water availability. Studies such as Silva and Rocha (2024) reinforce that coastal landscape management requires coordination between natural fragility and social vulnerability, highlighting the risks arising from the lack of land use planning.

In the case of Lençóis Maranhenses, the absence of dense vegetation cover and the high mobility of the dunes make the landscape particularly sensitive. The application of the concept of fragility is fundamental to delimit critical transition zones and guide the guidelines of the management plan.

Water Connectivity and the Function of Intermittent Rivers

Water connectivity is a key concept for understanding the flows of water, energy, sediments, and organisms in river systems. Ward (1989) defines three dimensions of connectivity: longitudinal (downstream), lateral (between the river and plains or lagoons), and vertical (river and aquifer). In coastal systems, such as the Lençóis Maranhenses, the presence of intermittent rivers is crucial for maintaining temporary aquatic ecosystems and interdune lagoons.

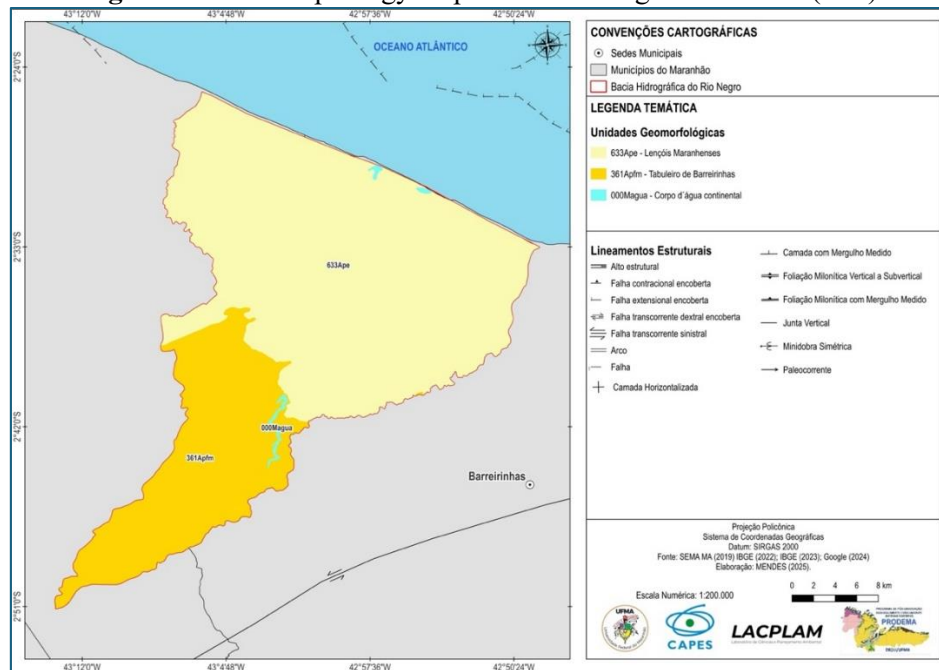
Haas *et al.* (2021) highlight that, even though they are not perennial, intermittent watercourses play a fundamental ecological role as connectors between water compartments. Studies such as those by BOULTON *et al.* (2022) and REES *et al.* (2023) reinforce that these rivers act as critical ecological corridors in vulnerable landscapes, with regulatory and biodiversity support functions. Silva *et al.* (2024) also recognize the function of vertical connectivity in hygrophilous interdune environments. In the case of the Rio Negro, the seasonality of the flow does not compromise its functional relevance, as its role as a connector between lagoons and underground aquifers makes it a structuring element of the geoecological system.

RESULTS AND DISCUSSION

Characterization of Relief and Slope

From a geomorphological perspective, the Rio Negro River Basin is in a region dominated by fixed and mobile dunes, with a predominantly undulating relief. These landforms date back to the Holocene period and are marked by wind and water balance processes that shape and make the local dynamics unique and, at the same time, create a landscape of high environmental fragility, as highlighted by CPRM (2011). Figure 2 shows the geomorphological compartmentalization of the watershed, with its main units.

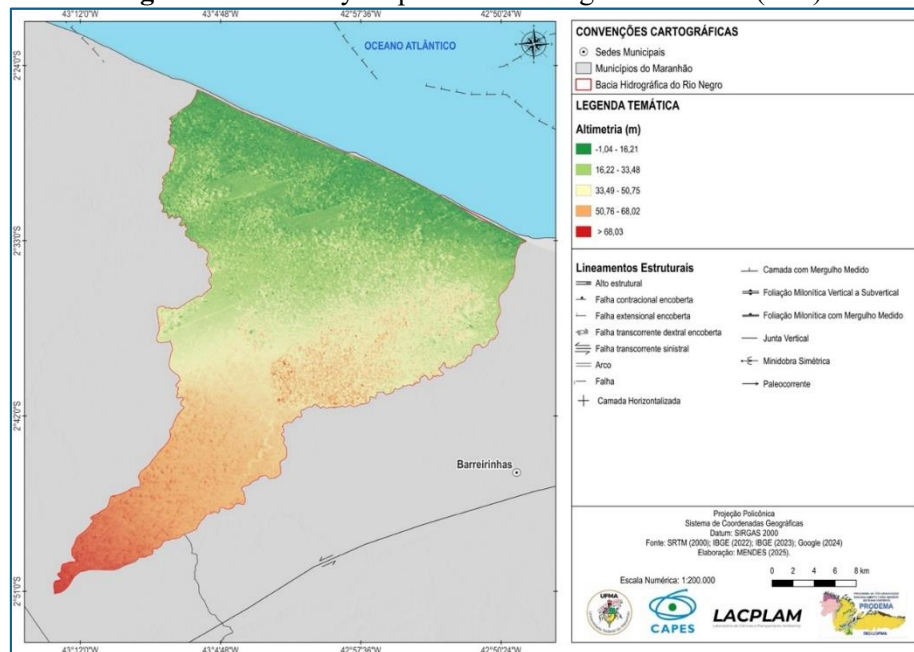
Figure 2 - Geomorphology map of the Rio Negro Watershed (MA)



Source: Own work.

As for the dynamics of the dune field, it is worth noting that its formation is linked to the action of trade winds, in addition to the water balance of the water table, which is linked to the rainy season that maintains the supply of lagoons in the PNLM region. However, this supply is significantly contributed to by regions with higher altitudes, which, through Digital Elevation Model diagnostics, were identified as 68 meters, as shown in Figure 3. This value is in the region outside the park, near the river's source.

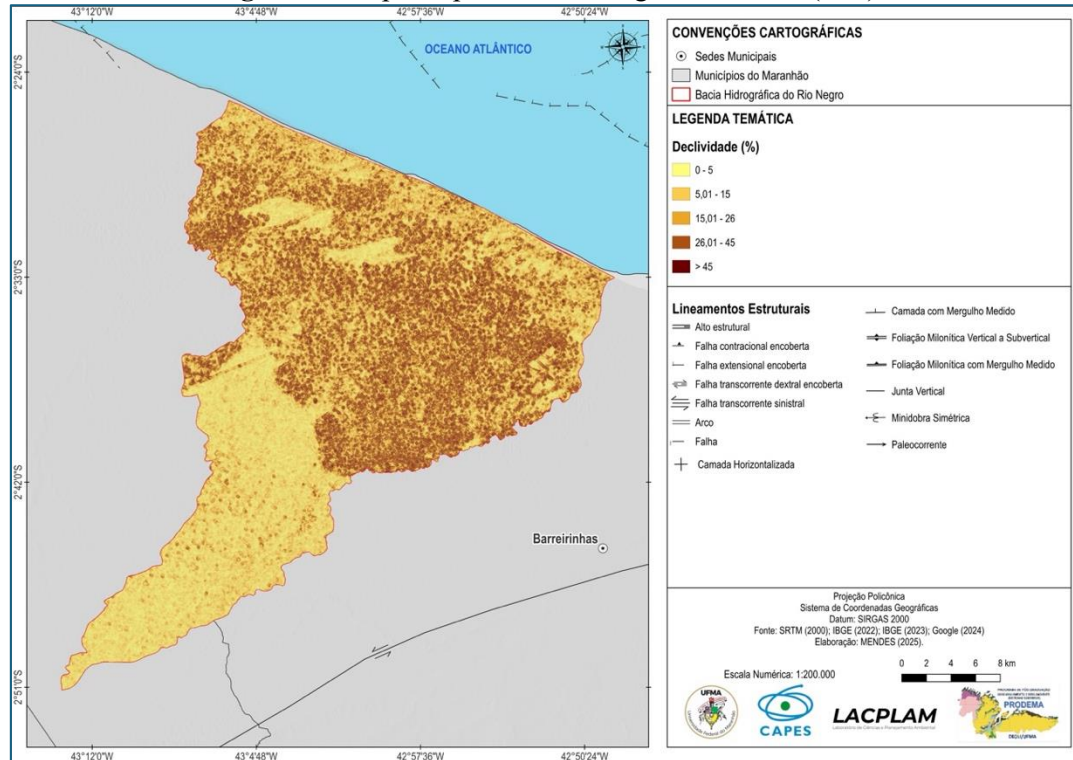
Figure 3 - Altimetry map of the Rio Negro Watershed (MA)



Source: Own work.

Furthermore, the slope of the region can be defined as one of the factors to be considered when quantifying the fragility of the river basin region. In this sense, Figure 4 shows the slope classification of the study area, highlighting the steepest slopes found in the dune field region inside the park.

Figure 4 - Slope map of the Rio Negro Watershed (MA)

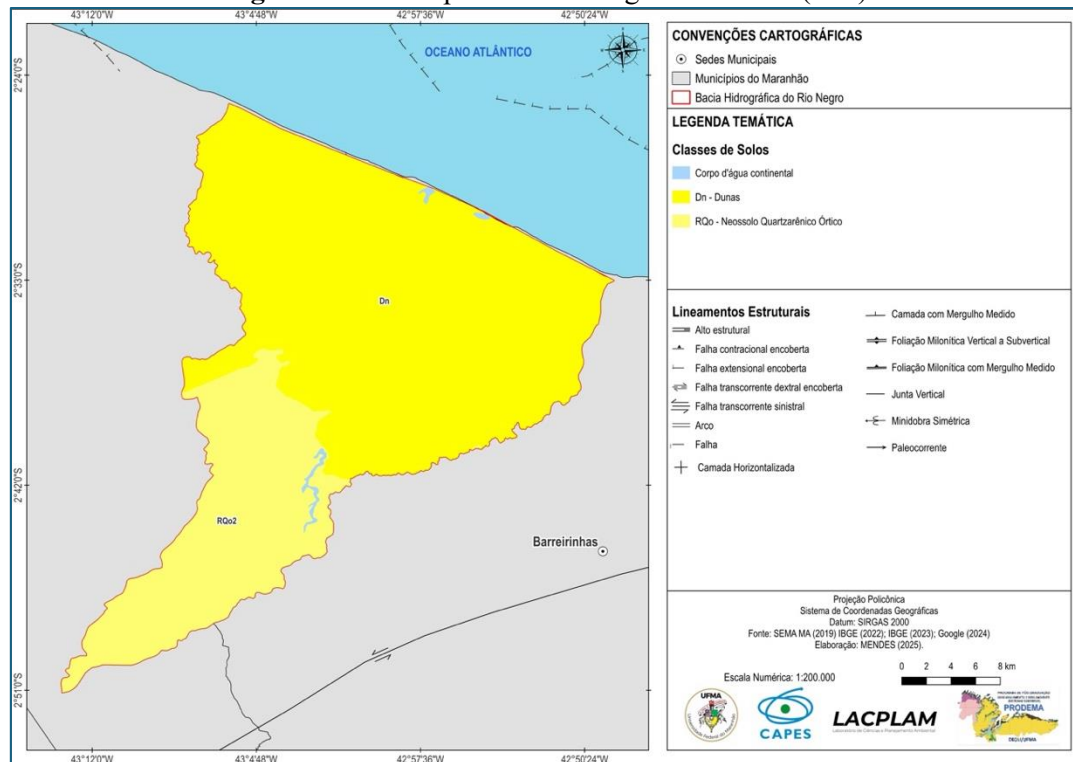


Source: Own work.

Soils and Fragility Potential

The Rio Negro watershed is dominated by sandy soils without a well-defined structure, reflecting their Holocene formation. The predominant soils in the region are Quartzarenic Neosols, found in areas outside the park and near the river's source. This type of soil has high permeability, low water retention, and low natural fertility indices, factors that contribute to its fragility and limited use (IBGE, 2023). Figure 5 shows the spatial distribution of soil classes in the watershed, illustrating their direct relationship with geomorphological compartments.

Figure 5 - Soil map of the Rio Negro Watershed (MA)



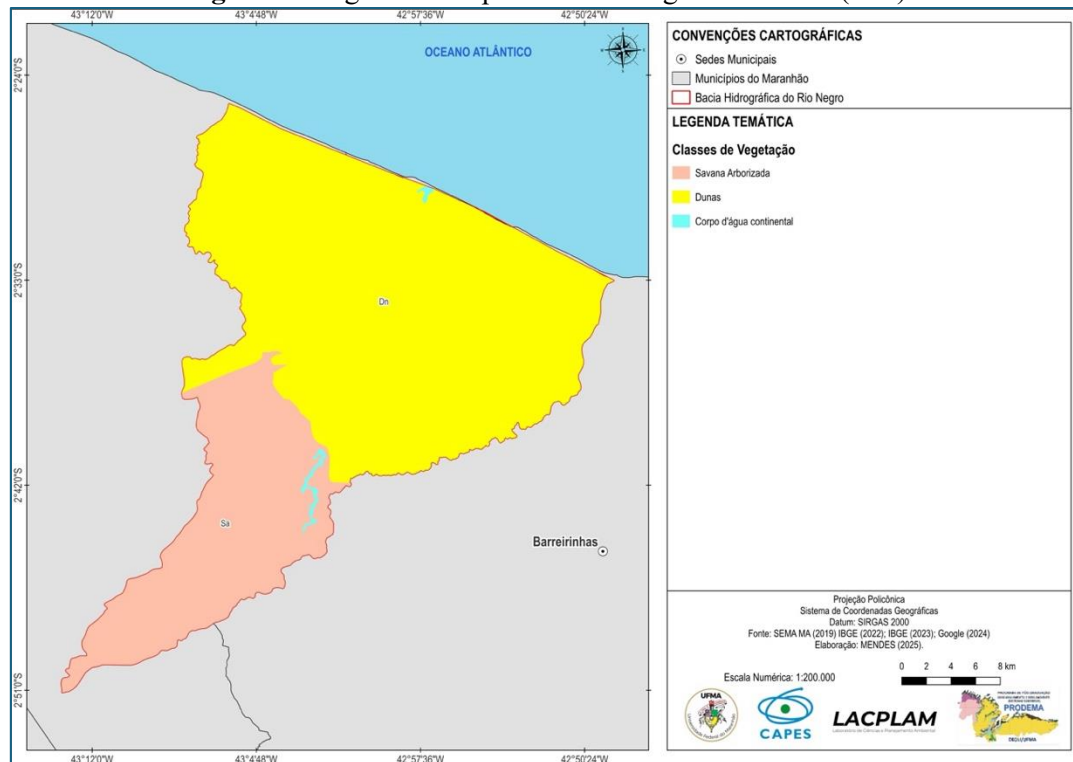
Source: Own work

Vegetation Cover and Landscape Interactions

In terms of vegetation, the Rio Negro watershed reflects the pedological and geomorphological conditions. The region's natural vegetation is dominated by species that have adapted to extreme temperatures, sandy soils, and varying water availability. In the park's humid regions, however, there is herbaceous vegetation that has adapted to areas with soils saturated by intermittent river flows.

However, there is a lack of connectivity due to wind conditions and dune movement, which prevents the dunes from becoming completely fixed, resulting in the characteristic landscape change that is common in the PNLM region. Figure 6 illustrates the current distribution of vegetation in the basin.

Figure 6 - Vegetation map of the Rio Negro Watershed (MA)



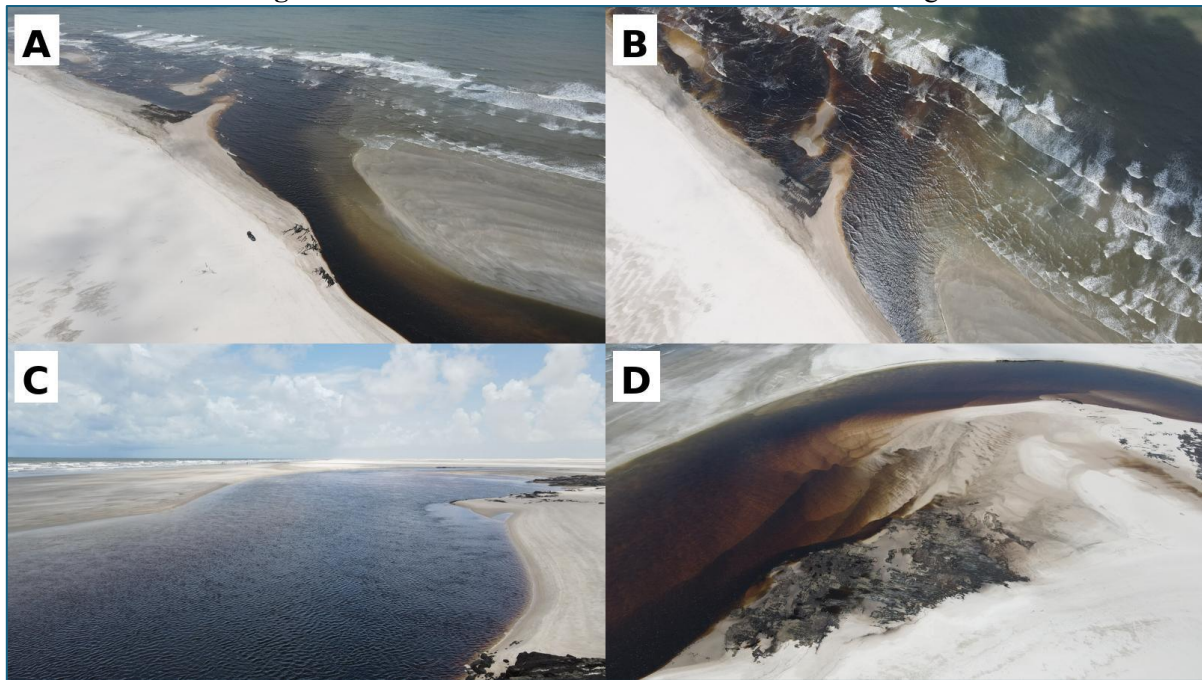
Source: Own work.

Mapping the Course of the Rio Negro and Water Connectivity

The course of the Rio Negro is seasonal and intermittent, being activated mainly during the rainy season, when rainfall and the rise in the water table make continuous surface runoff possible. Part of the interdune system of the Lençóis Maranhenses National Park, the river plays an essential role in water connectivity between seasonal lagoons, acting as a functional link between different compartments of the dune geosystem.

The delimitation of the Rio Negro's course was carried out based on the analysis of satellite images, digital elevation models (DEM/SRTM), and field validation in March 2025, with the support of local guides experienced in navigating between lagoons and trails. During this stage, it was possible to identify active drainage sections, intermittent channels, and the main mouth of the watercourse highlighted in Figure 7.

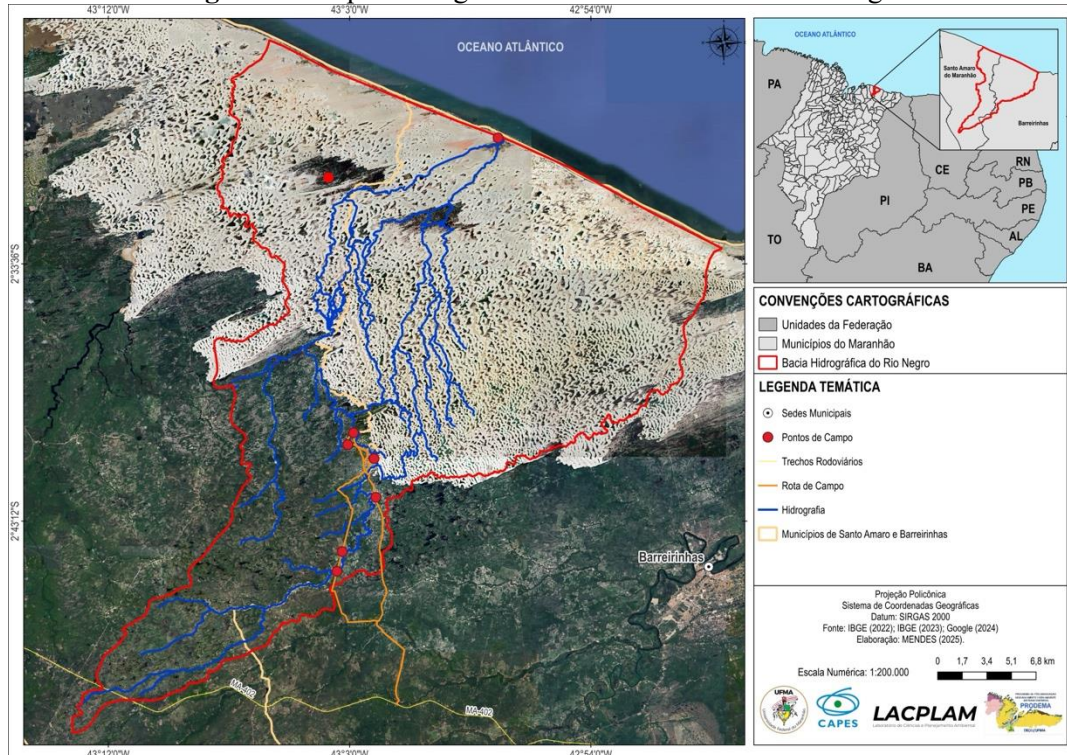
Figure 7 - Identification of the main mouth of the Rio Negro



Source: Own work.

Figure 8 shows the results of combining the physical aspect diagnoses with the field survey, with detailed mapping of the seasonal course superimposed on the 2025 satellite image and the boundaries of the BHRN.

Figure 8 - Map showing the seasonal course of the Rio Negro



Source: Own work.

During mapping, it was found that the course of the river establishes lateral and longitudinal connectivity with interdune lagoons, wetlands with vegetation, and infiltration zones. This arrangement confirms the hypothesis that, even though it is intermittent, the Rio Negro maintains a seasonal course and lateral and vertical hydrological connectivity with interdune lagoons and aquifers, reinforcing its importance as a functional unit within the geoecological system (Haas *et al.*, 2021).

The river's role as a dynamic geosystem, albeit seasonal, reinforces the importance of understanding it as a critical functional unit in the ecological structure of the Lençóis Maranhenses. Its water connectivity is essential for maintaining aquatic biodiversity, balancing the interdune water regime, and supporting ecotourism activities that depend on the presence of surface water.

CONCLUSIONS

The geo-environmental analysis of the Rio Negro River Basin highlighted the main natural and anthropogenic elements that contribute to its high environmental fragility. Based on a geosystemic approach and the integration of cartographic data and field observations, it was possible to delimit the main landscape units and recognize patterns that directly interfere with the ecological stability of the region.

The mapping of the seasonal course of the Rio Negro confirmed its relevance as a water connector between the interdune lagoons, reaffirming its functional importance even in an intermittent regime. Thus, the diagnosis contributes to the understanding of the environmental dynamics of the basin, offering technical and spatial support for land use planning, conservation, and management actions, especially in areas where natural fragility is aggravated by anthropogenic pressures.

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