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Papers

Geomorphological mapping as a tool for environmental management: a study applied to the municipality of São Benedito, Ceará, Brazil

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Abstract

Recognizing the current global context regarding crises caused by climate change, territorial planning is regarded as a tool with high potential for adapting to and mitigating the effects of such changes on natural elements, while also serving as a means of preventing environmental degradation (Ross, 2006). Using Ross's (1992) methodology, this study geomorphologically mapped the municipality of São Benedito on the Ibiapaba Plateau in Ceará, aiding its territorial planning and management. In addition, it involved consulting climatic, pedological, and geological maps, correlating the results with data from the latest demographic census, and complementing these analyses by conducting field surveys on land use and occupation patterns. Across the municipality, the research organized the landscape into six mapped units of similar morphological patterns and identified sixteen geomorphological forms (denudational, planation, and aggradational types) within them. By specifying the predominant processes in each unit and detailing the relief features resulting from these processes, the study seeks to generate knowledge about the geomorphological diversity of the Ibiapaba Plateau and, above all, to support potential environmental planning initiatives in the municipality.

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INTRODUCTION

In recent decades, environmental issues have taken a central place in scientific, political, and social agendas, establishing themselves as one of the most impactful contemporary challenges. Since the report Our Common Future (ONU, 1987), produced by the World Commission on Environment and Development, humanity has received warnings about the impacts of a development model based on the intensive exploitation of natural resources. Until the mid-2000s, discussions focused on the future consequences of this process. Today, however, the discourse has shifted: people no longer speak only about what may occur but also about what is already happening in concrete, perceptible, and uneven ways across different social groups and regions of the planet.

The global environmental crisis is a dual phenomenon, unfolding on both the planetary and local scales. This condition is particularly exacerbated in Brazil's northeastern semiarid region by the ecological fragility and socioeconomic vulnerability of its populations. Processes such as desertification, biodiversity loss, reduced water availability, and changes in rainfall regimes overlap with historical contexts of inequality, making local societies more susceptible to socio-environmental impacts. Therefore, effective public policies require an integrated understanding of the landscape and its structural elements to support mitigation and adaptation to environmental change.

In Brazil, the legal framework establishes instruments for territorial planning and management, with the Ecological-Economic Zoning (ZEE) and Water Resources Plans (PRH) as key examples. These instruments aim to regulate land use and occupation while considering the ecological limits of natural systems and social demands for development. Their effectiveness, however, requires high-quality information about the physical basis of the territory, particularly the relief.

Relief, as a fundamental element of the landscape, not only shapes the flow of water, energy, and matter but also organizes the distribution of soils, vegetation, and human occupation (Falcão Sobrinho, 2025a). As Abreu (1985) and Ross (1992, 1994) argue, relief serves as the material element that links all other components of the ecological system, integrating natural and social dimensions. Consequently, applied geomorphology is an essential field for directly supporting environmental and territorial planning.

In this process, geomorphological mapping is essential because it allows for the identification and cartographic representation of landforms, patterns, and processes across multiple scales of detail. More than a cartographic product, it functions as an analytical tool, since it helps explain the relationships among natural processes, lithological structures, climatic dynamics, and anthropogenic transformations. In Brazil, methodologies such as the one proposed by Ross (1992) established multiscale references that allow both the compartmentalization of large morphostructural units and the identification of specific landform types at local scales. This methodological advancement consolidated relief as a fundamental parameter for studies on environmental fragility, susceptibility to denudation, and the delimitation of geoenvironmental units.

Over the past decades, Brazilian geomorphological cartography has engaged in dialogue with international traditions, such as the German school, while remaining influenced by the integrated reading of structure, form, and process pioneered by Ab'Sáber (1969). Building on this foundation, a systemic perspective emerged in Brazilian geomorphology, defining environmental systems as dynamic units formed by multiple, continuously interacting elements. As highlighted by Souza *et al.* (2009) and Ross; Fierz (2017), this perspective proves particularly useful for addressing current environmental challenges, as it provides a framework to understand the complexity and interdependence between society and nature.

In Ceará, geomorphological studies have advanced primarily at regional scales, with special emphasis on the Ibiapaba Plateau (Falcão Sobrinho; Lima, 2024a), a landscape unit of great ecological and socioeconomic importance. Building on Ab'Sáber's classical works (1949), research has focused on the plateau's distinctive features, including steep escarpments, diverse lithology, circumscriptional denudational processes, and strong climatic influence. These characteristics make it an exceptional landscape relative to the surrounding sertão. Despite the regional study tradition, detailed geomorphological mapping is scarce at the municipal scale.

The municipality of São Benedito, situated on the Ibiapaba Plateau, fits this context and has been the focus of extensive recent research (Falcão Sobrinho; Lima, 2024a; Falcão Sobrinho *et al.*, 2024b; Fernandes; Falcão Sobrinho, 2025a; Fernandes *et al*, 2025b; Fernandes *et al,* 2023b; Carvalho, et al, 2022). IBGE (2021), indicates that the municipality's significant population growth in recent decades has increased pressure on natural resources. Urban expansion, agricultural development, and rising water demand create new challenges for environmental management, which requires reliable information on the physical basis of the territory. Nonetheless, the literature highlights gaps in local-scale geomorphological knowledge, making it hard to design effective strategies for territorial planning and environmental management.

To address this gap, this article applies Ross's (1992) methodology and its adaptations to conduct a detailed geomorphological mapping that identifies landform types (the fourth taxon). This approach provides technical and scientific support to guide environmental and territorial management practices, fostering a more balanced relationship between society and nature. Beyond cartography, the study integrates geomorphological knowledge with social demands for sustainable development by identifying and evaluating the potential and limitations of the local relief for specific uses.

Accordingly, the introduction frames the environmental issue at global and regional scales, highlights the importance of geomorphology as an applied science, and justifies the selection of São Benedito as the study area. The authors anticipate these results will address knowledge gaps and foster fairer, more effective environmental management policies, highlighting the essential role of geomorphological mapping in planning and decision-making.

MATERIAL AND METHODOLOGY

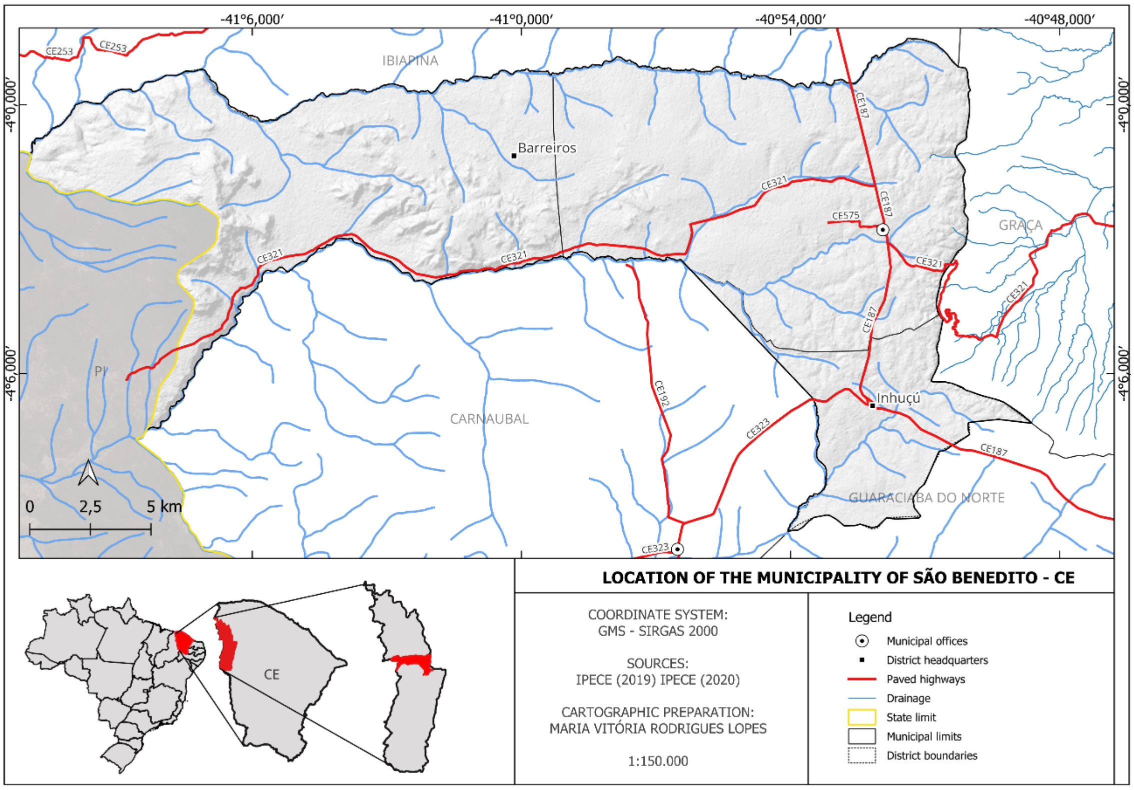
This section presents a more detailed discussion of the study area that serves as the empirical basis for this research – the municipal territory of São Benedito, Ceará, Brazil – as well as the materials and methods used to produce the results. It also outlines the methodological framework adopted in the study.

Study area

The study area lies in the northwestern portion of the state of Ceará (Figure 1). Lithologically, the area rests within the oldest layers of the Parnaíba sedimentary basin and occupies the eastern margin of this structure. The municipality extends from east to west, spanning from the cuestiform front of the Ibiapaba Plateau to its gently sloping reverse, which descends toward the state of Piauí (Fernandes; Falcão Sobrinho, 2023b). The municipal seat **sits** at 4°02′56″S and 40°51′54″W. In addition to the seat, the municipal territory includes two other population centers. This distribution may indicate the level of natural resource exploitation in the area and suggests a certain degree of settlement across the municipality, reinforcing the relevance of this research as a support for the territorial planning and management needed to ensure efficient performance of existing activities and land uses.

The main population clusters consist of the municipal seat of São Benedito and the district seats of Barreiros and Inhuçu. Besides these, smaller communities form less urbanized clusters, such as the community of Faveira, located near the banks of the Arabé River, which marks the boundary with the municipality of Carnaubal. Considering both natural and anthropogenic elements, the district of Barreiros lies entirely on the leeward slope, where rainfall dynamics resemble those of the *sertões*. In contrast, the municipal seat and Inhuçu are on the immediate summit of the plateau, within the windward slope, which corresponds to the wettest sector and records the highest average rainfall levels in the municipality.

Figure 1 – Location map of the municipality of São Benedito



Source: Elaborated by the authors (2025).

The most significant drainage systems in this territory originate on its humid slope and follow two principal axes. The first flows eastward, forming obsequent streams that drain into the river basins from Ceará, specifically the Acaraú Basin. The second flows westward, consisting of consequent streams that feed into the Parnaíba River Basin. The shaded relief (Figure 1) indicates marked variations in dissection, which result in distinct sets of landforms throughout the municipality. This variation leads to the identification of distinct geomorphological units, each reflecting the dominant processes within that zone. Evidence supporting these observations also appears in the geomorphological survey conducted during the Radambrasil (1981) project, which documented a range of patterns and landform types in the study area. When systematized in multiscale mapping, this information contributes directly to the goal of supporting environmental and territorial planning by providing insights into the dynamics present in each geomorphological unit.

METHODOLOGY

It is essential to emphasize that this study organizes the classification of relief into taxonomic levels, following Ross (1992) for the establishment and mapping of thematic geomorphological categories.

The research proceeded in different stages, each reflecting the materials and methods applied: 1) bibliographic research: review of theoretical and practical foundations of geomorphological mapping in Ceará and on the Ibiapaba Plateau; 2) collection of spatial and statistical data: consultation of geomorphological maps from official agencies, pedological, pluviometric, and geological surveys, land use and land cover data, and information from the latest demographic census; 3) analysis in a GIS environment: processing of collected materials, with the integration of Digital Elevation Models (DEM). This stage produced the initial compartmentalization of the relief; 4) fieldwork confirmation and analysis: verification of the landscape expressions of systematized information during and after the geomorphological mapping, with the registration of strategic field data.

For the classification of the study area at the first level – morphostructure – the research applied the division of Brazilian structural provinces, each defined as a morphostructural unit at this scale. Within the municipal extent of São Benedito, altitude and other morphometric parameters established the second level of analysis, morphosculpture. The definition of intervals indicating transitions between morphosculptures relied on field observations, DEM and 3D model analysis, and references to descriptions and parameters established by other authors who studied the morphosculptural units of the Ibiapaba Plateau and surrounding areas. At this first taxon, the study area fits entirely within a single polygon, showing no internal variation at the municipal scale; differentiation begins only at the second level.

The study utilized the ALOS PALSAR, ASF (2020) DEM (12.5 m resolution) for altimetric classification to facilitate geomorphological mapping at the second and third (hypsometry-influenced) taxa. The altitude intervals, previously defined through field observation for the delineation of morphosculptural units, enabled the identification of areas dominated by similar landforms within the territory of São Benedito. Identification of these two levels relied on altimetric data due to the particularities of landform distribution and evolution on the Ibiapaba Plateau. Citing Santos (2022), this classification was derived using the r.reclass tool, which is part of the GRASS package in QGIS version 3.30 (2023).

The process requires writing a programming expression to set altimetric intervals. The "thru" command defines the "up to" range, while the equality symbol assigns the class value, enabling class distinction. Subsequently, the sieve/filter tool is applied to remove polygons that are incompatible with the working scale.

The altimetric intervals defined depend on the specific characteristics of the area under analysis. Despite the use of altimetric data, geomorphological mapping does not constitute a hypsometric map. In geomorphological mapping, observations focus on the genesis and both past and present formation processes. Accordingly, Table 1 presents a summary of the materials used in the geomorphological mapping of the municipality of São Benedito.

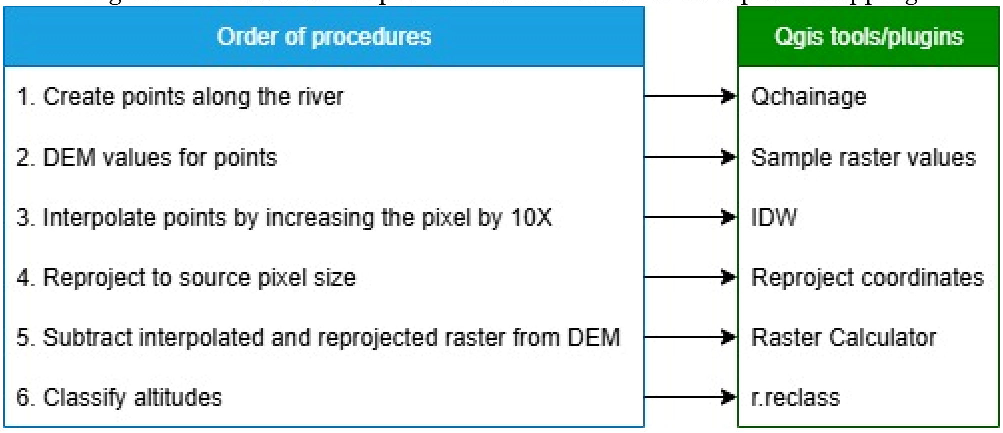
Table 1 – Materials used in the geomorphological mapping of the municipality of São Benedito

Taxon	Material	Attributes	Intervals (m)
1 – Morphostructure	Geological provinces	Parnaíba Basin	-
2 – Morphosculpture	DEM – ALOS PALSAR	Main river levels	> 2
		Hypsometry	< 200
			200 – 550
			550 <
3 – Landform patterns	MDE – ALOS PALSAR	Hypsometry	< 200
			200 - 350
			350 - 550
			550 - 840
			840 <
4 – Landform types	Geomorphological maps – AS24 and SB24	Forms	-

Source: Elaborated by the authors (2025).

The intervals used here are context-dependent and may vary across the Ibiapaba Plateau. Each case study requires field observations and consultation of diverse materials to define the boundaries in the respective units. In the taxa where hypsometry serves as the classification attribute, once the units are classified, appropriate nomenclature is assigned according to their characteristics, ensuring that the names convey information consistent with the corresponding taxon, in line with Ross (1992).

Figure 2 – Flowchart of procedures and tools for floodplain mapping



Source: Elaborated by the authors (2025).

Field observations defined the altimetric interval of fluvial plains, just as they did for the other units of the second and third taxa. In contrast, this classification utilized a different attribute: the base level of the main rivers (Table 1). In the GIS environment, the process assigned a zero-altitude value to the river thalweg by processing the DEM. Consequently, this adjustment facilitated the classification of altimetric ranges based on the river thalweg. To perform this procedure, it was necessary to use both a DEM and the linear feature representing the river course. The flowchart in Figure 2 illustrates the step-by-step process applied to each main river.

The identification of landform types (Table 1) integrated similar form patterns, derived from the procedures described here, with the geomorphological maps of the IBGE SA24 (Fortaleza) and SB24 (Jaguaribe) sheets (accessed via INDE). Despite the 1:250,000 scale, the landform types for the municipality of São Benedito largely matched those identified through the application of the technical procedures proposed by Tinós *et al.* (2014) for the study area. The advantage of this approach lies in the distinct delineation of boundaries among different landform types.

Geomorphological cartography applied to São Benedito as a basis for territorial planning

In addition to its fundamental role in territorial planning and management (Ross, 1992), knowledge of surface landforms also meets a crucial demand in environmental impact studies and reports. Aguiar *et al.* (2019) stress that detailed geomorphological analysis is indispensable before project implementation to mitigate detrimental effects from anthropogenic interventions. This study, therefore, provides information that can support both municipal public management initiatives and the mandatory environmental impact assessments required for potential projects.

This purpose becomes even clearer when considering the history of geomorphological studies in Brazil. The need for greater knowledge of Brazilian relief drove the Radambrasil project (Botelho; Pelech, 2019), continuing initiatives that federal public institutions began in this field since the 1940s. That project marked a turning point in the modernization and expansion of knowledge about the country's natural resources and landforms. The research community now applies these studies at the state and municipal scales to fulfill public management needs at those governmental levels. As Aguiar *et al.* (2019, p. 71) argue:

> "Geology and geomorphology studies are essential for understanding the ecosystem balance of localities, due to the morphostructural specificity of each area (Rodriguez; Silva, 2019). A systemic approach combined with environmental cartography enables decision-making processes that are fundamental for environmental and social quality in municipalities."

Thus, one can infer that producing geomorphological cartography at the municipal scale is essential for environmental and territorial management, providing a framework to assess both potentialities and vulnerabilities based on the dynamics captured in such materials. However, geomorphological mapping in Brazil still faces difficulties regarding methodological standardization. As Botelho; Pelech (2019) note, multiple methodologies coexist, which complicates the production of cartography at scales appropriate for municipalities. Nonetheless, the authors emphasize that only two multiscale classifications of Brazilian relief exist nationwide: the IBGE classification (2009) and Ross's framework (1992), which this study adopted.

First and Second Levels of Geomorphological Mapping

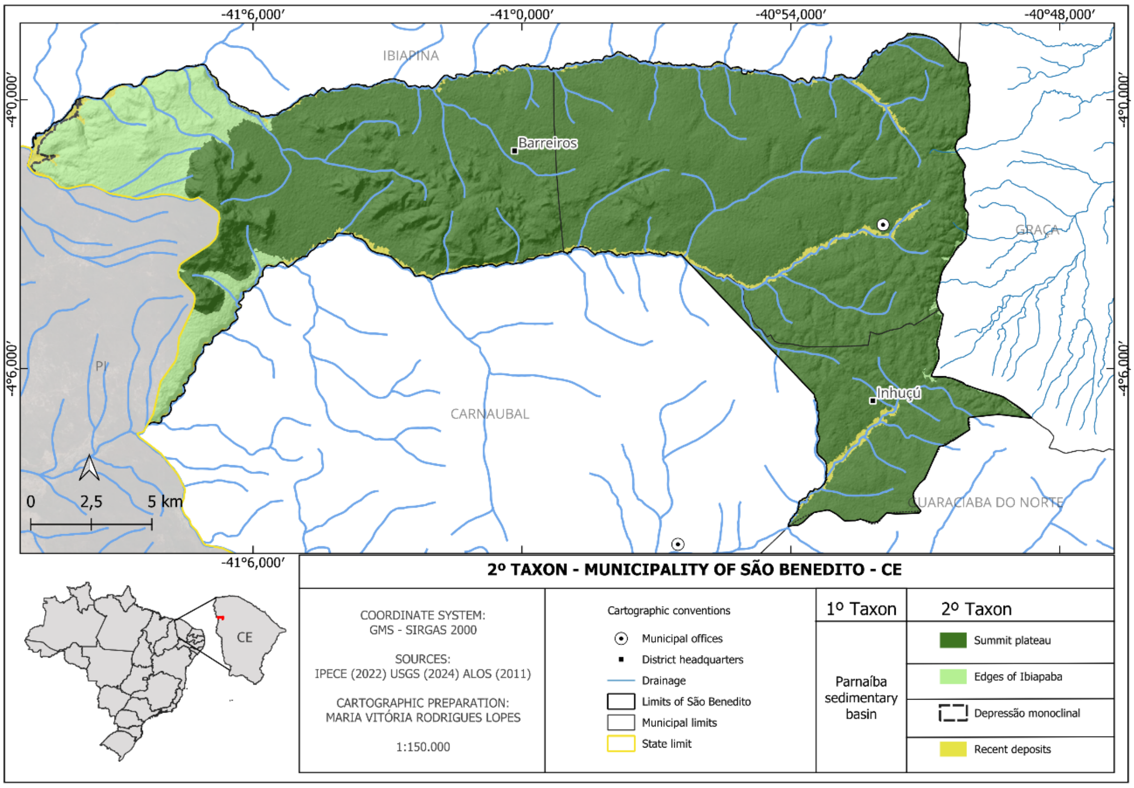
As previously discussed, Ross's (1992) methodology designates morphostructure as the first taxon of thematic landform mapping. This level of geomorphological cartography relates strictly to geology, specifically to the lithological structure of the relief. Ross (1990, p. 67) defines the units of the first taxon as those that "[...] correspond to the largest taxon and are defined by the genetic types of lithological groupings and their structural arrangements, which determine landform shapes [...]". Through geomorphological description, this framework explains the effects of endogenous and exogenous processes on landscape evolution.

As shown in Figure 3, the municipal territory of São Benedito, located in the northwestern region of Ceará, encompasses only one geological province: the Parnaíba Basin. This province characterizes the first taxonomic level in the study area and borders the crystalline basement morphostructure to the east. While most municipalities include both it and the Parnaíba Province, São Benedito does not. It lies entirely on the summit and back slope of the Ibiapaba Plateau.

The Parnaíba Sedimentary Basin, of which the Ibiapaba Plateau forms the eastern border, is a Paleo-Mesozoic basin composed of distinct lithological groups. In Ceará, however, only the Serra Grande Group outcrops. This group represents the oldest deposition within the basin, which makes it lithologically distinctive due to its structural resistance, expressed through greater particle cohesion compared to other sedimentary rocks (Crepani *et al.,* 2001).

Therefore, regarding morphostructure, the territory of São Benedito includes only the Parnaíba Sedimentary Basin. Consequently, the first taxon comprises only one unit —as illustrated in Figure 3 — with unit differentiation beginning only at the second level of landform classification.

Figure 3 – Map of the second taxon of the geomorphological mapping in São Benedito



Source: Elaborated by the authors (2025).

The Ibiapaba Plateau lies within a diverse set of morphosculptures supported by one of the largest Paleo-Mesozoic basins in Brazil. Ross *et al.* (2023) add that these basins:

> "[...] closed sedimentation in the Cretaceous, and throughout the Cenozoic, were uplifted by tectonic reactivation,

> placing them at varied altimetric levels, with more pronounced arching at the edges. In Eastern Amazonia, the edges reach 400 meters at their highest points; in the Parecis Basin, elevations range between 800 and 900 meters; while in the Paraná and Parnaíba-Sanfranciscana basins, the edges stand between 800 and 1,200 meters, and can reach up to 1,400 meters as seen in northeastern Rio Grande do Sul and eastern Santa Catarina." (Ross *et al.*, 2023, pp. 100–101).

The persistence of the plateau, as described above, results from the structural resistance of the sedimentary layers. This resistance varies along the abrupt escarpment that marks the plateau's cornice, which extends from north to south. The southern escarpments remain more robust, while the northern ones show greater erosion, as noted by Souza (1988). Such variation stems from the differential action of exogenous and endogenous factors. Vitte (2009) emphasizes that this understanding is critical for interpreting the genesis and evolution of Brazilian landforms.

The interaction of different agents acting with varying intensities on a heterogeneous structure has produced, in the Ibiapaba Plateau, a wide range of morphosculptures, patterns, and landform types. Santos; Nascimento (2019) demonstrate this in their study, where they also mapped the relief of Ubajara and Tianguá down to the fourth level of Ross's (1992) methodology.

The second level of geomorphological mapping characterizes units that reflect the influence of lithological resistance in relation to both present and past climatic conditions. Three distinct units define the Ibiapaba Plateau: the summit plateau (marked by the highest, gently sloping elevations); the plateau margins (with dissection similar to the eastern escarpments); and the monoclinal depression. This depression (a Parnaíba Basin sector) aligns with the Sertão surface in its geomorphological and climatic traits.

Within the municipality, the monoclinal depression occupies only a small portion. Souza (2000) characterizes it as a planation surface of the Parnaíba Basin, described as an undulating surface interrupted by the development of cuestas trending toward the basin axis.

Recent deposits extend across almost the entire municipality from east to west, following the main drainage channels. Water flow continually modifies these deposits, driven by the alternating processes of sediment accumulation and erosion. These deposits contain the most recently reworked sediments. They appear in east–west alignments that stretch across most of the municipality, but take on distinct features along the Ibiapaba margins. This sector exhibits steeper slopes and significant waterfalls, which intensify erosion and yield landscapes that stand in sharp contrast to upstream sections.

The third and fourth taxa in the classification of the relief of São Benedito

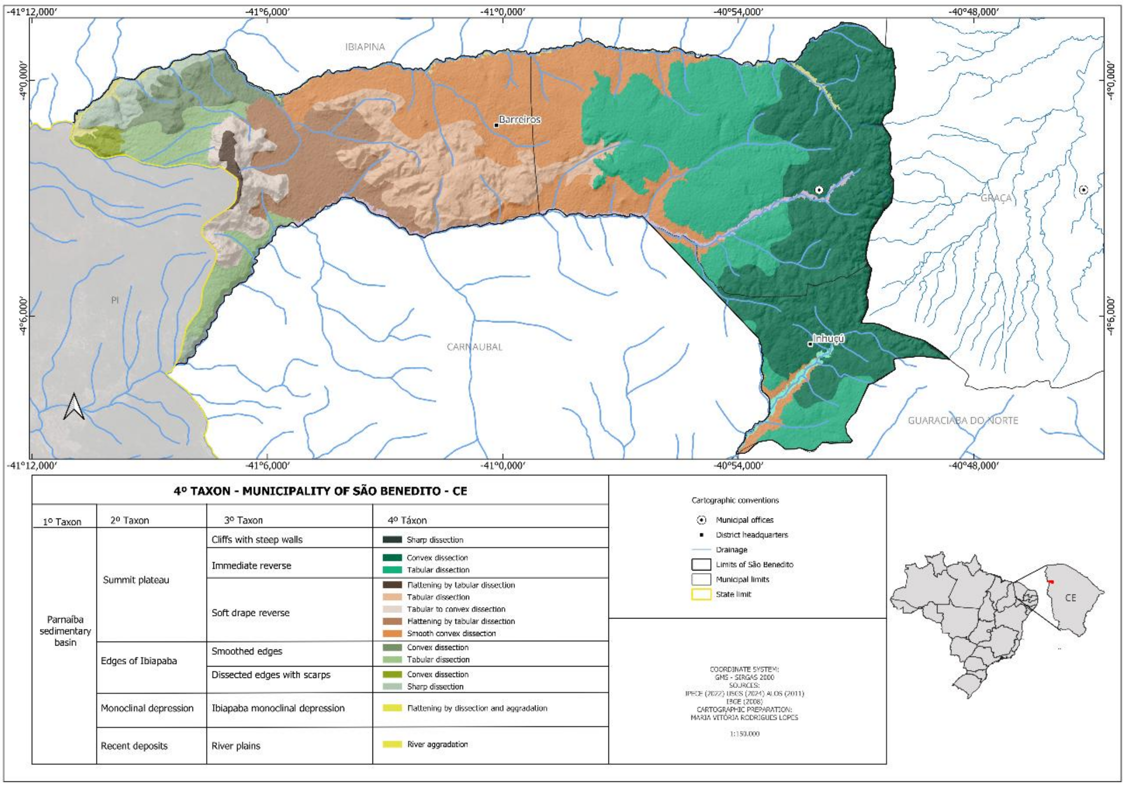
In defining the different patterns and landform types of the study area, one can observe closer relationships with humidity and vegetation characteristics. They highlight the strong correlation between geomorphological elements and other components of the landscape, including the influence of anthropogenic factors on landform configuration. The impact of these factors becomes more evident as the scale of geomorphological mapping increases. In this context, Peloggia (1997) notes that human interference can already be visible from the fourth taxon onward, when anthropogenic influence on relief intensifies, generating various risks to social integrity.

The intense transformations described by Peloggia (1997) do not occur in São Benedito, being more typical of large metropolitan areas. However, understanding the dynamics of the different units of patterns and landform types plays a crucial role in environmental planning, since it enables the assessment of which activities best suit each unit.

Regional studies have already identified recurring landform patterns in the Ibiapaba Plateau. For instance, Souza (1988) highlights the existence of sectors in Ibiapaba with contrasting humidity and rainfall conditions. These differences also impact geomorphological features, showing that geomorphological mapping is essentially systemic: like other natural elements, it both influences and is influenced by the dynamics of interconnected components. Thus, even at one of the levels proposed by Ross (1992), geomorphological mapping requires an integrated analysis. Florenzano (2008) reinforces this view by stating that geomorphological mapping is simultaneously a product and a tool of integrated environmental analysis.

Accordingly, the summit plateau and plateau margins of the Ibiapaba Plateau each yield two landform patterns. The monoclinal depression and recent deposits each contribute one pattern, totaling six patterns (see Figure 4). These patterns occur throughout the Ibiapaba Plateau, although their proportions vary within each municipal section.

Figure 4 – Geomorphological mapping: fourth taxon in São Benedito



Source: Elaborated by the authors (2025).

We emphasize that the identified patterns resemble those described in the works of Santos (2022).

Nascimento (2019), and Fernandes; Falcão Sobrinho (2025a). This similarity occurs because the study areas of these works are also in the northern Ibiapaba, where specific sectors share comparable geomorphological, floristic, and climatic characteristics. The mapped landform types also align with those delineated by Santos; Nascimento (2019). To enhance clarity, the classification of relief is presented in descending order, followed by a more detailed description of the predominant processes in each form. This approach aims to meet the demand for such knowledge in potential environmental planning and assessment projects.

Cliffs with steep walls and their different shapes

Among the units corresponding to the third taxon, the escarpment of cliffs appears with the minimum extent, reaching near invisibility at the adopted scale and occupying only 0.20% of the study area according to the municipal division of IBGE (2021). Planners must give critical attention to this feature in territorial planning, despite its limited municipal coverage, as municipal land-use management determines the sector's dynamics and stability.

Figure 5 – Ibiapaba Escarpment in São Benedito

Source: Elaborated by the authors (2024).

Sharp differential dissection forms develop there, as established in the IBGE's 1:250,000 scale landform mapping, which occurs due to the arrangement of the sedimentary layers and the curcundenudation process current in the plateau's escarpment, which is responsible for maintaining the right angle of the plateau in its first sector, characterized by the presence of the cornice (RADAMBRASIL, 1981).

In the study area, the escarpment marks the natural boundary between the municipalities of São Benedito and Graça. For this reason, it includes only the right-angled sector and not the less steep slopes that contain talus deposits. Due to their high degree of dissection and steepness, activities allocated to the escarpment areas and their surroundings must ensure the preservation of native vegetation, as it is essential for maintaining balance in highly sloping environments.

The immediate reverse and its types of forms

This unit stands out as the area where altimetric levels allow for greater humidity, making it a zone where vegetation remains green even during the second half of the year, a period when the rest of the semiarid region experiences rainfall scarcity and low atmospheric moisture. This characteristic of the immediate leeward slope—also referred to in other studies as the “humid leeward”—makes this sector the most densely populated in both municipalities of the northern Ibiapaba, and consequently, the most intensively exploited.

With altitudes above 850 m, the immediate leeward slope covers 162.32 km², corresponding to 46.27% of the municipal area under study. These figures reveal striking contrasts when compared with demographic data from the 2022 IBGE census, which show that 95.36% of the municipal population lives in the humid sector, that is, in less than 50% of the territory. Statistically, they confirm the intense occupation and, consequently, the heavy exploitation of its natural elements. These data are in Table 2. By extrapolating demographic data based on district headquarters, this interpretation is an approximation that does not reflect the population's precise spatial distribution across territorial divisions.

Table 2 – Population distribution based on relief units in São Benedito

Landform unit	Relief Area		Population		
	Km²	%	District	Inhabitants	%
Escarpment with an abrupt cliff	0,71	0,20	-	-	-
Immediate leeward slope	162,32	46,27	Seat	40 097	84,16
			Inhuçú	5 336	11,20
Gently sloping leeward slope	140,2	39,96	Barreiros	2 207	4,63
Smoothed escarpments	27,59	7,86	-	-	-
Dissected escarpments with scarps	8,93	2,55			
Monoclinal depression of the Ibiapaba	0,89	0,25			
Fluvial plains	11,04	3,15			

Source: Elaborated by the authors using their own data and data from IBGE (2021).

The relief patterns of the immediate leeward slope encompass two distinct landform types, which local activities intensely exploit. Deforestation is evident as people favor diversified agricultural areas. These landforms are observable both in the unit where convex hills dominate and, in the area, characterized by broad, flattened hilltops, as represented in Figure 4.

The convex dissection unit, responsible for the formation of undulating hills, is located immediately after the Ibiapaba escarpment within São Benedito. This process gives rise to landforms with predominant slope classes ranging from 8° to 20°, thus resulting in a predominantly undulating relief with a high drainage density caused by the incision of valleys formed by numerous first-order streams, a common feature in headwater areas. Both the municipal seat and the district seat of Inhuçú are situated in areas dominated by this landform type. Consequently, the cutting of hills for earthmoving activities before construction is common, along with the presence of risk-prone areas due to inadequate occupation of steep terrains, particularly observed in the municipal seat.

The tabular dissection unit, on the other hand, gives rise to a predominantly gently undulating relief, characterized by extensive flat-topped hills occasionally dissected by river valleys. In this sector, the rivers exhibit a relatively low erosive capacity despite being near their main headwaters, a peculiarity derived from the location of the study area on a sedimentary platform. In the convex dissection unit, land use and occupation practices often accelerate erosive processes (see Figure 6). In the tabular dissection unit, however, land use is largely expressed through agriculture, with diverse crops cultivated mainly in the vicinity of fluvial plains.

Figure 6 – Landform types in the immediate leeward slope: a) convex dissection forms in undulating hills; b) tabular dissection forms in broad hills

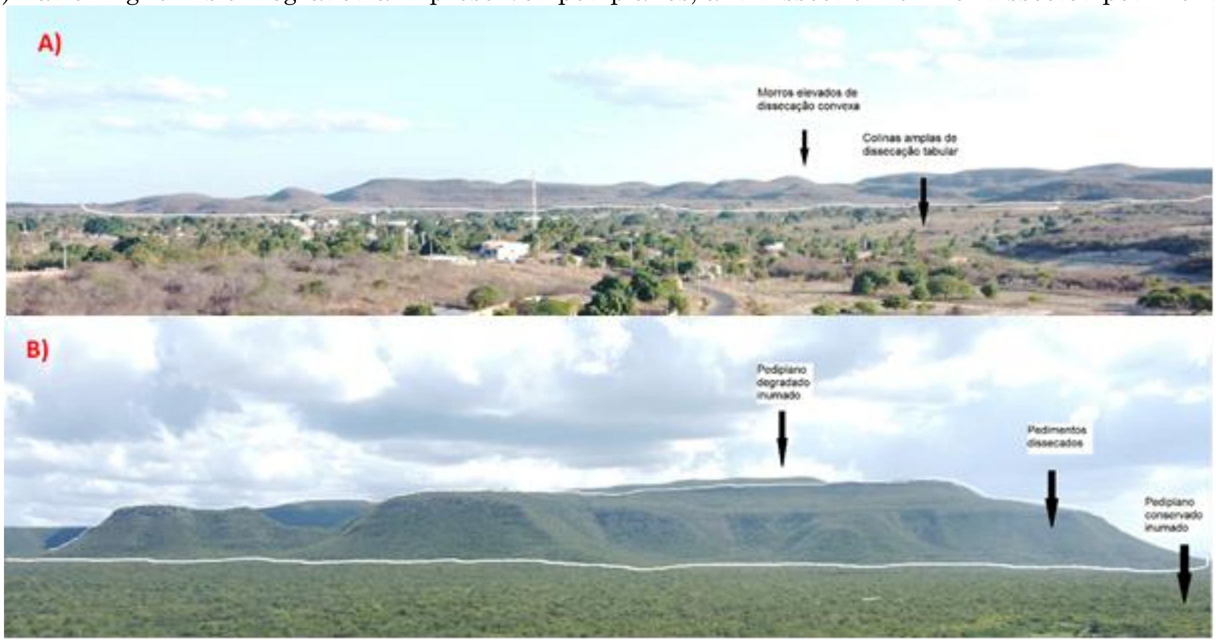
Source: Elaborated by the authors (2024/2025).

The smooth reverse and its types of shapes

This unit contains the greatest variety of landform types and is also the most spatially extensive. It includes tabular dissection, convex dissection, and planation forms. As shown in Table 2, this unit extends over about 39% of the municipality, where the district seat of Barreiros is located—the largest in territorial extent and the smallest in demographic terms—thus presenting another disparity which, like that of the immediate leeward slope, also derives from its physical-environmental characteristics.

It is observed that on the gentle leeward slope, the main features influencing demographics converge with those affecting cultivation and consequently economic dynamics, namely the lower rainfall and humidity resulting from its leeward location. Satellite imagery analysis for the year 2024 also reveals a greater permanence of native vegetation in this unit, indicating that climatic and geomorphological conditions exert a strong influence.

Figure 7 – Types of smooth reverse slopes; a) dissection forms of convex hills and broad-topped hills; b) flattening forms of degraded and preserved pediplanes, and dissection form of dissected pediments



Source: Elaborated by the authors (2024/2025).

Given the climatic influence on economic activities, the relief plays a decisive role in preserving native vegetation through the steep slopes present in the gentle leeward sector. These inclinations hinder agricultural practices, protecting the original vegetation by limiting accessibility and offering soils poorly suited to cultivation.

In this leeward area, three landform types occur: convex dissection, tabular dissection, and planation. They result in elevated surfaces that remain prominent while surrounding areas have been leveled, leaving two main sets of elevated forms—convex and tabular hilltops (Figure 7). In the westernmost sector lies an extensive tabular surface shaped by laminar erosion (Figure 7b). This elevated planation surface differs from the lower planation forms because it remains raised, representing a degraded pediplane. Its stepped pediments reveal ongoing processes of circumdenudation.

Other processes in this sector generate gentler slopes, such as tabular dissection forming wide tabular hilltops, and planation within the preserved, buried pediplane of the gentle leeward slope. In flatter areas of this leeward sector, subsistence farming is practiced, particularly rainfed cultivation restricted to the wet season. While both the tabular dissection and planation units show limited dissection, the former predominantly features gently undulating to undulating relief, whereas the latter consists mainly of flat terrain.

The types of shapes of the smoothed and dissected edges, the monoclinal depression of Ibiapaba, and the river plains

Adding together all landform patterns in the far west of São Benedito and the fluvial plains, these areas cover only 47.56 km², corresponding to 13.56% of the municipal territory, as shown in Table 1. They are characterized by low population density, with the exception of the fluvial plains. Although these plains do not host district seats, some sectors are settled, which suggests that, in territorial and demographic terms, the leeward units carry greater weight.

Despite their limited spatial extent within the municipal grid, the units highlighted in this section display significant diversity. In São Benedito, the Ibiapaba escarpments are classified into smoothed and dissected with scarps in the third taxon of Ross's (1992) methodology. To further distinguish their landform types, they subdivide into four distinct forms based on slope gradients, altimetric ranges, and topography. These subdivisions in the escarpments stem from the integration of data and divisions provided by the IBGE geomorphological mapping (2015) with those from the São Benedito geomorphological survey based on Ross (1992), resulting in differentiated patches that reveal varying degrees of dissection.

Figure 8 – Types of shapes of smoothed edges and dissected edges with escarpments: a) carved valley in dissected edges with escarpments; b) small hills with convex tops on smoothed edges; c) steep escarpment exposed on dissected edges

Source: Elaborated by the authors (2024/2025).

Within the smoothed escarpments, tabular dissection forms appear as transitional zones between the preserved pediplane and the escarpments. Moving further into the smoothed escarpments, convex dissection becomes dominant, producing complexes of small hills with slightly steeper slopes (Figure 8). The dissected escarpments with scarps, on the other hand, are mostly marked by intense dissection and significant altimetric amplitude. According to the adopted methodology, these divide at the fourth taxon into sharp dissection forms and convex dissection forms.

In the sector of sharp-crested dissection, cliff walls develop as the incised valley escarpments carved by the Pejuaba and Arabe rivers through headward erosion along fault structures (Figure 8). In the dissected escarpments where convex dissection dominates, the landscapes begin to resemble the Ibiapaba monoclinal depression. The distinction in this methodological framework arises mainly from higher altimetric levels and a slight increase in slope gradients, resulting in a strongly undulating relief, while the monoclinal depression predominantly shows flat to gently undulating relief.

Figure 9 – Types of use/occupation in forms of aggradation: a) Pejuaba River floodplain with a narrow strip of riparian vegetation surrounded by various types of crops; b) Arabe River floodplain showing sugarcane cultivation on its banks in the background and low presence of riparian forest

Source: Elaborated by the authors (2025/2024).

As shown above, the fluvial plains cross nearly all the geomorphological pattern units in the studied municipality. When they pass through the escarpments, these plains tend to disappear due to steep slopes that prevent sediment deposition. They reappear in less dissected terrains. In this context, the study area reveals an overlap between the Ibiapaba monoclinal depression and the Pejuaba River fluvial plain. Because the drainage channel lies in a low-slope sector, the characteristics of the fluvial plain prevail, and thus the monoclinal depression shares the same symbol as the Pejuaba River plain.

Floodplains represent the only areas of aggradational leveling in the study area. They show prevailing slopes of up to five degrees and a flat to gently undulating relief. These units and their surroundings are heavily used for crop cultivation, highlighting the need to preserve riparian forests, which have been completely cleared in some river stretches and remain sparsely vegetated in others (see Figure 9a). Deforested margins are vulnerable to accelerated siltation, which reduces channel depth and width. Such changes can generate not only environmental impacts but also social and economic risks, including flooding in inhabited and agricultural areas.

CONCLUSION

The presentation of information in this research aims to support potential initiatives for planning and organizing land occupation in one of the municipalities of the northern Ibiapaba region. The multiscale geomorphological survey applied Ross's (1992) methodology to hierarchically organize the data, allowing the identification of different environmental system boundaries. These encompass not only geomorphological elements but also their significant influence on other environmental components. This approach enables both the deduction of characteristics of present elements – as conducted by Santos (2022) to refine pedological and phytoecological mapping – and the identification of suitable anthropogenic activities for each potentially zoned unit.

The geomorphological mapping at various spatial levels highlights both the limitations and potentialities of the area. Combined with demographic and land-use data, it can reveal trends in the current landscape and provide a foundation for the development of a planned territorial scenario. Such applications represent one of the core uses of the geosystem concept within physical geography, primarily aimed at addressing environmental, social, and economic challenges faced by humanity.

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Maria Vitória Rodrigues Lopes: Conceptualization, Data analysis, Funding acquisition, Research, Methodology, Data presentation design, Writing of the original manuscript. José Falcão Sobrinho: Data analysis, Supervision and Writing - review and edition.