







Mapping and Geodiversity characterization in Linhares, Jaguaré and Sooretama (Espírito Santo, Brazil) and implications for regional development

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Abstract

This study, conducted in the municipalities of Linhares, Jaguaré, and Sooretama, in the state of Espírito Santo, southeastern Brazil, characterizes the regional geodiversity, providing essential information on the physical environment that can be used by public and private stakeholders in territorial planning, with a view to socioeconomic development (job and income generation) and sustainability (environmental protection and public health). Such information encompasses the potential of water resources (surface and groundwater), groundwater quality, and the geotechnical characterization of areas susceptible to geological and geotechnical events, which are crucial for appropriate land use and occupation.

To this end, the Geodiversity Map was produced at a scale of 1:100,000 by the Geological Survey of Brazil (SGB/CPRM), based on bibliographic research, field surveys, and analysis of physical aspects, including geology, geomorphology, soils, land use, and water quality. The mapping resulted in three geological-environmental domains, subdivided into seven units defined according to lithology and depositional environments. The unconsolidated sediment domain stands out, as it accounts for more than 88% of the mapped area. Predominantly represented by sediments of varied composition belonging to the Barreiras Formation, this domain is widely used for urban occupation and mineral exploitation, such as borrow material for civil construction and onshore petroleum production. This study provides an overview of the geodiversity of this region of the state of Espírito Santo, offering public and private managers and administrators baseline information to support the development of public policies aimed at land use, occupation, and the sustainable management of the physical environment.

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1. Introduction

The history of geodiversity is relatively recent; therefore, few authors have proposed a specific definition. According to Pfaltzgraff (2010), “the term ‘geodiversity’ was first used in 1993 at the Malvern Conference, United Kingdom, on ‘Geological and Landscape Conservation’”. Initially, the concept was applied to the management of environmental protection areas, as a counterpart to the term biodiversity, given the need for a concept encompassing the abiotic elements of the natural environment (Cañadas, 2007). However, the term had already been used earlier, in the 1940s, by the Argentine geographer Federico Alberto Daus, with a connotation related to Cultural Geography (Rojas in Cañadas, 2007).

CPRM (2006), however, adopts the following definition of geodiversity: “the study of abiotic nature (the physical environment), comprising a variety of environments, compositions, phenomena, and geological processes that give rise to landscapes, rocks, minerals, waters, fossils, soils, climate, and other surface deposits that support the development of life on Earth, encompassing intrinsic cultural, aesthetic, economic, scientific, educational, and touristic values.” Within this framework, the knowledge generated by geodiversity studies is of great importance for territorial planning, as it enables the identification of the potentials and constraints of a given area for the most appropriate land use (Figure 1).

Below are practical examples of the application of geodiversity as a tool for territorial planning. (1) **Occupation Restriction:** Delimitation of areas unsuitable for occupation, such as zones prone to flooding along riverbanks and floodplains, with the aim of restricting residential use. (2) **Construction Restriction:** Identification of areas unsuitable for construction in fluvio-lagoonal environments. These settings contain sedimentary deposits rich in organic matter, such as peat and soft clays, which are compressible soils that may lead to subsidence and differential settlement in buildings and public infrastructure. (3) **Use Definition:** Identification of land suitability for the development of urban, industrial, or agricultural activities. It also involves planning and implementing strategies to mitigate or reduce negative impacts that may affect the population, such as damage caused by natural disasters or other adverse events.

Thus, the selection of the study area for the preparation of the Geodiversity Map of Linhares, Jaguaré, and Sooretama (state of Espírito Santo, southeastern Brazil) is justified by the strategic economic relevance of these municipalities to the state. The map was developed based on information obtained from the literature, field surveys, and hydrochemical analyses. Its objective is to provide data on the region’s physical environment in a language accessible to both the general population and public and private stakeholders.

It is important to emphasize that this work represents, in practice, the refinement of a methodology originally proposed in 2006 (Silva, 2006) and further improved over the past two decades by technical teams from the Geological Survey of Brazil (SGB). The application of this methodology outside CPRM, particularly in the technical literature, remains extremely limited. The data obtained on the physical environment are essential for decision-making processes, enabling, for example, the allocation of areas for urban occupation where

the geotechnical characteristics of the terrain are favorable for the construction of housing developments or roads, as well as the identification of areas subject to destructive geological events, such as landslides and floods.

2. Location and characterization of the study area

The area covered by the Geodiversity Map of Linhares, Jaguaré, and Sooretama project is located approximately 120 km (Linhares and Sooretama) and 200 km (Jaguaré) north of the state capital, Vitória (Figure 2), in southeastern Brazil. It is a strategic region within both the state and national contexts, from economic and environmental perspectives, characterized by a strong agricultural vocation associated with intensive production systems and significant use of water resources.

Situated within a transition zone between the coastal region and the interior of the state, the area benefits from easy access to major federal and state highways, particularly BR-101 and ES-010. These transport corridors facilitate the flow of agricultural and livestock production and promote integration with the main urban and port centers of Espírito Santo.

The region is recognized as one of the main agricultural hubs of Espírito Santo, with emphasis on coffee cultivation, particularly conilon coffee, as well as the production of papaya, banana, coconut, rubber tree, and other permanent and temporary crops, most of which are associated with irrigation systems. This productive diversity gives the region high socioeconomic relevance, accounting for a significant share of employment and income generation in rural areas.

Extensive livestock farming is present throughout the study area, constituting a traditional land use across various biomes and geomorphological settings. In the fluvio-lacustrine plains, which extend from the surroundings of the municipality of Linhares to the coastal zone, livestock farming coexists spatially with sugarcane cultivation and other short-cycle crops, resulting in a mixed agro-pastoral landscape. In higher areas, corresponding to tablelands and more dissected terrains associated with denudational units developed over crystalline rocks, this activity predominantly shares space with the agricultural sector, particularly coffee cultivation, which has strong economic and territorial significance in this portion of the region (Figure 3).

In addition to agriculture and livestock farming, the municipality of Linhares stands out for onshore oil extraction, an activity mainly concentrated along the coastal strip. The presence of onshore wells, operated through sucker rod pumps, commonly known as pumpjacks, highlights the coexistence of primary sector activities, such as extensive livestock farming, with the energy industry, resulting in a territory characterized by multifunctional land use (Figure 4).

From the perspective of territorial planning, the municipalities of Linhares and Sooretama are part of the Rio Doce Planning Microregion, while the municipality of Jaguaré is included in the Northeast Planning Microregion (Figure 5). This division reflects administrative and functional differences, although the three municipalities exhibit strong economic and territorial integration.

The municipality of Linhares, the largest in territorial extent (3,496.263 km²) (IBGE, 2024), is located approximately 140 km from the state capital, Vitória. It has an estimated population of 166,786 inhabitants, resulting in a population

density of 47.70 inhabitants per km² (IBGE, 2022). The municipal Gross Domestic Product (GDP) per capita is R\$ 60,043.15, highlighting its economic importance within the state (IBGE, 2023).

Jaguará is located about 207 km from Vitória, with a population of 28,931 inhabitants, corresponding to a population density of 43.85 inhabitants per km² (IBGE, 2022). Its territorial area covers 659.751 km² (IBGE, 2024). The municipality's GDP per capita is R\$ 30,505.38 (IBGE, 2023), reflecting an economy strongly based on agriculture and livestock, with less industrial diversification compared to Linhares.

Sooretama, in turn, is located approximately 163 km from the state capital and has 26,502 inhabitants, resulting in a population density of 45.15 inhabitants per km² (IBGE, 2024). Its territorial extent of 587.036 km² (IBGE, 2022) and GDP per capita of R\$ 21,341.80 (IBGE, 2023) reinforce the predominantly rural character of the municipality, whose socioeconomic dynamics are closely associated with agricultural production and intensive land use.

The study area is predominantly characterized by low-relief terrains associated with coastal plains and the sedimentary tablelands of the Barreiras Group, conditions that favor the expansion of mechanized agriculture. These physical attributes, combined with soils of variable fertility, have historically driven agricultural occupation in the region.

One of the most distinctive features of the regional landscape is the presence of an extensive network of artificial drainage channels distributed across the coastal plain and adjacent areas. These channels were implemented primarily to mitigate recurrent flooding processes, which are common in low-lying areas with a high water table, as well as to enable the expansion of arable land (Figure 6).

Artificial drainage plays a fundamental role in the region's hydro-environmental dynamics, influencing both surface and groundwater regimes, as well as land use and occupation processes. Although it has significantly contributed to the development of the agricultural sector, this anthropogenic intervention also raises challenges related to water resource management, environmental conservation, and the sustainability of productive systems.

Thus, the study area is characterized as a territory of high socio-environmental complexity, marked by the intense interaction between agricultural activities, natural resource exploitation, and human interventions in the physical system. The combination of economic relevance, productive diversity, and environmental sensitivity makes the region particularly suitable for scientific investigations focused on spatial analysis, territorial planning, and the assessment of land use and land cover impacts.

In this context, the spatial framework adopted in this master's project allows for an integrated understanding of the natural and socioeconomic processes that shape the landscape of central-eastern Espírito Santo, contributing to the development of more efficient and sustainable territorial management strategies.

3. Materials and Methods

The methodology proposed for the characterization of geodiversity in Linhares, Jaguára, and Sooretama (ES) followed the guidelines of the *Methodological Manual for Geodiversity Survey at scales of 1:100,000 to 1:50,000*,

Volume 5, Version 4, of the Geodiversity Survey Program of Brazil, as presented by Maia et al. (2024). In the study area, three geoenvironmental domains were defined, established based on the geomechanical and intrinsic characteristics of each lithotype, such as mineralogy, texture, and degree of fracturing. The detailed description of these units aims to provide government stakeholders with robust technical support for territorial planning in the context of land use and increasing urban occupation.

Using this methodology (Figure 7), and integrating a substantial body of pre-existing data with new data obtained from fieldwork and bibliographic review, encompassing geology, geomorphology, hydrology, hydrogeology, and other aspects of the physical environment, it was possible to produce the Geodiversity Map of the municipalities of Linhares, Jaguára, and Sooretama at a scale of 1:100,000. The final cartographic product was generated in a GIS environment (Geographic Information Systems), using open-source software such as QGIS. Field data were collected, stored, and managed using mobile devices, such as tablets, equipped with QField software.

4. Results and Discussion

The processing and integrated analysis of data collected in the field, carried out in conjunction with office-based activities and laboratory analyses in the fields of geology, geomorphology, and pedology, resulted in the definition of three Geodiversity Domains and seven Geoenvironmental Units (UGAs) for the study area. These units are spatially represented in the map shown in Figure 8, and their specific characteristics, including lithology, water resources, and geodynamic aspects, are detailed below.

The detailed characterization of each UGA follows a high level of technical rigor, encompassing lithology, terrain morphometry, geomechanical behavior, including susceptibility to hazards, water resource potential, mineral resources, and suitability for land use and land cover, in strict accordance with the institutional methodology of the Geological Survey of Brazil (SGB).

4.1. UGA - DS1ind: Undifferentiated Unconsolidated Sediment

With a territorial extent of 2,161.88 km², this unit is characterized by the predominance of siliciclastic lithotypes, such as sands, clays, silts, and conglomerates (Figures 9 and 10). It occurs in morphosculptural domains of flat to gently undulating relief, located at higher elevations, and presents soil horizons of variable thickness. The associated landforms include floodplains, fluvio-lacustrine plains, tablelands, dissected tablelands, and low hills.

From a geotechnical perspective, the unit exhibits susceptibility to linear water erosion, including rill and gully erosion, flooding, and differential settlement in sectors where Gleysols, which are hydromorphic soils, are present. Additionally, there are risks of mass movements, particularly soil slides, although most of the unit shows low hazard levels regarding destructive geodynamic processes.

With respect to water resources, the hydrogeological potential is classified as high, with aquifers of good productivity, while the surface drainage network is

characterized by low discharge regimes. The geopedological association is diverse, comprising Acrisols, Cambisols, Spodosols, Gleysols, Latosols, and Neosols.

Although this unit contains several forest fragments, it is widely used for forestry, coffee cultivation, pasture, and agriculture. Urban expansion is considered technically feasible, provided it is supported by slope stability and drainage studies. In terms of mineral potential, deposits of sand, clay, and borrow material are noteworthy.

4.2. UGA - DS₁ptm: Coastal: Marine Plain/Terrace

This unit covers an area of 401.29 km² and is characterized by the predominance of Holocene siliciclastic deposits, composed of sands, silts, and clays (Figures 11 and 12). Morphologically, it is expressed as flat topographic surfaces, including beaches, coastal ridges (restingas), marine terraces, and fluvio-lacustrine plains.

From a geotechnical perspective, the unit is vulnerable to flooding, differential settlement, associated with the presence of Gleysols and organic soils, and erosional processes of marine, fluvial, or aeolian origin. Despite these constraints, most of the unit shows low susceptibility to destructive geodynamic events.

The hydrogeological potential is considered high, with aquifers capable of yielding significant discharge in tubular wells. This resource is strategic for supporting local agricultural activities, compensating for the limited natural surface drainage network. Regarding mineral resources, deposits of sand and clay are noteworthy.

The unit is used for pasture, agriculture, conservation of restinga ecosystems, forestry, and urban expansion. The coastal sector represents an important asset for geotourism. The geopedological association is complex, including Cambisols, Spodosols, Gleysols, Latosols, Neosols, and Organosols, which are soils with high organic matter content).

4.3. UGA - DS₁ptal: Fluvial: Alluvial Plain/Terrace

With an extent of 814.48 km², this unit consists of unconsolidated alluvial deposits derived from Holocene fluvial dynamics, including sands, silts, and clays, developed in floodplains (Figures 13 and 14). The predominant lithotypes comprise quartzose and arkosic sands, clays, silts, gravels, and polyimictic conglomerates. The associated landforms are part of the Quaternary depositional system, including floodplains, fluvio-marine plains such as mangroves, and fluvio-lacustrine plains.

The unit is characterized by soils with high natural fertility and, due to the primary porosity and permeability of its sediments, exhibits high water storage potential in alluvial aquifers. Surface water resources are abundant, with strategic volumes available for water allocation supporting agriculture, livestock, and public supply.

From a geotechnical perspective, the unit is classified as highly vulnerable to periodic flooding and is also susceptible to water erosion and pronounced differential settlement. The latter is directly associated with the presence of Organosols and Gleysols, which have low bearing capacity and high compressibility. Regarding mineral resources, the unit serves as a source of aggregates such as sand and clay, as well as borrow material for earthworks.

Land use and occupation are heterogeneous, including urban areas, forestry, coffee cultivation, pasture, and intensive agriculture. Urban occupation in this unit requires rigorous flood mitigation measures and the design of special foundation systems. The geopedological association is diverse, comprising Cambisols, Spodosols, Gleysols, Latosols, Neosols, and Organosols.

4.4. UGA - DS₁flc: Lacustrine: Fluvio-lacustrine Plain

This unit covers an area of 714.96 km² and is defined by unconsolidated deposits of fluvio-lacustrine origin, composed of silts, clays, sands, and gravels with a high concentration of organic matter (Figures 15 and 16). Its occurrence is associated with floodplain systems, fluvio-lacustrine plains, and infilled lagoonal environments. These deposits, resulting from overflow dynamics, mainly from the Doce River, and sedimentation in low-energy environments, confer extreme vulnerability to flooding events.

From a geological and geotechnical perspective, the area is subject to flooding, differential settlement due to the presence of peat, Organosols, and Gleysols, as well as erosion of marine, fluvial, or aeolian origin. However, it generally presents a very low likelihood of destructive geodynamic events.

Regarding water resources, both surface and hydrogeological potentials are classified as high, providing strategic water availability for agriculture, livestock, and public supply. Exploitable mineral resources include sand, clay, and borrow materials.

Land use and occupation within this unit include planted forests, native forests, pasture, agriculture, sugarcane cultivation, wetlands, restinga vegetation, and beach or dune environments. No significant potential for geotourism was identified. The associated geopedological soils include Cambisols, Spodosols, Gleysols, Latosols, Neosols, and Organosols.

4.5. UGA - DR₁liint: Plutonic/Intrusive: Intermediate Composition

This unit covers an area of 98.13 km² and is characterized by rock outcrops, either fresh or weathered, associated with weathering mantles, including saprolites of variable thickness (Figures 17 and 18). The predominant lithotypes include charnoenderbite, leucogranite, and gneissic granite. Morphologically, the unit occurs in rugged terrain, including high hills, undulating hills, ridges, mountainous domains, and escarpments at plateau margins.

From a geological and geotechnical perspective, the area is vulnerable to slope processes such as rockfalls, soil creep, soil and rock slides, representing mass movements, and accelerated erosion. These processes are controlled by steep slopes and the nature of the rock-soil interface. However, sectors with gentler relief exhibit low susceptibility to severe geodynamic events.

Regarding water resources, the surface drainage network consists of small streams that feed adjacent plains. The hydrogeological potential is classified as low, as water storage and circulation occur predominantly within fractured media, forming fissured aquifers. In contrast, the unit presents significant mineral potential, particularly for the extraction of dimension stone and crushed stone used in civil construction.

Land use and occupation include native forests, forestry, pasture, coffee cultivation, agriculture, urban areas, and exposed rock outcrops. The geopedological association is characterized by Acrisols, Latosols, and extensive Lithic Neosols, including rock outcrop areas.

4.6. UGA - DRliacd: Plutonic/Intrusive: Acid Composition

This unit is the least extensive in terms of territorial coverage, occupying only 5.18 km², and is characterized by rocky massifs with steep slopes (Figures 19 and 20). The predominant lithotypes are leucogranites and undifferentiated granites. The associated landforms include high hills and aligned mountainous ridges with abrupt slopes.

From a geological and geotechnical perspective, the unit exhibits extreme vulnerability to slope dynamics, with a high probability of block fall and rolling, as well as soil and rock mass movements, including landslides, controlled by slope geometry.

Regarding water resources, the surface drainage network consists of small streams that drain the slopes toward local base levels. The hydrogeological potential is classified as low, limited to water circulation within fractured media, including fractures and joints. In terms of mineral resources, the unit has extractive potential, being suitable for the exploitation of crushed stone and high-value dimension stone.

Due to severe morphological constraints, land use and occupation are restricted to the preservation of forest remnants, pasture, and subsistence agriculture. Urban occupation is technically inadvisable due to significant geological hazards. The geopedological association is relatively simple, predominantly composed of Lithic Neosols, including rock outcrops, and Latosols in areas with gentler slopes.

4.7. UGA - DRMortmain: Orthoderived Medium- to High-Grade: Intermediate Composition

This unit covers an area of 371.85 km² and is expressed in high-altitude and steep macrorelief, characterized by outcrops of metamorphic rocks, either fresh or weathered, and thin soil covers (Figures 21 and 22). The predominant lithotypes include garnet-biotite gneiss, granulite, calc-silicate rocks, and banded gneiss. The unit exhibits marked morphological heterogeneity, comprising colluvial ramps and talus deposits, low plateaus, hills, low hills, knolls and high hills, isolated ridges, mountain ranges, and escarpments at plateau margins.

From a geological and geotechnical standpoint, the unit shows pronounced vulnerability to surface dynamics, including block falls, mass movements such as soil and rock slides, and sheet and rill erosion, all controlled by the rugged relief. However, some sectors present low susceptibility to destructive geodynamic events.

Regarding water resources, the unit is drained by small streams with low discharge regimes. The hydrogeological potential is classified as low, with groundwater occurrence restricted to fractured media, forming fissured aquifers. In terms of mineral resources, the unit has economic relevance for the extraction of dimension stone and crushed stone, taking advantage of the hardness and aesthetic patterns of the igneous-metamorphic rocks. Land use and occupation include native forests, forestry, pasture, coffee cultivation, urban areas, exposed rock outcrops, and diversified agriculture.

5. Conclusion

The present study consolidates a systemic view of the geodiversity of the municipalities of Linhares, Jaguaré, and Sooretama, providing public and private stakeholders with essential technical parameters to support the formulation of public policies aimed at territorial planning, resilient occupation, and the optimized use of the physical environment.

The Geodiversity Map fulfills its purpose of translating complex geoscientific data into an accessible language, without compromising the technical rigor required for decision-making. The social value of this mapping is significant, as it provides the necessary guidelines for sustainable regional development, ensuring that territorial planning is aligned with the geodynamic potentials and constraints of the northern region of Espírito Santo.

Authorship credits

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A - Study design/ Conceptualization B - Investigation/ Data acquisition
 C - Data Interpretation/ Validation D - Writing
 E - Review/Editing F - Supervision/Project administration

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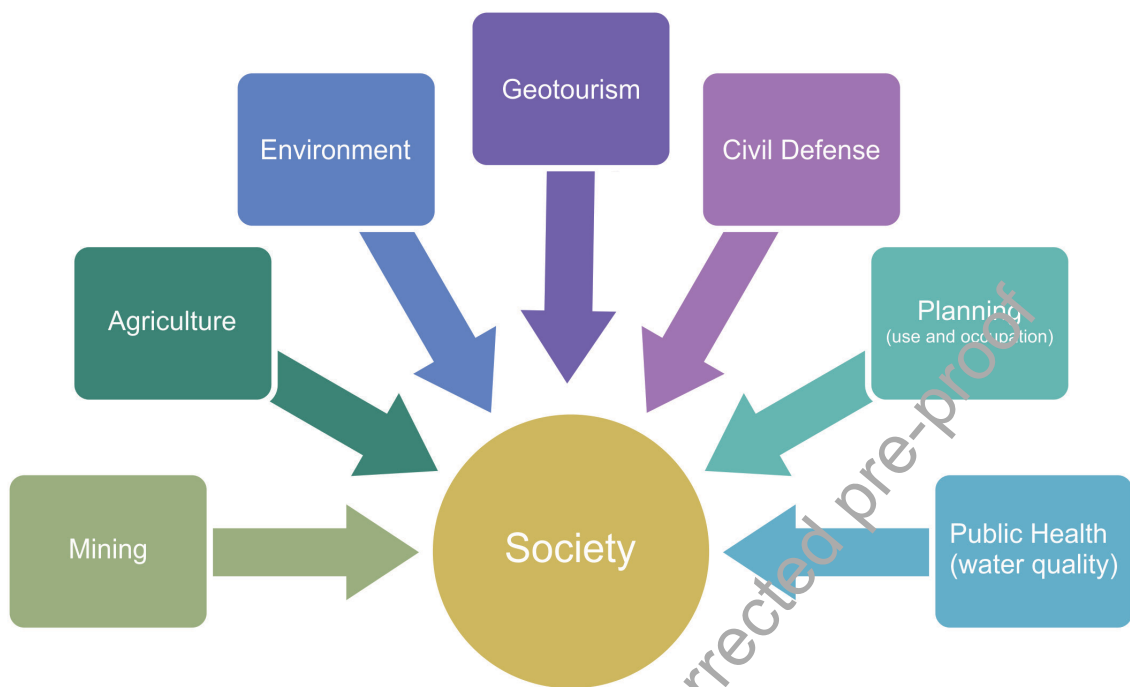


FIGURE 1. Various applications of geodiversity (Torres and Pfaltzgraff, 2024).

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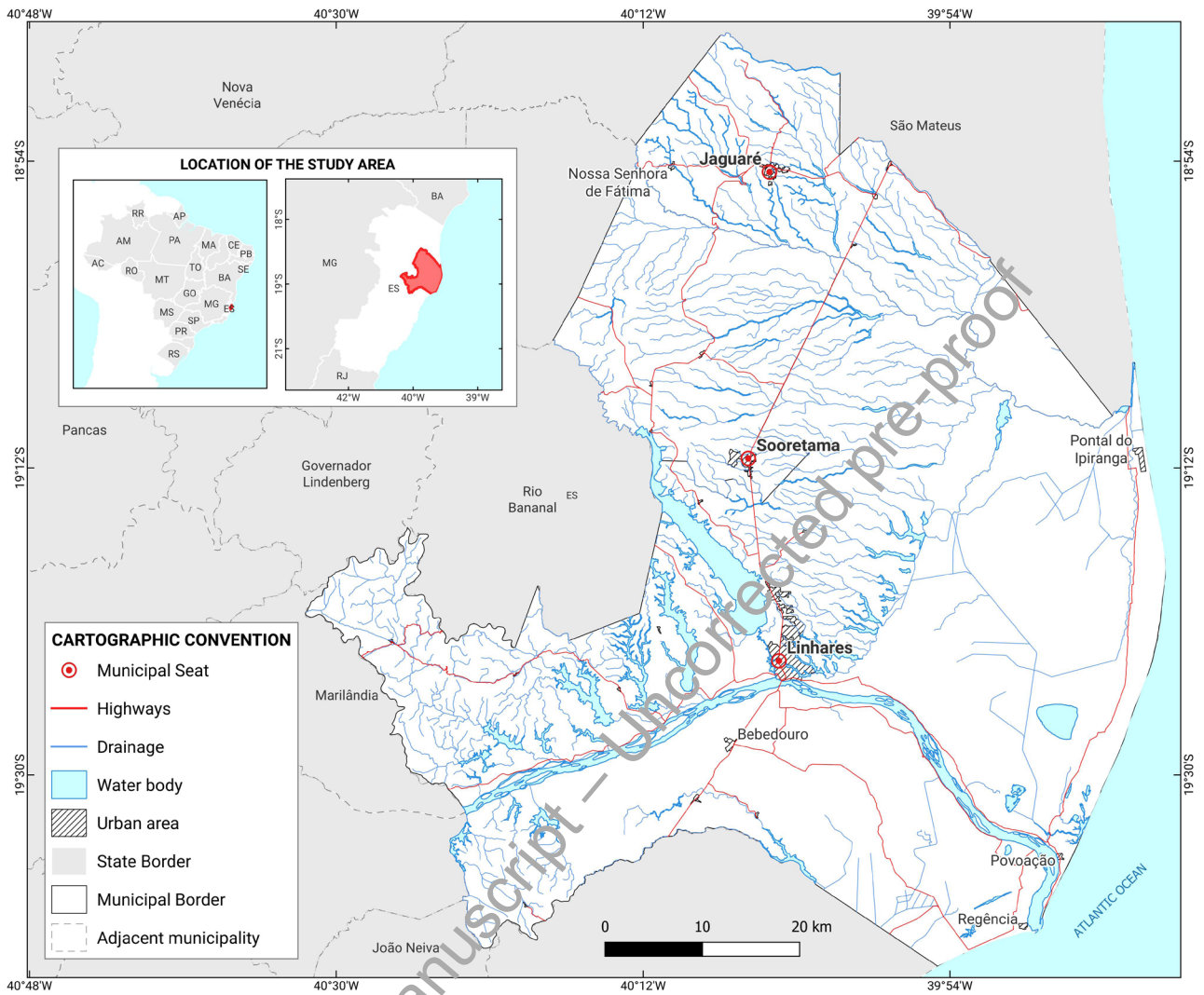


FIGURE 2. Location map of the study area.



FIGURE 3. Areas of extensive livestock farming: (a) in the lower-lying fluvio-lacustrine plains (photo by Alberto Franco Lacerda, 2025) and (b) in the more dissected terrains developed over crystalline rocks, in the municipality of Linhares.



FIGURE 4. Sucker rod pump (pumpjack) used for onshore oil extraction, municipality of Linhares (Photograph by Alberto Franco Lacerda, 2025).

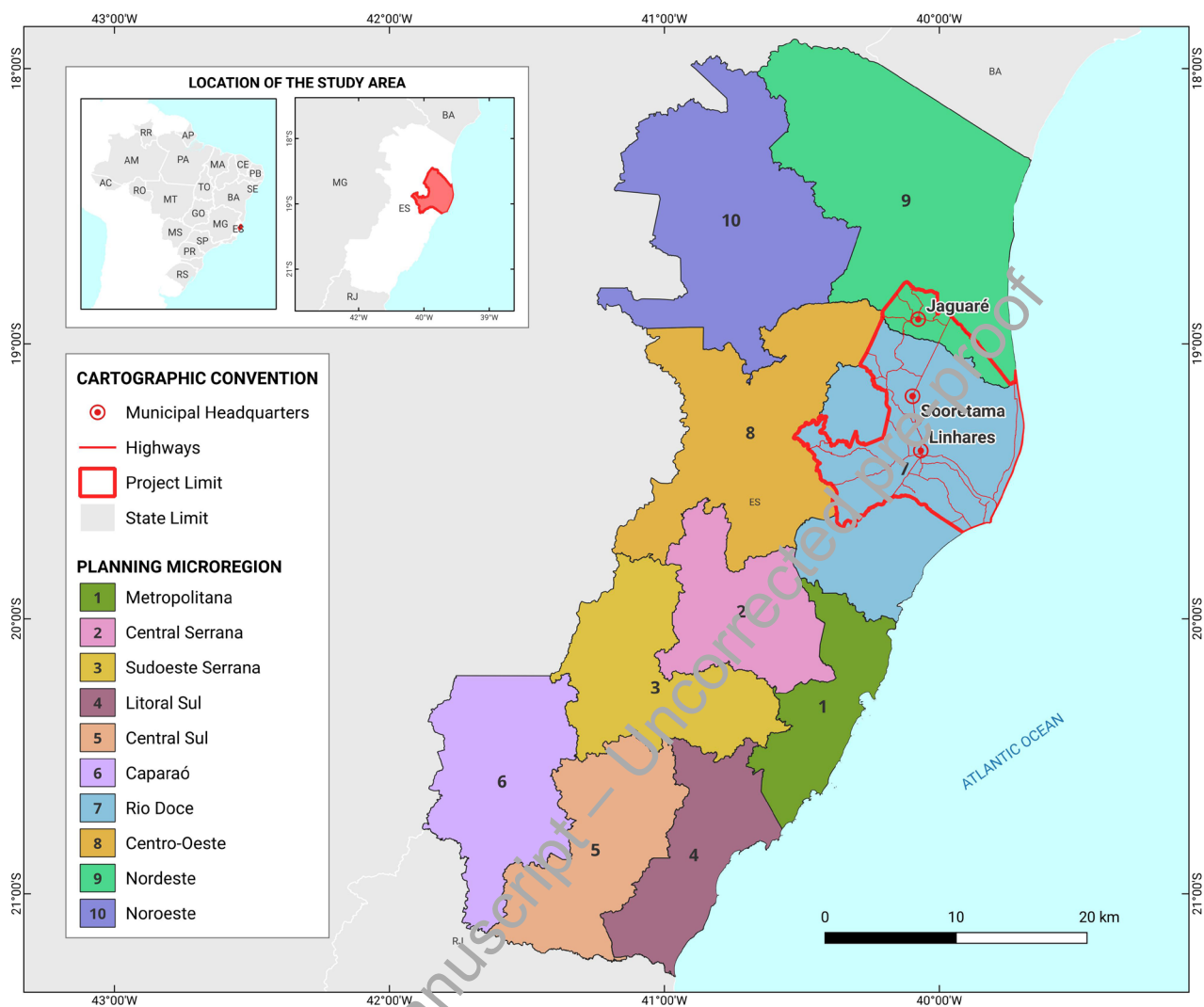


FIGURE 5. Division of the planning microregions of the state of Espírito Santo. Modified from the Government of the State of Espírito Santo (2025) and IBGE (2024).



FIGURE 6. Drainage channel, downstream view near Suruaca Lagoon, accessed via ES-010, municipality of Linhares (Photo by Marcelo Parente Henriques, 2025).

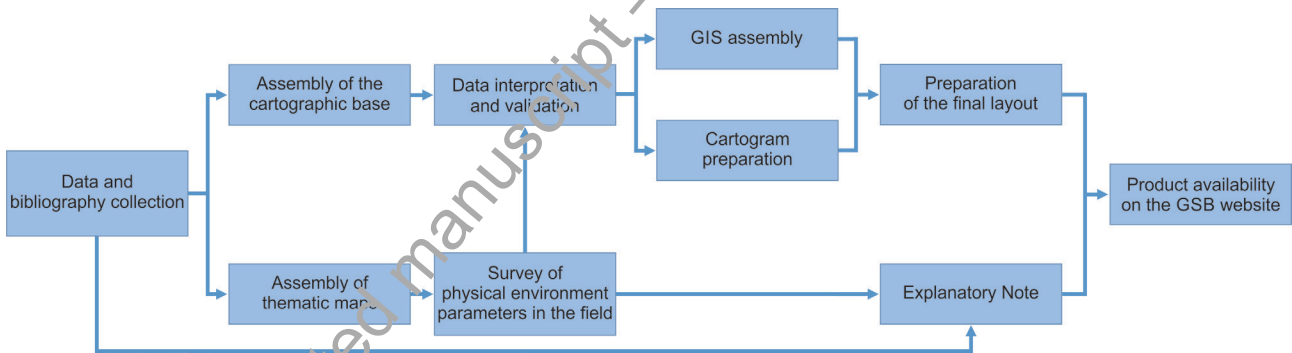


FIGURE 7. Methodology applied during the development of the Geodiversity maps (Torres and Pfaltzgraff, 2024).

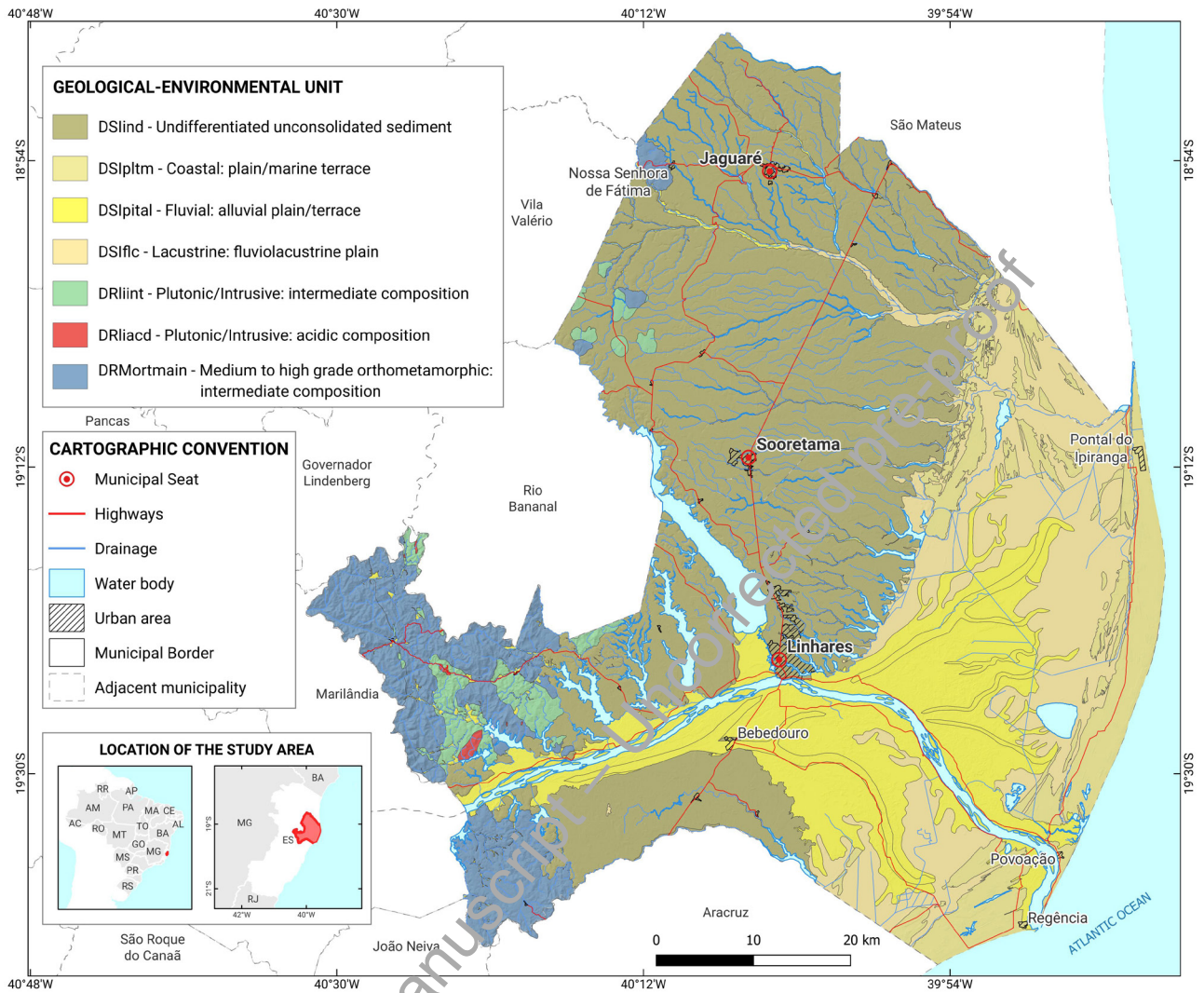


FIGURE 8. Map of the Geoenvironmental Units of the municipalities of Linhares, Jaguaré, and Sooretama.

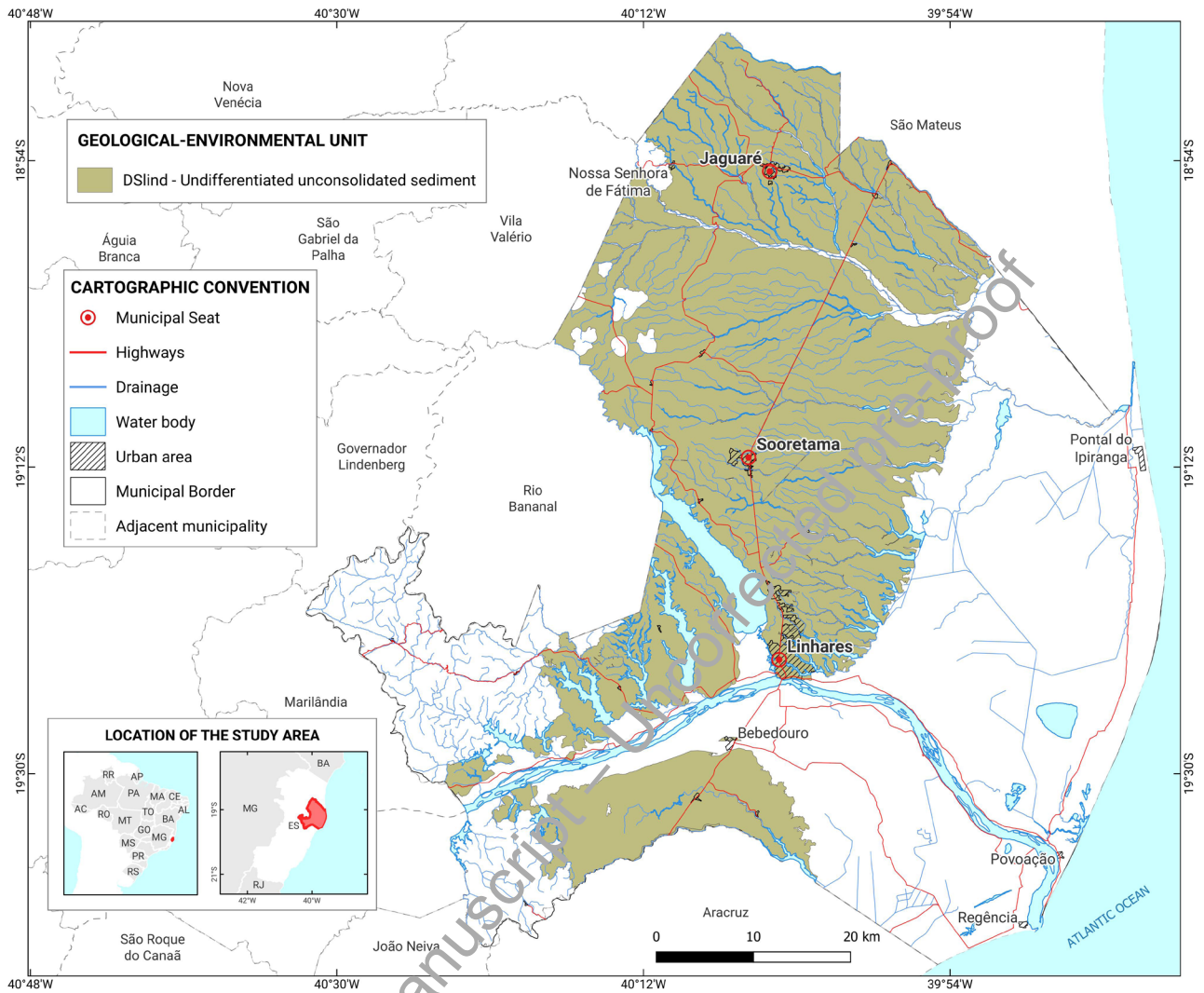


FIGURE 9. Location of the DSLind Geoenvironmental Unit.



FIGURE 10. Barreiras Group sediments located in the municipality of Jaguaré.

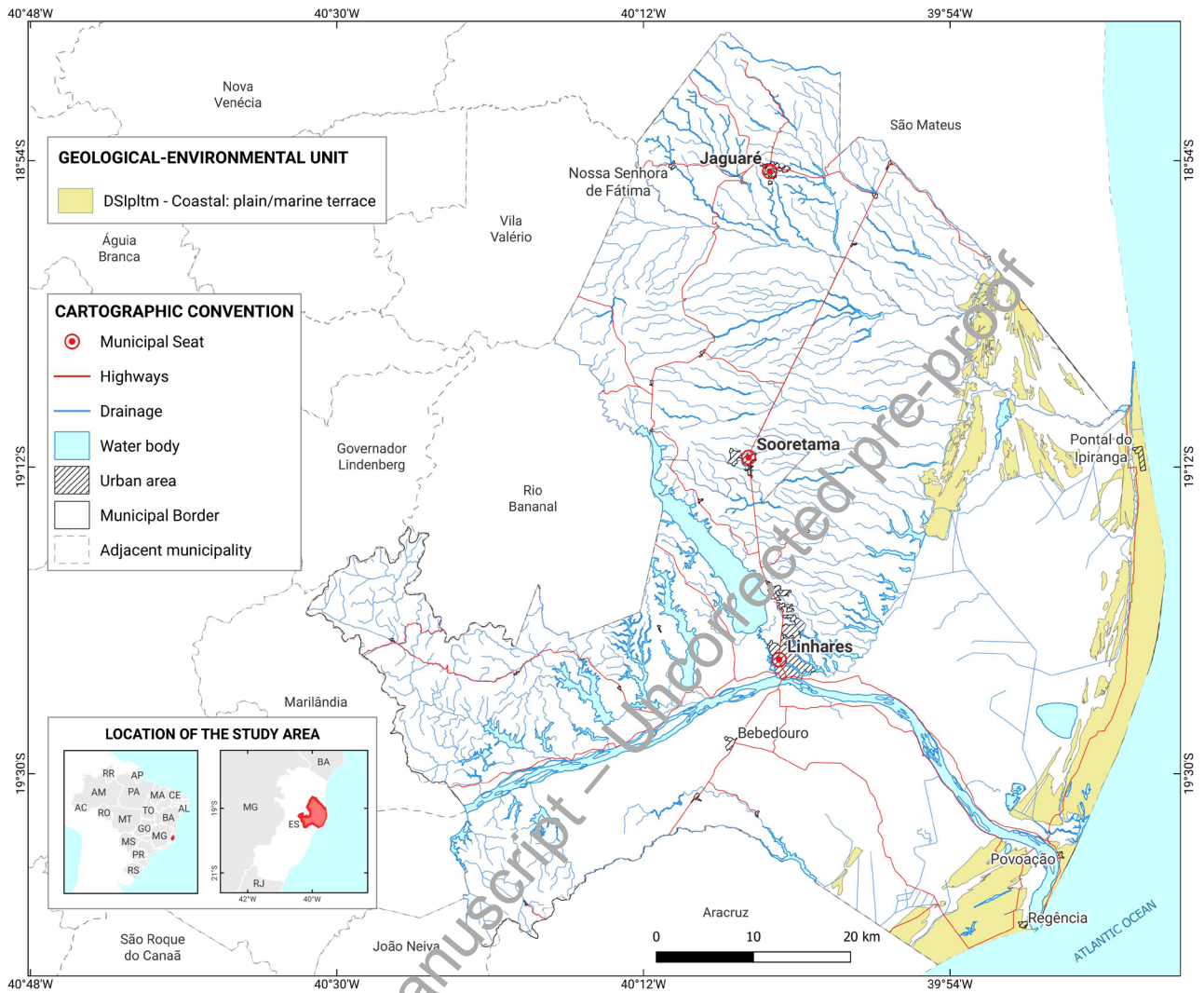


FIGURE 11. Location of the DSpltm Geoenvironmental Unit.



FIGURE 12. Recent sediments (Regência Beach), located in the municipality of Linhares.

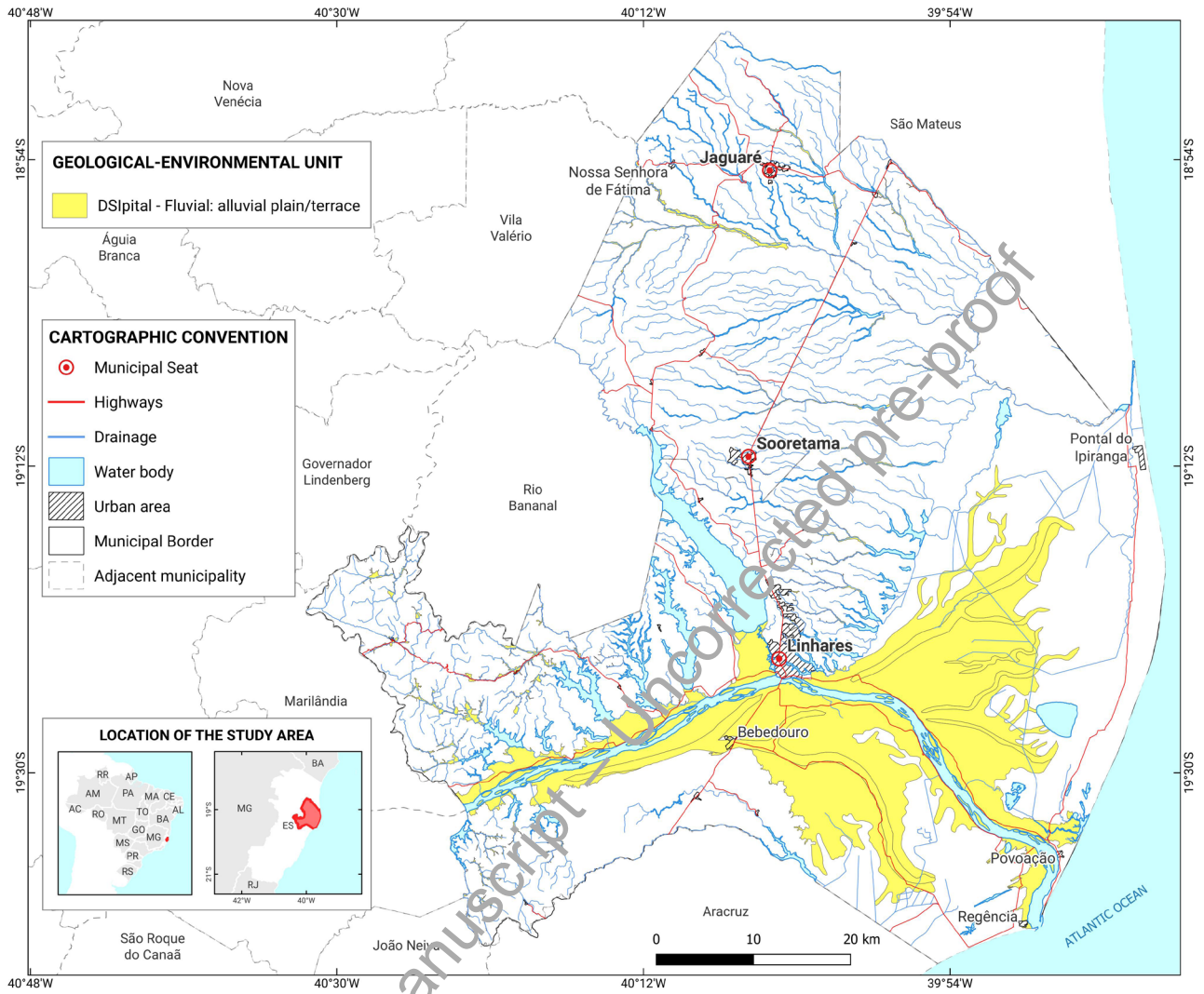


FIGURE 13. Location of the DSIptal Geoenvironmental Unit.



FIGURE 14. Anthropogenic occupation in the floodplain of the Doce River, municipality of Linhares.

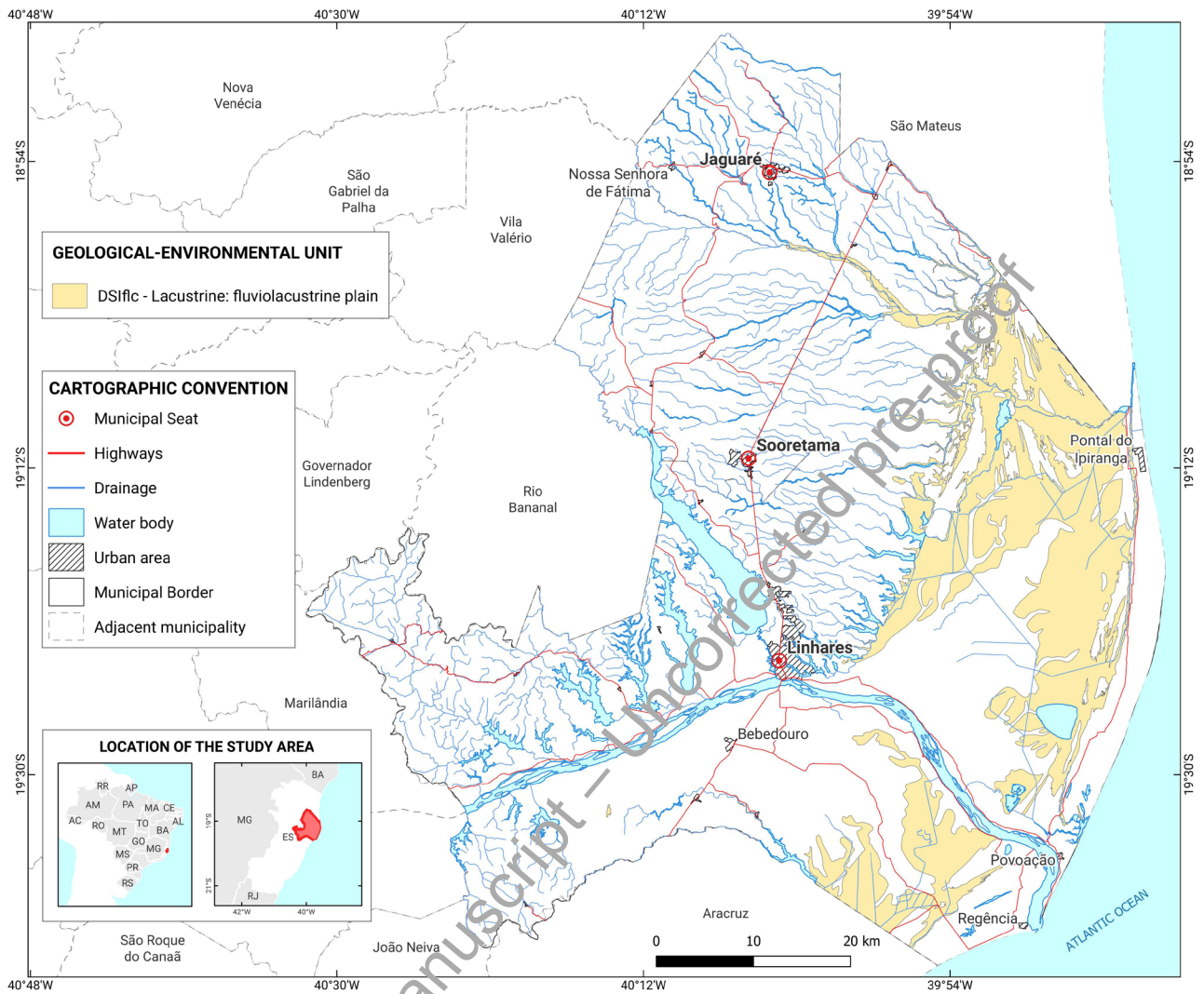


FIGURE 15. Location of the DSIfic Geoenvironmental Unit.



FIGURE 16. Fluvio-lacustrine plain used as pasture, municipality of Linhares.

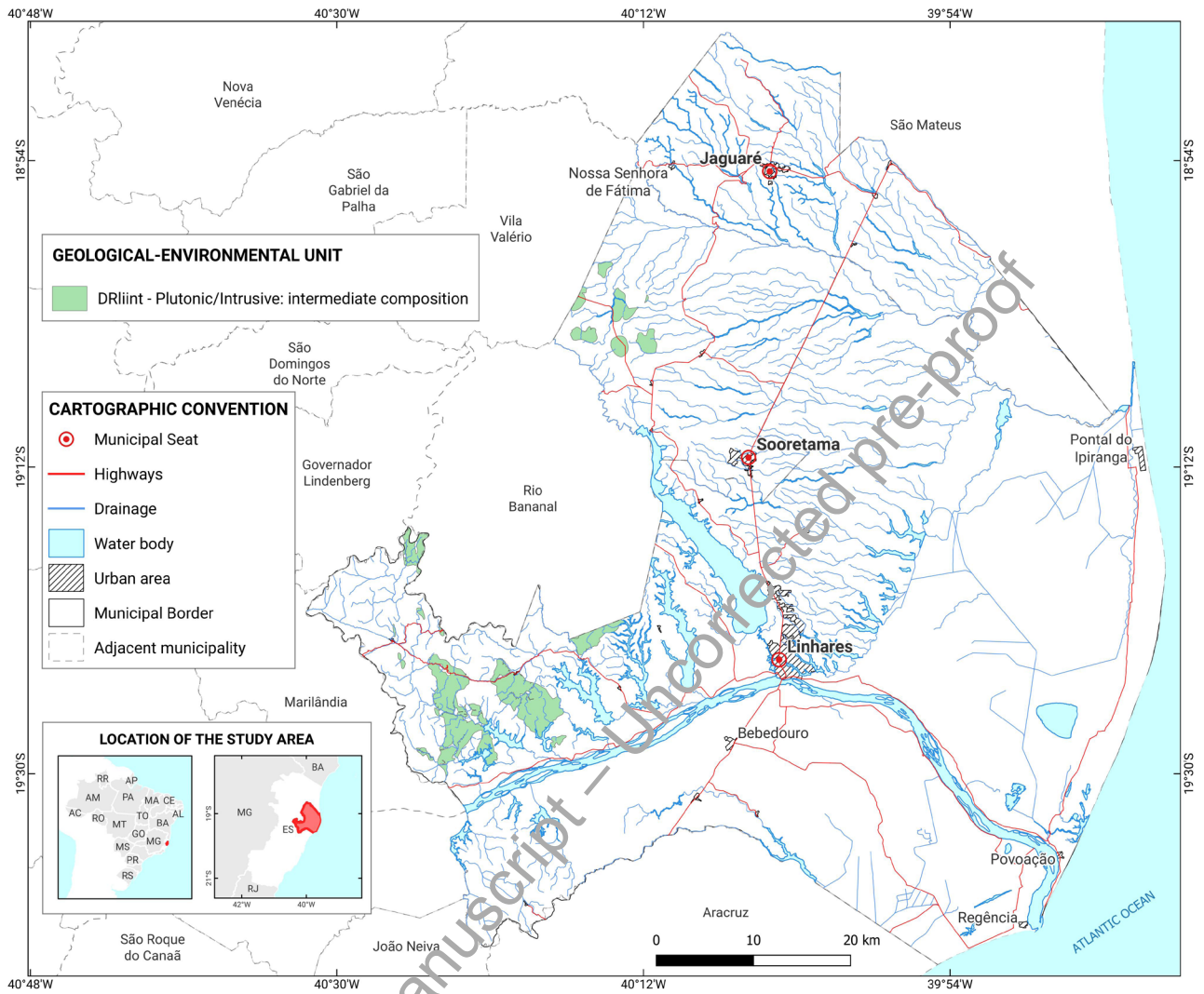


FIGURE 17. Location of the DRIIint Geoenvironmental Unit.



FIGURE 18. Coffee cultivation on slopes and small diversified crops on flat terrain, municipality of Linhares.

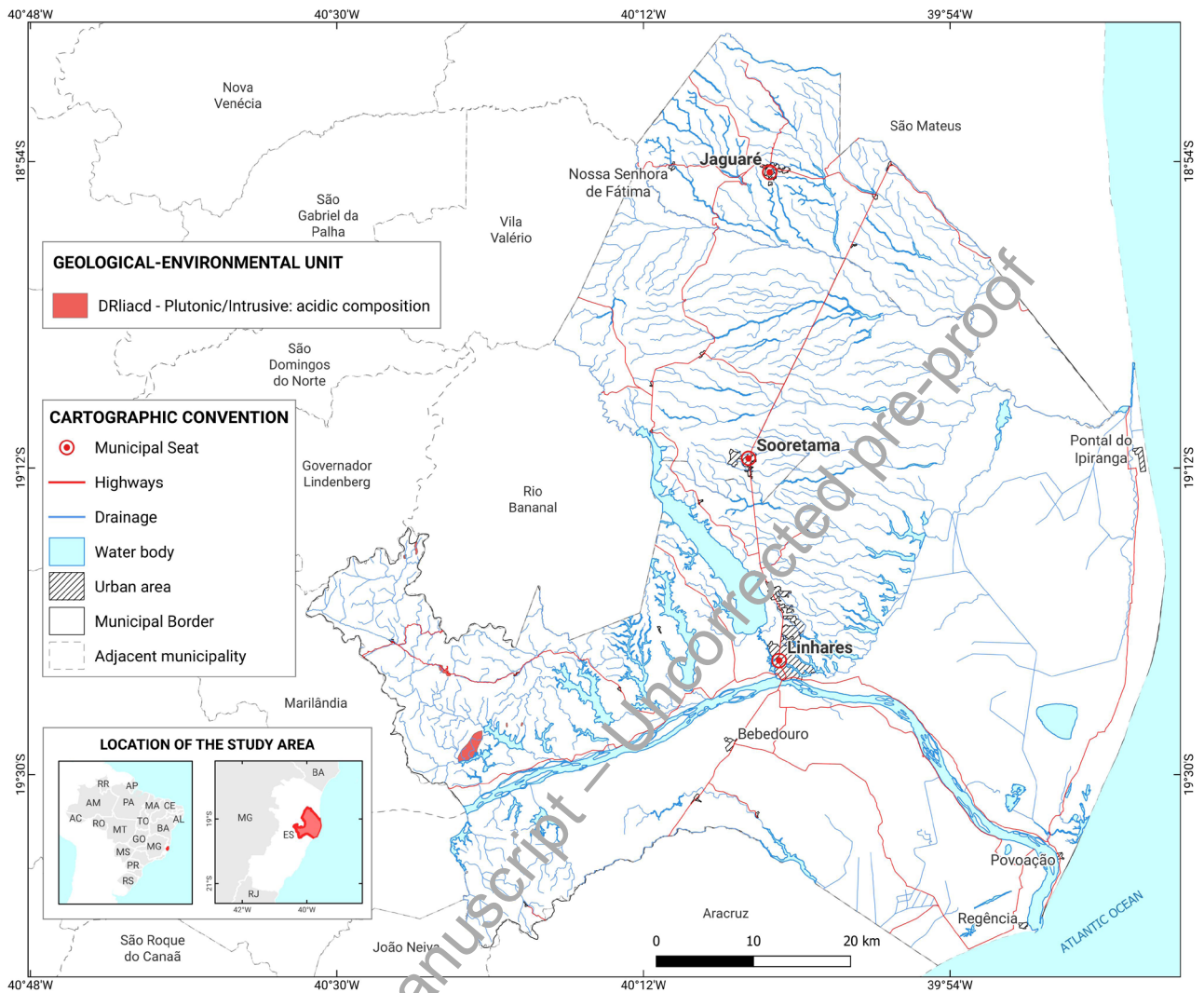


FIGURE 19. Location of the DRliacd Geoenvironmental Unit.



FIGURE 20. Extraction of dimension stone blocks in the western region of the municipality of Linhares.

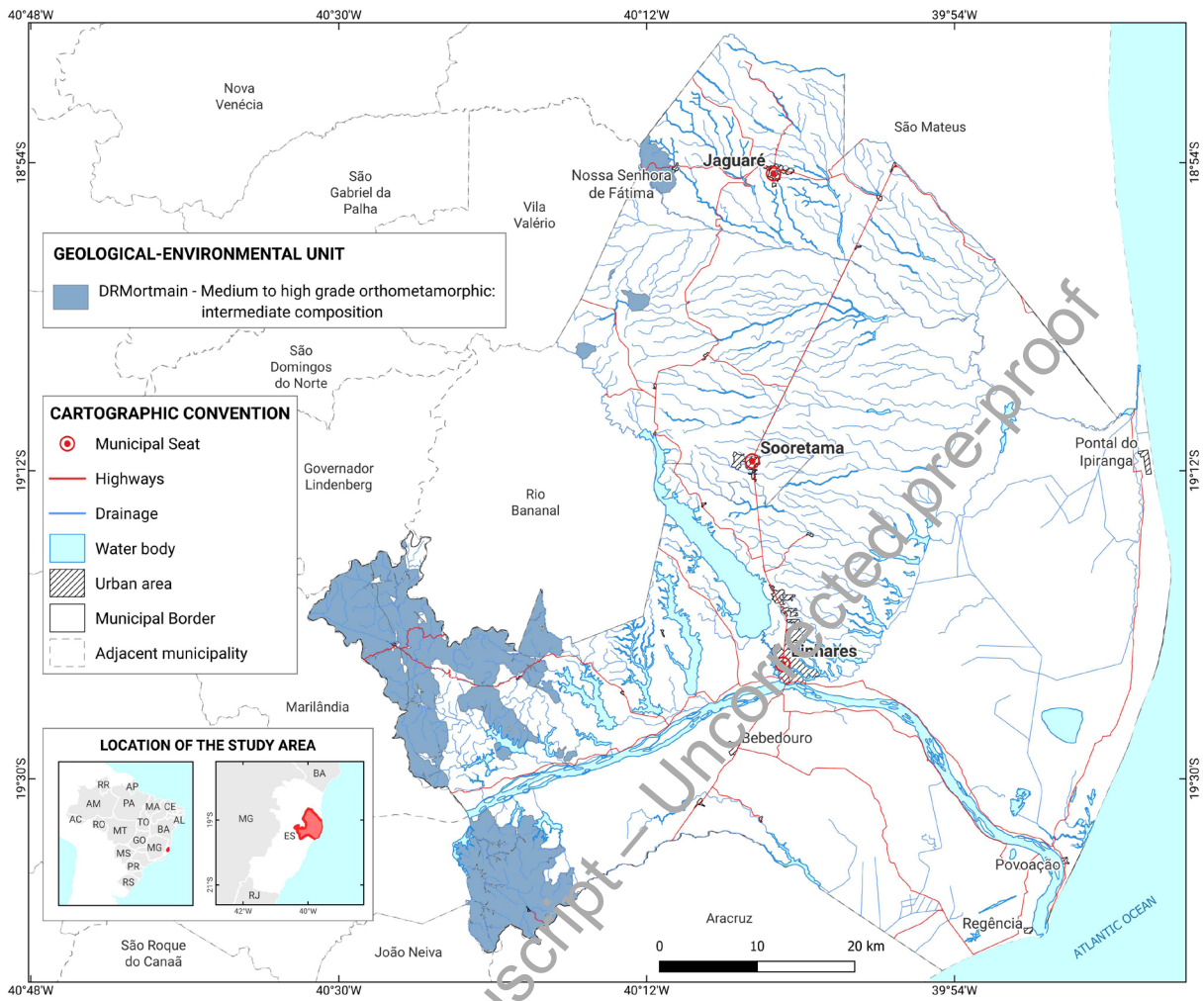


FIGURE 21. Location of the DR Mortmain in Geoenvironmental Unit.



FIGURE 22. High hill relief in the western region of the municipality of Linhares.