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Assessment of Abiotic Ecosystem Services in Exceptional Landscapes of the Municipality of Algodão de Jandaíra, in the Semi-Arid Region of Paraíba

Avaliação dos Serviços Ecossistêmicos Abióticos em Paisagens de Exceção do Município de Algodão de Jandaíra, no Semiárido Paraibano

Jéssica Oliveira Silva[1]; Viviane Ribeiro[2]; Romildo Ferreira da Silva Neto[3] ; Marcelo Alves de Souza [4] ; Wanderlan Waldez de Sousa Figueredo[5] ; Eliane Costa Oliveira[6]; João Soares da Silva [7] ; Marco Túlio Diniz Mendonça[8]; Rafael Albuquerque Xavier [9]

[1] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email jessica.silva2@aluno.uepb.edu.br
ORCID: https://orcid.org/0000-0003-0527-5313

[2] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email: ribeiro.viviane@aluno.uepb.edu.br
ORCID: https://orcid.org/0009-0000-4558-7253

[3] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email: r.neto@aluno.uepb.edu.br
ORCID: https://orcid.org/0009-0004-9693-2378

[4] State University Federal University of Rio Grande do Norte, Graduate Program in Geography, Caicó/ RN, Brazil. Email: marceloalvess450@gmail.com
ORCID: https://orcid.org/0009-0007-8157-088X

[5] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email: wanderlan.figueredo@aluno.uepb.edu.br
ORCID: https://orcid.org/0009-0008-2167-0309

[6] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/PB, Brazil. Email: elianecostaoliveira@ymail.com
ORCID: https://orcid.org/0009-0000-1141-3458

[7] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email: joao.soares.silva@aluno.uepb.edu.br
ORCID: https://orcid.org/0009-0000-9938-0354

[8] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/ PB, Brazil. Email: tuliogeografia@gmail.com
ORCID: 0000-0002-7676-4475

[9] State University of Paraíba (UEPB), Graduate Program in Regional Development, Campina Grande/PB, Brazil. Email: rafaelxavier@servidor.uepb.edu.br
ORCID: https://orcid.org/0000-0002-1737-7547

Abstract: The study addresses the importance of environmental preservation from the perspective of valuing ecosystem services, which are those that arise directly or indirectly from ecosystem functions and satisfy human needs, such as climate regulation, flood control, water supply, and raw material provision, among others. This approach is dedicated to analyzing nature from an abiotic perspective, understanding that the valuation of abiotic resources is essential for sustainable use practices in arid and semi-arid regions, promoting a

balance between local development and environmental conservation. This is a qualitative and quantitative study that used data collection and analysis techniques through field observation in the municipality of Algodão de Jandaíra, located in a semi-arid region in Paraíba. It was possible to recognize the area's potential in terms of abiotic ecosystem services, distributed across its exceptional landscapes, confirming the initial hypothesis that local geodiversity plays a fundamental role in providing direct and indirect benefits to the population. This confirmation is an important step toward encouraging environmentally responsible public policies, supporting environmental education, and promoting initiatives that integrate the preservation of natural resources, people's quality of life, and regional development.

Keywords: Algodão de Jandaíra; Abiotic ecosystem services; Exceptional landscapes Sustainability.

Resumo: O estudo aborda a importância da preservação ambiental, na perspectiva da valorização dos serviços ecossistêmicos, que são aqueles que decorrem, direta ou indiretamente das funções ecossistêmicas e que satisfazem as necessidades humanas, tais como regulação climática, controle de cheias, provisão de água, fornecimento de matéria-prima, entre outros. Essa abordagem se dedica a analisar a natureza sob sua ótica abiótica, compreendendo que a valorização dos recursos abióticos é essencial para práticas de uso sustentável em regiões áridas e semiáridas, promovendo o equilíbrio entre desenvolvimento local e conservação ambiental. Trata-se de uma pesquisa qualitativa e quantitativa, que utilizou a técnica de coleta e análise de dados, por meio da observação em campo, no município de Algodão de Jandaíra, localizado em região semiárida na Paraíba. Foi possível reconhecer a potencialidade da área no que diz respeito aos serviços ecossistêmicos abióticos, distribuídos em suas paisagens excepcionais, confirmando a hipótese inicial de que a geodiversidade local desempenha papel fundamental na provisão de benefícios diretos e indiretos para a população. Tal confirmação é um passo relevante para incentivar políticas públicas ambientalmente responsáveis, apoiar a educação ambiental e fomentar iniciativas que integrem a preservação dos recursos naturais, a qualidade de vida das pessoas e o desenvolvimento regional.

Palavras-chave: Algodão de Jandaíra; Serviços ecossistêmicos abióticos; Paisagens excepcionais. Sustentabilidade.

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1. Introduction

In recent years, there has been a growing awareness of the importance of environmental preservation, not only from a biotic perspective, but also from an abiotic one, as it has become clear that the inadequate management of ecosystems and intensive use of natural resources has several negative externalities for the quality of life in society. Gray (2004) is recognised as the leading authority in the field of geodiversity, having published the first work entirely dedicated to the subject, entitled: Geodiversity: Valuing and Conserving Abiotic Nature. According to the aforementioned author, the connection between geodiversity and biodiversity explores the intrinsic and social value of abiotic diversity and warns of contemporary threats to this natural heritage.

In this context, the topic of ecosystem services has gained prominence and relevance on the scientific agenda, as well as among public policy managers, who have been addressing the issue mainly with the aim of proposing instruments to help reduce the rates of loss of these services (Guedes; Seehusen, 2011 *apud* Gaudereto *et al.,* 2018).

According to Costanza et al. (1997) apud Gaudereto et al. (2018), ecosystem services are those that arise directly or indirectly from ecosystem functions and that satisfy human needs, such as climate regulation, flood control, water provision, and raw material supply, among others.

The valuation of ecosystem services must consider qualitative and quantitative criteria related to the supply and demand for natural resources. These analyses provide technical support for conservation and sustainable management strategies (Groot et al., 2010). In this sense, the valuation of abiotic resources is essential for sustainable use practices in arid and semi-arid regions, promoting a balance between local development and environmental conservation (Silva *et al*., 2018).

Understanding and valuing these abiotic ecosystem services such as soil, water, climate and minerals are fundamental to promoting sustainable land management, particularly in environmentally vulnerable regions. According to the United Nations (UN, 2015), ecosystem services comprise the benefits that humans obtain directly from ecosystems, with abiotic elements being essential for human well-being and the maintenance of biodiversity. In the context of the Semi-Arid region, assessing these services is a challenge, but also an opportunity to support public policies for conservation and sustainable development.

Semi-arid landscapes have high ecological and socio-environmental value, notable for formations such as plateaus, water storage areas and Caatinga mosaics (Sampaio et al., 2013). These environmental units play a strategic role in providing services such as climate regulation, soil stability and water supply. This complexity requires multidisciplinary approaches that integrate Geography, Ecology, and Environmental Management.

Recent studies, such as the Martins-Portalegre Massif Assessment Report (Araújo et al., 2024), have demonstrated the effectiveness of methodologies aimed at assessing abiotic ecosystem services in exceptional landscapes, focusing on the analysis of relief, water dynamics, and soil composition. Such experiences can be adapted and replicated in other areas of the Semi-Arid region, such as Algodão de Jandaíra, contributing to territorial planning and strengthening socio-environmental resilience.

The municipality of Algodão de Jandaíra, located in the state of Paraíba, is part of the Western Curimataú micro-region, according to the IBGE (2015) classification. The area is located in the northeastern semi-arid region, characterised by low rainfall and challenges associated with water security, as pointed out by Sampaio et al., 2013 and recent climate surveys by AESA (2025). However, the municipality has a unique geodiversity that adds significant value to the region's natural formation. The municipality stands out for its physical characteristics marked by rock formations and Caatinga vegetation that give the local landscape its uniqueness. Thus, the territory of the municipality under study has significant potential for providing abiotic ecosystem services, especially due to the presence of largely unaltered natural elements and its strategic geographical position in relation to water storage areas and residual relief, which are important for maintaining groundwater.

Therefore, recognising the potential of the municipality of Algodão de Jandaíra for abiotic ecosystem services is an important step towards encouraging environmentally responsible public policies, supporting environmental education and promoting initiatives that integrate the preservation of natural resources with the well-being of the local population. In this sense, this article aims to analyse and quantify the abiotic ecosystem services provided by the relief units in the area, highlighting their ecological, social and economic relevance in the context of the semi-arid region of Paraíba.

The relevance of this study lies in the direct relationship between geodiversity, abiotic ecosystem services, and global sustainability goals. By recognising the importance of these services for maintaining ecosystems and the quality of life of the local population, the study provides important insights for environmental conservation and territorial planning, especially in vulnerable regions such as Brazil's semi-arid region. Furthermore, this integration reinforces the need to incorporate geoconservation as a fundamental pillar of regional development. Geoconservation stems from the understanding that geodiversity has significant value and is subject to a series of risks and threats that require protective measures (Gray, 2005).

2. Field of Study

The municipality of Algodão de Jandaíra is located in the Brazilian semi-arid region, in the micro-region of Curimataú Ocidental Paraibano (Figure 1). According to Koppen, the climate of the area is BSwh, defined as hot semi-arid, characterized by scarce and irregular rainfall throughout the year (Silva, 2015).

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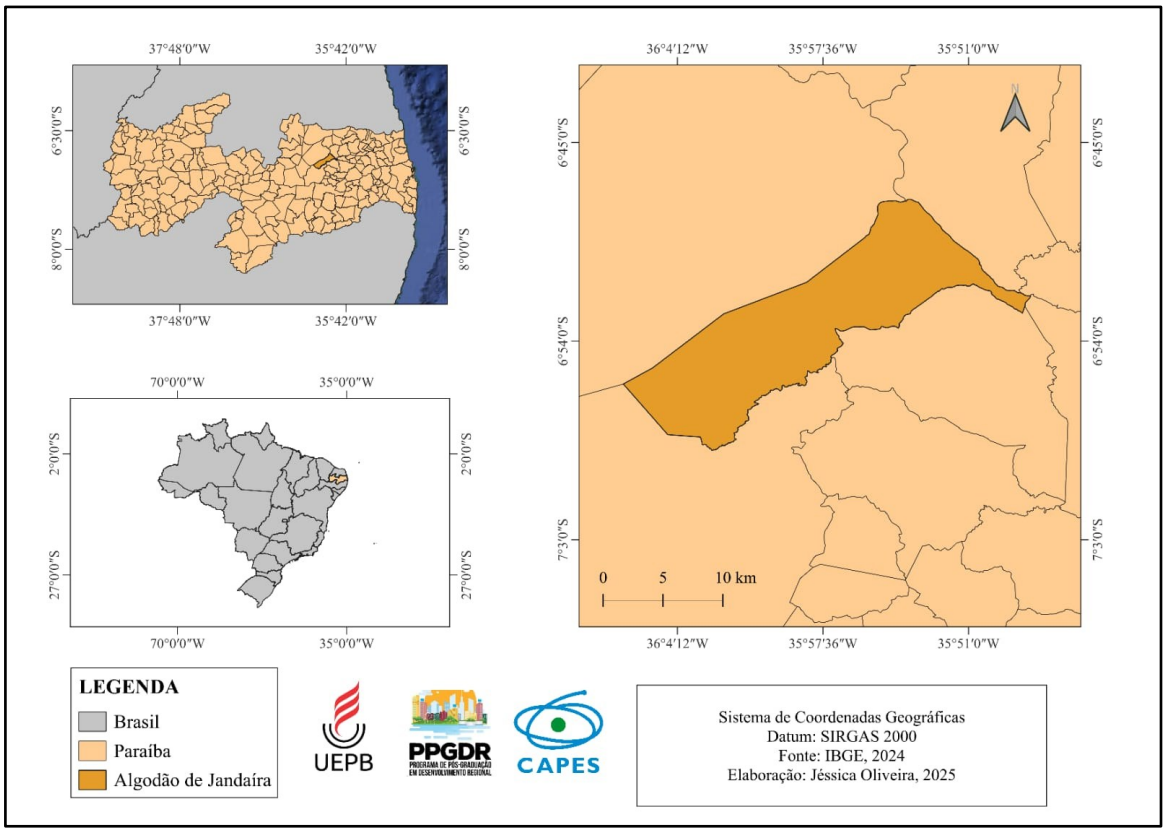

Figure 1: Location of the municipality of Algodão de Jandaíra
Source: Prepared by the authors (2025).

The area has an average annual rainfall of 352.7 mm and an average temperature of 22.8 °C (AESA, 2025; Silva, 2015), and is considered the municipality with the lowest rainfall rate in Paraíba (AESA, 2025). The area stands out for its physical characteristics marked by crystalline rock formations, shallow soils, and vegetation typical of the Caatinga biome, which give the local landscape its uniqueness. The municipality is part of the Curimataú River Basin, specifically integrating the geo-environmental unit characterized by hills, inselbergs, and residual massifs (Figure 2). The hypsometric map shows the three compartments analyzed, namely the Flattened Surface (A), River Plain (B), and Mountains (C).

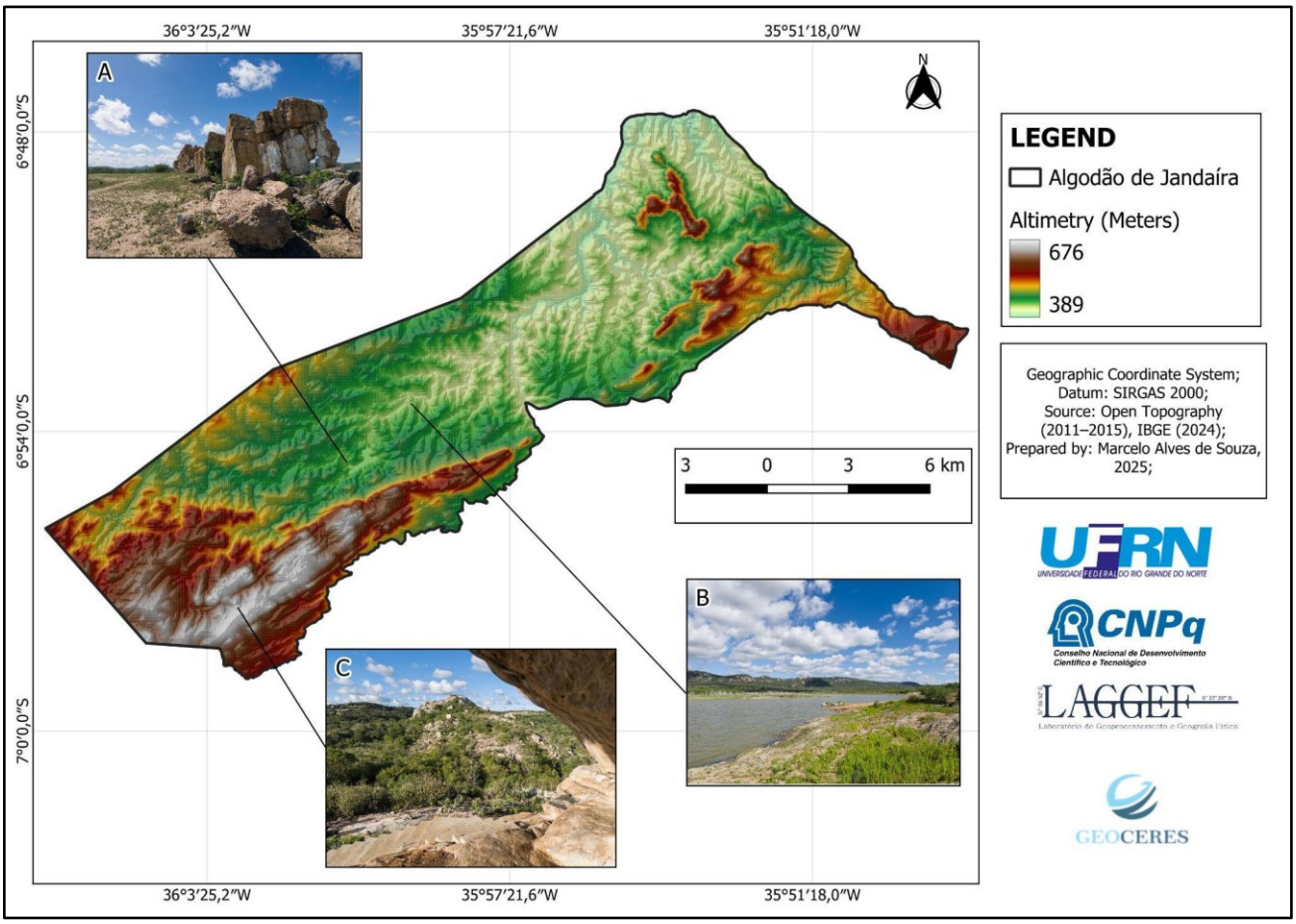

Figure 2: Hypsometric map of Algodão de Jandaíra - PB.
Source: Prepared by the authors (2025).

The areas corresponding to the Leveling Surface and the River Plain have a predominantly flat or gently undulating relief, a condition that favors human occupation and the development of agricultural activities. Thus, historically, these flatter areas have been intensively used for productive purposes, especially in the context of agricultural activities in the semi-arid region of Paraíba.

These geomorphological formations are the result of complex geological processes that developed over long periods of time, spanning millions of years of geological evolution. Their lithological composition is diverse, including plutonic bodies, the Seridó Formation, and orthogneissic rocks from the Serrinha–Pedro Velho Unit (CPRM, 2004) (Figure 3).

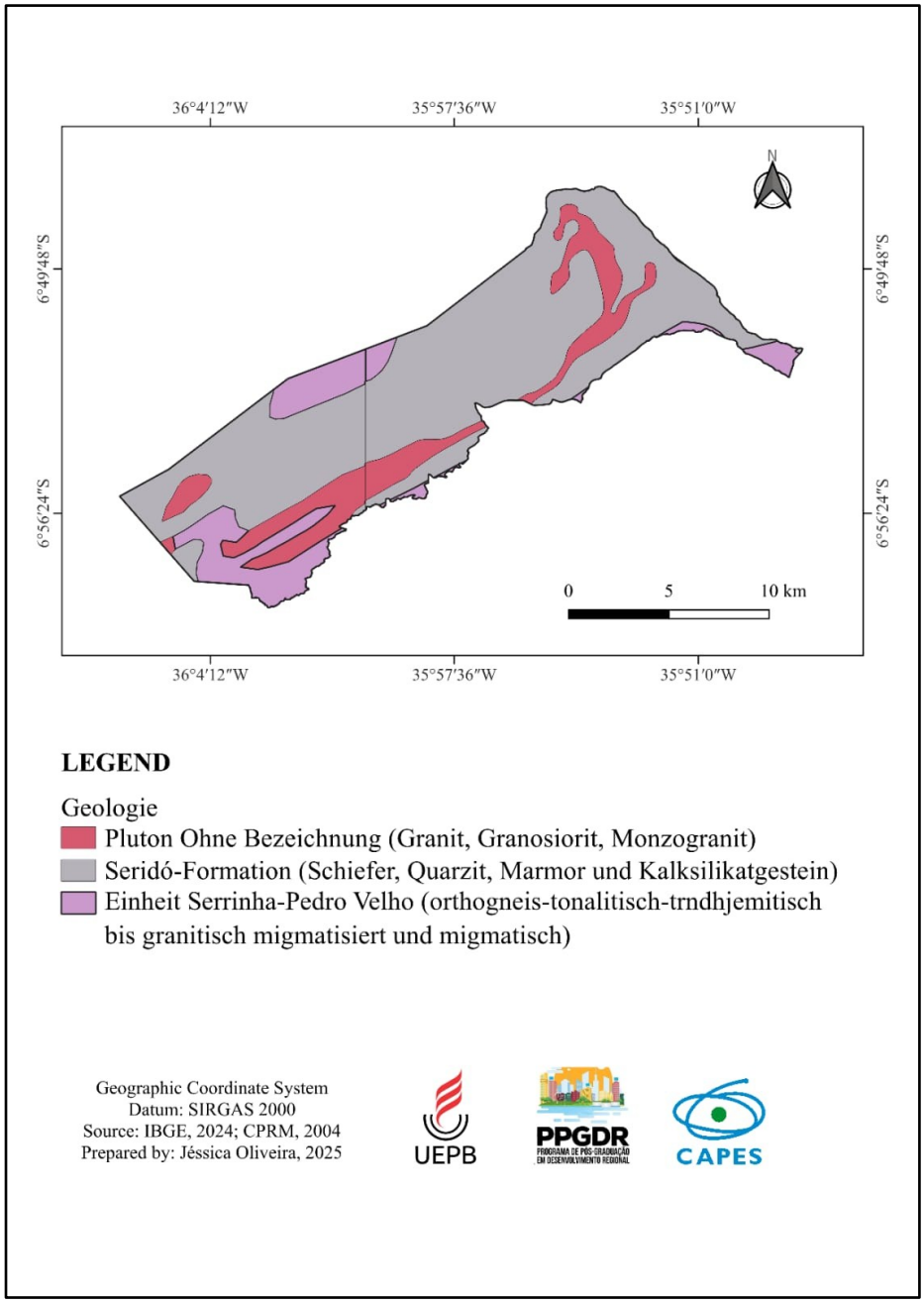

Figure 3: Geological Map of Algodão de Jandaíra - PB.
Source: Prepared by the authors (2025).

The residual reliefs and rocky outcrops present in the municipal territory contain significant records of rock art, providing archaeological evidence of fundamental importance for understanding the daily life and cultural practices of the indigenous peoples who inhabited these lands in prehistoric times. These records highlight the importance of effective conservation strategies for the preservation of geological heritage (Santos *et al.,* 2025).

3. Methodological procedures

3.1. Research classification

This research is exploratory and descriptive in nature, as it aims to analyse the provision of abiotic ecosystem services by the relief units in the study area, as well as describing the social, economic and ecological importance of the ecosystem.

In this sense, the research has a qualitative and quantitative approach, because in addition to quantifying the ecosystem services available in the studied area and measuring the degree of relevance of these services on a numerical scale, the work also discusses, in light of the literature, the social and economic implications that the provision of ecosystem services has on the reality of the municipality and the impacts on people's way of life.

With regard to data collection and analysis techniques, this was done through field observation, using criteria defined based on the research by Araújo, Diniz and Souza (2024), whose methodology is most suited to the objective of this study.

The observation was of the direct extensive type, using a form with sufficient accuracy of information to satisfy the proposed objective.

The field activity took place on 26 June 2025, when three distinct relief units were visited and surveys were conducted on the quantity and relevance of the ecosystem services observed in each relief unit. It should be noted that the field research phases require bibliographic research. The methodology used to assess ecosystem services is presented below.

3.2. Field data collection

Data collection was carried out through extensive direct observation in three previously selected compartments, based on their geomorphological and sociocultural representativeness. The first compartment is located on the Aplainamento Surface, more precisely in the rock formation known as Muralha Maior (Figure 4A), a striking geological structure in the local landscape. The second corresponds to the Jandaíra River plain, with data collection carried out in the vicinity of the Algodão Dam (Figure 4B), an important water body in the municipality. Finally, the third point is located in an area of high relief, at the top of a mountain range, where Pedra do Caboclo (Figure 4C) is found, a rocky outcrop that, in addition to standing out for its geological characteristics, has strong cultural importance for the local community.

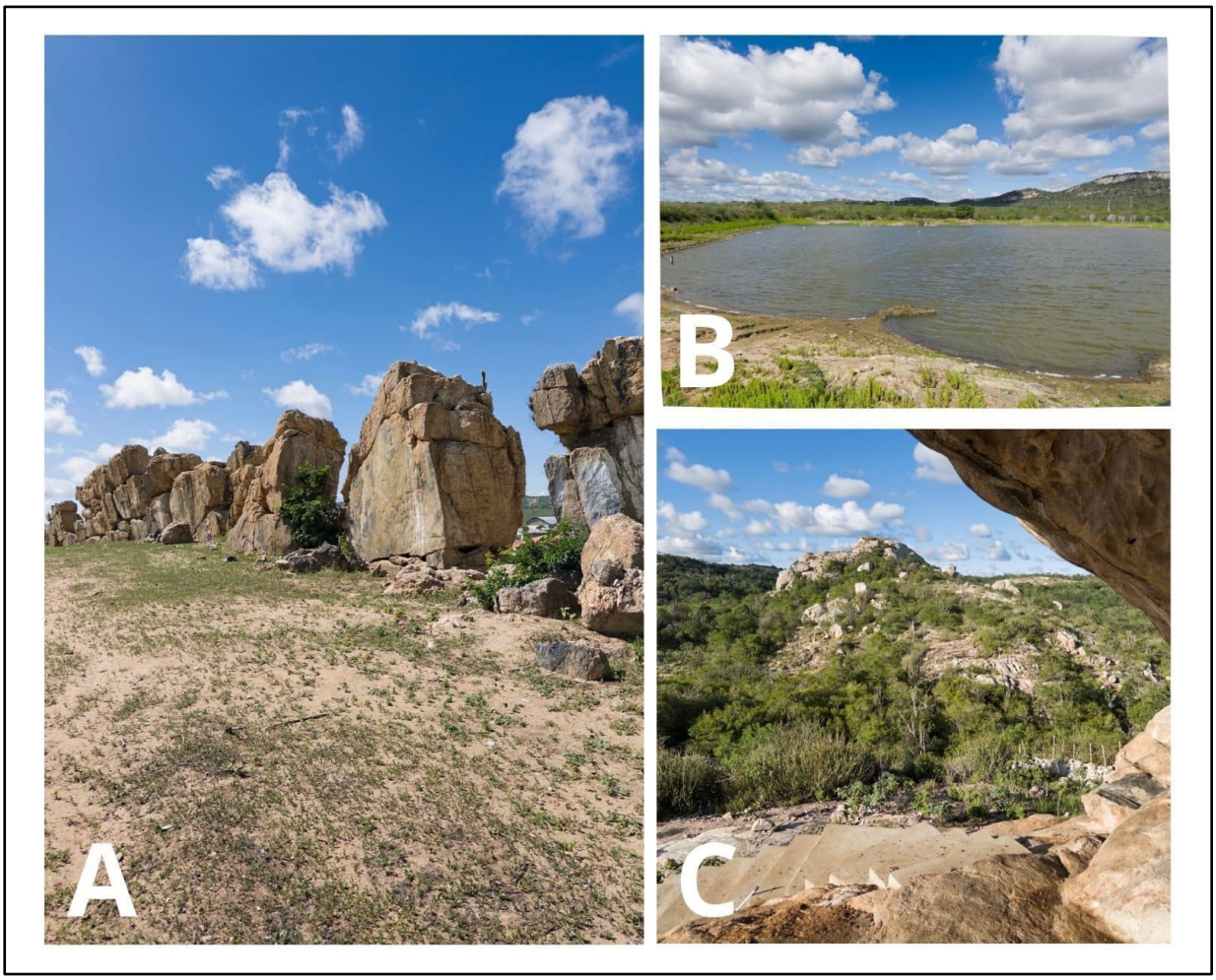

Figure 4A: Muralha Maior; Figure 4B: Jandaíra River; Figure 4C: Pedra do Caboclo
Source: Authors (2025).

In each compartment, the abiotic ecosystem services present were observed and recorded, according to criteria previously established in Araújo, Diniz, and Souza (2024).

3.3. Assessment of Ecosystem Services

To assess the provision of ecosystem services, the methodology presented by Araújo, Diniz and Souza (2024) was used. The first stage of the assessment consisted of an approach that divides ecosystem services into four categories: regulatory, provisioning, cultural and knowledge services, and supporting services. Each service is subdivided into several benefits, the provision of which can be classified as direct, indirect or absent, as shown in Table 1.

Table 1: Abiotic Ecosystem Services – Categories and Supply.

SERVICES	CATEGORIES/BENEFITS	OFFER
1. REGULATION These processes aim to naturally control environmental conditions, whether in the air, water, or soil. They control the availability of these resources, their quantity, and their quality.	**1.1 Climate Regulation -** Geodiversity influences climate locally and globally (e.g., through the effects of topography on temperature and precipitation). Geological and geomorphological processes and soils play a key role in regulating climate through rock weathering, carbon sequestration, and greenhouse gas release.	**Direct:** The characteristics of the area determine certain climatic features. **Indirect:** The physical characteristics of the area have a slight influence on the local climate. **Absent:** There is no influence of any kind.
	1.2 Air Quality Regulation - Ecosystems contribute to and extract chemicals from the atmosphere, influencing many aspects of air quality.	**Direct:** The physical characteristics of the environment directly influence air quality. **Indirect:** Some characteristic of the area provides services that influence air quality. **Absent:** There is no influence of any kind.
	1.3 Water Regulation - The timing and magnitude of runoff, flooding, water storage, and aquifer recharge can be strongly influenced by topography, soil, surface deposits, and bedrock.	**Direct:** when there is a contribution to natural risk mitigation, water quality, drinking water supply, habitat provision, and recreational opportunities (e.g., water sports). **Absent:** No influence of any kind occurs.
	1.4 Water Quality/Water Purification and Waste Treatment - Rocks, surface deposits, and soil act as natural filters, providing the "fabric" for regulating water quality. The unsaturated zone (soil and subsurface geology that purifies percolating water) filters particles, organic waste, and other pollutants before they reach groundwater storage. This service recognizes the ability of geodiversity components and processes to contain, dilute, mitigate, and decompose pollutants.	**Direct:** economic benefits through reduced subsequent requirements for water supply treatment. **Indirect:** "cleaner" water for inland aquifers and surface water bodies and their dependent habitats. **Non-use**: aesthetic benefits of unpolluted water bodies.

SERVICES	CATEGORIES/BENEFITS	OFFER
	1.5 Flood control - Flood control is often listed as an ecosystem service, but many of the processes involved are physical and ecological. For example, soil and subsoil sediments absorb large amounts of rainwater and thus reduce surface runoff, i.e., they delay and soften the delivery of rainwater to river channels, thereby reducing flooding.	**Direct:** The particularities of the abiotic environment play a fundamental role in reducing the impacts of flooding. **Indirect:** It has a slight influence on reducing the impacts of flooding, sharing this with the biotic environment. **Absent:** There is no influence of any kind.
	1.6 Atmospheric and Oceanic Regulation - Atmospheric and oceanic circulations play a vital role in regulating the world's climate and habitability.	**Direct:** The abiotic environment and associated geomorphological aspects play a decisive role in atmospheric and oceanic regulation. **Indirect:** It has some influence on atmospheric and oceanic circulation and, consequently, on climate, habitats, and living conditions. **Absent:** There is no influence of any kind.
	1.7 Natural Risk and Erosion Control - Protection of people, property, and land against natural hazards such as floods, erosion, and landslides.	**Direct:** when the abiotic environment contributes to: • Regulation of river flooding through natural forms of defense against flooding and inundation of natural floodplains and/or anthropogenic excavations (such as quarries); • Protection against erosion of rivers and floodplains and protection from sediment deposition by maintaining natural channel flows and sediment regimes; • Regulation of coastal flooding through natural migration from the sea inland and protection by natural forms of flood defense (salt marshes, sand dunes); • Protection against coastal erosion by maintaining dunes and beach elevations and natural sediment circulation; and

SERVICES	CATEGORIES/BENEFITS	OFFER
		• Slope protection and soil erosion and risk assessment through analysis of rock and soil properties, slope stability, and previous patterns of process activity.
2. PROVISION It is responsible for providing material goods to human societies. It is the easiest to understand because, in most cases, it has a monetary value associated with the good, which is then treated as a product.	**2.1 Freshwater supply -** Geology provides the fabric for aquifers and supports surface water systems. Soils, subsurface geology, and topography influence surface water storage potential, while aquifer properties influence groundwater storage and production potential.	**Direct:** Natural sources of fresh water from surface or groundwater; also mineral water. Collection of surface or groundwater for public supply, industrial supply, or private domestic supply. **Indirect:** A source to sustain water-dependent habitats and maintain base flow to rivers. **Absent:** No evidence.
	2.2 Industrial materials – Abiotic resources are responsible for providing the raw materials and inputs that are essential for industries to function.	**Direct:** Resources used in industry are exploited in the area. **Indirect:** Incipient exploitation occurs in the area, with reserves of raw materials that may be used in industry in the future. **Absent:** There are no industrial resources in the area.
	2.3 Energy (renewable and non-renewable) - Geology, topography, and natural processes help provide renewable forms of energy (hydroelectric, geothermal, tidal, wave, and wind) and non-renewable forms (coal, oil, natural gas, etc.).	**Direct:** The abiotic environment directly provides energy resources with high potential. **Indirect:** The abiotic environment provides the basis for energy exploitation, but with limited potential. **Absent:** Does not provide the means for energy exploitation.

SERVICES	CATEGORIES/BENEFITS	OFFER
	2.4 Nutrients and minerals for healthy growth - Minerals and nutrients are generally obtained from foods in considerable amounts, which in turn obtain them from the soil.	**Direct:** Soil type, combined with mineralogical characteristics, are determining factors for adequate growth or a given activity. **Indirect:** Soil characteristics influence a given activity. **Absent:** There are no relationships.
	2.5 Ornamental resources - Supply of rocks, fossils, minerals, and aggregates for decoration and landscaping.	**Direct:** When there is mining of precious and semi-precious stones and metals in the area, granite countertops and slate floors in kitchens, rocks and river stones in gardens, slabs. Caithness for paving slabs and slate, fossils, polished stones, and minerals for home decorations. **Absent:** There are no relations.
	2.6 Construction materials - Extraction of rocks, sediments, and other materials for civil construction.	**Direct:** Extraction of key inputs for civil construction: sediments, rocks, sand, water. **Indirect:** Exploitation of materials linked to civil construction for its operation. Example: extraction of limestone for cement production. **Absent:** There are no relationships.
	2.7 Food, fiber, fuel, biochemicals, pharmaceuticals, and natural medicines (through nutrients provided by soils) - Food products derived from plants, animals, and microbes; Fiber products, including wood, jute, cotton, hemp, silk, and wool; Wood, manure, and other biological materials; Many medicines, biocides, food additives such as alginates, and biological materials are derived from ecosystems.	**Indirect:** Through nutrients provided by the soil. **Absent:** None Food, fiber, fuel, biochemicals, pharmaceuticals, and natural medicines (through nutrients provided by the soil).

SERVICES	CATEGORIES/BENEFITS	OFFER
3. CULTURAL AND KNOWLEDGE The relationship between society and some abiotic aspect of the environment due to its social or community significance. Knowledge services are related to proposals for using the abiotic environment as a classroom and laboratory, with its exploitation being purely scientific and educational.	**3.1 Cultural diversity -** The diversity of the physical environment is a factor that influences cultural diversity and cultural identity.	**Direct:** The cultural diversity of the place is directly related to its geodiversity (churches and cities carved into the rock, for example). **Indirect:** The physical environment influences local cultural characteristics. **Absent:** There are no relationships.
	3.2 Spiritual and religious values and cultural meanings - Natural rock formations and landfills often have religious or spiritual values associated with them, including in local folklore and legends.	**Indirect:** There is a strong relationship between the physical environment and local spiritual, religious, and cultural values. **Absent:** There are no relationships.
	3.3 Knowledge systems - Society benefits from knowledge of the physical properties, materials, processes, and history of the Earth in many ways (e.g., through applied geology, engineering and environmental geology, medical geology, and geoforenics). Records of past climate and environmental change preserved in a variety of archives (e.g., ice cores, ocean sediments, landfills, and lake sediments) provide a long-term perspective on Earth system processes and ecosystem dynamics, trends, and human interactions. They provide baselines for environmental monitoring and prediction, and can indicate possible ecosystem responses to future changes in climate and other factors.	**Direct:** Environmental peculiarities are a good example and/or provide fundamental support for knowledge systems. **Indirect:** Environmental peculiarities provide some support for knowledge systems. **Absent:** There are no relationships.
	3.4 Education - Geodiversity provides the basis for both formal and informal education for people of all ages through learning and outdoor learning opportunities.	**Direct:** Environmental peculiarities are a good example and can be used for education at all levels: elementary, secondary, and higher education. **Indirect:** Environmental peculiarities provide examples and can only be used for higher education. **Absent:** There are no relationships.

SERVICES	CATEGORIES/BENEFITS	OFFER
	3.5 Artistic inspiration - Geodiversity provides a rich source of inspiration for art, literature, poetry, music, sculpture, national symbols, architecture, built heritage, and gardens.	**Direct:** There are bibliographies, evidence, and reports that geodiversity was a source of inspiration. **Absent:** There are no reports/evidence of artistic inspiration.
	3.6 Aesthetics - Many people find natural beauty and aesthetic value in various aspects of the natural environment, landscapes and scenic views, interesting/beautiful/dramatic scenery, and silence/tranquility/peace.	**Direct:** A landscape that is aesthetically rich and pleasant. **Indirect:** A landscape that stands out for one aspect, without necessarily being spectacular.
	3.7 Social relations - Changes in ecosystem services (e.g., freshwater availability, flood or erosion regulation) can affect social relations, particularly in cultures that have maintained strong links to their local environments. Volunteering through Local Geoconservation Groups can also provide opportunities for social interaction.	**Direct:** Ecosystem services play a fundamental role in the functioning of the local society. **Indirect:** Ecosystem services have a considerable influence on the functioning of society. **Absent:** There are no relationships.
	3.8 Sense of place - Many people value the sense of place associated with the recognizable features of their environment, such as natural rock formations and landscapes, and the perception of "safety" is a characteristic created by these features.	**Direct:** The physical characteristics of the area are appreciated by residents and visitors, who attribute a sense of place to it. **Indirect:** The place is valued only by visitors. **Absent:** There are no relationships.

SERVICES	CATEGORIES/BENEFITS	OFFER
	3.9 Cultural heritage and geopatrimony - Geosites associated with major developments in geoscience are part of the cultural value of geopatrimony. Other geosites are significant for their historical, literary, or artistic associations or other cultural meanings. Geodiversity underpins the landscape and seascape character of the sea and different types of cultural landscape. The use of local or traditional stone and other geological materials within the built environment and the conservation of cultural landscapes contribute to the cultural heritage of an area and its landscape character. Cultural memories are often expressed through natural features such as mountains, waterfalls, and rock formations.	**Direct:** The area has sites that are relevant in more than one parameter. **Indirect:** The area has sites that are relevant only in a specific parameter. **Absent:** There are no relevant sites in the area.
	3.10 Environmental quality - Geodiversity and geopatrimony contribute to environmental quality that supports human health and well-being.	**Direct:** The area has physical and natural characteristics that play a decisive role in environmental quality in various aspects, such as air, water, soil, and biodiversity quality, etc. **Indirect:** The area has physical and natural characteristics that play a decisive role in environmental quality in only one aspect. **Absent:** There are no relationships.

SERVICES	CATEGORIES/BENEFITS	OFFER
	3.11 Recreation and nature-based tourism - People often choose where to spend their leisure time based on the natural or cultural characteristics of a particular area. Physical characteristics (geodiversity) underpin the landscape character, valued habitats and ecosystems, and the aesthetic and other cultural qualities of an area. They provide opportunities for outdoor recreation (e.g., hiking, rock climbing, caving, skiing, and outdoor adventure) and leisure, or a quiet retreat where people can relax and reflect, and contribute to people's health and well-being. They also support geotourism, which in turn provides a source of employment (e.g., in geoparks) and a range of relational and other benefits described above that contribute to people's health and well-being and to their lifelong educational and personal development.	**Direct:** The area has sites that are considered major destinations for recreational activities by the local population and normally receives some tourists. **Indirect:** The area has sites that are commonly used for recreation, being partially frequented only by the local population. **Absent:** The area is not used for recreational activities.
4. SUPPORT SERVICE These are areas where geodiversity provides resources for human activities or nature itself, and which depend directly on soils and rocks to be carried out. It includes the provision of resources for certain human activities and the planet's biota.	**4.1 Soil formation processes -** The rate of soil formation through the weathering of rocks and other source materials (including those derived from erosion and sediment deposition) is a key factor in providing a medium for plant growth and supporting habitats.	**Direct:** Soil formation is crucial for establishing healthy ecosystems. **Indirect:** Many supply services depend on soil formation and fertility.
	4.2 Burial and storage - The physical resources of the earth have long been used for human burial, placing bodies in the ground (as in graves) or in monuments built above ground, such as pyramids or - on a smaller scale - cairns or dolmens. A diverse range of rock types is also used by modern stonemasons to make gravestones, although an important property here is durability, particularly in retaining inscriptions.	**Direct:** Used for nuclear waste storage, burial, or as raw material for the construction of mausoleums. **Absent:** There are no relations.
	4.3 Platform for human activity - Geodiversity provides a platform for construction and infrastructure (e.g., flat land on elevated beaches or river terraces).	**Direct:** Economic benefits arise from the platform provided by geodiversity. **Absent:** Not used as a platform for human activities.

SERVICES	CATEGORIES/BENEFITS	OFFER
	4.4 Biogeochemical cycling – The continuous natural circulation of vital elements (e.g., carbon and nitrogen), comprising exchanges between the atmosphere, the geosphere, and living organisms.	**Direct:** Provision of minerals and nutrients necessary for the cycle to function. **Indirect:** Support for the function and integrity of other ecosystem services. **Absent:** There are no relationships.
	4.5 Habitat Provision - The physical environment generally plays a huge role in providing habitats for biodiversity, but this seems to be rarely recognized by ecologists.	**Direct:** The physical environment determines the characteristics of the habitat. **Indirect:** The physical environment influences the habitat. **Absent:** There are no relationships.

Source: Araújo, Diniz and Souza (2024).

Using Table 2 in the field survey, it was possible to measure how many ecosystem services were identified within each category (regulation, provision, cultural and knowledge, and support). After obtaining the number of services provided by category, the next step was to assess the degree of relevance of these services.

To assess the degree of relevance of ecosystem services, we used the methodology proposed by Araújo, Diniz and Souza (2024), which corresponds to an adaptation of Burkhard's proposal (2017). In this stage of the research, a numerical scale composed of six value classes assigns the degree of relevance (Table 2). After identifying the relevance capacity of each compartment, the degree of relevance was assigned in general terms as follows: no relevance is assigned a value of 0; low relevance 1; relevant demand 2; medium relevance 3; high relevance 4 and very high relevance 5.

Table 2: Degree of Relevance of Ecosystem Services

Categories	Number of services	Degree of relevance in relation to the number of services provided	Capacity for relevance
Regulatory Services	7	0 - No service provided	No relevance
		1 service provided	Low relevance
		2 services provided	Relevant demand
		3-4 services provided	Medium relevance
		5-6 services provided	High relevance
Provision Services	6	7 services provided	Very high relevance
		0 - No service provided	No relevance
		1 service provided	Low relevance
		2 services provided	Relevant demand
		3-4 services provided	Medium relevance
		5 services provided	High relevance
		6 services provided	Very high relevance
Cultural and Knowledge Services	11	0 - No service providedo	No relevance
		1-2 services provided	Low relevance

		3-4 services provided	Relevant demand
		5-6 services provided	Medium relevance
		7-9 services provided	High relevance
		10-11 services provided	Very high relevance
Support Services	5	0 - No service provided	No relevance
		1 service provided	Low relevance
		2 services provided	Relevant demand
		3 services provided	Medium relevance
		4 services provided	High relevance
		5 services provided	Very high relevance

Source: Araújo, Diniz and Souza (2024).

After measuring the quantity and degree of relevance of the abiotic ecosystem services provided in each category, it was possible to relate the types of services provided to each relief unit in the study area.

4. Results and discussions

The geodiversity present in the study area plays a fundamental role in providing abiotic ecosystem services, especially in areas classified as exceptional landscapes. Elements such as geomorphological, geological, pedological, and archaeological aspects not only shape the physical environment but also promote a wide diversity of ecosystem functions. In each compartment analyzed, different types of abiotic ecosystem services were identified, which directly or indirectly support the life and well-being of the municipality's population. Distinct services, with varying degrees of relevance, were found in the three compartments evaluated.

Table 3 presents a description of the abiotic ecosystem services identified in the three points analyzed in the municipality of Algodão de Jandaíra.

Table 3: Abiotic Ecosystem Services of the compartments visited – Categories and Supply.

Section	**Category/Benefit**	**Compartments**		
		Flattening Surface (Muralha Maior)	**Plain (Açude de Algodão)**	**Mountain Range (Pedra do Caboclo)**
		Supply (direct/indirect/absent)		
1. Regulation	1.1 Climate Regulation	Absent	Indirect	Direct
	1.2 Air Quality Regulation	Indirect	Indirect	Indirect
	1.3 Water Regulation	Direct	Direct	Direct
	1.4 Water Quality / Water Purification and Waste Treatment	Indirect	Direct	Indirect
	1.5 Flood Control	Indirect	Direct	Absent
	1.6 Atmospheric and Oceanic Regulation	Absent	Indirect	Indirect
	1.7 Natural Risk and Erosion Regulation	Absent	Indirect	Absent
Quantity		4	7	5
2. Provision	2.1 Freshwater supply	Indirect	Direct	Indirect

Section	Category/Benefit	Compartments		
		Flattening Surface (Muralha Maior)	Plain (Açude de Algodão)	Mountain Range (Pedra do Caboclo)
		Supply (direct/indirect/absent)		
	2.2 Industrial materials	Absent	Direct	Absent
	2.3 Energy (renewable and non-renewable)	Absent	Absent	Absent
	2.4 Nutrients and minerals for healthy growth	Indirect	Direct	Direct
	2.5 Ornamental resources	Absent	Absent	Absent
	2.6 Construction materials	Absent	Direct	Absent
	2.7 Food, fiber, fuel, biochemicals, pharmaceuticals, and natural medicines (through nutrients provided by soils)	Absent	Indirect	Indirect
Quantity		2	5	3
3.Culture and knowledge	3.1 Cultural diversity	Absent	Absent	Direct
	3.2 Spiritual and religious values and cultural meanings	Absent	Absent	Indirect
	3.3 Knowledge systems	Direct	Absent	Direct
	3.4 Education	Indirect	Direct	Indirect
	3.5 Artistic inspiration	Absent	Absent	Direct
	3.6 Aesthetics	Direct	Direct	Direct
	3.7 Social relations	Direct	Direct	Direct
	3.8 Sense of place	Absent	Direct	Direct
	3.9 Cultural heritage and geopatrimony	Direct	Absent	Direct
	3.10 Environmental quality	Absent	Direct	Direct
	3.11 Nature-based recreation and tourism	Direct	Direct	Direct
Quantity		6	6	11
4. Support	4.1 Soil formation processes	Direct	Direct	Direct
	4.2 Burial and storage	Direct	Absent	Absent
	4.3 Platform for human activity	Direct	Direct	Direct

Section	Category/Benefit	Compartments		
		Flattening Surface (Muralha Maior)	Plain (Açude de Algodão)	Mountain Range (Pedra do Caboclo)
		Supply (direct/indirect/absent)		
	4.4 Biogeochemical cycling	Direct	Direct	Direct
	4.5 Habitat provision	Direct	Direct	Direct
Quantity		5	4	4

Source: Authors, 2025.

Table 4 below quantifies these services in different landscape compartments, considering the number of services provided, their degree of importance, and their relevance. This analysis provides a deeper understanding of how local geodiversity influences the supply and performance of abiotic ecosystem services in the context of the semi-arid region of Paraíba.

Table 4: Degree of Relevance of the Ecosystem Services visited.

Services	Reference Units	Number of services provided	Degree of Relevance	Capacity for Relevance
1. Regulation	Flat Surface (Muralha Maior)	4	3	Medium relevance
	Plain (Açude de Algodão)	7	5	Very high relevance
	Mountain Range (Pedra do Caboclo)	5	4	High relevance
2. Provision	Flat Surface (Muralha Maior)	2	2	Relevant demand
	Plain (Açude de Algodão)	5	4	High relevance
	Mountain Range (Pedra do Caboclo)	3	3	Medium relevance
3. Cultural and knowledge	Flat Surface (Muralha Maior)	6	3	Medium relevance
	Plain (Açude de Algodão)	6	3	Medium relevance
	Mountain Range (Pedra do Caboclo)	11	5	Very high relevance
4. Support	Flat Surface (Muralha Maior)	5	5	Very high relevance
	Plain (Açude de Algodão)	4	4	High relevance
	Mountain Range (Pedra do Caboclo)	4	4	High relevance

Source: Authors, 2025.

Based on the data presented, it can be observed that, in the category of regulatory services, the Jandaíra River floodplain compartment was the only one to present all seven benefits, reaching a maximum capacity of "very high relevance." This

result stems from the fact that all benefits are used directly and indirectly, either by the population or for the maintenance of local ecosystems. The population uses the reservoir, clay, and sand, which consequently helps prevent silting of the reservoir. In addition, climate regulation and air quality are favored by local humidity, which aids in thermal stability. Although the water is classified as brackish according to salinity parameters, it is suitable for recreational activities. Although the water is classified as brackish, defined by CONAMA Resolution No. 357/2005 (Brazil, 2005) as water with salinity greater than 0.5‰ and less than 30‰, this condition does not prevent its use for primary and secondary recreational activities. According to CONAMA (Brazil, 2000), Class 1 brackish waters can be used for recreation, provided that the bathing water quality parameters established in CONAMA Resolution No. 274/2000 are respected. Therefore, the recreational suitability observed in the field (bathing, leisure) is technically feasible within this legal framework, provided that it is monitored.

Flood control is also effective, since the presence of the dam allows for adequate drainage and reduces risks for nearby residents. In other words, the vegetation of the Caatinga, being deciduous and often sparse, offers limited interception during the most intense torrential rains. Therefore, it is the geometry of the relief and geotechnological intervention (the dam) that do the heavy lifting of cushioning.

In contrast, the Serra presented five regulation services, classified as "highly relevant," according to Table 4. Although it does not have surface water availability like the plain, it demonstrates significant regulation capacity through vegetation adapted to the rocky environment, such as bromeliads and small shrubs, in addition to maintaining (micro) habitats. Because it is higher than the surrounding terrain, it also contributes indirectly to atmospheric regulation, influencing air flows and acting as a natural barrier that interferes with local microclimates.

The Leveling Surface, in turn, recorded four regulation services, with a relevance rating of three and a capacity classified as "medium" (Table 4). This limitation stems from the fragmentation of the landscape, considering that the collection point is located in an urbanized area, with conservation restricted to the Muralha Maior. Water regulation proved to be the only factor with a direct influence identified. Despite the impermeable nature of the rock outcrop, by restricting rainwater infiltration, the soil prevents total surface runoff. This retention has an influence, albeit a slight one, on flood control.

In this sense, the results reinforce the importance of exceptional landscapes for maintaining regulatory services. Studies conducted in semi-arid contexts show that natural landscapes associated with geodiversity play a fundamental role in providing services, especially with regard to regulation and maintenance. As an example, research conducted in the São José Stream Basin in Pernambuco shows that ecosystem services in semi-arid landscapes vary according to the type of land cover and anthropogenic activities, since areas with natural vegetation tend to be more efficient in providing regulation and maintenance services, while areas under agricultural use concentrate a broader and more diversified supply of provisioning services (Chaves et al., 2021). This finding is consistent with the results of the present study, demonstrating that the distribution of ecosystem services is directly associated with environmental characteristics and the forms of use of different landscape compartments.

With regard to provisioning services, the greatest diversity and relevance were recorded in the plain (reservoir), with "high relevance" (Table 4), where five services were identified. The supply of fresh water proved to be particularly significant, as evidenced by the observation, during field collection, of a water truck drawing water directly from the reservoir (Figure 5) to supply the population.

Figure 5: Water truck collecting water from the Jandaíra River
Source: Authors, 2025.

It can therefore be seen that the results obtained are fully consistent with studies on the importance of water resources in semi-arid regions, such as Silva et al. (2018), reinforcing the strategic role of water bodies in maintaining the quality of life of local populations. In addition to water resources, other resources are also used by the local population. Sediment deposition along the river plain contributes to the formation of clay pits, from which clay is extracted and used as raw material by a ceramics industry located in the region, highlighting the direct relationship between natural processes and local economic activities. Similarly, the extraction of sand for civil construction is associated with the accumulation of sandy sediments transported by the watercourse. Added to this is the provision of nutrients and minerals, since the nutrients present in the water sustain the local ichthyofauna, enabling the community to fish, which uses fish as an important source of subsistence.

In addition, the characteristics of the soils in this area favor the development of vegetation in general, due to the availability of nutrients. Among the vegetation, medicinal plant species stand out, such as: Juá (Zyziphus joazeiro Mart.) and Aroeira-do-sertão (Myracrodruom urundeuva F. Allemão), traditionally used by the population in the production of natural medicines.

In the Serra compartment, three ecosystem services were identified with a capacity considered to be of “medium relevance.” Meanwhile, in the Aplainamento Surface, two provisioning services were found, one of which was considered to be of “relevant demand.” In these areas, some communities still use artesian wells to obtain water, which, although unsuitable for human consumption, is used for non-potable purposes. In addition, the use of medicinal plants by the population is also common.

As for cultural and knowledge services, these achieved significant representation in the Serra compartment, reaching the maximum score of “very high relevance,” with 11 services provided. The Flat Surface and River Plain quantified six services, presenting “medium relevance,” which reinforces the symbolic and traditional links with the landscapes. It should be noted that, in the Serra compartment, the presence of Pedra do Caboclo is one of the main factors contributing to the significant unification of cultural and knowledge services observed in the area. This finding is in line with the observations of Moreira and Vale (2018) on the geotourism potential of unique rock formations in Northeast Brazil.

The compartment presents significant cultural diversity, with spiritual and religious values, evidenced by the presence of images of Catholic saints and devotional practices (Figure 6). The site also arouses interest for geological studies, especially on granite. From an aesthetic point of view, the landscape stands out for its scenic beauty and pleasant character. The social relations linked to the space are striking: the rocky outcrop is the target of interventions, such as graffiti, but at the same time, it constitutes an important element of identity and belonging, being widely appreciated by residents and visitors.

Figure 6: Catholic place of worship at Pedra do Caboclo
Source: Authors, 2025.

The area is home to rock inscriptions that bear witness to the presence and culture of ancestral peoples (Figure 7). From an environmental point of view, the site maintains good quality in several aspects, such as air, water, soil, and biodiversity. In addition, it is widely used for recreational activities, such as hiking, climbing, and leisure activities, reinforcing its cultural, historical, natural, and tourist relevance to the region.

With colonization and the introduction of agropastoral society, the function of Pedra do Caboclo changed, but it did not lose its relevance. The transition from indigenous mystical-ritual use to Catholic religious-devotional use demonstrates the power of the place.

The installation of images of saints and the performance of devotional practices in the rock formations indicate that the local community continues to perceive the mountain range as a place of connection with the divine. Geology provides the "natural cathedral." Furthermore, the identity of the Algodão de Jandaíra community is fused with the landscape; Pedra do Caboclo is an icon of belonging, a landmark that differentiates its territory from others.

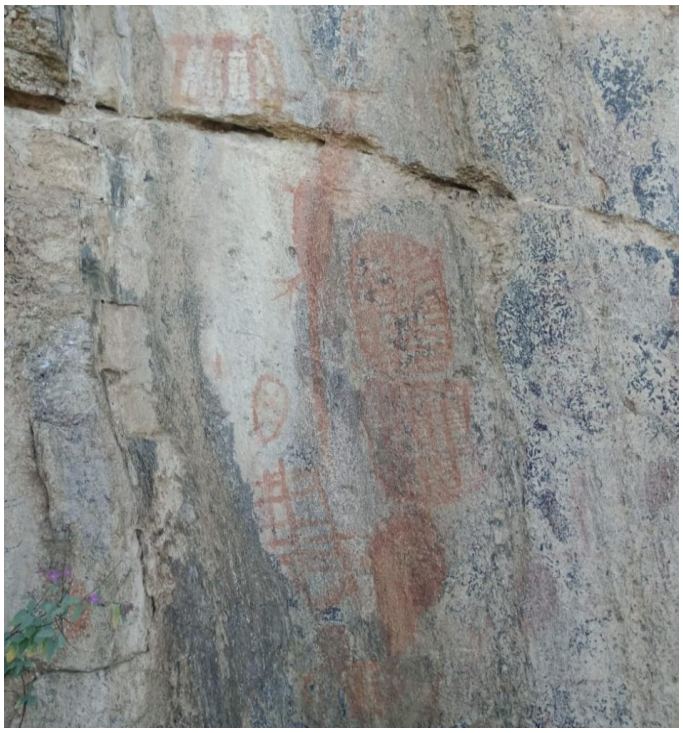

Figure 7: Cave paintings at Pedra do Caboclo
Source: Authors, 2025.

In the compartments of the Flattening Surface and the Plain, some common services were identified. Among them, the educational potential stands out: classes and visits are held on the Flattening Surface, mainly on the Wall, while the dam on the river plain offers conditions for field activities, although it is little used for this purpose. From an aesthetic point of view, both locations offer great scenic beauty, with the Flattening Surface standing out for the presence of the Great Wall and the Plain for the dam. The wall-shaped rock outcrop is a geomorphological heritage site with potential for tourist activities. In both locations, social relationships linked to the use and appreciation of these landscapes can be observed.

With regard to geopatrimony services and the knowledge system, the Muralha Maior stands out as it constitutes a fundamental geological record for understanding the history of the Earth and the processes that occur within it, evidenced by the fractures observed in the rock. This relevance makes it an element of great value for research and scientific dissemination.

Finally, support services were rated as “very high relevance” in the Flattening Surface and “high relevance” in the Plain and the Mountains. The only benefit not found in the Plain and the Mountains was “burial and storage,” indicating that these abiotic environments are not used for human burials.

Figure 8 shows the degree of relevance of ecosystem services in the study area. In the three compartments, the results ranged from “relevant demand” to “very high relevance.” This finding reinforces the environmental importance of the region, which stands out as an exceptional landscape in the semiarid region and constitutes a prominent area in the Caatinga biome.

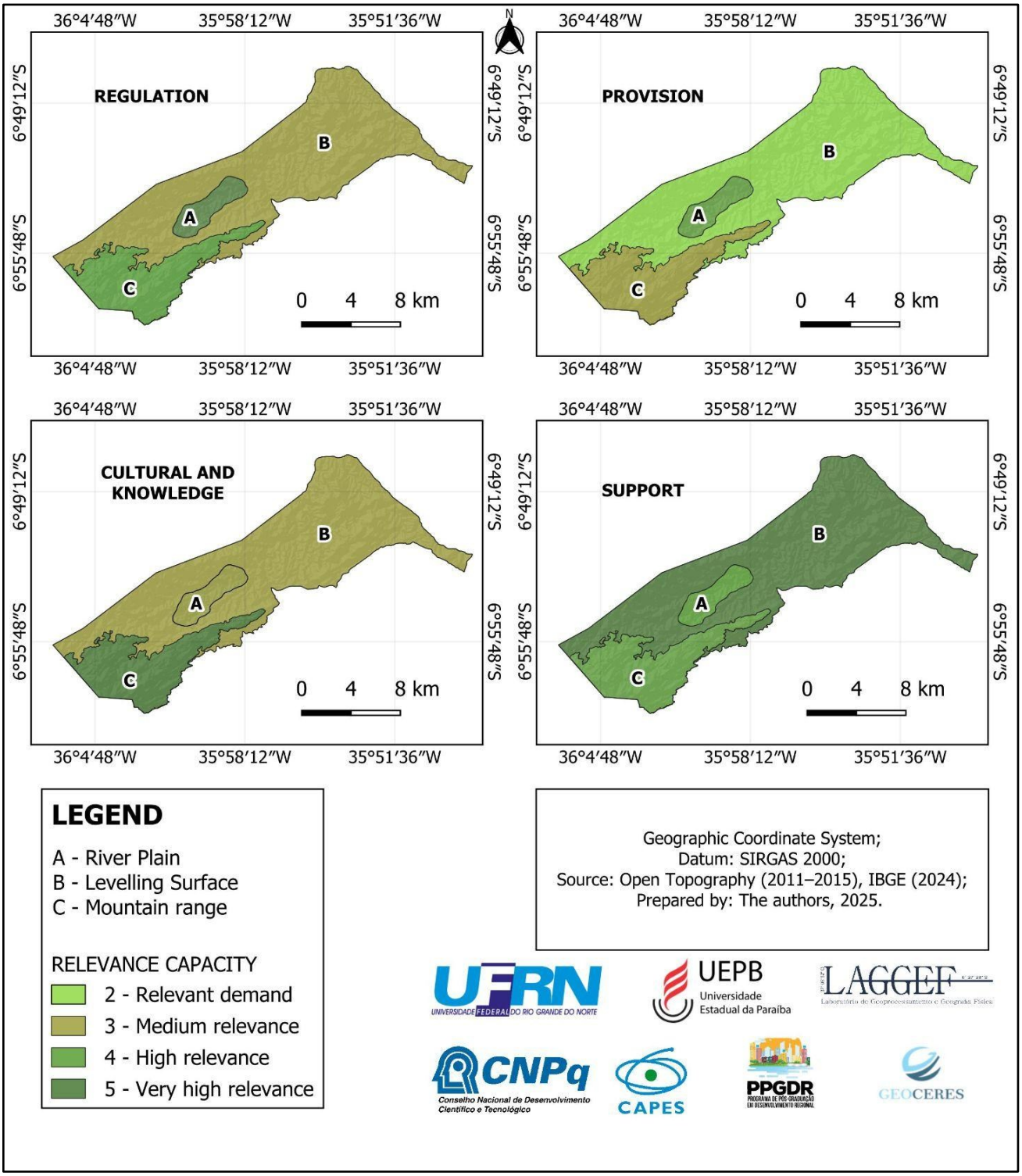

Figure 8: Relevance capacity of ecosystem services.
Source: Prepared by the authors, 2025

The high degree of relevance observed proves that abiotic aspects, especially those conditioned by relief, play a fundamental role in providing services that directly influence the quality of life and well-being of the local population. The conservation and sustainable use of these compartments are essential to ensure the continuity of the ecosystem services provided by geodiversity, contributing to environmental resilience and the development of the region.

In general, distinct economic benefits are observed: agricultural activities predominate in flatter areas, while rocky outcrops stand out for their tourism potential. Subsistence agriculture in these areas represents the most direct manifestation of the use of abiotic provisioning services. Continuous use, however, leads to landscape modification, which is the result of anthropic interaction with the compartments.

In summary, the diversity of uses and benefits associated with each compartment highlights the importance of these spaces both for the local economy and for environmental and cultural enhancement, reinforcing the need for management strategies that reconcile conservation and sustainable use.

5. Final thoughts

This research demonstrated that the municipality of Algodão de Jandaíra has a significant diversity of abiotic ecosystem services distributed across its exceptional landscapes, confirming the initial hypothesis that local geodiversity plays a fundamental role in providing direct and indirect benefits to the population and ecosystems. The methodology adopted proved to be adequate for the systematic evaluation of these services, highlighting relevant differences between the geomorphological compartments analysed.

Overall, the results indicate that the Jandaíra River plain, represented by the Algodão Dam, plays a central role in providing provisioning and regulating services, especially those related to water supply and support for local productive activities. The observation of direct water collection by tanker trucks during fieldwork illustrates, in a concrete way, the community's dependence on the ecosystem services provided by this compartment.

In turn, the Serra compartment stood out for its significant offer of cultural and knowledge services, associated with the symbolic, scenic, recreational and educational values attributed to the rock formations, reinforcing its importance to the region's natural and cultural heritage. The Levelling Surface, represented by the Muralha Maior, revealed particular relevance in support services, achieving a very high relevance in this category. It can be said that the rock formation present in the area has an inestimable scientific value, constituting a true natural laboratory for understanding regional geological processes.

These results show that each compartment performs specific and complementary functions, reinforcing the need for an integrated approach to the analysis and management of ecosystem services. While the plains require policies aimed at protecting water resources and regulating the extraction of materials, the mountains require actions to enhance cultural heritage and develop sustainable tourism. The flattened surface, on the other hand, needs geoconservation measures to ensure the preservation of its unique geological records.

In this sense, the findings of this research contribute to the advancement of knowledge about abiotic ecosystem services in a semi-arid context, an area that has been little explored in national scientific literature. Furthermore, they reinforce the importance of considering geomorphological and environmental particularities in territorial planning and management of areas within the semi-arid region, in order to reconcile environmental conservation, sustainable use of natural resources, and improvement of the living conditions of the local population.

The methodology employed proved to be appropriate for the local context and could be replicated in other municipalities in the semi-arid regions of Paraíba and the Northeast, contributing to the construction of a broader regional overview of the provision of these services. From a practical point of view, the results support the development of more effective environmental public policies, providing a scientific basis for territorial management instruments that integrate environmental conservation and socioeconomic development. The quantification and classification of abiotic ecosystem services can guide environmental licensing processes, municipal master plans, and environmental education strategies aimed at valuing natural heritage.

However, some limitations of the study should be highlighted, suggesting avenues for future research. The analysis was restricted to three representative compartments, and expansion to other relevant units in the municipality is recommended. Furthermore, the incorporation of methods for economic valuation of the identified services could enrich subsequent analyses, providing additional support for public policy decision-making.

In summary, the study shows that Algodão de Jandaíra, despite its small size, is home to a significant wealth of abiotic ecosystem services that support both human activities and the integrity of local ecosystems. Recognising and valuing this

functional diversity are fundamental steps towards promoting sustainable development in the challenging context of the Brazilian semi-arid region, demonstrating that even small municipalities can play strategic roles in environmental conservation and the well-being of local populations.

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