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Geodiversity of Vale do Jacaré, Regeneration, Piauí, Brazil: potential and values

Geodiversidade do Vale do Jacaré, Regeneração, Piauí, Brasil: potencialidades e valores

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Abstract: In Piauí, research involving geodiversity has been developed in the last decade, and despite the growing number, they are still insufficient. Given this scenario, the work aimed to inventory the geodiversity of Vale do Jacaré, municipality of Regeneração, Piauí, emphasizing its potential and associated values. A literature review, office and field research were carried out. The studied municipality reveals potentialities from the point of view of its geological, geomorphological and hydrological heritage, in view of the occurrence of mountains, caves, lakes and canyons. It is recommended that these locations be used as a way to boost geoconservation strategies and the local-based economy, enabling the municipality's economy to become more dynamic. It is expected that the work of different spheres of public power, combined with private initiatives, especially local residents, will implement measures that guarantee the conservation, dissemination and promotion of this valuable geodiversity.

Keywords: Geodiversity; Valoracion; Piauí.

Resumo: No Piauí, as pesquisas envolvendo a geodiversidade vêm sendo desenvolvidas na última década, e apesar do número crescente, ainda são insuficientes. Diante desse cenário, o trabalho teve como objetivo inventariar a geodiversidade do Vale do Jacaré, município de Regeneração, Piauí, enfatizando suas potencialidades e valores associados. Foram realizadas revisão bibliográfica, pesquisas de gabinete e de campo. O município estudado revela potencialidades do ponto de vista de seu patrimônio geológico, geomorfológico e hidrológico, tendo em vista a ocorrência de serras, furnas, lagoas e cânions. Recomenda-se, que esses locais sejam utilizados como forma de impulsionar estratégias de geoconservação e da economia de base local, viabilizando a dinamização da economia do município. Espera-se que o trabalho das diferentes esferas do poder público, aliadas a iniciativas privadas, em especial dos moradores locais, efetivem medidas que garantam a conservação, divulgação e promoção desta valiosa geodiversidade.

Palavras-chave: Geodiversidade; Valoração; Piauí.

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1. Introduction

In the current context, studies related to geodiversity and correlated themes (geoconservation, geotourism, among others) are of utmost importance. Understood as the abiotic system in its entirety, geodiversity is characterized as the natural abiotic diversity, encompassing relationships, properties, interpretations, and systems. It thus comprises the non-living aspects of the planet, not only the testimonies of the geological past but also the natural processes occurring today, generating new testimonies (GRAY, 2013).

In the state of Piauí, research in this field is highly relevant, as it contributes to the exploration and recognition of new areas. This is a subject with expansion potential since many regions lack in-depth studies. Particularly when considered in a state-wide context, understanding abiotic environmental characteristics becomes fundamental (SILVA *et al*., 2021). With a vast territorial extension, Piauí is endowed with a complex set of geoenvironmental characteristics.

This observation, combined with the lack of studies of this nature and the limited exploration and dissemination within the Piauí context, justifies the present research. Aiming to value and promote geodiversity in Piauí, the municipality of Regeneração was selected as the study area.

Given this scenario, this study aimed to inventory the geodiversity of the Vale do Jacaré, located in the municipality of Regeneração, in the central-northern region of Piauí, emphasizing its potential and associated values. It is worth noting that the identified potentials can be leveraged by geotourism, a tourism activity and geoconservation strategy centered on the sustainable enjoyment of abiotic heritage.

As the understanding of abiotic nature and its importance as the foundation of life becomes more accessible to the community, managers, and tourists, the relationship with these sites may foster greater awareness of the need for their preservation.

2. Methodological Procedures

Initially, a bibliographic review on the subject was conducted, along with data collection from documents and technical reports on the environmental aspects of the municipality of Regeneração, Piauí (geology, geomorphology, pedology, climatology, hydrography, and vegetation aspects). These sources provided preliminary knowledge about the area, its potential, capabilities, and values.

Additionally, Geographic Information Systems (GIS) tools were used for map creation. Image processing (visualization, analysis, and digitization) was carried out using the open-source *software* QGIS (version 2.8.1).

The research also included fieldwork and data collection, which began in 2012. A GPS receiver (*Global Positioning System*) was used to collect coordinates. Furthermore, direct observation was conducted, with photographic records and the completion of an inventory form adapted from Oliveira (2015), considered suitable for areas of any size.

3. Values of Geodiversity, Geological Heritage, Geomorphological Heritage, and Hydrological Heritage

Murray Gray (2013) defines geodiversity as “the natural variety [...] of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil, and hydrological elements” (p. 12). Geodiversity thus encompasses the non-living aspects of the planet (physical/abiotic environment), not only limited to geological past testimonies but also including current natural processes that generate new records. It comprises the variety of rocks, minerals, fossils, landforms, sediments, water, and soil, along with the natural processes that form and transform them (BRILHA, 2005; 2016).

Gray (2004) classifies geodiversity into six value categories: intrinsic, cultural, aesthetic, economic, functional, and scientific/educational. Due to its abstract nature, *intrinsic value* is challenging to understand and quantify, as it refers to the significance of geodiversity elements by themselves, independent of their potential use by society. Each culture interacts with nature’s elements in its own way (PEREIRA, 2010; NASCIMENTO; MANSUR; MOREIRA, 2015).

Cultural value, in turn, according to Mochiutti et al. (2012, p. 175), “is revealed in the numerous relationships that exist between society and the natural world surrounding it, in which it is embedded and to which it belongs.” According to Gray (2004), this is one of the most practical and objective categories among the values assigned to geodiversity. Constructions, gastronomy, archaeological, and historical aspects are also directly linked to geodiversity in some locations.

Similar to intrinsic value, *aesthetic value* is difficult to measure, as it cannot be quantified — each person perceives beauty differently. That is, subjectivity is inherent to the observer. Brilha (2005) highlights that

geodiversity's aesthetic value is visible in various landscapes, leading some people to find satisfaction in merely observing geodiversity as an instinctive and pleasant act.

Economic value, or the financial value of geodiversity, according to Gray (2004), has been exploited for centuries by human societies that find in these elements a vast range of materials essential for modern technological progress (mineral, industrial, commercial, construction, metallic, precious, aggregate, and energy resources).

The *functional value* of geodiversity is assigned based on the natural element's contribution to human well-being. This value is linked to nature's role as a support and facilitator of anthropogenic activities, as well as the foundation for biomes and biodiversity elements (GRAY, 2004; MOCHIUTTI *et al*., 2011). According to Brilha (2005), functional value relates to the use of geodiversity in its original location as support for various activities (e.g., groundwater storage in aquifers, soil for agriculture, landfill sites for waste, among others). It also serves as the basis for flora and fauna.

Finally, *scientific and educational values*, according to Mochiutti et al. (2012), are perhaps the most valuable aspects attributed to geodiversity. Investigations into certain aspects of the abiotic environment allow for the reconstruction of Earth's long history, the prediction of future regional scenarios, risk prevention, and numerous other applications.

When geodiversity elements acquire utility for society, they are recognized as geological heritage, geomorphological heritage, and hydrological heritage. These, along with broader geodiversity research, have seen increasing advancements.

Understanding that geodiversity encompasses all abiotic elements of the planet, it is important to note that "the study of geological heritage is independent of the study of geodiversity, even though they are somewhat related" (CARCAVILLA *et al*., 2008, p. 3001). Thus, these two concepts are not synonymous.

According to Muñoz (1988), as cited by Mantesso-Neto (2009, p. 05), geological heritage is

> Constituted by cultural georesources, which are non-renewable resources of a cultural nature, that contribute to the recognition and interpretation of the geological processes that shaped Planet Earth and that can be characterized according to their value (scientific, didactic), their utility (scientific, pedagogical, museological, touristic), and their relevance (local, regional, national, and international).

Brilha (2005) emphasizes that these locations are classified as geosites — geological sites that are inventoried and characterized within a given area, region, or country, where one or more geodiversity elements hold unique scientific, pedagogical, cultural, touristic, ecological, or other values.

Nascimento, Ruchkys, and Mantesso-Neto (2008) state that although closely related to the concept of geodiversity, the concept of geological heritage is represented by the collection of geological sites, or geosites — places where geological occurrences have undeniable scientific, pedagogical, cultural, or touristic value.

Geomorphological heritage consists of geomorphological elements, including landform sets (geoforms, processes) and associated deposits that exhibit one or more types of values, rarity, and/or uniqueness at various scales (VIEIRA; CUNHA, 2004). According to Rodrigues and Fonseca (2008), it is formed by a set of geomorphological elements, at different scales, possessing one or more types of values, identified through scientific assessment, and should be subject to protection and enhancement processes.

Hydrological heritage, according to Rodrigues (2019, p. 274), is composed of "the set of oceanic and continental waters (seas, lakes, watercourses, underground and hydrothermal reservoirs) as well as the associated dynamics, processes, and forms," which possess exceptional value and rarity. When recognized for their diversity and beauty, they can be appreciated and aligned with the objectives of geotourism practices.

Hydrological heritage is a segment of a region's hydrological diversity and encompasses elements related to locations that include:

> [...] groundwater (hydromorphological units) and surface water (hydrographic basins, lakes, rivers, and other drainage forms), hydric geosites (waterfalls, wetlands, diffuse discharge and recharge zones, etc.), thermal areas and springs, and other hydrological points of interest (springs dried up due to overexploitation or natural causes, fluvial or karst springs (surface or underground), such as karst cavities (caves and galleries) or other typical hydrological phenomena of karst areas, such as sinkholes, exsurgences, resurgences, or karst canyons, and even classified wetlands or those requiring protection measures. (AZEVEDO; RODRIGUES, 2015, p. 208).

4. Study Area Location and Geoenvironmental Aspects

The municipality of Regeneração is located in the Médio Parnaíba Piauiense microregion, bordering the municipalities of Angical do Piauí and Jardim do Mulato to the north, Arraial to the south, Amarante to the west, and Elesbão Veloso and Francinópolis to the east. The municipal seat is situated at the geographic coordinates 06°14'16"

south latitude and 42°41'18" west longitude, approximately 147 km from Teresina (AGUIAR; GOMES, 2004) (Figure 1).

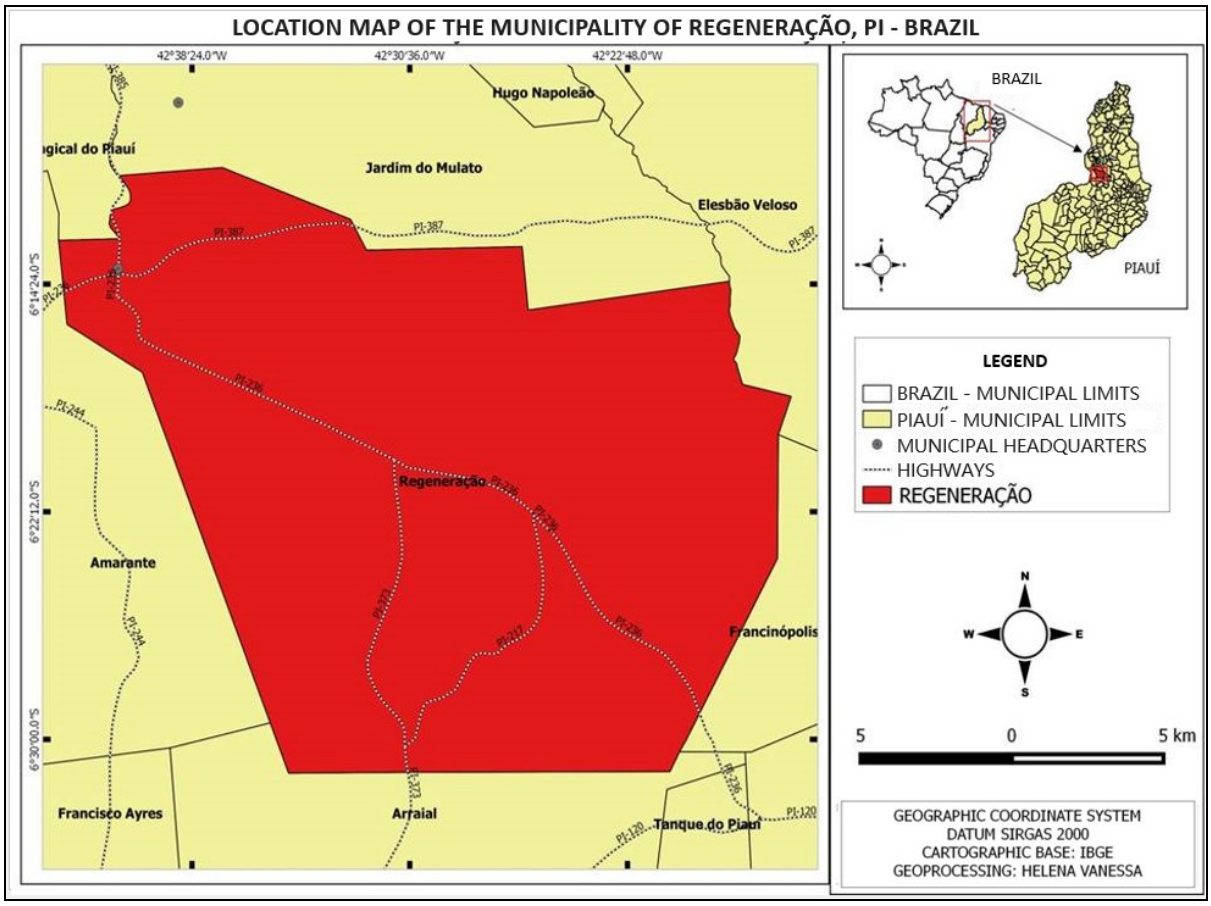

Figure 1 – Location of the study area.
Source: Authors (2021).

4.1 Jacaré Stream Valley

The Jacaré Valley originates in the locality of Cabeceiras, situated in the rural area of the municipality of Regeneração, in the Médio Parnaíba Piauiense region. The stream springs from the slopes of Chapada Grande, approximately 40 km southwest of the municipal seat. It is an area of significant biodiversity and geodiversity, with considerable geoenvironmental, historical, and archaeological relevance (COSTA, 2015).

The stream flows into the Canindé River in the locality of Prata, in the rural area of the municipality of Amarante-PI, at the geographic coordinates S 06º26'10.1" and W 42º42'44.4". Access to the valley is via the PI-236 highway, followed by the PI-217, which leads to the municipality of Arraial do Piauí. The great natural wealth of the Jacaré Valley lies in its geological and hydrographic components, as well as the notable presence of the babassu palm forest.

The first springs of the Jacaré Stream are located near the slopes of Chapada Grande and the hills of Lavragem and Mesa, which exhibit gully erosion, outcropping of bedrock, and the presence of several sandstone blocks, gravel, and sand. The erosive processes in the region gradually intensify, eventually shaping the valley into a canyon (Figure 2).

Figure 2 – Erosive activity in the Chapada Grande region, Regeneração, Piauí, Poço da Marquinha, Vale do Jacaré.
Source: Authors (2020).

The bed of the Jacaré Stream, from its sources to its mouth, is predominantly rocky. Due to the erosive action of rainwater, it has formed a canyon approximately 500 meters long, extending from the headwaters to the bridge on the PI-217 highway, with rock walls over 4 meters high. Although the stream is not perennial, sediment deposition along its course creates pools of water that persist during the dry months of the year. At its confluence with the Canindé River, the streambed is highly silted, with a significant presence of gravel and sand (COSTA, 2015).

4.2 Geological and Geomorphological Aspects

The Jacaré Valley is part of the Maranhão-Piauí Sedimentary Basin, which covers an area of 600,000 km² and spans the states of Maranhão and Piauí. This basin was formed during the Paleozoic and Mesozoic Eras through the erosion of surrounding crystalline shields. According to Araújo (2006), these shields were intensely weathered by rain, wind, ancient rivers, and ocean waters during interglacial periods when marine transgressions occurred. The combined action of these agents wore down the rocks, transporting and depositing sediments into depressions that once housed large seas between the shields.

These deposits gradually formed sedimentary rocks, which accumulated in successive layers, shaping the region's geological formations. The characteristics of these sedimentary rocks — such as sediment size, grain compaction or cementation, and pressure directly influence the permeability levels of each formation, a key factor in groundwater infiltration and aquifer formation (ARAÚJO, 2006).

Regarding geological units, the region is predominantly composed of sedimentary rocks, including friable and silicified sandstone, as well as flint and quartz. According to Campelo (2010), the most prominent geological formation in the area is the Pedra de Fogo Formation, consisting of sandstone, shale, and limestone. Other significant formations include the Poti Formation (sandstone, siltstone, shale, and limestone) and the Corda Formation (sandstone, shale, and siltstone) (Figure 3).

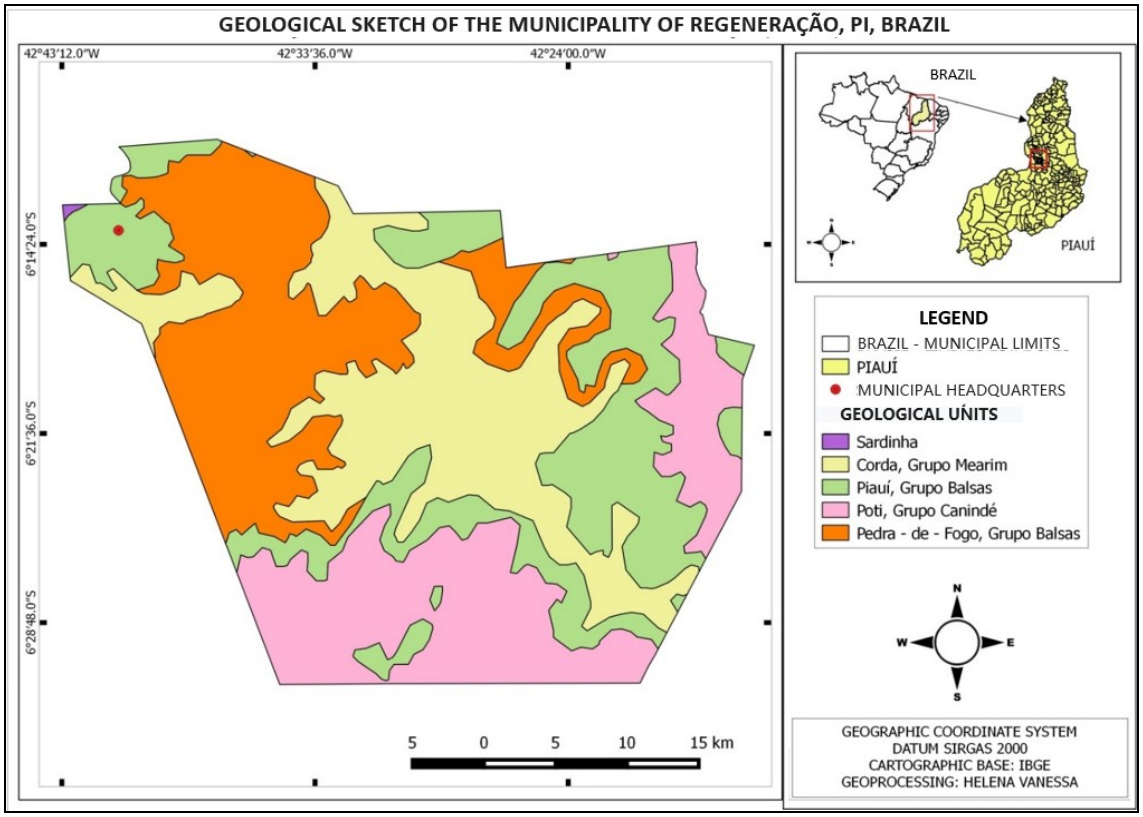

Figure 3 – Geological units of the municipality of Regeneração, Piauí.
Source: Authors (2021).

Regarding the relief of Regeneração, Aguiar and Gomes (2004) describe it as comprising reworked tabular surfaces (low plateaus), characterized by flat terrain with gently undulating areas and altitudes ranging from 150 to 300 meters; tabular summit surfaces (high plateaus), with flat relief, altitudes between 400 and 500 meters, and large dissected mesas; and undulating surfaces with rugged terrain, including slopes, residual plateau extensions, valleys with steeper slopes, and elevated landforms such as mountain ranges, hills, and knolls, with altitudes varying between 150 and 500 meters.

The relief of the study area belongs to the Chapada Grande Complex, an extensive region that encompasses the municipalities of Regeneração, Jardim do Mulato, Arraial, Amarante, Francinópolis, Várzea Grande, Tanque do Piauí, Oeiras, Barra D'Alcântara, Santa Rosa do Piauí, and Novo Oriente do Piauí.

The relief of the study area is mesa-like, featuring straight slopes and horizontal summits. In some sections, it appears as peaks, characteristic of the dissected low plateaus of Médio Parnaíba (Figure 4). These landforms serve as topographic divides between the Berlengas River basin, the lower course of the Poti River, the middle and lower courses of the Canindé River, and part of the tributaries of the Parnaíba River, such as the Mulato River Valley (FERREIRA; DANTAS, 2010).

Figure 4 – Dissected plateaus of Médio Parnaíba, municipality of Regeneração, Piauí, view from the access to Vale do Jacaré.
Source: Authors (2020).

Regarding the geomorphological aspects of the Jacaré Valley, the landscape is characterized by intense shaping and reshaping, as well as the presence of sandstone rocks, resulting from severe weathering processes that contribute to erosion and sediment deposition. In addition to natural agents, human activities have altered the relief through the construction of roads, deforestation, and burning, further accelerating degradation in some areas.

Erosive activity is particularly noticeable near the banks of the Jacaré, in the Várzea dos Patos area. Due to the intense runoff of rainwater, the formation of gullies and ravines is frequent. This erosional process resembles large basins, which, during the rainy season, accumulate water throughout the valley. Some hillsides show visible leaching processes, caused by rainwater action, leading to progressive surface wear (Figure 5).

Figure 5 – Leaching process in slope areas, near Vale do Jacaré, municipality of Regeneração, Piauí.
Source: Authors (2020).

4.3 Hydrographic and Climatic Aspects

The hydrographic context of the municipality of Regeneração (Figure 6) is situated between three hydrographic basins: the Diffuse Basins of Médio Parnaíba, the Canindé Basin, and the Poti Basin. The municipality also features some perennial water sources, such as the Mulato River microbasin, which extends between the municipalities of Regeneração and Jardim do Mulato. This microbasin integrates the Diffuse Basins of Médio Parnaíba, located near the municipal seat, in the region between the Chapadas dos Pombos and São Domingos.

Additionally, there is the Macacos Stream, whose headwaters originate in the Chapada do Brejo, part of the Chapada Grande geomorphological complex. Another important watercourse is the Riachão Stream, which rises on the slopes of Chapada Grande and is a tributary of the Jacaré Stream. Finally, there is the Berlengas River, a tributary of the Poti River, with headwaters located in the rural area of Novo Oriente. The Berlengas River also flows through Regeneração, near Chapada Grande, moving eastward along the border with the municipality of Elesbão Veloso.

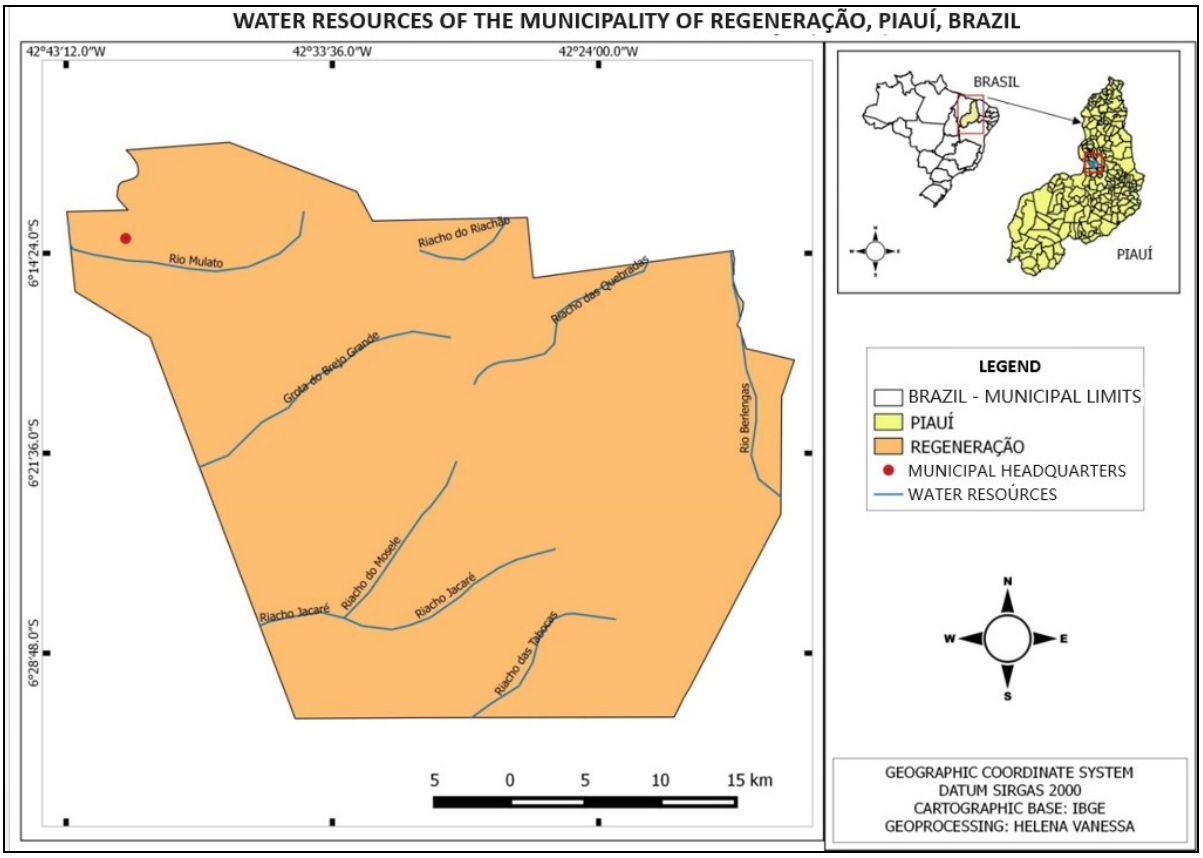

Figure 6 – Hydrographic Aspects of the Municipality of Regeneração, Piauí.
Source: Authors (2021).

Deforestation of the riparian forest in the valley has been causing significant environmental impacts on the stream. It no longer has a perennial course, although some headwater points retain standing water, especially during dry periods, forming lush natural pools, also called "poços". Part of this water seeps into the groundwater table, feeding certain sections of the Jacaré Stream and contributing to the maintenance of other pools. These include Poço do Angico, Poço da Mariquinha, Poço do Estreito, and Poço dos Patos. There are also lagoons surrounded by palm forests, among which Lagoa da Inhuma stands out, bordered by carnauba and babaçu palms, providing fish resources for the region's inhabitants.

Among the main headwaters, the following are noteworthy: Cabeceiras, Olho d'Água Buriti do Meio, Olho d'Água do Caboclo Velho, Olho d'Água do Manoel Raimundo, Olho d'Água do Patuá, Olho d'Água do Musele, Olho d'Água do Riachão, Brejinho, Olho d'Água do Morro do Pico (Figure 7), among others. Due to the presence of several hills, there are also numerous shallow water crossings, which serve as drainage points for rainwater runoff, especially during the rainy season.

Figure 7 – Riacho do Pico, tributaries of the Jacaré River.
Source: Authors (2020).

The climatic conditions of the municipality of Regeneração show minimum temperatures of 23ºC and maximum temperatures of 36ºC, with a hot tropical climate (Figure 8).

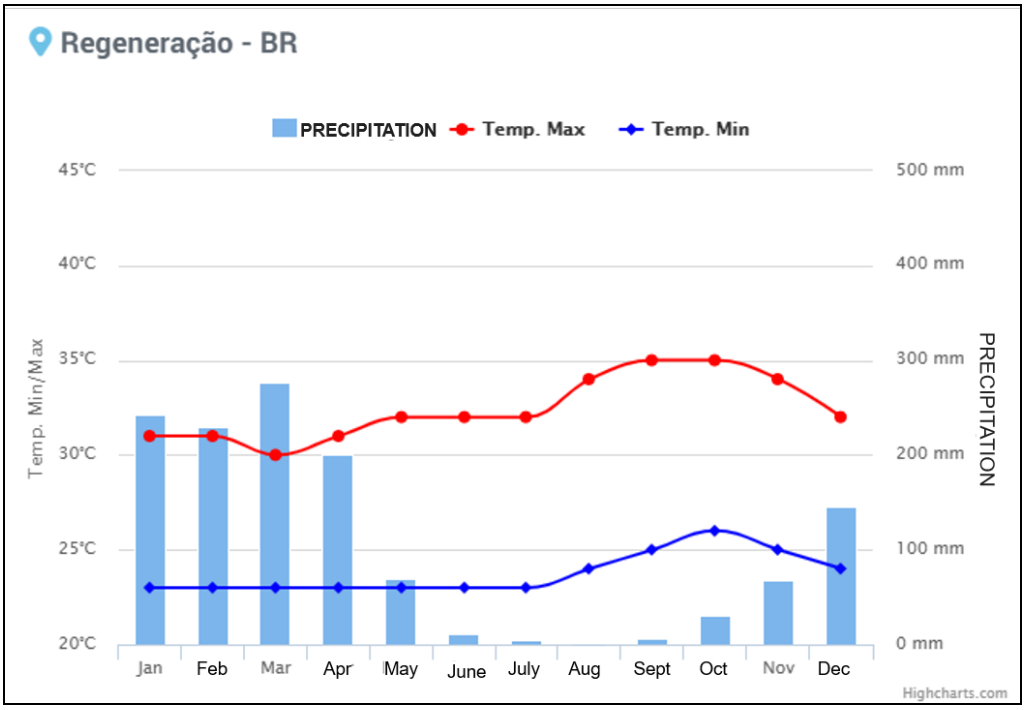

Figure 8 – Climograph of the Municipality of Regeneração, Piauí.
Source: https://www.climatempo.com.br/climatologia.

The annual average rainfall (with a recorded 1,250 mm in the municipal headquarters) is defined under the Continental Equatorial Regime, with annual isohyets ranging from 800 to 1,400 mm. The climatic classification of the municipality, according to Köppen's climate types, is Aw' (tropical with maximum rainfall in autumn) and Bsh

(semi-arid). Part of the Jacaré Valley falls under the Bsh classification as it belongs to the Canindé sub-basin (AGUIAR; GOMES, 2004).

In Jacaré Valley and part of its surroundings, due to altitudes such as Chapada Grande and other adjacent areas, the rainfall regime may undergo some variations depending on the meteorological conditions of the rainy season. The main rainy period in the region, according to Araújo (2006), is between February and late April, classified as Aw', although rainfall during the winter months (June and July) may occur as atypical phenomena.

5. Results and Discussions

Based on the inventory, ten sites of geological, geomorphological, and hydrological interest were identified in the study area (Figure 9). Considering the potential presented by the municipality, Table 01 below provides a summary of the inventoried sites in the area.

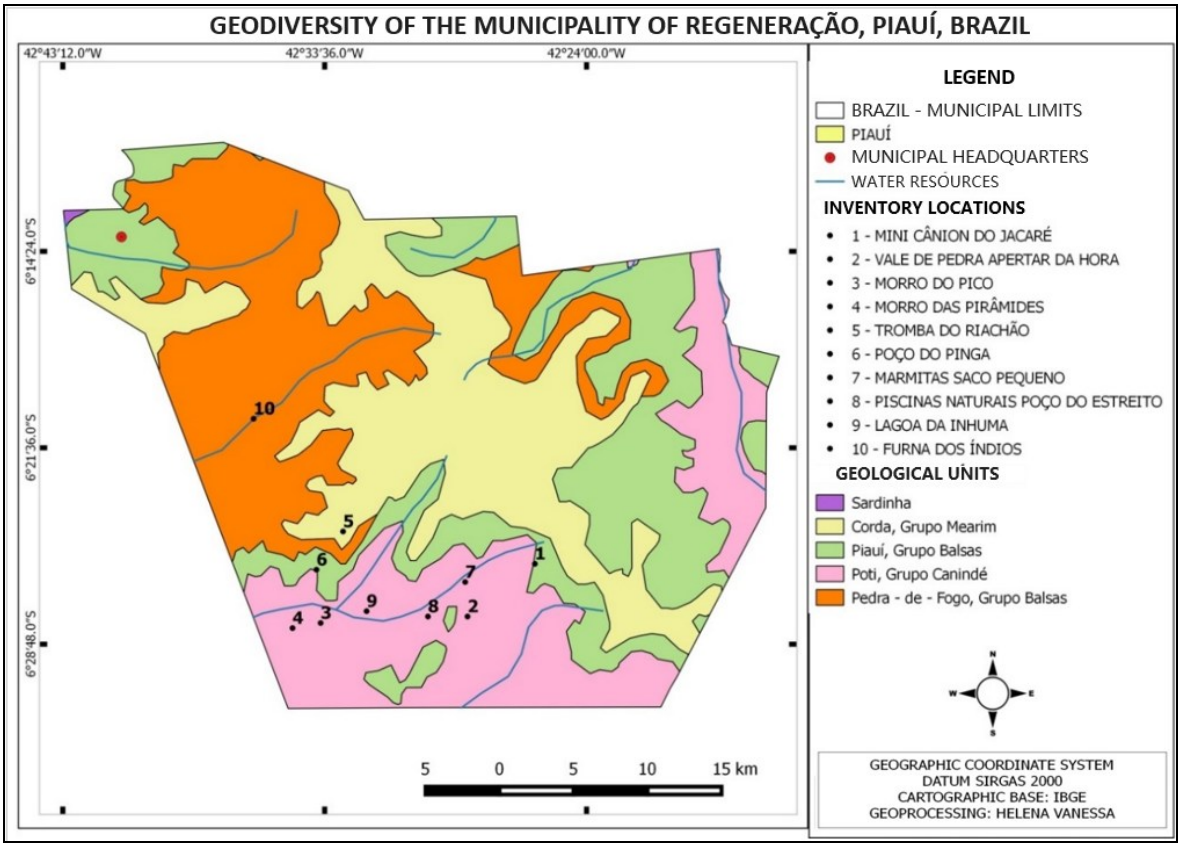

Figure 9 – Geodiversity of the Jacaré Valley in the Municipality of Regeneração, Piauí.
Source: Authors (2021).

Table 2 – Summary of the Inventoried Sites in the Municipality of Regeneração, Piauí.

Points	Description/ Features natural	Ownership/ Access conditions	Strengths/ Associated values
1 - Jacaré Mini Canyon	Approximately 500 m long, from the headwaters to the bridge on the PI 217 highway, it has rocky walls over 4 m high;	Private Very affordable	Water supply for the population and animals. Values: cultural, aesthetic, tourist, ecological and educational.
2 - Vale de Pedra Apertar da Hora	Sandstone blocks that stand out in the landscape. A place of geological interest located at the headwaters of the stream of the same name.	Public Very affordable	A natural heritage site considered by the Piauí State Foundation for Culture (FUNDAC) to be known as the stone forest. Values: aesthetic,

			tourist and educational.
3 - Pico Hill	It belongs to the group of isolated peak-shaped hills in the topographic context of the Chapada Grande Complex in the lower Canindé valley, with altitudes of over 300m.	PublicNot very accessible	There are plant fossils all over the hill. Values: cultural, aesthetic, tourist, ecological and educational.
4 - Pyramid Hills	They are located near the Jacaré River in the Carnaíbas community and are called Morro do Preto and Morro do Sítio Velho, at altitudes of over 300m.	Private Very affordable	There are plant fossils all over the hill. Values: aesthetic, tourist and educational.
5 - Tromba do Riachão	A table-shaped hill forms part of the Chapada Grande plateau in the municipality of Regeneração, at altitudes of over 400m.	Private Not very accessible	On the slopes of this hill there are nests of scarlet macaws. At the foot there are the springs of the Riachão, a tributary of the Jacaré river. Values: aesthetic, tourist, ecological and educational.
6 - Poço do Pinga	It is located next to a stretch of the Riachão river and is so named because of the flow of water that comes out in drips.	Private Not very accessible	A pool of crystal- clear water used for fishing by local residents. There are plant fossils on the banks of the stream. Values: cultural, tourist, ecological and educational.
7 - Small bag lunch boxes	It is located in the grotto of Olho d'água do Brejo Grande. It is a stretch of the Saco Pequeno stream where you can see numerous marmitas, processes of rock dissolution caused by rain erosion (GUERRA, 1993).	Private Very affordable	Potential from the point of view of water, with crystal clear water emerging. Values: cultural, aesthetic, tourist, ecological and educational;
8 - Poço do Estreito natural pools	During the dry season, some pools of clear water appear in the Jacaré River, acting as natural swimming pools.	Private Very affordable	As well as being used by locals for fishing, for example, there is archaeological evidence of rock engravings at the site.
9 - Inhuma Lagoon	Lagoon located in a flat area with predominantly carnauba forest between the Jacaré and Musele streams.	Private Very affordable	Used by local residents for fishing and animal feed. Values: tourist, ecological and educational.
10 - Furna dos índios	A deep cavity in the side of a rock which, according to the locals, served as a resting place during the long and tiring hikes taken by the Indians.	Private Not very accessible	Presence of springs to supply the community. Values: cultural, aesthetic, tourist, ecological and educational;

Source: Authors (2021).

In Figure 10, photographic records of the 10 geological, geomorphological, and hydrological sites inventoried for the study area are presented.


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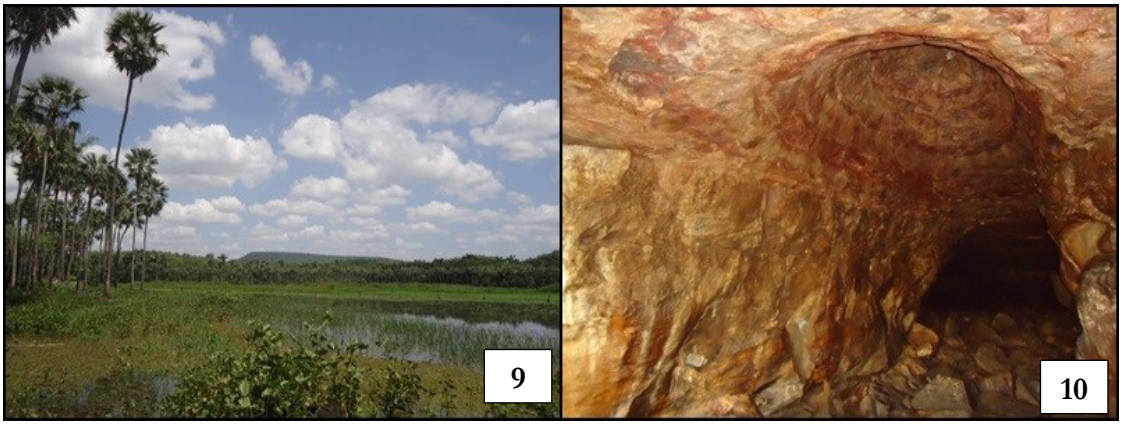

Figure 10 – Inventoried Sites of Geological, Geomorphological, and Hydrological Interest.
1 - Mini Canyon of Jacaré; 2 - Pedra Apertar da Hora Valley; 3 - Morro do Pico; 4 - Pyramid Hills; 5 - Tromba do Riachão; 6 - Poço do Pinga; 7 - Marmitas Saco Pequeno; 8 - Natural Pools of Poço do Estreito; 9 - Lagoa da Inhuma; and 10 - Furna dos Índios.
Source: Authors (2020).

Regarding the existence of vulnerabilities and deterioration, during field research, it was possible to observe, in addition to natural causes such as the erosive effects of rainwater, several occurrences of environmental impacts caused by human activity, such as deforestation for wood commercialization and fires set by farmers and especially hunters between August and November.

To mitigate these impacts, heritage education and environmental education initiatives were developed, including the installation of signage, through the projects "Nossa Vila Nossa Gente Nossa História" and "Escola Ecológica Comunidade Sustentável", in partnership with the Municipal Government of Regeneração, public and private schools, local residents, and the Piauí Cultural Foundation (FUNDAC).

6. Final Considerations

Based on the inventory of geological, geomorphological, and hydrological sites in Jacaré Valley, in the municipality of Regeneração, State of Piauí, the potential, unique characteristics, and associated values of these locations become evident. These important sites, which can be primarily utilized for geotourism purposes, deserve conservation efforts.

It is emphasized that their rational and sustainable exploration could serve as an alternative source of income for the local community. However, public policies for tourism development remain insufficient, especially considering the urgent need for access roads to most of the identified sites.

Given the relevance of these locations as promoters of scientific research, field activities, and tourism, it is essential to enhance their recognition and dissemination. In addition to their geological, geomorphological, and hydrological potential, the presence of rock engravings on exposed outcrops represents part of the historical memory of the people who once lived in the region.

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