GEODIVERSITY HOTSPOTS IN ITABIRITO

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ABSTRACT

Objectives: The objective of this work is to establish the Geodiversity Index for the municipality of Itabirito. It is expected to identify Geodiversity Hotspots, priority areas for conservation.

Theoretical Framework: The literature review addressed geological resources, geodiversity and geoconservation of the Iron Quadrangle. Currently, the relevance of geodiversity is growing among scientific journals, research groups and government programs.

Method: As a methodology, based on a bibliographical review of scientific works to determine the Geodiversity Index, and collection of secondary data on the physical environment of Itabirito, a grid polygon was created in the QGIS software, measuring 250x250m. To define the degree of influence of each of the variables considered, the Analytic Hierarchy Process method was used. Next, maps were created for each of the six variables as well as for the Geodiversity Index.

Results and conclusion: The result of the Analytic Hierarchy Process method obtained a consistency rate of 3.7% to determine the weights of each adopted variable. Then the equation can be established to determine the Itabirito Geodiversity Index.

Implications of the research: Exactly in areas that presented high to very high IGD, geodiversity hotspots can be determined. The mapping and analyzes carried out confirm that the municipality of Itabirito has regions considered Geodiversity Hotspots.

Originality/Value: This work contributes significantly to the knowledge of the geodiversity of the municipality of Itabirito. The establishment of the IGD for the Itabirito territory is relevant to guide the creation of mechanisms to promote geoconservation and geotourism.

Keywords: Geoconservation, Geodiversity, Hotspots, Geotourism and Geoethics.

GEODIVERSIDAD HOTSPOTS EN ITABIRITO

RESUMEN

Objetivos: El objetivo de este trabajo es establecer el Índice de Geodiversidad del municipio de Itabirito. La esperanza es identificar los puntos candentes de la Geodiversidad, áreas prioritarias para la conservación.

Referencias teóricas: La revisión de la literatura abarcó los recursos geológicos, la geodiversidad y la geoconservación del Ferrifero Quadrilátero. En la actualidad, está aumentando la importancia de la diversidad biológica entre las publicaciones científicas, los grupos de investigación y los programas gubernamentales.

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Método: Como metodología, a partir de una revisión bibliográfica de trabajos científicos para determinar el Índice de Geodiversidad, y de un estudio de datos secundarios sobre el entorno físico de Itabirito, se creó un polígono de red en el software QGIS, de dimensiones 250x250m. Se utilizó el método Proceso de Jerarquía Analítica para definir el grado de influencia de cada una de las variables consideradas. A continuación, se elaboraron mapas para cada una de las seis variables así como para el Índice de Geodiversidad.

Resultados y Finalización: El resultado del proceso de jerarquía analítica obtuvo una tasa de consistencia del 3,7% para determinar las ponderaciones de cada variable adoptada. La ecuación puede entonces establecerse para determinar el Índice de Geodiversidad de Itabirito.

Implicaciones de la investigación: Exactamente en las áreas que mostraron IGD alta a muy alta, se pueden determinar los puntos candentes de la geodiversidad. Los mapeos y análisis realizados confirman que el municipio de Itabirito cuenta con regiones consideradas como puntos candentes de la Geodiversidad.

Originalidad/Valor: Este trabajo contribuye significativamente al conocimiento de la geodiversidad del municipio de Itabirito. El establecimiento de la IGD para el territorio de Itabirito resulta pertinente para orientar la creación de mecanismos de fomento de la geoconservación y el geoturismo.

Palabras clave: Geoconservación, Geodiversidad, Puntos Críticos, Geotomrismo y Geoética.

1 INTRODUCTION

The Iron Quadrangle is a territorial portion of important mineral wealth, located in the central region of the state of Minas Gerais. This area, delimited by some orogenic massifs of the Paleoproterozoic, is the focus of an academic study that seeks to evaluate the relevance of this mining territory in terms of geological resources, geodiversity and geoconservation. Ruchkys (2007), Ruchkys (2009), Ruchkys et al. (2012), Ruchkys and Machado (2013) are examples of work carried out on these topics, produced mainly from the first decade of the 21st century. Currently, the relevance of geodiversity is growing among scientific journals, research groups and government programs.

Castro and Ruchys (2017) demonstrated the growth of scientific work in this region, highlighting the important aspects to continue promoting the conservation of geological heritage in the context of one of the most important mineral provinces of the world.

The municipality of Itabirito is located in the central region of the Iron Quadrangle. With an area of 544,027 km² (IBGE, 2021), it has some municipal boundaries defined by rocky uprisings, namely the Serra da Moeda to the west and the Serras do Capanema, Jaguara and Gandarela to the east. This municipality of recognized mining vocation since the 18th century, with emphasis on gold production in the 19th century and iron ore extraction from the 20th century, is located in the upper part of the Río das Velhas hydrographic basin. It houses hundreds of springs that form dozens of streams such as Bação and Carioca, streams such as Aedes, Mata Porcos and Silva, members of the sub-basin of the Itabirito River, which in turn is a direct tributary of the Río das Velhas. The recognized geodiversity of the municipality is also composed by the occurrence of natural cavities in iron formations, studied by Pereira and Souza (2009), Brandi et al. (2016) and Souza (2018), among others.

The aim of this paper is to establish a Geodiversity Index for the municipality of Itabirito, in order to identify areas recognized as Geodiversity Hotspots, which have high and very high rates of geodiversity. These areas can be the subject of research and public policies.
that seek to deepen the knowledge of local geodiversity and promote geoconservation and sustainable use of natural resources.

2 FRAMEWORK

2.1 The concept of geodiversity

Gray (2004) refers to geodiversity as the natural diversity of geological and geomorphological elements, including minerals, fossils, soils, landscapes and their processes. The term Geodiversity has been used in reference to the physical environment, covering abiotic elements such as rocks, geographic features, soils and springs and rivers (Manosso and Ondicoli, 2012).

In addition to the abiotic elements, Pereira (2010) complements the concept of geodiversity, including the physico-chemical processes associated with the internal and external dynamics of the planet, materialized in rock formations and geological or edaphological compartments, endowed with intrinsic values, which can be scientific, educational, tourist, conservation and sustainable use through the adoption of management policies.

In the Iron Quadrangle, as well as in Itabirito, the floristic variability combined with the geological, geomorphological and edaphological complexity presented, allows the formation of a mosaic of diverse landscapes (Oliveira, 2013). The elements that make up the geodiversity of Itabirito are highlighted in some scientific articles, monographs and theses, through different spatial sections, such as the sub-basins of the Itabirito River and the region of the Alto Rio das Velhas.

Solá (2008 apud Goulart, 2013) describes the geological formations of the Ribeirão do Silva basin, composed mainly of itabirites, quartzites, dolomites, phyllites, shales, granites and metaarenisks. These formations that make up the structure of the Sinclinal de Moeda are able to accumulate considerable amounts of water and maintain the base flows of the watercourses (Goulart, 2013).

Bastos (2015) carried out a classification of environmental pressure in areas of water springs in the Alto Rio das Velhas region. 3056 springs were identified, of which 219 are in urban areas, 211 in mining areas, 1893 in agricultural areas, 212 in forest areas and 521 in Conservation Units.

The main regional aquifers are represented by itabirites from the Cauê Formation (Cauê aquifer), quartzites from the Moeda Formation and Cercadinho Formation, as well as dolomies from the Gandarela Formation. (Coelho, 2018)

Considering the geological aspects, the municipality is inserted in the Supergroup Rio das Velhas, Granitic Complexes - Gnaísticos do Bação and Grupo Nova Lima, formed by a succession of mica shales with beds, lenses and areas of iron formations, grauvacas and sub-grauvacas, quartzites, conglomerates, metavolcanic rocks, graphite shales and phyllites, quartz-ankerite shales and other metasediments (CPRM, 2005). The Super Grupo Minas, meanwhile, is formed by the Groups: Caraça, Itabira and Piracicaba (Renger, 1995).

In the Caraça Group, the Moeda Formation stands out, composed of medium to coarse grained quartzites, pebbles, pebbles and rounded granules of smoked quartz, veined quartz, distributed in a phyllitic quartzite matrix.

The Itabira Group consists of the Cauê and Gandarela Formations. The Cauê Formation consists of Itabirites with subordinate lenses of dolomite, compact and friable hematite, phyllites and marble (Dorr and Barbosa, 1963). The Gandarela Formation is composed of dolomite, marble, phyllite and dolomitic itabirite with intercalations of hematite and manganese zones (Dorret al., 1959).
The Piracicaba Group is defined by being formed by clastic metasedimentary rocks (sand, quartzite, phyllite and carbonaceous phyllite) and sporadic lenses of dolomite (Dorret et al., 1957, apud CPRM, 2005). The groups and formations described were updated and detailed in a mapping carried out in 2019 in a project funded by Vale and organized by the Department of Geology of the School of Mines - UFOP (Endo et al., 2019).

According to Canet et al. (2017), geological maps are mapping representations of the different outcropping rock units arranged on the surface in a given area. They can be defined by their lithological characteristics and age, allowing to establish geometric and temporal relationships between lithological compositions. They may indicate the appearance of faults, direction of dips or folds, structures and stratigraphic planes. (e.g. Igme, 2016; CGS, 2016).

Other mapping methodologies can be adopted to analyze impacts on the elements of geodiversity. Da Silva and Dantas (2010, apud Vedovello, 2004) state that:

"geo-environmental mapping can be understood broadly, as is the whole process of obtaining, analyzing, representing, communicating and applying data and information from the physical environment, considering the natural potentialities and weaknesses of the terrain, as well as the dangers, risks, impacts and conflicts arising from the interaction between human actions and the physiographic environment."

According to Brilha (2005), in the same way that biodiversity can be lost, when certain biotic species that have not yet been fully studied are lost, elements of geodiversity can also be lost, often due to lack of knowledge about the spatial distribution, content and historical, scientific, educational and cultural importance. In this sense, it is important to establish quantitative analyzes in relation to the geodiversity of a given territory, in order to support public policies or private initiatives to ensure geoconservation.

The quantification of geodiversity can summarize all the elements of the abiotic complex in a unique value, accessible to the managers of nature. Interventions and explorations that present some type of threat can be limited or controlled, thus promoting geoconservation (Manosso and Ondicol, 2012).

In this context, geoconservation is understood as an area within the Earth Sciences in which the knowledge produced can be used to prevent, correct and minimize environmental impacts that cause risk to geodiversity and geopatrimony (Carcavilla 2012, Henriques et al., 2011, apud Moura et al., 2017).

Stanley (2000) apud Pires et al. (2021), defines Geodiversity from a systemic approach, as “the variety of geological environments, phenomena and active processes that shape the landscape, rocks, minerals, fossils, soils and other surface deposits that sustain and serve as the basis for life on Earth”. This definition was adopted by the Royal Society for Nature Conservations in the United Kingdom.

2.2 Geodiversity indices

The study of geodiversity aims to identify, understand, evaluate and describe the abiotic elements of the landscape (geological, geomorphological, edaphological, paleontological, aquatic, among others) with the aim of promoting conservation, sustainable visitation and the development of geotourism projects, when applicable, providing economic and social benefits for nearby communities.

Meira and Morais (2016) emphasize that the inseparable relationship between Biodiversity and Geodiversity is the basis for the development of different types of landscape. However, the academic world has difficulties to carry out a systemic analysis of geodiversity,
since, historically, biotic aspects are subject to analysis in a much more recurrent way compared to abiotic aspects.

According to Bradbury (2014), the state of the art of geoconservation is several decades behind studies conducted to assess biodiversity conservation. Therefore, the development of classification models covering the entire geodiversity is considered an essential step to close this gap.

The term Geodiversity was introduced mainly by the Argentine geographer Federico Alberto Daus, back in the 1940s (Pires et al., 2018). Currently, the terms geodiversity, geoconservation and geotourism are focused by researchers in different environments, nationally and internationally.

Pires (2021) considers the attribution of values to the elements of the abiotic environment with respect to geodiversity to be fundamental, since these will determine the strategies of geoconservation. Determining values and quantifying geodiversity emerges as one of the important challenges of the 21st century, since the quantification of geodiversity is based on the didactic transposition of methods from the ecology applied to the abiotic environment, such as the calculations of diversity such as those of richness, frequency and distribution of elements and processes, using mathematical operators (Martínez et al. 2021).

Geodiversity assessment and quantification methods can be used as an innovative tool for integrated landscape analysis for the preservation of the natural environment, territorial planning and understanding of ecological relationships considering the balance between geodiversity and biodiversity (Dantas et al., 2015).

Dantas et al. (2015); Santos et al. (2019) apud Pires et al. (2018) state that methods of quantifying geodiversity can be considered for landscape assessment, in order to promote territorial zoning and sustainable use of natural environments, linking the concepts of geodiversity and biodiversity. Serrano and Ruiz-Flaño (2007) used the concept of landscape to carry out a study to quantify the geodiversity. In addition to providing a more assertive analysis in relation to the landscape, the carrying out of studies to quantify the local or regional geodiversity allows us to assess traits of abiotic nature and create referents that relate human actions and the natural environment in which the populations are located.

Nascimento and Castro (2016) applied a method proposing modeling in the Mariana Anticlinal through the geodiversity index, considering anthropogenic actions from mining processes. This geodiversity index was developed considering geological and geomorphological variables, integrated with anthropogenic mining elements and regional hydrographic data. The study included a total of 119 elements distributed over an area of approximately 235 km². The mapping of geodiversity carried out by the researchers showed that: “The highest values are found in regions with greater roughness and slope, as well as in areas with greater density of lineaments and drainage. The edges of the Marian Anticline and its hinge area are those with the greatest diversity of geological elements.” (Nascimento y Castro, 2016).

Mussi (2017) carried out a mapping of marine geodiversity in the coast of Santa Catarina, seeking to characterize the particularities of the physical environment of the regional seabed, relating the physical aspects with the dynamics of the landscape and the distribution of organisms. According to the author, the characterization of geodiversity allows “a systemic understanding of the landscape, and such understanding can provide support for the identification and management of goods and services of ocean ecosystems.”

Pereira et al. (2013) developed a methodology for the quantitative assessment of geodiversity, applied in Paraná, a Brazilian state with an area of about 200,000 km². The method applied was based on the superposition of a grid on different maps at scales ranging from 1/500,000 to 1/650,000, with the final Geodiversity Index being the sum of five partial indexes calculated on a grid of 25 × 25 km. Partial indices represent the major components of
geodiversity, including geology (stratigraphy and lithology), geomorphology, paleontology and soils.

Silva and Barreto (2014) mapped the geodiversity of the Legal Amazon of Maranhão, using a methodology developed by Pereira et al. (2013). The final product of this study was presented in the form of a map that delimits the areas of greater representation in relation to geodiversity. The study indicated that the areas with higher rates of geodiversity in the Legal Amazon of Maranhão have restricted legal protection. The basin of the Itapecuru River and the headwaters of the Mearim River were highlighted as areas of great relevance in relation to Geodiversity, but with few protected areas as conservation units, concentrating the largest conservation units in the coastal zone of the territory of Maranhão.

Similar examples can be seen in work done outside Brazil. The Iberian Peninsula was the subject of a research to evaluate regional geodiversity, developed in collaboration by Benito-Calvo et al. (2009). We seek to quantify and compare geodiversity in several geodynamic zones. A geographic information system (GIS) procedure was used to perform a regional land classification based on geodiversity factors. The data collected was used to create maps, using a classification system of parameters.

Hjort and Luoto (2010) carried out a systematic inventory of geodiversity in an area of 285 km² in the Finnish subarctic. Topographic parameters and spatial variations of geodiversity were quantified using a landscape-scale spatial grid system in quadrants of 500 × 500 m. One of the main results presented was the variation in the total elements of the geodiversity, between 2 and 22 per grid cell. The spatial pattern of total geodiversity, the variability of the geomorphological process and the index of geodiversity were quite similar, while the measure of temporal diversity differed the most from the other measures of geodiversity (Hjort and Luoto, 2010).

Pereira et al. (2013) developed a modeling to establish a Geodiversity Index in the Southern Environmental Protection Area, in the state of MG. using geospatial secondary data on a scale not less than 1:50,000, processed by Arcgis 10.1 software. The methodology used to calculate the index was referenced in Hjort & Luoto (2010). The following equation was adopted:

\[ Gd = \frac{Eg R}{\ln S} \]  

3 METHODOLOGY

3.1 Material

To obtain the Geodiversity Index for the municipality of Itabirito, 6 different geographic data were selected, depending on the objective of the research in conjunction with the literature. All data was used in shapefile format and processed in QGIS software version 3.22.

1. Lithological Mapping (LRCP). Scale 1:25,000;
2. Registered Cavities (Cecav). Scale 1:500,000;
3. Outcrops. Scale 1:240,000;
4. Mining Occurrences (UFOP/UFLA). Scale 1:150,000;
5. Structural Geology (CPRM). Scale 1:240,000;
6. Hydrology (ANA) Scale 1:200,000.

From the data obtained it was possible to determine the variables used to calculate the Geodiversity index:

1. Lithological Diversity;
2. Diversity of cavities;
3. Diversity of outcrops
4. Mining Occurrences;
5. Structural Diversity;

It is important to note that some relevant data for the determination of the IGD, such as pedological mapping, were not used considering the lack of available data on a scale compatible with the scales of the mapping performed.

3.2 Methods

Initially, the mapping of indexes of geodiversity in the municipality of Itabirito to determine the geodiversity hotspots was based on a methodology proposed by Pereira et al (2013), adapted by the authors, considering the characteristics of the study area. Using the Qgis 3.16 software, the territory was divided into 36 quadrants of 5 km x 5 km, with the determination of the respective centroids, duly displaced taking into account the municipal boundary layer so that they were not located in neighboring municipalities. The coverage area was defined in order to achieve a homogeneous distribution of centroids without the covered area being too large, diluting the results to contain a high number of entities. Figure 1 shows the result of this first attempt.

![Illustration 1. IGD adopting territorial divisão em quadrantes of 5km x 5km](image)

**Fonte:** Departamento do Meio Ambiente de Itabirito e próprio investigador.

The need to reassess the proposed methodology was noted, as the size of the quadrants could distort the data used, and even with the determination of the centroids, the IGD would be compromised.

In order to perform the mapping at a suitable scale, a grid polygon was created in the QGIS software, using the function create grid, 250x250m, taking as perimeter the boundaries of the municipality of Itabirito.

After this step, for the polygon and linear vectors (Lithological Mapping, Mining Occurrences, Structural Geology and Hydrology), the following procedure was performed:
1. Rasterize the vector using the tool: convert vector to raster;
2. Use of the Zonal Statistics tool, using the input layer as the grid polygon and the rasterized layers, using as statistics to calculate the variability, to know the number of structures in each quadrant (except Mining occurrences that was the average was used, since it was rated from 1 to 5);
   For point vectors (cavities and outcrops), the tool of random points within the polygons was used to count the occurrences in each quadrant. To define the degree of influence of each of the variables used and reduce randomness in the definition of weights, the Analytical Hierarchy Process - AHP method (SAATY, 1994) was used.
   Then maps were created for each of the six variables as well as for the Geodiversity Index - GDI.
   Both variables and indices were classified into five classes: Very low; Low; Average; High and Very High. Defined using the Jenks method of natural breaks (JENKS, 1977). This method, natural breaks, adjusts class boundaries according to the distribution of data, identifying breakpoints between classes, through a statistical analysis that is based on the variability of data (FERNANDES et al., 2013). For this work, this method helped to reduce variance within a class and maximized the way to emphasize and identify differences between classes.

3.3 Purpose of study

The aim of this paper is to establish a Geodiversity Index for the municipality of Itabirito, in order to identify areas recognized as Geodiversity Hotspots, which have high and very high rates of geodiversity. These areas can be the subject of research and public policies that seek to deepen the knowledge of local geodiversity and promote geoconservation and sustainable use of natural resources.

4 RESULTS

4.1 Parameters

Using abiotic parameters obtained from the public mapping of secondary data, it is possible to collect and organize information on the physical environment of the municipality of Itabirito.

Tarloy (2018) analyzed several methodologies and concluded that dividing territories using hexagonal boundaries reduces edge effects, doubling the level of detail of neighboring effects. However, it was decided to maintain the quadrangular division, according to the methodology of Pereira et al. (2013), using the tools already mentioned.

Figure 2 presents the geospatialization of the parameters used to determine the IGD. Which are: Lithological Diversity, Cavity Diversity, Outcrop Diversity, Mining Occurrences, Structural Diversity, Hydrological Diversity. Considering the geospatialization of these parameters in the territory of Itabirito, a geodiversity score was determined in each quadrant, with their respective isolines.
4.2 Obtaining the Geodiversity Index

The result of the Analytical Hierarchy Process Method - AHP (SAATY, 1994) is shown in table 3 where a consistency index of 3.7% was obtained.

Table 3 - Application of the Analytical Hierarchy Process method to rank the parameters that established the IGD.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Rank</th>
<th>Percentagem</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V1)</td>
<td>Lithological diversity</td>
<td>1</td>
<td>30,6</td>
</tr>
<tr>
<td>(V2)</td>
<td>Diversity of cavities</td>
<td>5</td>
<td>8,9</td>
</tr>
<tr>
<td>(V3)</td>
<td>Diversity of outcrops</td>
<td>6</td>
<td>4,3</td>
</tr>
<tr>
<td>(V4)</td>
<td>Mining occurrences</td>
<td>2</td>
<td>28,2</td>
</tr>
<tr>
<td>(V5)</td>
<td>Structural diversity</td>
<td>4</td>
<td>12,7</td>
</tr>
<tr>
<td>(V6)</td>
<td>Hydrological Diversity</td>
<td>3</td>
<td>15,3</td>
</tr>
</tbody>
</table>

Fonte: Department of the Environment of Itabirito e proprio investigador.

After considering the weights of each variable adopted, the equation (2) was established to determine the Itabirito Geodiversity Index. Whatever:

$$ IGD = V1 \times 0.306 + V2 \times 0.089 + V3 \times 0.043 + V4 \times 0.282 + V5 \times 0.127 + V6 \times 0.153 \ (2) $$

Where:

- IGD = Geodiversity Index;
- V1 = Lithological Diversity;
- V2 = cavity diversity;
- V3 = Diversity of outcrops;
- V4 = Mining Occurrences;
- V5 = Structural Diversity;
- V6 = Hydrological Diversity.
The parameters lithological diversity and mining occurrence had the best classifications in the established ranking, being more relevant in relation to the geodiversity and the main economic activity of the municipality. Considering Equation (2), the IGD can be presented in Figure 4.

Fonte: Department of the Environment of Itabirito e proprio investigador.

5 DISCUSSION

From the map of Figure 4 it can be observed that the head of the municipality has a predominantly low index of geodiversity, with some points of average index. This fact can be justified precisely by the anthropization of natural spaces, the theft of real estate expansion and population growth.

In general, the areas of high and very high geodiversity are located along some rocky uprisings, such as the Serra do Gandarela (component of the Serra do Espinhaço), the east side of the Serra da Moeda and the Serra da Serrinha, where the Morro do Cristo de Itabirito and old gold mines of the eighteenth and nineteenth centuries are included. Exactly in areas that showed high to very high IGD can be determined HOTSPOTS of geodiversity.

6 CONCLUSION

The maps and analyzes carried out confirm that the municipality of Itabirito has regions considered as Geodiversity Hotspots, located mainly near the border with Ouro Preto, in the district of São Gonçalo do Bação, and Rio Asima, in the district of Acuruí. In addition to these, areas of great relevance for geodiversity were defined as regions that today host mining projects in preliminary analysis or already in operation, in the headlands of Ribeirão Silva and Mata Porcos. These hotspots should be points of attention when granting environmental licenses for activities in this segment, and it is important to analyze mitigation and compensation measures related to geoconversation.

It is necessary to elaborate studies on geodiversity in these places, mainly in regions of mining exploration, so that environmental bodies can analyze measures to mitigate and compensate for impacts on the rich geodiverse heritage of Ibiza.
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