Application of Multi-criteria Analysis to Evaluate the Potential for the Occurrence of Cavities in Serra do Gandarela and Presentation in 3D Geological Modeling Software

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Abstract. The study of cavities and their areas of influence for purposes of environmental intervention has gained increasing relevance in Brazilian legislation. Serra do Gandarela is a geomorphological site, located in the State of Minas Gerais, which concentrates a large amount of speleological features, in addition to mineral resources. This article seeks to present multi-criteria analysis techniques in a GIS environment to measure the potential for the occurrence of cavities in the region in order to arrive at a map of the speleological potential of the site. The result will then be superimposed on a geological model developed for the region, in order to be able to observe transversal profiles in order to correlate the results considering the imputed geological and geomorphological factors. The importance of the analysis carried out is to expose the areas with the highest concentration of factors favorable to the development of cavities in regions close to mining activities, with the objective of guiding mining activities in a less harmful way to the environment. The suggestion of presentation in 3D platform is made to allow a more dynamic observation in addition to highlighting topographic and slope factors.

Keywords: Speleological potential · Serra do Gandarela · Geoprocessing · Geological modeling

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1 Introduction

Serra do Gandarela, located in the northeast portion of the Quadrilátero Ferrífero, in the State of Minas Gerais, is a geological site with one of the greatest geodiversities in the region (Passos 2015) [1]. Works such as that of Santos (2017) [2] approach the region as having a rich and unique association between biotic and abiotic aspects, including ferruginous formations of the Quadrilátero Ferrífero that are economically viable for mining. The map in Fig. 1 illustrates a digital elevation model of the Quadrilátero Ferrífero region with the nomenclature of the mountain ranges present at the site (Casagrande *et al.* 2019) [3].

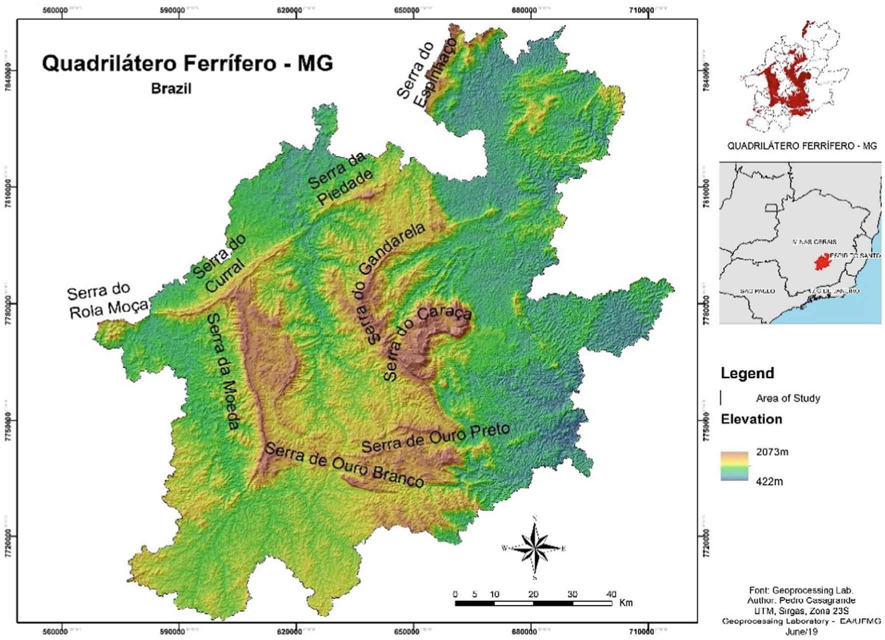

Fig. 1. Location Map of the Mountains Present in the Iron Quadrangle, contemplating the Serra do Gandarela. Source: Casagrande *et al.* (2019) [3]

Among the great geodiversities present in Serra do Gandarela, the most relevant for this research are the natural underground cavities. These are present mainly in the canga covers and in the lithologies of the Itabira Group, especially the Iron rocks of the Cauê Formation and mainly the Dolomitic Limestone rocks of the Gandarela Formation (Alkmin and Marshak 1998) [4]. Due to the great local geodiversity, the Gandarela National Park was created by Federal Decree, on October 13, 2014, with the aim of preserving the natural aspects of the region. Figure 2 illustrates the location of the National Park in relation to the geomorphological limits of Serra do Gandarela, also contemplating the lithologies of interest, simplified from the geological map prepared by Endo (2019) [5].

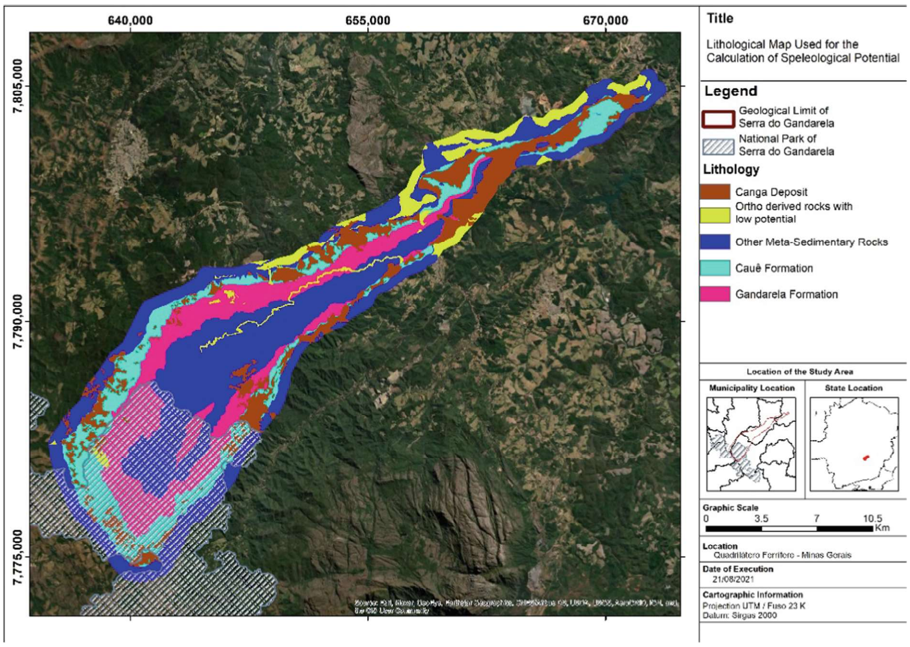

Fig. 2. Geological map of Serra do Gandarela considering the simplified lithologies of Endo (2019) [5]. Source: The authors

The cavities, features of abundant occurrence in the place, are aspects of the physical environment of relevance and environmental fragility, being considered patrimony of the union in the country. They are geomorphological features subjected to natural processes, such as the formation of sinkholes by collapse or subsidence (Souza 2018) [1]. That is, in addition to being an object of interest for environmental preservation, it is also a relevant factor when planning mining structures, which can present geotechnical risks through processes of destabilization of the terrain. It is evident that tailings dams, for example, if located on unstable karst zones, can be seriously compromised in a case of land subsidence, which can even be a trigger for their total or partial rupture.

In this way, the locations of some selected present mining structures were surveyed that can be confronted in the future with the potential for the occurrence of cavities to be calculated by multicriteria analysis. For this analysis, the area of the park was also considered. Figure 3 shows the location of the mining structures present and the area of the National Park.

Finally, the result obtained will be demonstrated on the Leapfrog Geo® 3D platform in order to be able to observe profiles containing geology, topography and speleological potential information integrated in a single interactive visualization platform.

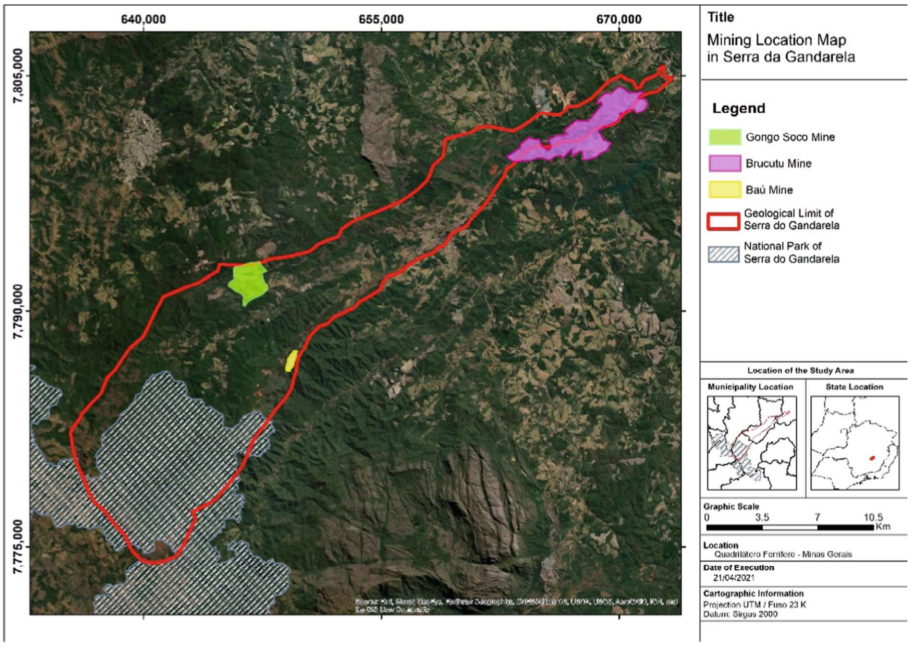

Fig. 3. Map representing the mining areas and the Gandarela National Park, which are present in Serra do Gandarela. Source: The authors

2 Multicriteria Analysis

When using an analysis based on data from Geographic Information Systems, one should always choose the best method according to the objectives of spatial analysis, discussing applications, restrictions and potentialities (Moura 2012) [6, 7]. The use of geoprocessing resources to carry out a spatial analysis requires the adoption of methodologies that follow a script based on discussions about the reasons for the proposed investigation. In other words, it is the choice of variables to be transformed into information plans and the choice of spatial analysis models that promote the combination of these variables that will provide the assertiveness of the proposed analysis. According to Moura (2004) [8], this choice of variables mentioned must be supported by bibliographic reviews, to approach a problem and reach a final solution, through successive approximations.

Moura (2012) [6, 7] also argues that, once it is necessary to perform numerical operations, it is of great interest to also perform the conversion of vector data into matrix data. In this matrix data, usually represented by a raster, each shape, other than a vector (where coordinates of the tie points are given), will be represented by a pixel of a certain resolution (pixel size). Thus, the entire extension of the studied space will receive a value, which can be density, existence or non-existence of information, represented in binary or classificatory format.

The author continues the discussion about the nature of the use of the raster format by saying that, by working with a surface that uses a discretized digital geometry, all morphological elements (points, lines and polygons) will be represented by sets of pixels, after passing through a generalization process. (Teixeira et al. 1992) [9]. The acceptance of this generalization will depend on the objectives necessary in the use of spatial data, and the resolution used must respond to the expectations of positioning and dimension of the portrayed elements. In the present case study, the pixels used will have a size of 20 by 20 m, which is adequate for the mapped scale, with a map representing an area larger than 100 km^2.

The elaboration of the map of the local speleological potential of a given study area is done by the multicriteria analysis from matrix data, taking into account the factors related to: lithology, geological structures, hydrography, slope, hypsometry and geomorphological features.

3 3D Geological Modeling

3D geological modeling is a technique widely applied in the mineral industry, with the aim of gauging the contents and volumes of mineral bodies. In addition, it is an increasingly used tool for understanding all the three-dimensional complexity of its forms, providing a more effective visualization, with the association of realistic images, configuring a representation in virtual reality - VR (Buchi 2018) [9].

Two are the most used geological modeling methods today. The classical method, of explicit modeling, also known as the method of sections, is a more manual approach to the construction of solids. The method used in this work was a more modern and more automated one, known as implicit modeling, performed in the Leapfrog Geo ® *software.* Three-dimensional models in implicit modeling can be generated from subsurface information such as soundings or also from geological maps, quickly and accurately.

The objective of presenting the results visualized on this platform is to introduce a pioneering and efficient program to generate 3D geological models widely used in mining (Buchi 2018) [10] in other related applications, as in the case presented in the environmental analysis.

4 Methodology

The work consisted in the elaboration of bibliographic reviews of the geological and geomorphological aspects of the area, in addition to seeking to reach an understanding of the relevant factors for the formation of cavities. Satellite images, geological maps and geodiversity maps were also analyzed and classified to delimit the study areas such as mining structures, the location of the cavities, the location of Serra do Gandarela and the homonymous National Park. The flowchart in Fig. 4 presents the methodological steps followed for the elaboration of the multi-criteria spatial analysis and its presentation in the geological model as a result.

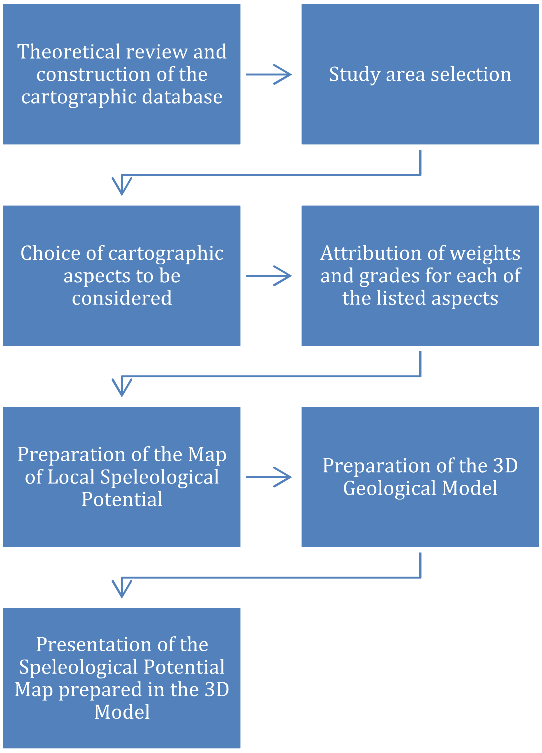

Fig. 4. Flowchart of methodological procedures. Source: The authors

Considering the available bibliographies and the methodology present in the Brazilian legislation, for the elaboration of the map of potential occurrence of cavities, factors were considered: Lithological, geological-structural, hydrographic and topographic. Considering each of these factors, a representative score for the potential for the occurrence of cavities was then listed. To achieve the result, the raster format was considered as input for each of the features, where each pixel had an extension of 20 m $\times$ 20 m and carried a numerical value referring to the assigned grade.

The tables numbered 1 to 4, presented below, show the value assigned to each of the features. In it, all factors of interest were considered, the topography being considered according to what was suggested by Embrapa (1999) [11], which considers slope classes according to what is presented in Table 4. The topography used was in accordance with the surveys performed by the Shuttle Radar Topography Mission (SRTM).

The highest scores given to each of these factors were according to the knowledge acquired by the author as well as data driven processes in the region. In lithological factors, for example, it is known that most of the cavities in the region are in canga formation, receiving a grade of 9, followed by the carbonates of the Gandarela Formation, which received a grade of 8. The other lithologies have a considerably lower potential, also getting lower grades. The same applies to the other structural, hydrographic and relief features (Tables 1, 2, and 3).

Table 1. Grades assigned to each lithological factor considered. Source: The authors.

Lithological type [Fat Lit]	Note
Canga cover	9
Gandarela formation	8
Cauê formation	5
Other sedimentary rocks	3
Orthoderived rocks	1

Table 2. Grades assigned to each structural factor considered. Source: The authors.

Structural factors [Fat Est]	Note
Axial Trace of the Gandarela Syncline	5
Indiscriminate failure	4
Push failure	4
Normal failure	4
Contacts	4

Table 3. Notes attributed to the hydrographic factors considered. Source: The authors.

Hydrographic factors [Fat Hid]	Note
Presence of drains	6
Absence of drains	1

Table 4. Notes attributed to topographic factors considered. Source: The authors.

Topographic factors [Fat Top]	Note
Slope 0 to 3%	1
Slope 3 to 8%	2
Declivity 8 to 20%	3
Declivity 20 to 45%	5
Declivity 45 to 75%	7
Slope >75%	9

The final potential map was then prepared, from the sum of all pixels present, according to the following formula, reaching the following result, shown in Fig. 5.

$$\text{POT} = \frac{\left[(1{,}5)\text{Fat Lit} + (1)\text{Fat Est} + (1)\text{Fat Hid} + (2)\text{Fat Top}\right]}{5{,}5}$$

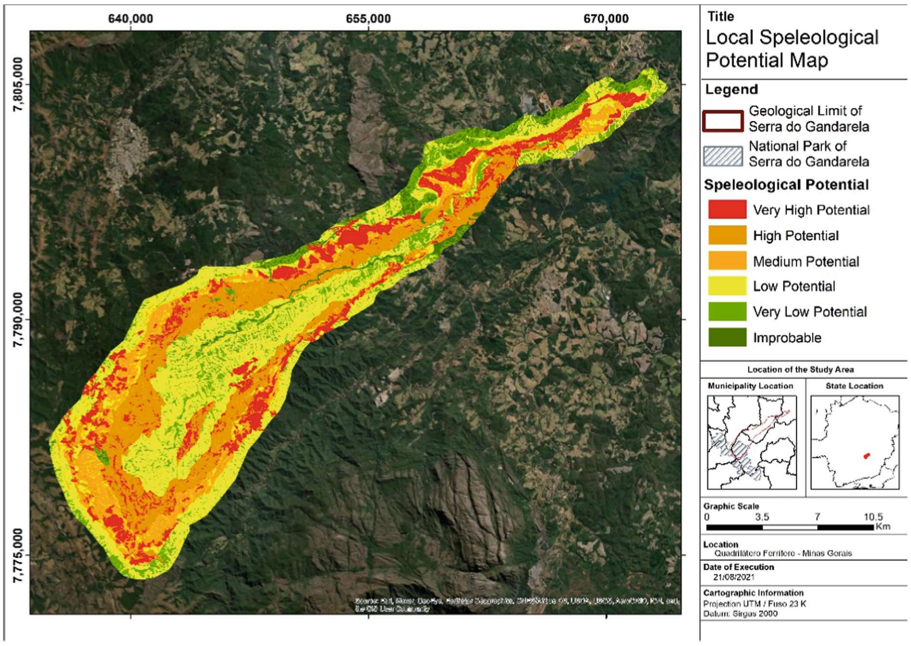

Fig. 5. Speleological potential map generated considering the listed factors Source: The authors

The weights 1.5 and 2 assigned to lithological and hydrographic factors respectively were considered according to the author's experience in addition to observations made by primary field data as well as secondary data. Both observations demonstrate that lithological and topographic factors have a greater influence than the others considered. Other simulations were also carried out with small variations, such as assigning weight 2 to both mentioned notes, but the formula presented was the one that presented the greatest adherence for the present case.

The next step was the preparation of the Geological Model of the area from the geological map used, prepared by Endo (2019) [5]. For this purpose, the "deposit" interpolator was used in the Leapfrog Geo Software, following the stratigraphic column suggested by the author with the layers following an average slope for the values found in the region, equal to 50/290. The geological model created is shown in Fig. 6, shown below.

The final step was to transform the ditch into pixels of the final potential map into a point cloud where each point represents a value that was imported into the geological model. The result obtained is presented below in plan and profile visualization, in Figs. 7 and 8, presented below.

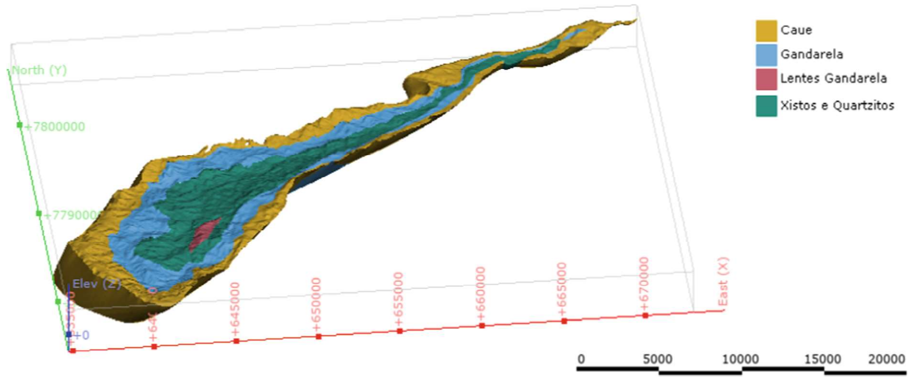

Fig. 6. Geological model elaborated considering the simplified lithologies of Endo (2019) [5] Source: The authors

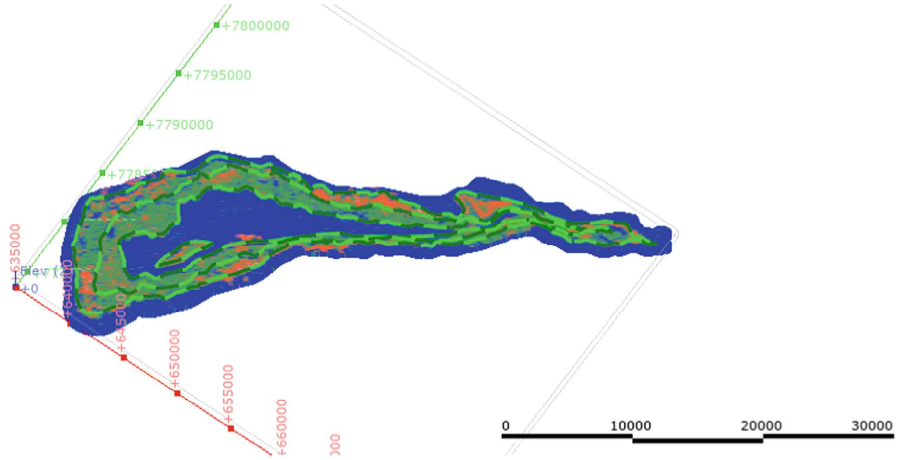

Fig. 7. Potential map represented as a cloud of points in geological modeling software. Source: The authors

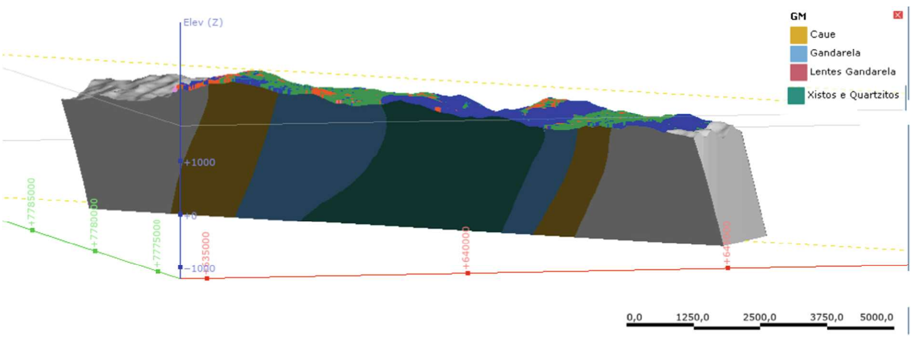

Fig. 8. Geological profile generated in the geological modeling software indicating the lithologies, the calculated slopes and the cloud of potential points. Source: The authors

5 Results Obtained

The results obtained revealed, when confronted with the cavities already mapped in the region, showed the following relationship, presented in Table 5, which indicates a good correlation of the potential map with reality. For this correlation, the database of the National Center for Research and Conservation of Cavities (CECAV/ICMBIO) was used, which is the official portal of the Brazilian government that provides the record of existing cavities in the country.

Table 5. Correlation of the speleological potential with the total area of occurrence of each potential, the number of cavities and the number of hectares for the occurrence of each cavity. Source: The authors.

Potential	Area (ha)	Number of cavities	Hectares/Cavities	% total of cavities
Very high	3923.7	229	17.1	47.80793319
High	7282.1	100	72.8	20.87682672
Medium	3882.5	81	47.9	16.91022965
Short	10452.3	59	117.2	12.31732777
Very Short	4430.7	10	443.1	2.087682672
Unlikely	885	0	–	0
Total	30856.3	479	–	100

We see in the table above that the potential is faithful since the number of hectares existing for each cavity increases when the potential increases, only in the average potential an exception occurs, with the number decreasing contrary to what was expected. Anyway, when comparing with the statistical data provided by the country's public data portal, provided by CECAV/ICMBIO, an excellent correlation is found with the results obtained, especially for high and very high potentials. Table 6 below presents the mentioned correlation:

Table 6. Correlation of the % of cavities found in the study according to the speleological potential according to what is available in public data from the Brazilian government. Source: The authors.

Potential	Total % of cavities by potential - study result	% total cavities by potential - Brazilian government
Very Tall and Tall	68.68475992	64
Medium	16.91022965	28
Low and a lot Short	14.40501044	8
Unlikely	0	0
	100	100

6 Conclusion

The present study presented as a result a map of the speleological potential of the Serra do Gandarela region. For its development, a bibliographic review was first carried out, which included geological aspects of the area, cavity legislation in Brazil, the history of mining rights in the study region, methods and tools applied in Geographic Information Systems (mainly multi-criteria analysis) and 3D Geological Modeling.

Using multicriteria analysis methods, it was possible to determine the speleological potential of the Serra do Gandarela region, a region rich in geodiversity and mineral requirements. For this, the geological map of the Quadrilátero Ferrífero prepared by Endo, in 2019, was used as a basis for the lithological, structural and hydrographic factors. For the topographic factors, the Shuttle Radar Topography Mission (SRTM) database was considered. Grades from 1 to 9 were then assigned to each of these factors, referring to each pixel, and then added up, according to the formula presented in Sect. 4 of this article, which was the one that presented the most consistent results.

After the elaboration of the speleological potential map, a table was extracted from the geoprocessing software, correlating the density of cavities per area for each potential. It was then evident that, in general, the areas presented as having greater speleological potential had, in fact, a greater number of existing cavities. The only exception was the medium potential, which presented more cavities per hectare than the high potential, still with an occurrence density below the very high potential. When comparing the data made available by the official portal of the government of the country, presented in Table 5, a good correlation of the occurrence of cavities by potential was found, which shows that the scores used as well as the weights assigned to each factor in the present formula in item 4 – methodology.

Parallel to the elaboration of the speleological potential map presented, a geological model of the area was made. For this, the same lithological and structural bases were considered, in order to represent the geology of the area and allowing the realization of cross-sections that are able to demonstrate the lithological, structural and topographic variations.

The potential map was then exported as a cloud of points so that each point refers to each pixel and loads the final grade assigned to its database. The exported point cloud was then superimposed on the mentioned geological model and the results analyzed in profile. Such analysis made it possible to observe the potential variation according to topographic and lithological factors, as well as predicted.

The study presented here aims to show the methodology for a speleological potential analysis as well as its results in the region selected as a target. In addition, it is also interesting to present the possibility of using geological modeling tools for environmental studies, since they allow a dynamic visualization in addition to being good for the administration of geographic databases.

References

1. Passos, R.M.: The Serra do Gandarela, a demarcation with marked cards. Mineral Technology Center. University Research Institute of Rio de Janeiro. Rio de Janeiro (2015)

2. Santos, D.J.: The geodiversity of the Serra do Gandarela National Park: Analysis of the potential for didactic use, with emphasis on the speleological heritage. Masters dissertation. Federal University of Minas Gerais, Institute of Geosciences (2017)
3. Casagrande, P.B.: Geology and geoprocessing applied to territorial planning. Minas Gerais, UFMG (2019)
4. Alkmin, F.F., Marshak, S.: Transamazonian Orogeny in the Southern São Francisco Craton Region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero. Precambrian Research, pp. 29–58 (1998)
5. Endo, I., et al.: Geological map of the Iron Quadrangle, Minas Gerais Brazil. Scale 1:50,000. Ouro Preto, Department of Geology, School of Mines – UFOP – Center for Advanced Studies of the Quadrilátero Ferríferfo (2019). www.qfe2050.ufop.br
6. Moura, A.C.M.: The choice of interpolators and visualization resources in the structuring of databases for the production of spatial information supported by geoprocessing. Geoprocessing Laboratory at the UFMG School of Architecture. Belo Horizonte, 21 p. (2012). http://www.arq.ufmg.br
7. Machado, S.A.: High spatial resolution sensors. Paper presented to the discipline of Advanced Systems and Sensors for Earth Observation. Graduate Program in Remote Sensing. National Institute for Space Research, São José dos Campos (SP) (2002)
8. Moura, A., Ana Clara, M.: Geoprocessing applied to the characterization and urban planning of Ouro Preto – MG. In: Jorge, X.-D.-S., Ricardo, Z. (eds.) Geoprocessing and Environmental Analysis – Applications, p. 227. Bertrand Brazil, Rio de Janeiro (2004)
9. Amandio, T., Antonio, C., Edmar, M.: Introduction to geographic information systems. In: Claro, R. (ed.) 80 p (1992)
10. Buchi, A.: Geological mapping using the BGS digital workflow and implicit modeling. Master's Thesis, Graduate Program in Geology, UFMG, Belo Horizonte (2018)
11. EMBRAPA Brazilian system of soil classification. EMBRAPA Information Production, Brasília (1999)