SPELEOLOGICAL POTENTIAL OF THE SUMIDOURO STATE PARK / MG

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Abstract: Thematic mapping for the speleological potential of the Sumidouro State Park / mg. The Sumidouro State Park (PESU) constitutes a Conservation Unit located in the Environmental Protection Area (APA) Karst Lagoa Santa, between the municipalities of Lagoa Santa and Pedro Leopoldo, northern portion of the Metropolitan Region of Belo Horizonte, housing a rich speleological heritage. Currently, there are 49 known cavities registered in the database of the National Center for Research and Conservation of Caves (CECAV). It is estimated that there are more caves inserted in the park not yet registered by the agency. Thus, this work aimed to develop a predictive model in order to indicate areas with a higher potential for the occurrence of caves, in the light of geotechnologies. In order to perform the speleological potential calculation, data were collected on the existing features that are intrinsically linked to the formation of caves: geology, hydrography, exokarstic features present in the study area, hypsometry and slope. After data acquisition, values were assigned to them and, through map algebra, it was possible to identify areas with a higher and very higher degree of potential for the occurrence of caves. Because of the development of this model, it is expected that it will have application in other areas of study. Future fieldwork should be carried out to confirm and register new cavities pointed out in the mapped areas, especially those registered as having high potential.

Keywords: *karst; Apa; Lagoa Santa; speleological potential; multicriteria analysis.*

INTRODUCTION

The Sumidouro State Park (PESU) constitutes a Conservation Unit created on January 3, 1980, through State Decree No. 20,375 (Minas Gerais, 1980a), as amended by Decrees No. 20,598, of June 4, 1980 (Minas Gerais, 1980b), nº 44,935 of November 3, 2008 (Minas Gerais, 2008) and defined by Law 19,998, of December 29, 2011 (Minas Gerais, 2011), being coordinated by the Instituto Estadual de Florestas de Minas Gerais (IEF-MG). Located between the municipalities of Lagoa Santa and Pedro Leopoldo, northern portion of the Metropolitan Region of Belo Horizonte, the 2,004 ha park comprises the total of the Environmental Preservation Area (APA) Karst of Lagoa Santa and presents a rich speleological heritage (Figure 1) in UTM 23 South Hemisphere Zone.

The karst environment develops on soluble rocks and its relief presents landscapes of unquestionable scenic beauty. The dissolution process of the rocks due to acid pH water, characteristic of carbonate rocks, makes it possible to cut these rocks differently. Research about this thematic can be observed in Fabri et al. (2013), Cristo et al. (2013), Braga et al. (2017), Munhoz and Lobo (2018), Santos et al. (2018) (this last tree articles about protection caverns lows), Andrade et al. (2019), Gomes et al. (2019), Şener et al. (2020).

Currently, the Sumidouro State Park houses 49 cavities registered in the database of the National Center for Research and Conservation of Caves (CECAV), developed in carbonate rocks constituted by calcisiltites, calcarenites and marl, in addition to a metapelitic sequence constituted of metassiltites and metargilites belonging to the Bambuí Group (CPRM, 1998). Some PESU caves are of great historical and cultural importance and have beautiful speleothems, as is the case of Gruta da Lapinha located in the municipality of Lagoa Santa - MG, the only cave open to the public for visitation within the limits of the Park.

According to Piló and Auler (2011) less than 5% of the natural underground cavities outcropped in carbonate rocks are known in Brazil. Considering the relevance of the speleological heritage, especially concerning scientific and landscape issues, the recognition of these sites in protected areas fuels their environmental, historical, cultural and economic interest. If we consider the speleology, we can fix the job developed by Braga et al. (2017).

An ample description made by Berbert - Born (2002) about the Lagoa Santa region highlighted that the area has typical and well-diversified geomorphological characteristics with the presence of features that deserve to be highlighted: a) a large number of dolines in a variety of sizes, shapes, and genetic patterns; b) large rocky outcrops or partially covered; c) lakes with different water behaviors, associated with dolines or on broad low plains, and d) a complex network of underground ducts, commonly connected with the superficial relief defining a landscape of great scenic and tourist merit. Besides, the karst of Lagoa Santa has a special significance for the history of Brazilian science and culture, being considered the cradle of paleontology, archeology, and caving. The author also points out that the region has the largest number of caves per area; this huge number of caves and shelters holds a large number of pleistocene fossils in addition to important traces of prehistoric human

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occupation, including rock panels, utensils, and bones. Dates indicated that the oldest records refer to approximately 12,000 B.P. (Prous et al., 1998). However, the expressive anthropic occupation in its surroundings imposes risks to its integrity. Berbert-Born (2002) highlights that the region undergoes demographic expansion and represents an industrial and mining pole of extreme economic importance, which mainly compromises water resources and vegetation.

This research aims to predict the existence of caves with the use of geoprocessing techniques. Thus, it is worth highlighting works that assess the potential for geomorphological transformation (presented in Capoane et al., 2015), as Pereira and Bonetti (2018) used spatial techniques to perform a multicriteria analysis to predict areas subject to landslides (Brito and Weber, 2017) and also works such as the automation of the definition of the dissection index (Guimarães et al., 2017), the planning of areas for urbanization (Souza and Sobreira, 2017) to propose a methodology for geomorphological cartographic representation (Marques Neto and Ferraro, 2018).

Some authors have worked on elucidating the speleological potential of the respective study areas through prospecting and topographic surveys, among other techniques, to register the cavities (Pereira et al., 2012; Vieira et al., 2013; Batisteli et al., 2015; Oliveira et al., 2015; Rocha et al., 2018; Oliveira et al., 2019).

The Service Instruction of the Minas Gerais State Secretariat for the Environment and Sustainable Development number 08 of the year 2017, called IS 08/2017 (Minas Gerais, 2018), has the procedures for analyzing the environmental licensing processes of enterprises and effective or potential impacting activities on natural underground cavities. Six main parameters are required by IS to represent the speleological potential of the area in a map to be licensed: lithology, geological structures, hydrography, slope, hypsometry and geomorphological features. One of the ways to represent these multicriteria is through maps and the geotechnologies can help effectively in this context.

It is possible that in PESU there are more cavities than those registered by the environmental agency since there was no systematic survey in the entire area of the park.

At this point, multicriteria analysis emerges as an important method for predicting areas where the occurrence of caves is possible, based on the definition of values and weights for each variable that influences speleological formation. An example, but in seismic occurrence prediction, has presented in Kremer et al. (2020), where the authors use the caves' occurrence data.

In studies of vulnerability mapping, Crepani (2001) stresses the importance of considering thematic data on the physical environment to determine each unit's vulnerability indexes according to the purpose of the project.

From this perspective, the research aims to develop a predictive model to indicate areas with higher and very higher potential for caves' occurrence, using map algebra, based on the methodological proposal of value hierarchy (Crepani, 2001).

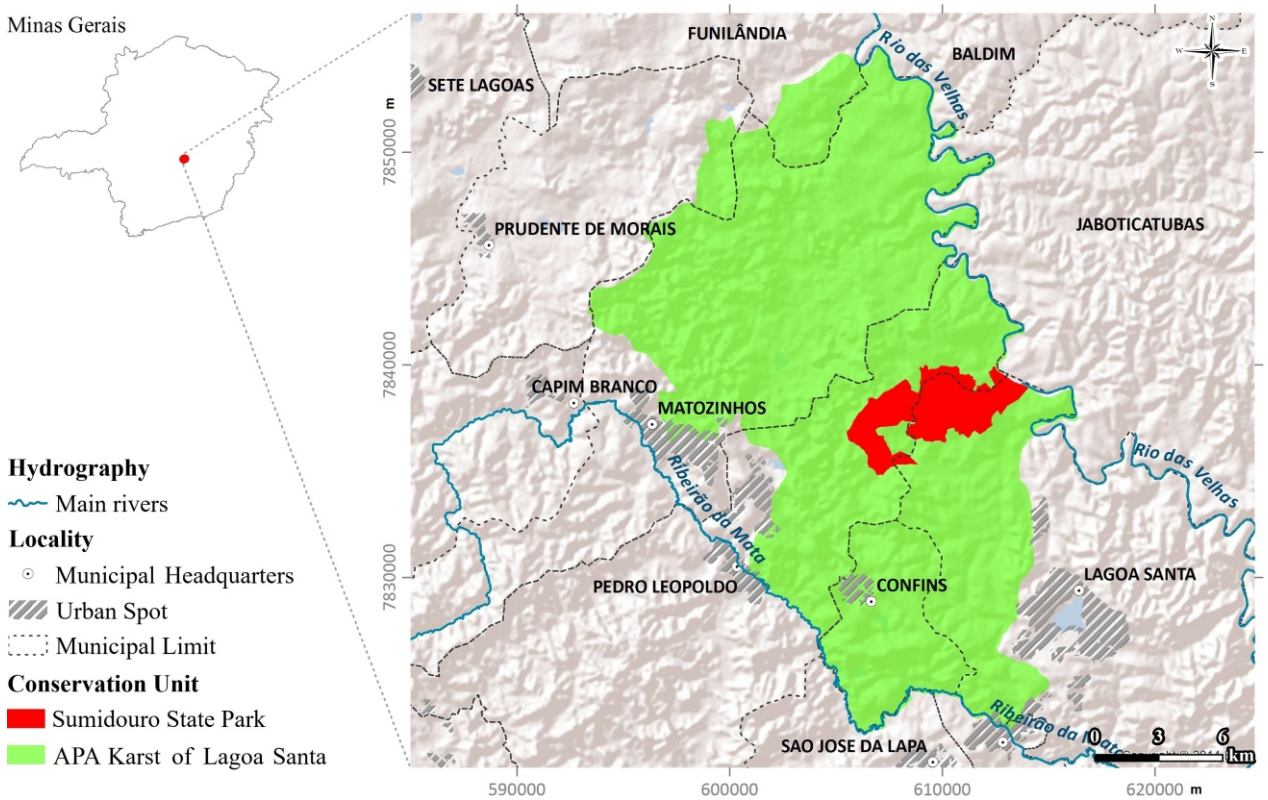

Figure 1. Location of the study area. Source: Elaborated by the authors (2018)

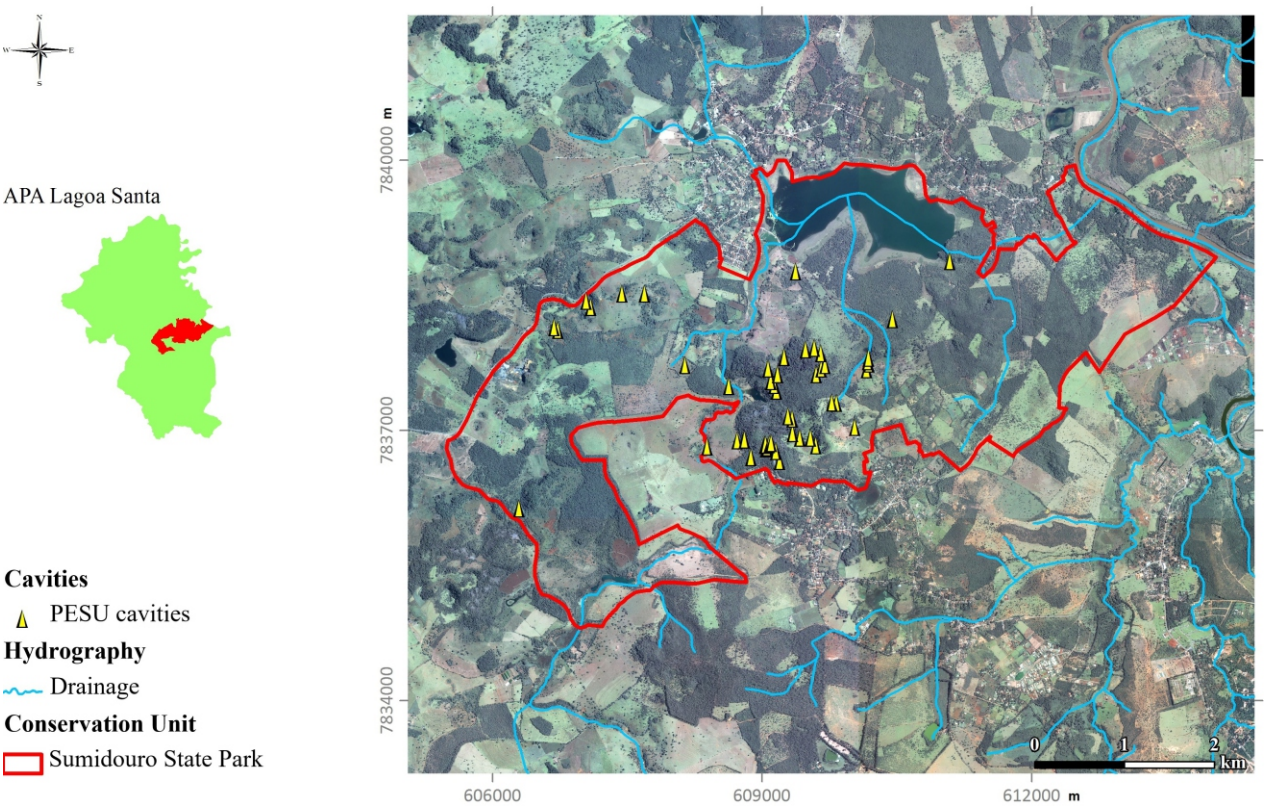

Figure 2. Location of cavities present in the study area. Source: Elaborated by the authors (2018)

MATERIALS AND METHODS

In the view of IS 08/2017 (Minas Gerais, 2018), one of the processes required for the environmental licensing of enterprises and activities effective or potential causing impacts on natural underground cavities is the prior representation of the speleological potential of the area to be licensed. This Service Instruction (IS) classifies at least six factors considered in this representation: lithology, geological structures, hydrography, slope, hypsometry, and geomorphological features.

Brazil suffers an expressive lack of detailed mapping (geographic and geological) and even with the unavailability of some cartographic bases, a fact that can limit or even make the result infeasible by map algebra. For this definition, this study had the support of specialists in caving, karst environments, capable of assisting in applying weights and notes, essential for cartographic algebra. This is not an entirely empirical work, and the relationship between the presence of cave x proposed factors were taken into consideration. In this way, it becomes possible to guarantee a more refined and more coherent result.

For the delimitation of the study area, cartographic bases provided by IEF-MG were used. The Institute was also responsible for providing RapidEye satellite images of the park area with a spatial resolution of 5 m, dated from 2010.

The database referring to the cavity location points (Figure 2) was obtained directly from the CECAV website (CECAV, 2019), using the data available from December 2018.

To be able to work on map algebra in a geographic information system (GIS) environment, it was necessary to determine which aspects influence this study and the values for multicriteria analysis. For this definition, this study had the guidance of specialists who work in the specific field of caving and karst environments and with the necessary knowledge to assist in applying weights and notes, essential for map algebra.

In this way, the evidenced attributes were defined to determine the speleological potential. The selection of the applied attributes considered its relationships with the cave's development process, resulting in the following: hydrography, exokarstic features, geology, hypsometry, and slope, which are described below:

- drainage for being an important attribute, if they originate in another type of lithology (for example siliciclastic) considering its action on soluble rocks, due to the acidity of the water, promoting on the surface exocarp features and in depth the formation of caves;
- geology being a condition in the formation of the relief and in the degree of solubility of the rock is a fundamental attribute in the formation of caves;
- hypsometry and slope due to the type of relief and the evolutionary processes that occurred in the area.

The digital data of hydrography, exokarstic features and geology used in this work were extracted from Sampaio (2010, 2014) who prepared a digital inventory consisting of rich georeferenced data from the physical environment referring to the APA Carste Lagoa Santa, MG. All data used are in the scale 1: 50.000, datum

Sirgas 2000, Universal Transverse Mercator projection - UTM, spindle 23 South.

For the construction of hypsometry and slope maps, the synthetic aperture radar image (Synthetic Aperture Radar - SAR) operating in the microwave region, ALOS PALSAR, made available by ASF - Alaska Satellite Facility, responsible for processing, archiving and distributing, was used specific remote sensing data (NASA - EARTHDATA - ASF, 2020).

The ALOS PALSAR images are obtained using the three instruments of the ALOS satellite (Advanced Land Observing Satellite-1 ALOS), developed to contribute in the fields of mapping, disaster monitoring, accurate observation of regional land coverage and survey of resources, being a product of Japanese aerospace exploration agency - Japan Aerospace Exploration Agency (JAXA). It has three observation sensors: the high-resolution stereo mapping sensor (PRISM), a radiometer operating in the visible and near infrared (AVNIR-2) and a synthetic aperture radar operating in the L band, being high-performance systems.

The L-band synthetic aperture radar (PALSAR; 1,270 MHz / 23.5 cm) onboard ALOS can observe a large number of combinations of polarization, off-nadir angles, and resolution.

ASF offers RTC - Radiometrically Terrain Corrected products in which it performed the geometric and radiometric correction on the radar images, presenting the data in geoTIFF format in high and low resolution (respectively 12.5 m and 30.0 m) in the UTM coordinate system. The product used in this work was a Digital Elevation Model (MDE) with high resolution, a band, TIFF format, 16 bit, double polarization (FBD), off-nadir angle: 34.3°.

However, this elevation model can contain anomalies on the surface that can lead to errors and it is then necessary to identify and correct these anomalies. These errors are often in the form of sinks that are represented by a cell or group of cells surrounded by cells of higher elevation (Mitchell, 2005). The ArcGIS Geoprocessing area's computer program has specific resources for further processing of these models, the most used being the Sink and Fill tools. The Sink feature generates a raster surface identifying all the pits (Figure 3). The Fill feature fills the pits by creating a second raster in which all these small imperfections have been removed by changing the cell value to be equal to the value of the surrounding cell with the lowest elevation value, which is also reported in Mitchell (2005). This representation is shown in Figure 4.

From the corrected images, 10m level curves were generated using the tools available in the ArcGIS software, version 10.1. In Figure 5, it is possible to observe all the data mentioned above to perform the multicriteria analysis.

After consolidating the cartographic base, the hydrography and exokarstic features data were processed to obtain Euclidean distances or metric distances. From these, raster data was generated to perform algebraic calculations.

For the determination of the speleological potentiality indexes, the information of the indicators capable of influencing the development of cavity formation processes were considered. For the index's definition, the criteria for the attribution of the weights were established, using an adequacy of the methodology developed by Crepani et al. (2001) from the concepts of Ecodynamics idealized by Tricart (1977) that allows the generation of charts of natural vulnerability to soil loss. This methodology adopts different information plans (such as geology, geomorphology, pedology, vegetation and rainfall) to estimate this vulnerability. In this case of study, the criteria determined by IS08 / 2017 (Minas Gerais, 2018) will be used. The qualitative criteria adopted for this study are shown in Table 1, according to their variables.

In this study, values were adopted according to the degree of potential existence of caves. These values are between 1 and 5 and were defined according to the CECAV classification:

1. Unlikely occurrence of cavities
2. Low degree of potential
3. Medium degree of potential
4. High degree of potential
5. Very high degree of potential

In order to carry out the multicriteria analysis, feature classes and weighting for each defined variable were established considering their importance for the study and regional context. Table 2 presents the notes, defined by the potential value, and weights assigned to the variables and their elements.

For hydrography and exokarstic features, considering that they deal with linear features, the values established for these criteria obeyed a linear relationship with the distance (the closer, the greater the possibility of occurrence), using the kernel density (which indicates the concentration of cavities' occurrences). The empirical knowledge of the study area allowed the verification of the hydrography and the local exokarst to establish the adopted metrics since the karst environment, and the formation of caves are intrinsically linked to the presence of geomorphological features.

The assignment of slope values was based on the classification of the National Institute of Colonization and Agrarian Reform (INCRA, 2006) which determines seven relief classes (flat, smooth wavy, wavy, moderately wavy, strongly wavy, mountainous and steep). This classification has been adapted for five classes according to the local relief.

As for the elevation level, Crepani et al. (2001) relate this attribute to the deepening of dissection, since the higher the point on the ground that is reached by precipitation, the greater the kinetic energy of the water and the greater the capacity for soil erosion or morphogenesis. Thus, the values attributed to hypsometry (as well as the others, classified from 1 to 5) were made at equal intervals according to the local terrain.

With the values determined, the maps were reclassified according to the feature classes. Figure 6 illustrates the distribution of the defined potential values.

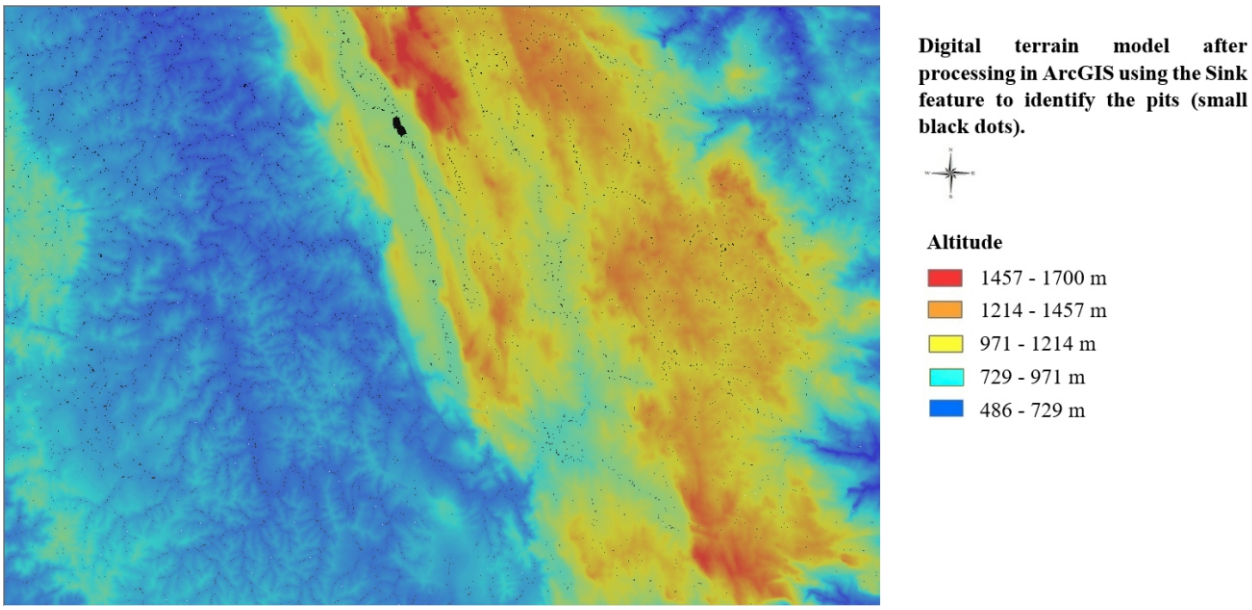

Figure 3. Digital terrain model after processing in ArcGIS using the Sink feature to identify the pits (small black dots). Source: Elaborated by the authors (2018)

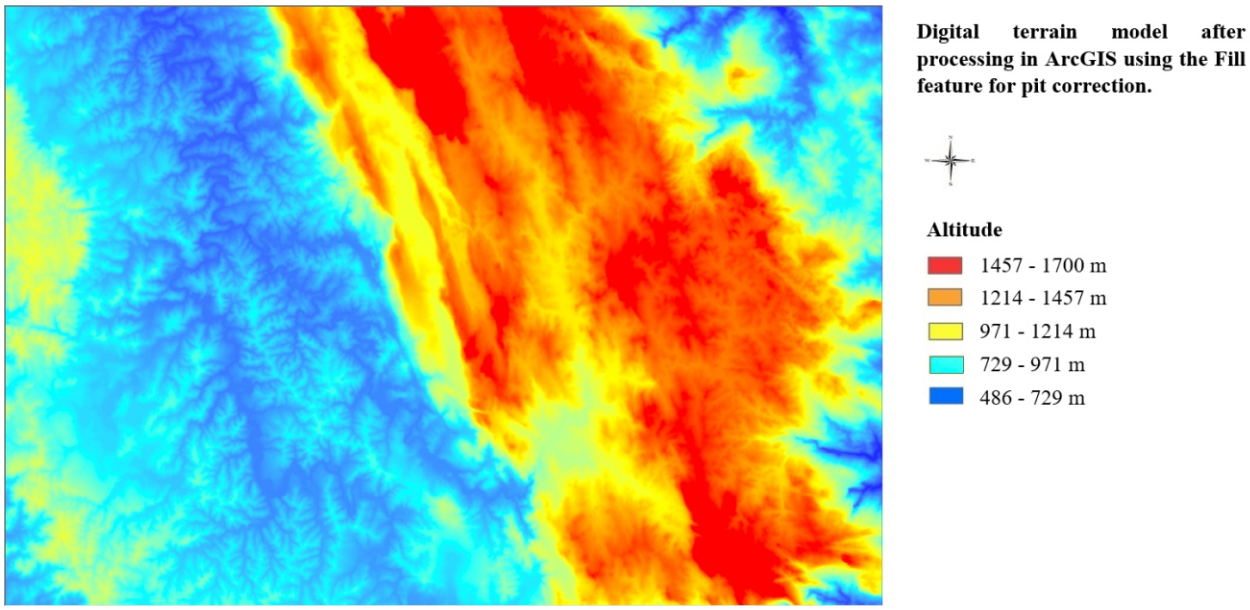

Figure 4. Digital terrain model after processing in ArcGIS using the Fill feature for pit correction. Source: Elaborated by the authors (2018)

Having the variables, criteria and weights defined, it was possible to generate the map indicating the areas with the degrees of potentiality established. Thus, an equation was applied in a GIS environment, where each feature class was multiplied by their respective weights and finally added to each other. The equation used was elaborated as follows to generate the potentiality map (P):

P = (G x 0.40) + (H x 0.20) + (F x 0.20) + (D x 0.10) + (Hip x 0.10) Equation 1

Where:

P = Potentiality; G = Geology; H = Hydrography; F = Exokarstic Features;
D = Slope; Hip = Hypsometry

RESULTS AND DISCUSSION

The use of multicriteria analysis showed results that allowed identifying areas where natural cavities are less or more likely to occur. Supported by the use of map algebra, it was possible to indicate areas with the most diverse degrees of potentiality for the occurrence of caves in Sumidouro State Park, varying between areas of unlikely occurrence of caves to areas with very high potential, represented by Figure 7 and Figure 8. The percentual distribution of natural cavities is presented by a graph in Figure 9.

CONCLUSION

The results indicate that 86.80% of the area of the conservation unit has potential for the occurrence of caves.

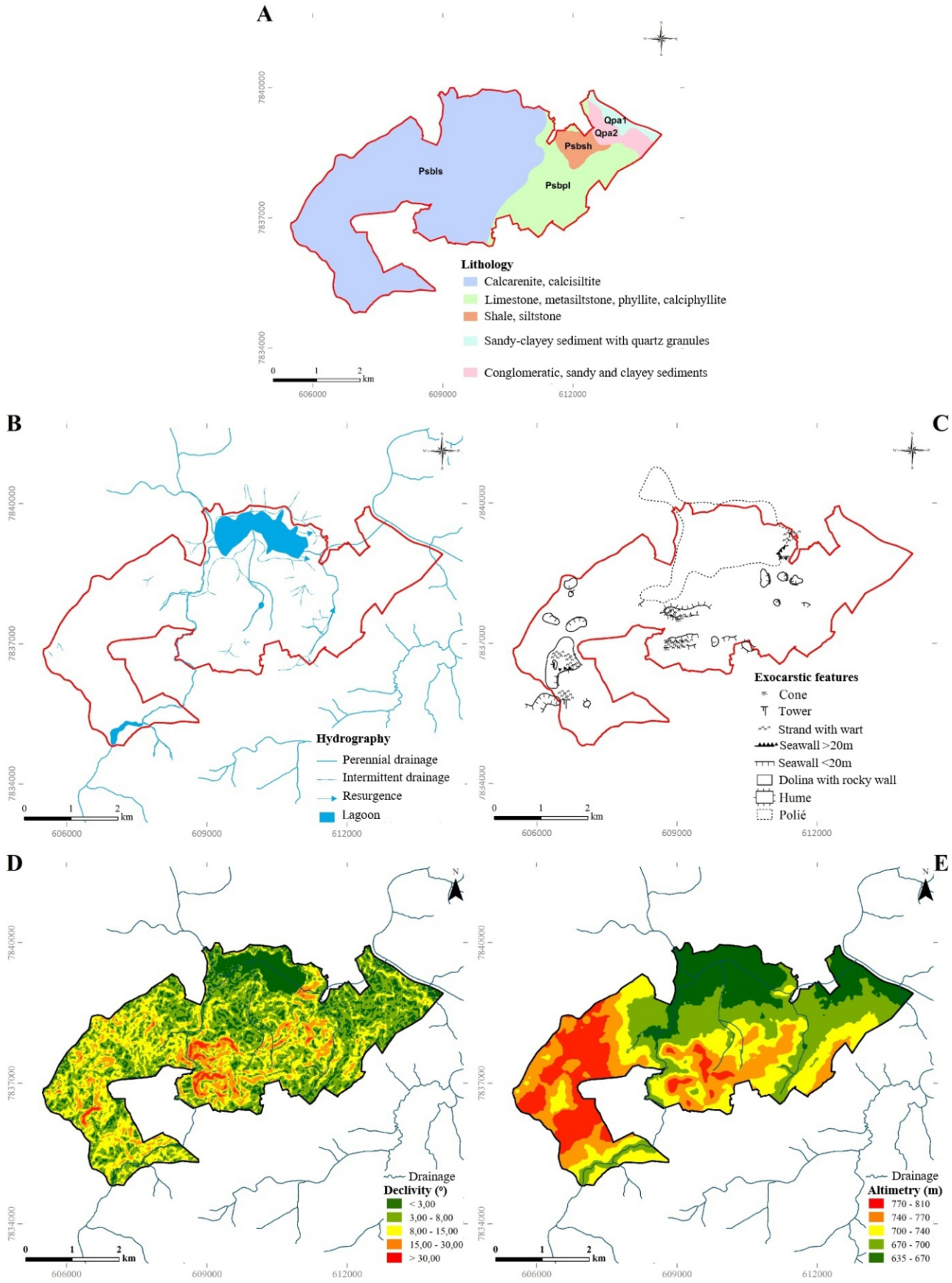

Figure 5. Maps of the selected attributes for multicriteria analysis. (A) geology; (B) hydrography; (C) exokarstic features; (D) slope; (E) hypsometry. Source: Elaborated by the authors (2018)

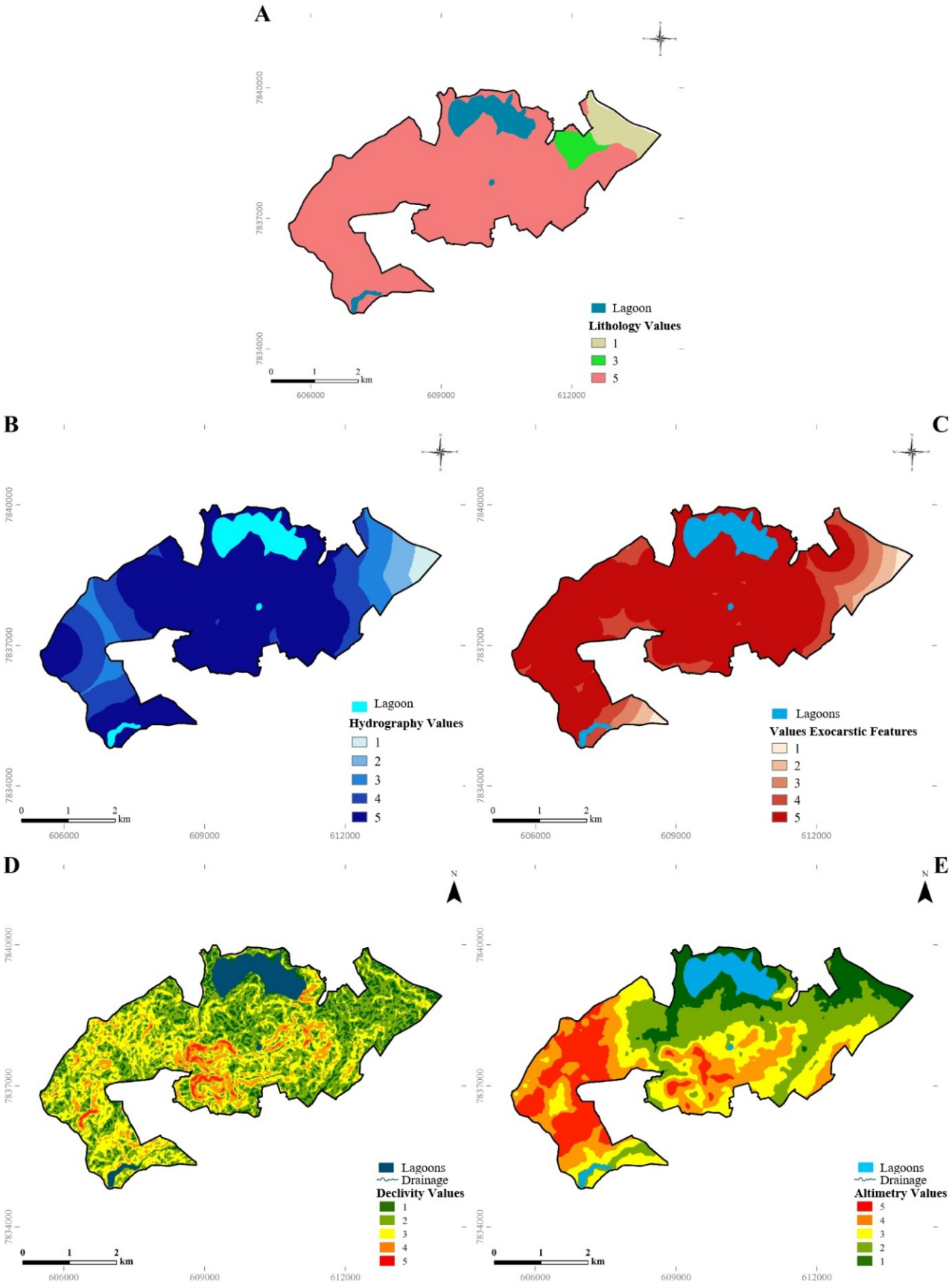

Figure 6. Maps of the selected attributes with notes and weights applied to the variables and their elements. Values referring to: (A) geology; (B) hydrography; (C) exokarstic features; (D) slope; (E) hypsometry. Source: Elaborated by the authors (2018)

Table 1. Qualitative criteria adopted. Source: Elaborated by the authors (2018)

Geology	Type of lithology
Hydrography	Drainage distance
Exocarstic features	Proximity of features
Declivity	Slope variation
Hypsometry	Altimetry variation

Table 2. Potentiality value and weights assigned to the variables and their classes for establishing geology values, the classification adopted by Jansen et al. (2012), who determined the degree of potential for the occurrence of caves considering only the lithology in which they are inserted. The authors present, for each lithology, the same classification values as the CECAV, which vary from 1 to 5. Source: Elaborated by the authors (2018)

VARIABLE	FEATURE CLASSES	POTENTIAL VALUE	WEIGHTS
Geology	Calcarenite, calcisiltite	5	40%
	Limestone, metasiltstone, phyllite and calciphyllite	5	
	Shale, siltstone	3	
	Sandy-clayey sediment with quartz granules	1	
	Conglomeratic, sandy and clayey sediments	1	
Hydrography	< 500 m	5	20%
	500 -1000 m	4	
	1001-1500 m	3	
	1501-2000 m	2	
	> 2000 m	1	
Exocarstic Features	< 300 m	5	20%
	300-600 m	4	
	600-900 m	3	
	900-1200 m	2	
	> 1200 m	1	
Declivity	> 30 degrees	5	10%
	15 – 30 degrees	4	
	7 – 15 degrees	3	
	3 – 7 degrees	2	
	< 3 degrees	1	
Hypsometry	770 – 810 m	5	10%
	740 – 770 m	4	
	700 – 740 m	3	
	670 – 700 m	2	
	640 – 670 m	1	

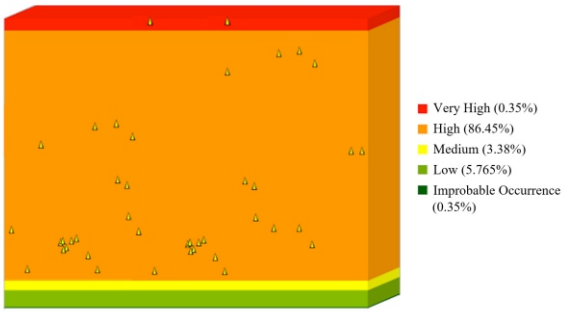

Figure 9. Distribution of cavities by potential class with percentual distribution. Source: Elaborated by the authors (2018)

The result obtained through the map of potential occurrences of caves contributes to a more precise direction in the study of the areas.

As most of the karst caves in Lagoa Santa have been undergoing direct or indirect anthropic interference, the most common is those of an aesthetic nature: the breaking of speleothems, graffiti, and accumulation of garbage. However, other injuries considered serious to the cave environment exist, although less evident to the unsuspecting observer. These are the ones that cause transformations that affect less noticeable but no less important components, such as fauna, the sedimentary deposits that support it, and water activity. These are examples of the covering or surface impregnation by soot from bonfires or other corrosive compounds, the growth of algae induced by artificial lighting, the covering of areas by mobilized sediments, floods, drought, changes in the physicochemical and biological composition of water and modifications of natural watercourses that alter the speleothems' activity cycle, as well as the natural evolution of shapes and the development of fauna.

The map analysis defines actions for the planning and management processes of activities in the park area and identifies areas that deserve to be investigated in the future for the identification of caves. In addition, the result of the research can direct measures to mitigate direct impacts in areas with high or very high potential for natural cavities to occur.

The use of the multicriteria tool showed results that met expectations regarding the identification of areas with the occurrence of natural cavities. It is important to consider that the multicriteria methodology used in this study has a constructive approach.

The evaluation of the data through the multicriteria analysis predicts the target areas of interest. The applied methodology proved to be effective; however, it should be used in conjunction with other studies for a more assertive result.

The cavities are already registered to coincide with the areas with potential for the occurrence of cavities, which validates the method used. The southernmost portion of the map showed the potential for cavities to occur, with no cavities recorded. Fieldwork is suggested for confirmation and registration of cavities not yet registered with CECAV.

I emphasize that this work serves as a subsidy concerning applying this methodology in other areas of study.

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