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BRAZILIAN GEOGRAPHICAL JOURNAL
GEOSCIENCES AND HUMANITIES RESEARCH MEDIUM

ISSN 2179-2321
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A GIS-BASED SPATIAL ANALYSIS OF THE DISTRIBUTION OF CAVES IN BRAZIL

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ABSTRACT:
This work analyses the spatial distribution of the Brazilian caves by using geoprocessing techniques and associating these caves to different thematic maps. According to the Brazilian Center for Research and Conservation of Caves (CECAV) database, there are 16,089 known caves in Brazil. The spatial analysis of these caves was performed by combining their location with other information, such as the Brazilian states, biomes, drainage basins, geologic maps and potential data for the occurrence of more caves. In some regions, due to a large number of caves, the caves hid one another when represented by points by overlapping and could not be seen on some maps. Therefore, the Kernel Density Estimation (KDE) technique was carried out to view regions based on their number of caves. All of these analyses were performed using the Geographical Information System (GIS) package ArcGIS v.10.3. The Brazilian states with the most significant numbers of caves are Minas Gerais (6,301 caves - 39.16%) and Pará (2,473 caves - 15.37%). On the other hand, there are no known caves in Acre, the only state with no caves. Caves occur in all the Brazilian biomes and drainage basins, mainly in the Cerrado biome and in the São Francisco basin and are associated mainly with carbonate rocks and Banded Iron Formations (BIFs), but also occur in other lithologies, such as quartzites and sandstones. The potential map for the occurrence of caves, made based on the CECAV database, is also beneficial and shows us where else we may find more caves so that one can preserve them. This work will also serve as a contribution for a worldwide map of cave regions.
Keywords: Caves; Brazilian speleology; Speleological potential; Spatial analysis; GIS.

ANÁLISE ESPACIAL BASEADO EM SIG DA DISTRIBUIÇÃO DE CAVERNAS NO BRASIL

RESUMO:
Este trabalho analisa a distribuição espacial das cavernas brasileiras usando técnicas de geoprocessamento e associando essas cavernas a diferentes mapas temáticos. De acordo com o banco de dados do Centro Brasileiro de Pesquisa e Conservação de Cavernas (CECAV), existem 16.089 cavernas conhecidas no Brasil. A análise espacial dessas cavernas foi realizada combinando sua localização com outras informações, como estados brasileiros, biomas, bacias de drenagem, mapas geológicos e dados potenciais para a ocorrência de mais cavernas. Em algumas regiões, devido a um grande número de cavernas, elas não apareciam quando representadas por pontos em decorrência da sobreposição das informações e não podiam ser vistas em alguns mapas. Portanto, a técnica Kernel Density Estimation (KDE) foi realizada para visualizar regiões com base no número de cavernas. Todas essas análises foram realizadas utilizando-se do Sistema de Informação Geográfica (SIG) ArcGIS v.10.3. Os estados brasileiros com maior número de cavernas são Minas Gerais (6.301 cavernas - 39,16%) e Pará (2.473 cavernas - 15,37%). Por outro lado, não há cavernas conhecidas no Acre, o único estado sem cavernas. As cavernas ocorrem em todos os biomas brasileiros e bacias de drenagem, principalmente no bioma Cerrado e na bacia de São Francisco e estão associadas principalmente a rochas carbonáticas e formações de ferro em faixas (BIFs), mas também ocorrem em outras litologias, como quartzitos e arenitos. O mapa potencial para a ocorrência de cavernas, feito com base no banco de dados do CECAV, também é benéfico e mostra onde mais podemos encontrar mais cavernas para que possamos preservá-las. Este trabalho também servirá de contribuição para um mapa mundial das regiões de cavernas.
Palavras-chave: Cavernas; Espeleologia brasileira; Potencial espeleológico; Análise espacial; SIG.

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INTRODUÇÃO

Caves are defined as a natural opening in the ground extending beyond the zone of light and large enough to permit the entry of man, according to the U.S. Geological Survey. They occur in different lithologies, such as carbonate rocks, iron formation, sandstones, quartzites and others and play a vital role in understanding the history of our planet and of several forms of life. Fortunately, over the last decades, developments in science and technology are allowing us to investigate caves further. For instance, nowadays, it is possible to characterise precisely the materials that they are composed of or draw them by using modern computers and programs.

The Brazilian Center for Research and Conservation of Caves (CECAV), through the National Register for Speleological Information (CANIE), provides the location of the 16,089 currently known caves in Brazil. More information about the caves is also available on their website. However, we will use their location in this work primarily. The data provided by the CECAV is in the shapefile format, which means they can be manipulated in a GIS environment, allowing us to analyse the spatial distribution of the caves throughout the country. The database was last updated on March 31, 2017.

This work will analyse the spatial distribution of the Brazilian caves using geoprocessing techniques and associating these caves to different thematic maps. The location of these caves, when combined with the thematic maps, generates essential data that are presented and discussed in this paper. Thus, considering how essential caves are and their high sensitivity and vulnerability, the spatial analysis of the known Brazilian caves will be an important contribution to understanding where caves occur mostly, how to preserve them, and even where to explore to find more caves.

Brazil is the largest country in South America and has 26 states and one federal district. The map in Fig. 1 shows Brazil and its states. The spatial analysis of the Brazilian caves will be performed combining the cave locations throughout Brazil with thematic maps, such as the Brazilian states, biomes, drainage basins, geologic maps and potential data for the occurrence of more caves, as well as analysing the density map of caves generated using the KDE method.

Figure 1. Map of Brazil showing its 26 states and Brasília, the federal district of Brazil.

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MATERIALS AND METHODS

This study used a shapefile provided by the CANIE, containing the geographic location (latitude, longitude, and elevation) of the Brazilian caves, as well as their names and the state and county they are located. A point in this map represents each cave. In a GIS environment, these points were combined with other shape files containing information about the Brazilian states, geology, biomes, drainage basins, and potential data for the occurrence of more caves. Moreover, the KDE technique was performed using the cave shapefile.

The organisation, processing, editing, viewing, and interpretation of the digital data were done using the programs ArcMap 10.3, ArcToolBox 10.3, Global Mapper 18, and CorelDraw X8. The graphs were created in Microsoft Office Excel. The stages of this study are detailed in the following sections.

Caves by state

The shapefile has an attribute table indicating the cave names, as well as the states and municipalities where they are located in and their geographical coordinates. Based on that information, it was possible to see the distribution of the caves by state, both on the map and in graphs, and the geographical coordinates allowed us to locate the exact cave locations so that one can view them on the maps.

Caves by biome

The cave locations and the Brazilian biomes were combined in order to find how many caves occur within the limits of each biome. The shapefile containing information about the biomes were obtained from the Ministry of the Environment (MMA).

Caves by watershed

The cave locations and the Brazilian drainage basins were combined in order to find the number of caves that occur within the limits of each hydrographic basin. The shapefile containing information about the basins was obtained from the National Water Agency (ANA), through the National Water Resources Information System (SNIRH).

Caves by lithology

The cave locations and the rock type data were combined to give us an idea of the approximate amount of caves that occur associated with each lithology. The shapefile containing information about the rock type data was obtained from the Brazilian Geological Survey (CPRM), through the Brazilian Geological Information Service (GeoSGB).

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Density map of caves by the Kernel Density Estimation (KDE) method

Point density analysis is a technique that permits the viewing and consideration of clusters in a spatial dataset and facilitates comparison of trends (Conolly & Lake 2006). In this study, we used this approach to undertake an evaluation of cave distribution across Brazil. By taking the cave shapefile containing the cave locations as the input point layer, a continuous, circular, and smooth density surface is generated. Applying the Kernel Density Estimation (KDE), a nonparametric technique (Illian et al., 2008; Wand & Jones 1995), the probabilistic density of cave is then calculated within a circular area, also known as the KDE search radius. The density value of each output raster cell is obtained by summing the values of all the Kernel surfaces calculated for the population of points. Calculations were applied to the entire number of the known caves, and the density maps of caves are displayed using density trends represented by different colours.

The potential for the occurrence of caves

The shapefile containing the potentiality data for the occurrence of caves was obtained from the CECAV, and the map for the occurrence of caves was made based on that data. This map categorises Brazil in five potential ranges for the occurrence of caves: 1) Very high; 2) High; 3) Medium; 4) Low, and 5) Very low.

RESULTS AND DISCUSSION

Caves by state

Of the 16,089 known caves existing in Brazil, the state of Minas Gerais contains 6,301 caves, corresponding to 39.16%. It is the state with the most significant number of caves, followed by the state of Pará, with 2,473 caves (15.37%). On the other hand, there are no known caves in Acre, the only state with no caves. The distribution of caves by State can be seen on the map in Fig. 2, where each point represents a cave. Because of the scale adopted, in areas where many caves occur, the points overlap one another, and thus it is not possible to see all the points. Therefore, to better view the distribution of caves by states, the states are represented in colour, where each colour represents a range of quantity of caves. Additionally, the exact amount of caves by State is shown in the graph in Fig. 3.

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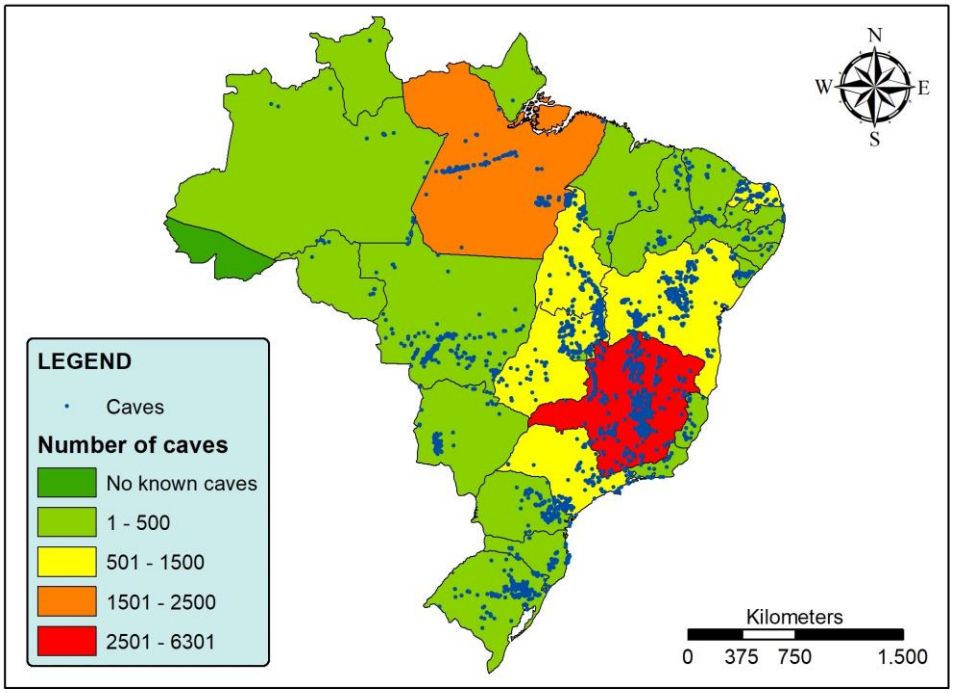
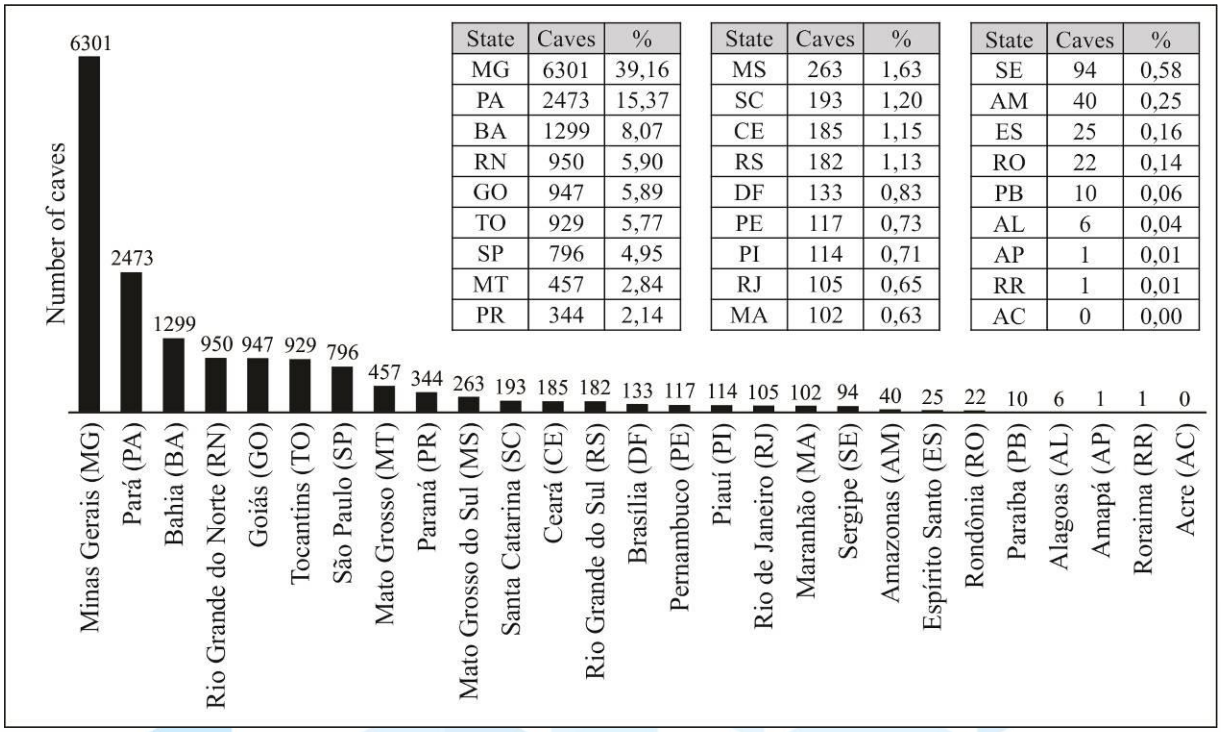


Figure 2. Geographic distribution of caves by state. The states of Minas Gerais (red) and Pará (orange) have the most caves and Acre (dark green) has no known caves.



State	Caves	%
MG	6301	39,16
PA	2473	15,37
BA	1299	8,07
RN	950	5,90
GO	947	5,89
TO	929	5,77
SP	796	4,95
MT	457	2,84
PR	344	2,14

State	Caves	%
MS	263	1,63
SC	193	1,20
CE	185	1,15
RS	182	1,13
DF	133	0,83
PE	117	0,73
PI	114	0,71
RJ	105	0,65
MA	102	0,63

State	Caves	%
SE	94	0,58
AM	40	0,25
ES	25	0,16
RO	22	0,14
PB	10	0,06
AL	6	0,04
AP	1	0,01
RR	1	0,01
AC	0	0,00

Figure 3. Number of caves by state.

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Caves by biome

Biomes are a set of vegetation types that cover large continuous areas, on a regional scale, with similar flora and fauna, defined by the physical conditions prevailing in the regions. According to the Brazilian Institute of Geography and Statistics (IBGE), Brazil has six biomes: 1) Amazon; 2) Cerrado; 3) Atlantic forest; 4) Caatinga; 5) Pampa; and 6) Pantanal.

By integrating the cave locations with the Brazilian biomes, it was possible to determine the exact number of caves that occur in each biome. The map in Fig. 4 shows the caves and the biomes combined, as well as the number and percentage of the known caves in each biome. Caves occur in all the Brazilian biomes, mainly in Cerrado, which contains 8,005 caves, representing 49.75%. On the other hand, the biome with the smallest number of caves is Pantanal, with only 16 caves, representing 0.10% of the total number of caves.

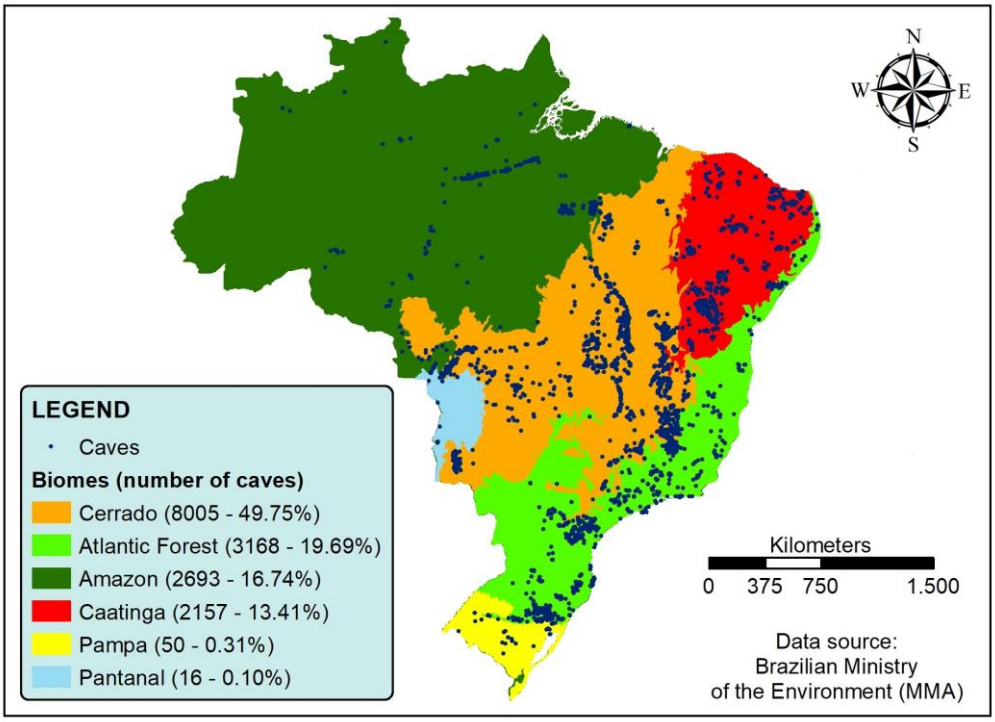

Figure 4. Locations of the known caves in the Brazilian biomes. The number and percentage of the known caves in each biome are also shown.

Caves by watershed

According to the USGS, a watershed is an area of land that drains all streams and rainfall to a conventional outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel. The National Water Agency (ANA) defined eight drainage basins for Brazil: 1) Amazon; 2) Tocantins; 3) Paraná; 4) Uruguay; 5) São Francisco; 6) Atlantic - North & Northeast regions; 7) Atlantic - Southeast region; and 8) Atlantic - East region.

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By integrating the cave locations with the Brazilian drainage basins, it was possible to find the exact number of caves that occur in each basin. The map in Fig. 5 shows the caves and the basins combined, as well as the number and percentage of the known caves in each basin. The São Francisco basin contains 6,314 caves, out of 16,089, representing 39,24% of all the Brazilian caves. On the other hand, the basin with the smallest number of caves is the Uruguay basin, which contains only 94 caves, representing 0.58% of the total number of caves.

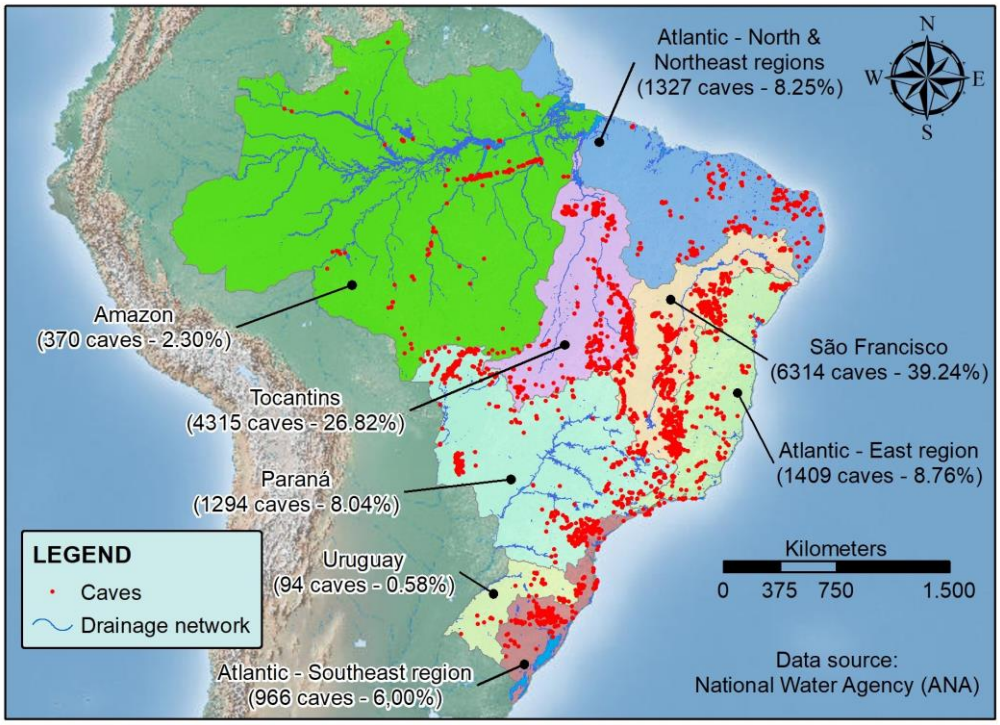

Figure 5. Locations of the known caves in the Brazilian watersheds. The number and percentage of the known caves in each basin are also shown.

Density map of caves by the Kernel Density Estimation (KDE) method

The density map of caves, created using the Kernel Density Estimation (KDE) method, made it easier to view regions regarding the number of caves. In this map, each colour represents a range of quantity of caves. For example, red represents the areas where most caves occur and dark green shows the areas with no known caves up to now (Fig. 6).

Analyzing the density map of caves, we can see that it is consistent with the statistical data of caves by state previously shown (Figs. 2 and 3), because states such as Minas Gerais and Pará, where most caves occur, also present the main density peaks or hot spots, which delimits the areas with more caves. On the other hand, states, where only a few or no caves occur, are represented mostly by the green colour, such as Acre (no caves), Amapá (one cave), and Roraima (one cave). Therefore, this map solves the overlap problem, allowing us to see where most caves occur across Brazil.

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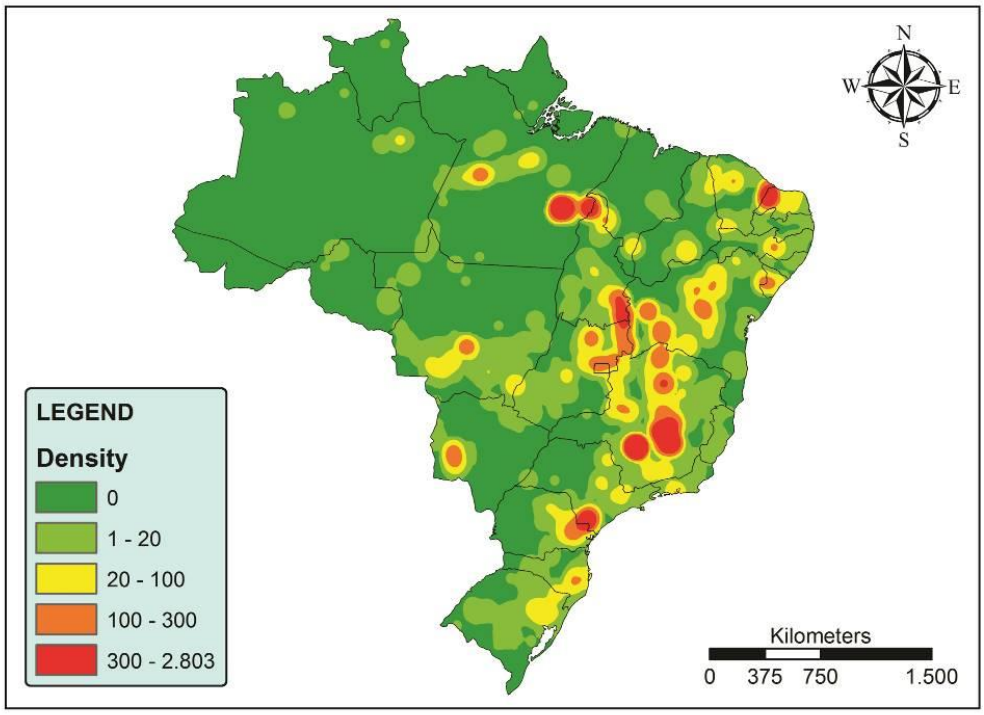

Figure 6. Density map of caves showing the spatial distribution of caves in Brazil.

Caves by lithology

There is no updated data on the distribution of caves by lithology. However, Jansen et al. 2012 estimated, according to the CECAV database of 2012 and from the estimation made by Piló & Auler (2011), when there were only 10,220 known caves in Brazil, that they were distributed by lithology as follows: 1) carbonate rocks: ~7,000 caves; 2) iron ore: ~2,000 caves; 3) quartzite: ~510 caves; 4) sandstone ~510 caves; And 5) other rocks: ~200 caves.

By integrating the cave locations with the geological map of Brazil, it was possible to see what types of rock they tend to occur associated with (Fig. 7). However, it was decided not to use this map to determine the number of caves that occur by each type of rock, because lithologies, unlike biomes and watersheds, are not always large areas. Rock units can occur as small bodies or layers; thus, in the adopted scale, these rocks could not be seen on the map. In other words, rock units can be very local and therefore combining the cave locations with the geological map of the whole country to estimate the exact number of caves by type of rock would not be efficient. Studies have been carried out to characterise caves regarding lithology and determine what types of rock they occur associated with.

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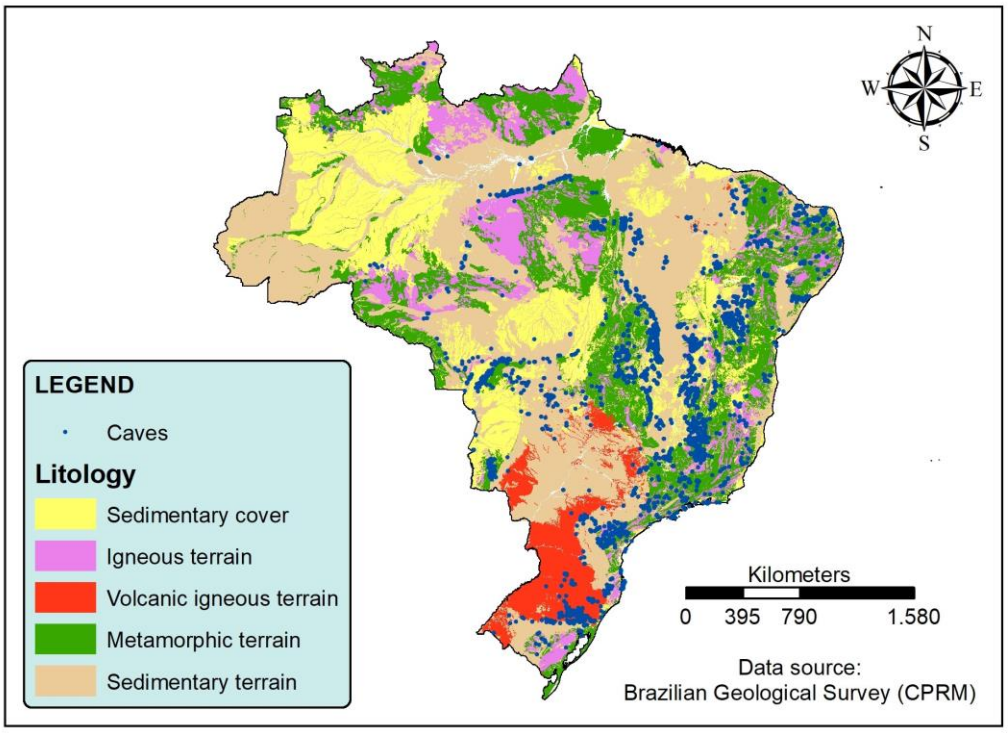

Figure 7. Locations of the known caves on the Geological Map of Brazil. Most caves occur associated with metamorphic terrains.

Distribution of caves by types of rock: examples from the state of Minas Gerais

As previously mentioned, Minas Gerais is the Brazilian state with the most significant number of known caves, which currently is 6,301. Therefore, based on the density map of caves in Minas Gerais (Fig. 8), two areas were selected to demonstrate that caves in Brazil tend to occur associated with certain types of rocks, mainly carbonate rocks and iron formation. The map in Fig. 9 shows an area with 2,165 caves, where most of them are associated with carbonate rocks, whereas the map in Fig. 10 shows another area with 1,273 caves, mostly associated with iron formation.

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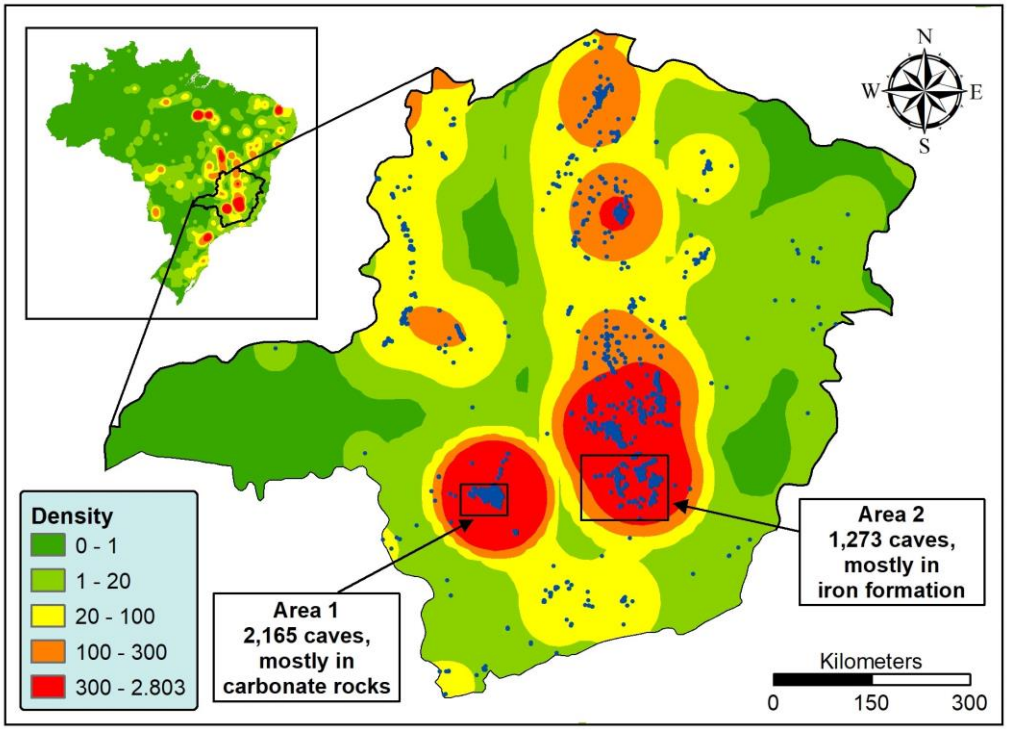

Figure 8. Distribution of caves in the state of Minas Gerais and the polygons representing the selected areas. Note that in Area 1 most caves occur associated with carbonate rocks and in Area 2 with iron formation.

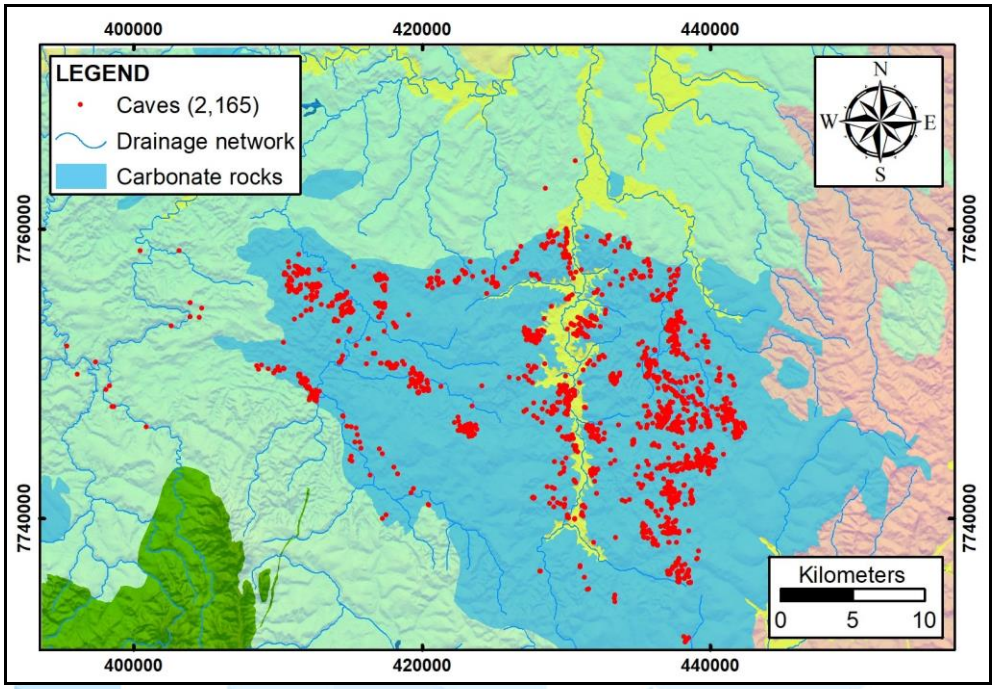

Figure 9. Geological map of Area 1 showing that the caves occur mostly associated with carbonate rocks (Source of the geological data: CPRM).

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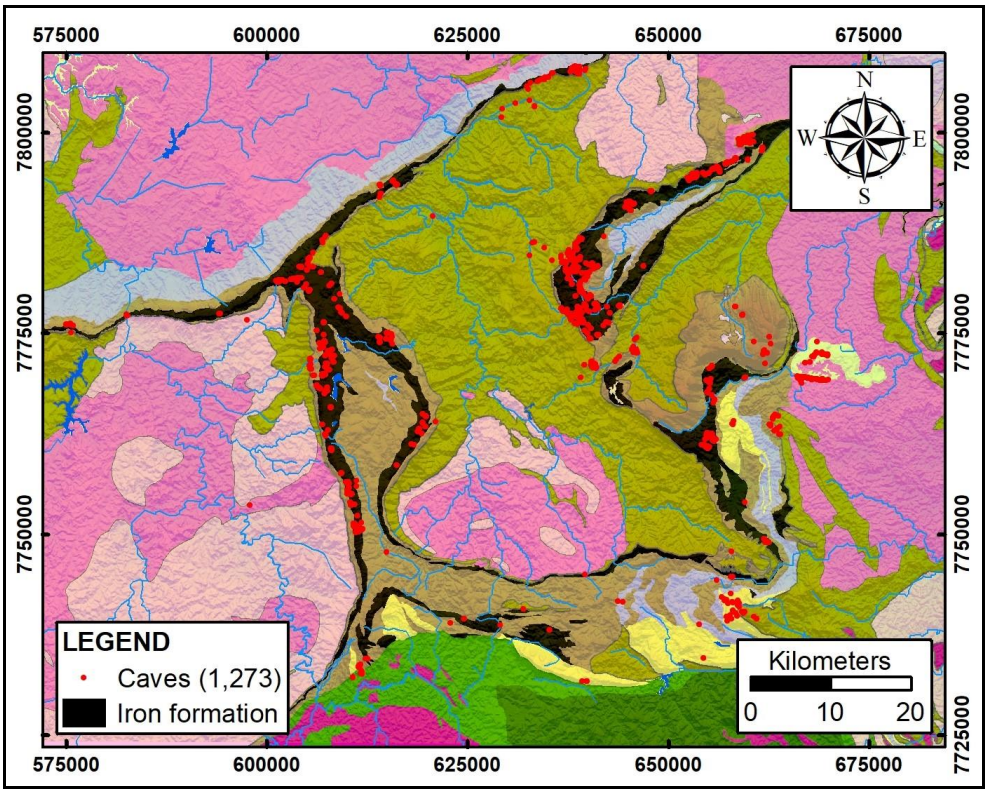

Figure 10. Geological map of Area 2 showing that the caves occur mostly associated with iron formation (Source of the geological data: CPRM).

The potential for the occurrence of caves

Piló & Auler (2011) said that although the Brazilian speleological potential lies in the range of some 100,000 caves, less than 5% of Brazilian natural underground caves were known up to 2011. Thus, these authors suggested the adoption of a reference for the construction of a potential speleological model in the country, based on estimated data and the number of known caves in the main lithologies. This way, based on the CECAV database, Jansen et al. 2012 developed a map of potentiality for the occurrence of caves in Brazil, which shows the caves and the potential areas. The map categorises Brazil in five potential ranges for the occurrence of caves: 1) Very high; 2) High; 3) Medium; 4) Low, and 5) Very low. In this work, we also present a map of potentiality made using the CECAV database. However, differently, from Jansen et al. 2012, our map does not show the cave locations, since they have already been shown in the previous maps of this study (Fig. 11). Moreover, the cave points would make it difficult to look some potential areas as they can be large but also small areas. The potential map for the occurrence of caves, made based on the CECAV database, is beneficial and shows us where else we may find and study more caves so that one can preserve them.

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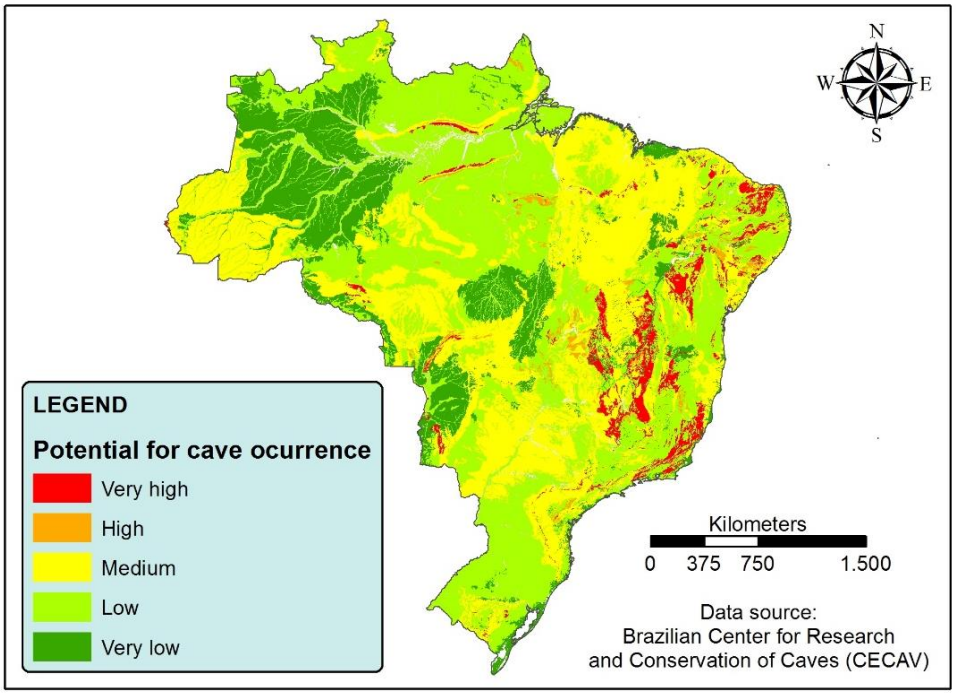

Figure 11. Potential map for the occurrence of caves in Brazil (after Jansen et al., 2012).

The study done by Jansen et al. 2012 pointed out that 78.4% of the caves are located in areas of very high and high potentiality ranges, which are mostly associated with carbonate rocks and iron formation; 12.8% in areas of medium potentiality range, which are associated with sandstones and quartzites; and 8.7% in areas of low and very low potentiality ranges. The lithologies associated with each potentiality range are shown in Table 1.

Lithology	Potential
Limestone, dolomite, evaporite, and iron formation	Very high
Calcrete, carbonatite, marble, and marlstone	High
Sandstone, conglomerate, filite, shale, fosforite, greywacke, metaconglomerate, metapelite, metassiltite, milonite, quartzite, pelite, rhyolite, rhythmite, calcium-silicate rock, siltstone, and schist	Medium
Anortosite, arcaneum, augengnaisse, basalt, charnockite, diamictite, enderbite, gabbro, gnaisse, granite, granodiorite, hornfels, kinzigite, komatite, laterite, metachert, migmatite, monzogranite, ortoamphibolite, syenite, sienogranite, tonalite, trondhjemite, among other lithotypes	Low
Alluvium, sand, clay, gravel, lenhite, and other sediments	Very low

Table 1: Lithologies associated with each potentiality of occurrence of caves in Brazil (after Jansen et al., 2012).

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CONCLUSIONS

This work analysed the spatial distribution of the Brazilian caves using geoprocessing techniques in a GIS environment and associating the caves to different thematic maps. The generation, analysis, and discussion of these maps are an essential step toward making useful information available to the decision makers and conservation practitioners in Brazil and around the world. Additionally, showing the distribution of all known caves across the country is a contribution for a global map of cave regions. Organising and publishing information about cave research in Brazil should also encourage collaboration among institutions and researchers who also have geographical information about caves. The maps created and analysed in this study play an important role assisting focus on studying, conserving, and preserving cave regions, as well as suggest that further research is needed to explore the real cave potential in Brazil.

ACKNOWLEDGEMENTS

The authors thank the CECAV for providing us with the location of the Brazilian caves. No funding was received from any organisation, institution, or individual by any of the authors for this study.

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Recebido em: 21/10/2017

Aprovado para publicação em: 30/06/2018