sociedade & natureza

DOI: 10.14393/SN-v35-2023-68709
Receveid: March 15, 2023 | Accepted: July 12, 2023 | Published: August 09, 2023

Papers

Relief Dissection Potential and its Relationship with Geodiversity in a Karstic Region of Brazil

Fabiano Érico Vieira de Souza [1]
Úrsula Ruchkysa de Azevedo [2]
Bráulio Magalhães Fonseca [3]
Carlos Lobo [4]

Keywords
Geodiversity
Geostatistics
Quantification
Relief rugosity

Abstract
The quantification of abiotic features is a process in Geodiversity focused studies to indicate priority areas for conservation. Although some quantification methods are in use, doubts remain as to their applicability, particularly the relationship between coefficients of geodiversity and rugosity. In this perspective, this study proposes to analyze this relationship through the geostatistical models of Local Moran's I and Geographically Weighted Regression (GWR), applied in sub-basins of one of the most important karstic regions in Brazil. To simulate the rugosity coefficient, the Global Relief Dissection Index was used, which consists of a combination of morphometric indices that enable the estimation of a given region's power of dissection. The application of Local Moran's I showed geodiversity and relief dissection potential behavior patterns, demonstrating that the variables have spatial dependence and are correlated at certain points. The application of GWR was successful, although the model was not able to explain the regional relationship between the coefficients of geodiversity and relief dissection. Nevertheless, it enabled local analysis of different behaviors through the spatialization of local R2 and residuals. It can be inferred that there are other variables that interfere in the local geodiversity, especially, for being a geosystem with characteristics specific.

[1] Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, MG, Brazil. fabianoerico@hotmail.com
[2] Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, MG, Brazil. tularuchkys@yahoo.com.br
[3] Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, MG, Brazil. brauliomagalhaes@gmail.com
[4] Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, MG, Brazil. carlosfflobo@gmail.com

INTRODUCTION

Geodiversity can be understood as the variety of abiotic elements, including their formation processes and the relationship between these elements (BRILHA, 2016; GRAY, 2004; RUBAN, 2017). Some authors have associated the conception of geodiversity with Gaia Theory (LOVELOCK, 1972), with the prefix "geo" in Geodiversity, meaning "Earth" and "environment", attributing a holistic perspective to the concept (RUBAN; YASHALOVA, 2018; RUCHKYS et al., 2018).

Studies focused on geodiversity seek to present, and even quantify, the relevance of physical elements to the operation of environmental systems. The combination of these elements is essential for the functioning of an environmental system, which, in complete equilibrium, provides various fundamental services to society, such as the maintenance of aquifers and springs, control of erosive processes, and even the formation of landscapes used for leisure and contemplation.

The quantification of the elements that make up geodiversity has an important role, since it provides technical support for the preliminary identification of areas with potential for conservation. The advantage of its application arises from the high degree of objectivity in the results. One of the main aims of quantification is the indication of areas with greater geodiversity, which assists in planning and administration (HJORT; LOUTO, 2010; PELLITERO, 2012; PEREIRA et al., 2013).

A well-known methodology for calculating geodiversity is that proposed by Serrano and Ruiz-Flanõ (2007), applied in Tiermes Caracena, Spain. The generated index consists of the sum of physical elements present in a determined area (geological, geomorphological, hydrological, and pedological) multiplied by relief rugosity. However, the use of the rugosity coefficient is a discussion present in studies based on Serrano and Ruiz-Flanõ (2007), as it presents a statistically low correlation with geodiversity (HJORT; LOUTO, 2010; PELLITERO, 2012). In some studies, such as those by Pellitero (2012), Pereira et al. (2013), and, subsequently, Sena (2015) and Pereira and Ruchkys (2016), rugosity is not considered in the geodiversity index calculation.

The original expression (Equation 1) of the index is given as follows:

$$Gd = Eg\ R / \ln S \quad \text{(Equation 1)}$$

Where: Gd = geodiversity index; Eg = number of elements present; R = rugosity coefficient; ln = Neperian logarithm; S = surface area.

For Serrano and Ruiz-Flanõ (2007), the use of rugosity in their index is justified, since the rugosity coefficient represents the topography and the microclimatic and topoclimatic variations, thus being considered an integrating parameter reflected in the diversity and distribution of forms and processes.

In the context of Geosciences, especially geomorphological studies to obtain morphometric indices, it is essential the understand of the studied relief. In addition to rugosity, other indexes that can be used are Hack's Stream Length-Gradient Index, or SL Index (HACK, 1973) Drainage Density (HORTON, 1945) and the Relief Dissection Index (RDI). As Silva et al. (2019) highlight, for geodiversity studies, various authors have tested and used indices based on topographic attributes that consider relief dissection as an element of landscape structuring (BENITO-CALVO et al., 2009; ZWOLIŃSKI; GUDOWICZ, 2015; KOT, 2018; MELELLI et al., 2017).

Based on known indices, Souza et al. (2017) proposed the Global Relief Dissection Index - GRDI, through the conjunction of three geomorphological indices already consolidated in the literature: the Rugosity Concentration Index – RCI (SAMPAIO, 2008), Hack's Index (HACK, 1973), and the Drainage Density Index (HORTON, 1945). The GRDI enables the delimitation of relief compartments considering drainage density, relief rugosity, and the energetic vigor of the drainage channels, estimated through the slope-length relationship. Therefore, it is emphasized that the GRDI is the result of the integration of morphometric parameters capable of mapping forms resulting from vertical subsidence processes of the relief (downwearing) and the horizontal retraction of slopes through the incision of drainage channels (backwearing).

Brazil, and especially the state of Minas Gerais, has significant karstic geosystems, some of which are internationally recognized for their ecological importance, such as the Sítio Ramsar Lund Warming, declared Sitio Ramsar by Unesco in 2017 (SENA et al., 2022). Karsts are characterized by dynamic geological complexes in constant modification, mainly through the action of water, leading to the formation and modeling of their typical landscape (GILBERT et al., 1994).

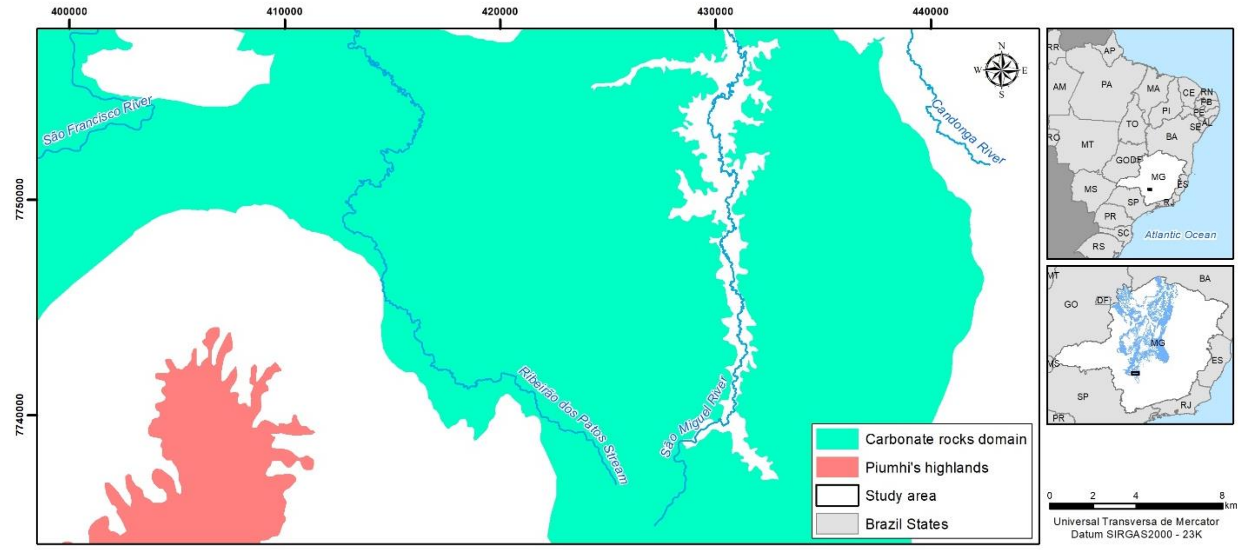
These geosystems are both extremely beautiful and extremely complex, being recognized for their unique subterranean and surface relief forms, for being significant sources of potable water, for their economic value, and for their associated paleontological and archaeological heritage (TRAVASSOS, 2019; SENA et al., 2022). Such peculiar characteristics have led to 2021 being recognized as the International Year of Caves and Karst (IYCC), an initiative of the International Union of Speleology (IUS), based in Slovenia, a pioneering country in the study of karst.

The management of land use in these areas is complex, especially given the presence of mining and agribusiness activities developed on the karst. In light of the above, this study aims to quantify the geodiversity of the Província Cárstica de Arcos-Pains-Doresópolis (PCAPD) (Arcos-Pains-Doresópolis Karstic Province) and analyze, through spatial statistics, the relationship of the relief dissection potential with the geodiversity indices.

Study Area

The study area (Figure 1) is found in the Mesoregion of West Minas, encompassing the municipalities of Bambuí, Piumhi, Doresópolis, Pains, Pimenta, Córrego Fundo, Arcos, Iguatama, and Formiga. It involves the quadrant contemplated by the Projeto Arcos Pains Espeleologia (Arcos Pains Speleology Project) – PROAPE, with around 1,152 km².

Figure 1– Location of the study area.



Source: CPRM (2008).

The region is known for being an important hub for mining and industry due to the occurrence of thick strata of limestone rock from the Grupo Bambuí that serve as raw material in the production of cement, lime, and soil amendment, among other products. In addition, these geological-geomorphological characteristics are associated with beautiful landscapes and important speleological heritage, with sites of archaeological and paleontological importance.

The PCAPD is in the southern portion of the São Francisco Craton, an extensive cratonic nucleus established at the end of the Paleoprotozoic (ALMEIDA, 1977). This karstic region is composed of highly metamorphosed carbonate metasedimentary rocks of the Grupo Bambuí, from the Neoproterozoic, with pelitic facie rocks (siltites and argillites) at the base and carbonated facie rocks (marls, limestones, and dolomites) at the top. From the stratigraphic point of view, the rocks of the Grupo Bambuí are found in discordant contact with rocks from the granite-gneiss basement and with phyllites of the Canastra group (MAGALHÃES, 1989). The area of interest also encompasses metamorphic rocks of the Serra de Piumhi, located in the southern/south-western portion of the quadrant (MADALOSSO; VERONESE,1978).

The relief is predominantly characterized by typically karstic features, shaped by endogenous and exogenous processes derived from the dissolution of carbonate rocks or through processes of abatement. The smoothed topography is the result of weathering of the carbonate rocks intercalated with pelitic rocks, presenting dolines and uvalas (nested sinkholes), limestone pavements, flood zones, blind valleys and other features (TEIXEIRA;

DIAS, 2003; SEE, 2012). Alluvial deposits also condition the smoothness of the relief. The areas with high declivity occur as a result of the carbonate outcrops and the crests of the Serra de Piumhi.

The climate of the study area is tropical, having two distinct periods: A period of hydric surplus, from November to April and the other with hydric deficiency, from May to September (SEE, 2012). The seasonality of water dynamics modifies landscapes between wet and dry seasons. In the wet season, the large water volumes allow the emergence of beautiful scenarios in sinkholes, upwellings and the activation of dry valleys (MENEGASSE et al. 2002).

MATERIALS AND METHODS

The first stage was the definition of the spatial unit of analysis. The delimitation of sub-basins was chosen as their use as spatial units enables isolated analyses, individualizing each situation, mainly for being considered systemic units composed of other subsystems. In total, 1,921 sub-basins of the Grande and São Francisco River basins were considered.

The abiotic variables used to calculate the indices of geodiversity are presented in Table 1. Their selection was based on Pereira et al. (2013) and Gray (2004), taking abiotic forms and processes into account.

Table 1 – Variables used in the calculation of Geodiversity

Variable	Taxa	Format	Source	Scale
Outcrops	Area /basin area Quantity/ basin area	Polygon Point	Martins (2013) CPRM (2008)	1:150.000
Cavities	Quantity/ basin area	Point	SEE (2012)	1:10.000
Flood zones/Sinkholes	Quantity/ basin area	Point	SEE (2012)	1:10.000
Lineaments/Structures	Extension/ basin area	Line	SEE (2012) Martins (2013)	1:150.000
Features	Area / basin area	Polygon	Martins (2013)	1:150.000
Lithology	Quantity/ basin area	Polygon	CPRM (2008)	1:150.000
Geomorphological units	Area / basin area	Polygon	Martins (2013)	1:150.000
Drainage network	Extension/ basin area	Line	USGS (2018)	30m
Recent erosive processes	Area / basin area	Polygon	USGS (2018)	30m
Recent depositional processes	Area / basin area	Polygon	USGS (2018)	30m

Source: The authors (2018).

The data were manipulated into vectorial format and distinct structures (point, line, polygon). The digital bases were extracted from secondary maps, cartographic documents made available by environmental bodies, and data extracted from subproducts generated from the Shuttle Radar Topography Mission – SRTM/NASA (sheet 21S046W - spatial resolution of 30m) image, more precisely, horizontal and vertical slope and curvature data. A cartographic base with different scales was used, since there were no analyzes that depended on the direct relationship between the bases

As a result of the data structure and the size difference of the sub-basins, normalized parameters were created for each variable, which were defined by the relationship between the number of existing occurrences, extension/length or area of the feature divided by the total area of the basin. This process was carried out using geoprocessing techniques, with the use of the Intersect and Dissolve tools, available on ArcMap/Arcigis 10.3, in which the geometric information of the variables is indexed to the quadrant of the basin. Finally, the geodiversity index of each basin was composed of the simple arithmetic mean of the indices of the variables.

The entire process for obtaining the Global Relief Dissection Index - GRDI, in addition to the configurations of the used tools, was based on Souza et al. (2017). The procedures were carried out using ArcMap/Arcigis 10.3, with the assistance of Kernel Density tools and the Inverse Distance Weighted interpolator. The topographic data used in this stage were extracted from the SRTM images mentioned above.

After testing with different values of radius as input parameter of the Kernel Density tool, a radius of 3km was used to best adapt to the physical context of the study area.

Equation 2, used to calculate the GRDI, which corresponds to matrix algebra by weighted mean, whose variables have the same weight, is described below:

(RCI × 0.33) + (HI × 0.33) + (Dra.Den × 0.33) (Equation 2)

The methodological procedures to acquire the RCI and Hack's Index are summarized in Figures 2 and 3.

Attribution of the GRDI values to the basins was carried out through the Zonal Statistics as Table tool, whereby the mean of the values of the pixels situated within each basin polygons was removed.

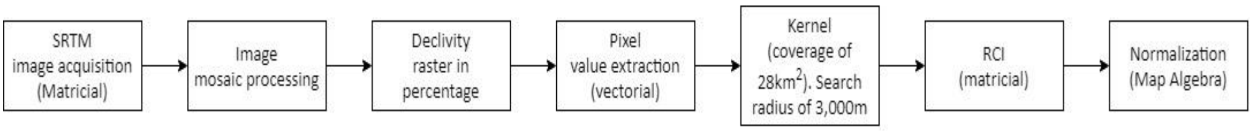
Spatial autocorrelation maps were created with the aim of analyzing the local spatial dependence of the Geodiversity Index and the GRDI, and thereby correlate them through pattern analysis, or clusters. For this stage, the tool known as Local Moran's I, on ArcGIS 10.3, was used. This tool consists of a Local Indicator of Spatial Association – LISA, which acts based on the analysis of the covariances between the different area units, in this case, the sub-basins, in a neighborhood defined in function of a distance (ANSELIN, 1995). The neighborhood criteria used was the distance fixed with the Euclidian distance method and a bandwidth of 3km.

This model enables analysis of the behavior of the variables based on the spatialization of clusters and outliers, according to the association between values of a determined area (Z-score). A high, positive Z-score value means that the objects have similar values, regardless of being high or low.

Finally, the Geographically Weighted Regression (GWR) model, available on ArcGIS 10.3, was used to evaluate the geodiversity prediction (dependent variable) according to rugosity (independent variable), represented by the GRDI.

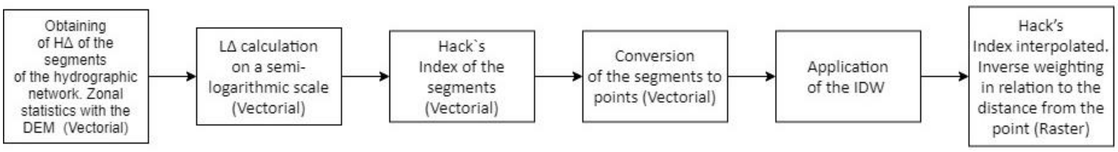
This model consists of a linear regression method, applied spatially on a local level, considering a coverage radius or bandwidth to weight the observations, here established as fixed distance. Bandwidth acquisition was pre-established using the Akaike Information Criterion (AICC) method, which, in turn, stipulates the ideal radius based on the observed data.

Figure 2 – Flow chart for obtaining the RCI



Source: Souza et al. (2017).

Figure 3 – Flow chart for obtaining Hack's Index.

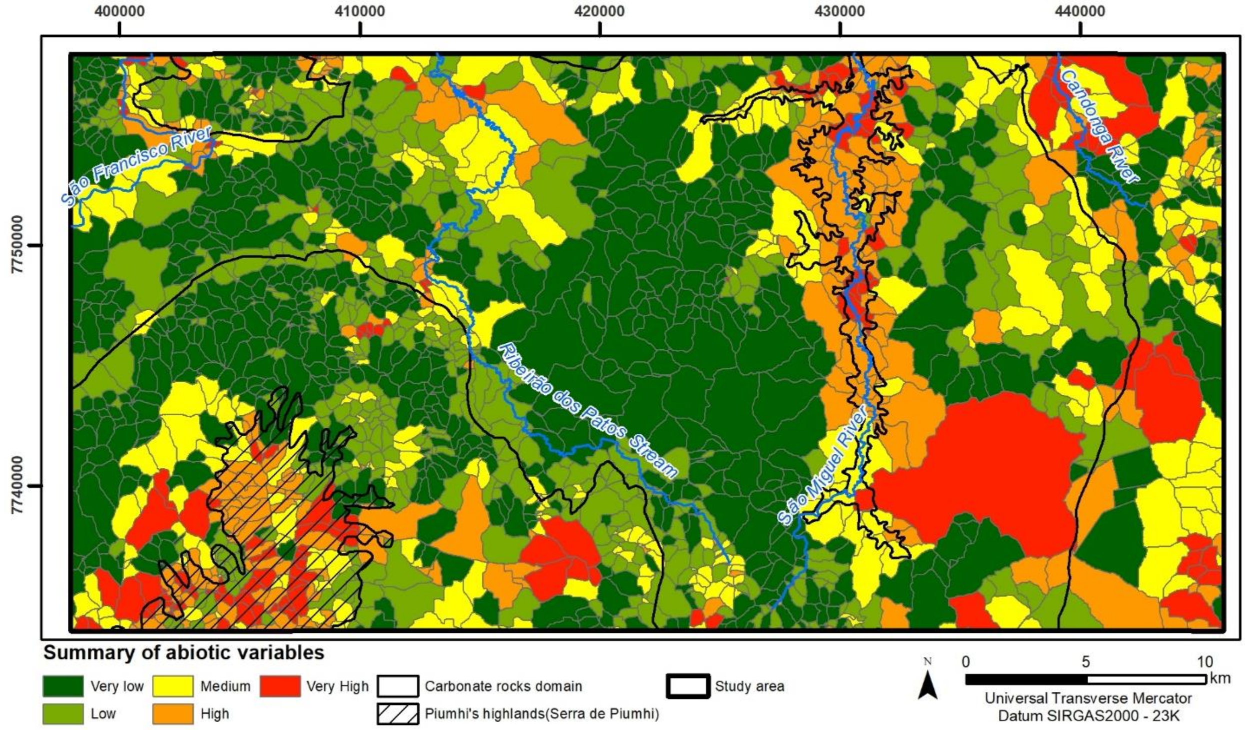


Source: Souza et al. (2017).

ANALYSIS AND DISCUSSION OF THE RESULTS

The geodiversity quantification result (Figure 4) can be reported considering the two distinct systems existing in the study area: the standard system, consisting of an excess of physical and geochemical processes, and the karstic system, where the type of rock has a predominant role in the development of features by dissolution.

Figure 4 – Geodiversity index of the Arcos-Pains-Doresópolis Karstic Region.



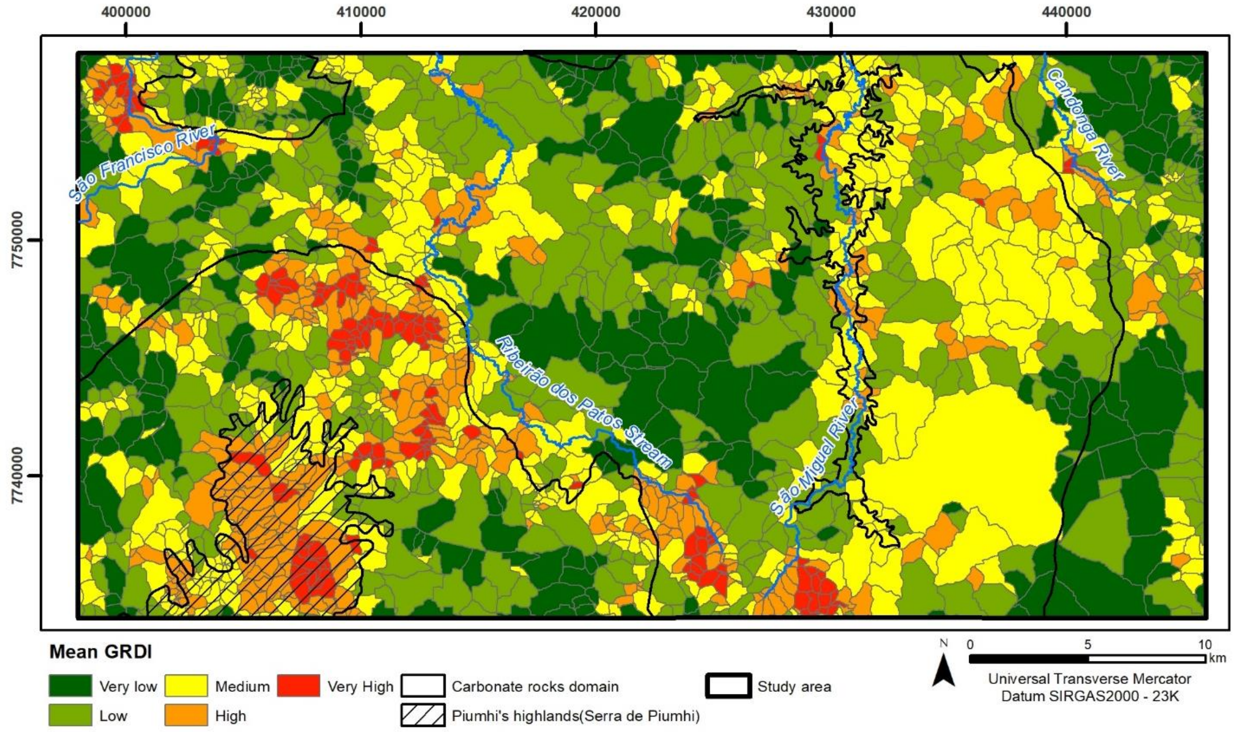
Source: The authors (2018).

From this perspective, in the karstic system, the sub-basins close to the main water courses stand out, especially in the vicinity of the São Miguel River, where there is a significant grouping of basins with a high geodiversity value. This region has a high concentration of carbonate outcrops and natural subterranean cavities, and, according to the studies of SEE (2012), it is the section where the carbonate rocks most outcrop. More recent alluvial deposition processes are also present.

The southern portion of the study area also stands out for high geodiversity values, the region being dominated by the Serra de Piumhi, supported by igneous and metamorphic rocks, where more active erosive processes and structures are concentrated. The large concentration of basins with very low geodiversity in the center and extreme west of the study area also stand out. Despite many basins being associated with the karstic domain, sedimentary deposits predominate in these regions.

The application of the GRDI (Figure 5) showed greater denudation activity in the Serra de Piumhi region, where, in fact, the relief is more rugged and has a greater density of drainage headwaters. The sub-basins close to the contact between the two regions, in addition to those located at the headwaters of the main rivers also stand out for the high indices of geodiversity. In the northwest, the high index values may be linked to the rugged relief, provided by the canyons of the São Francisco River. The low values are related to the deposition areas and low drainage density.

Figure 5 – Mean of the Global Relief Dissection Index of the Arcos-Pains-Doresópolis Karstic Region sub-basins.

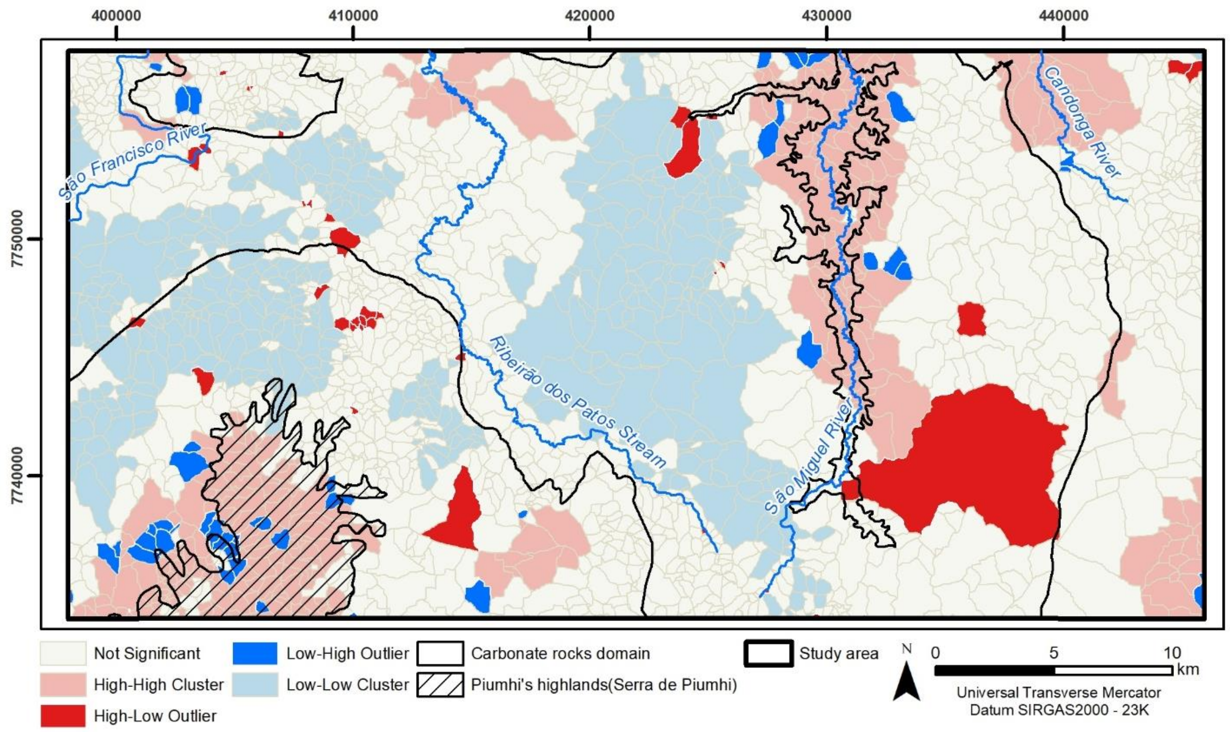


Source: The authors (2018).

Analysis of Local Moran's I

In general, the application of Local Moran's I showed well-defined patterns of geodiversity behavior and relief dissection potential, demonstrating that the values of these variables are not randomly distributed in the study area, as can be seen in Figures 6 and 7.

Figure 6 – Sub-basin groupings in the Arcos-Pains-Doresópolis Karstic Region in relation to the geodiversity index.

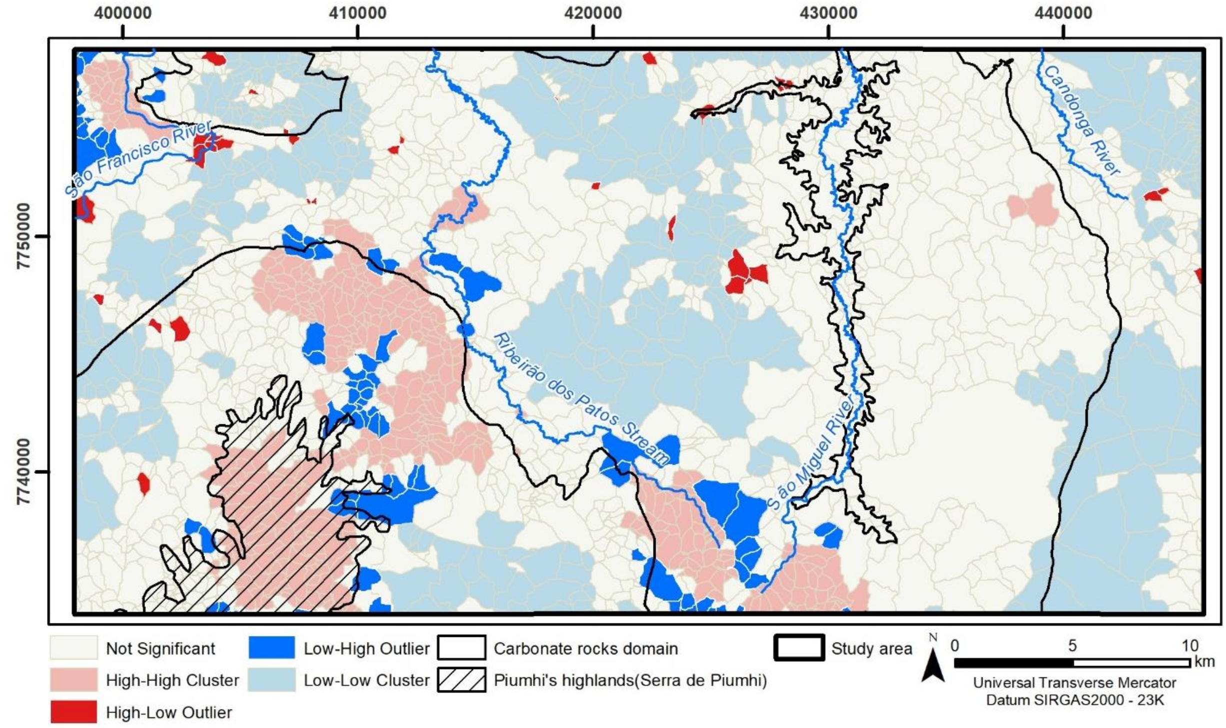


Source: The authors (2018).

Figure 6 corresponds to the grouping of sub-basins according to geodiversity. Reinforcing previous comments, it is evident that the regions with high geodiversity, represented by the *High-High* clusters, are mainly concentrated in the vicinity of the São Miguel River and around the Serra de Piumhi. The *Low-Low* groupings reinforce the relationship of low geodiversity with sedimentary deposits in the two systems presented in the study. The *High-Low* groupings correspond to the basins that stand out for high geodiversity in relation to the neighboring basins. Lastly, the *Low-High* groupings refer to the opposite of the previous situation.

Figure 7 demonstrates that there are many significant *Low-Low* groupings, indicating low erosive potential in a large part of the study area. Moreover, as previously mentioned, the *High-High* groupings are mainly related to the headwaters of the water courses, parts of the traditional system associated with the relief of the Serra de Piumhi region, and the canyons of the São Francisco River.

Figure 7 – Sub-basin groupings in the Arcos-Pains-Doresópolis Karstic Region in relation to the GRDI.



Source: The authors (2018).

Upon comparing the two products, the central and the western portions stand out, where the basins have low geodiversity and low dissection potential. Also standing out are the *High-High* overlaps of the basins in the vicinity of the Serra de Piumhi and some of those close to the São Francisco River, indicating a positive correlation between the two variables. However, there are basins in which the variables are negatively correlated, such as the basins at the headwaters of the São Miguel River, in the region of the Candonga River, among others belonging to the traditional system.

Tables 2 and 3, below, present, respectively, the proportion of the relationship between the classes of the Geodiversity index and the GRDI with their groups of clusters distributed in the basins of the study area.

Table 2 – Geodiversity index relationship and its cluster groups, in percentage (%).

Geodiversity index	Sub-basin Cluster groupings				
	HH	HL	LH	LL	Not Significant
Very Low	0,00	0,00	5,85	48,35	45,80
Low	0,00	0,00	1,91	2,33	95,76
Medium	19,64	3,02	0,00	0,00	77,34
High	63,86	7,43	0,00	0,00	28,71
Very High	74,62	9,23	0,00	0,00	16,15

Source: The authors (2018).

Table 3 – Relationship GRDI index and its cluster groups, in percentage (%).

Mean GRDI	Sub-basin Cluster groupings				
	HH	HL	LH	LL	Not Significant
Very Low	0,00	0,00	6,65	80,38	12,97
Low	0,00	0,00	12,20	29,72	58,07
Medium	6,54	0,71	0,35	0,00	92,40
High	62,23	7,34	0,00	0,00	30,43
Very High	93,25	2,45	0,00	0,00	4,29

Source: The authors (2018).

When analyzing Table 2, it is noticed the significant grouping of the High (63.86%) and Very High (74.62%) classes of the Geodiversity index in relation to the total of their basins. Regarding the *High-Low* outliers of the High and Very High Classes, we have, respectively, 7.43% and 9.23%, demonstrating low representation in their basins. In the Very Low class scenario, the data show 48.35% of cluster and low representation of *Low-High* outlier (5.85%). 95.76% of the basins in the Low class did not show spatial correlation.

The data presented in Table 3 demonstrate that 93.25% of the Very High class basins have spatial correlation. The outliers are 2.45%. The High class presents 62.23% of *High-High* grouping and 7.34% of outliers. 80.38% of the basins in the Very Low class have a spatial correlation of 6.65% of outliers. The Low class presents a relevant proportion of uncorrelated basins (58.07%), 29.72% of clusters and 12.20% of outliers.

Table 4 presents the proportion of each GRDI class present in the Geodiversity index classes.

Table 4 – Proportion between GRDI and Geodiversity index classes, in percentage (%).

Geodiversity index	GRDI				
	Very Low	Low	Medium	High	Very High
Very Low	25,6	31,3	24,0	13,6	5,5
Low	10,4	21,8	33,5	22,7	11,7
Medium	13,0	27,2	31,4	19,3	9,1
High	5,9	22,8	37,6	25,2	8,4
Very High	8,5	17,7	30,0	30,0	13,8

Source: The authors (2018).

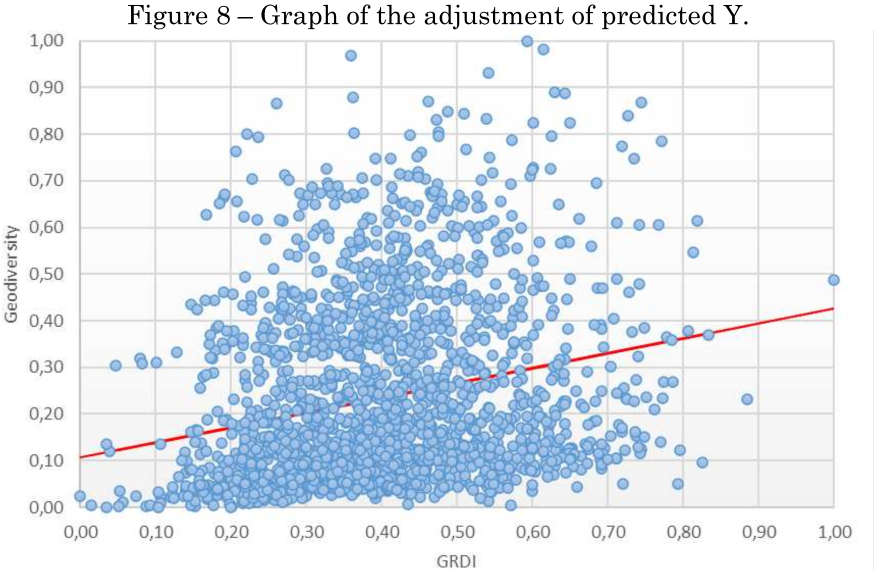
When analyzing the data, it is verified that the basins with Very High and High Geodiversity index are contemplated, respectively, with 13.8% and 25.2% of the Very High and High RGDI classes, appearing that there is no strong correlation between the indices. 25.6% of the Very Low GRDI class is correlated with the Very Low class of geodiversity and 10.4% of the Low class correlates with the Low class of geodiversity.

Analysis of the Geographically Weighted Regression Model

The simple linear regression, applied on a global level using a 95% confidence level, demonstrated that the variables are positively correlated, according to the interpretation of the degree of inclination of the straight line plotted on Figure 5. However, the determination coefficient R^2 adjusted, in which at 0 there is no correlation and at 1 the independent variable explains all the variation in the observations) was very low (0.05), referring to the low capacity of prediction between geodiversity and the GRDI. Thus, this model is not the most appropriate for analyzing the current proposal, especially for dealing with a relationship between variables that behave continuously in space.

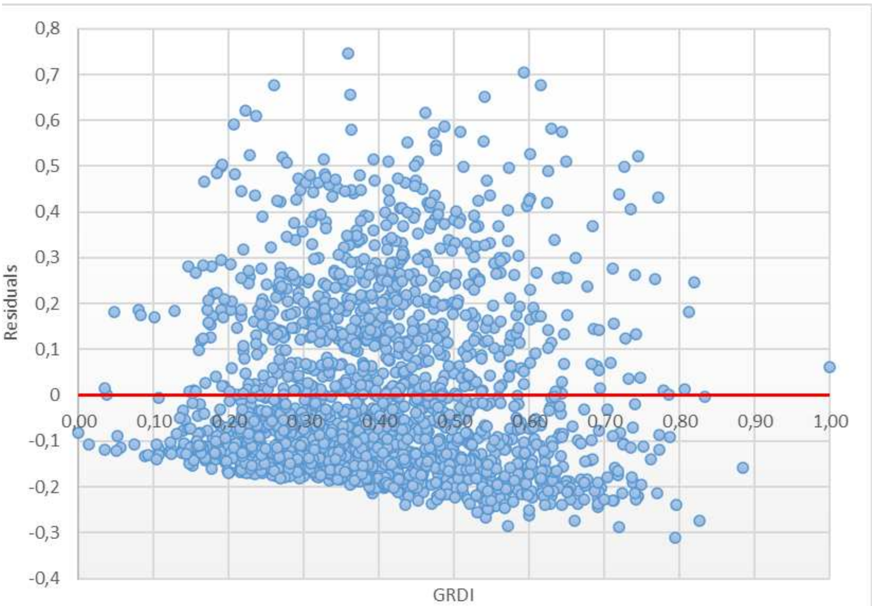
Figures 8 and 9 correspond, respectively, to the plots of predicted Y and the residuals, it being possible to identify the greater dispersion of outliers at geodiversity values above predicted Y. In contrast, the results of the GWR model demonstrated that there are better adjustments at a local level (Figure 10).

Figure 8 – Graph of the adjustment of predicted Y.



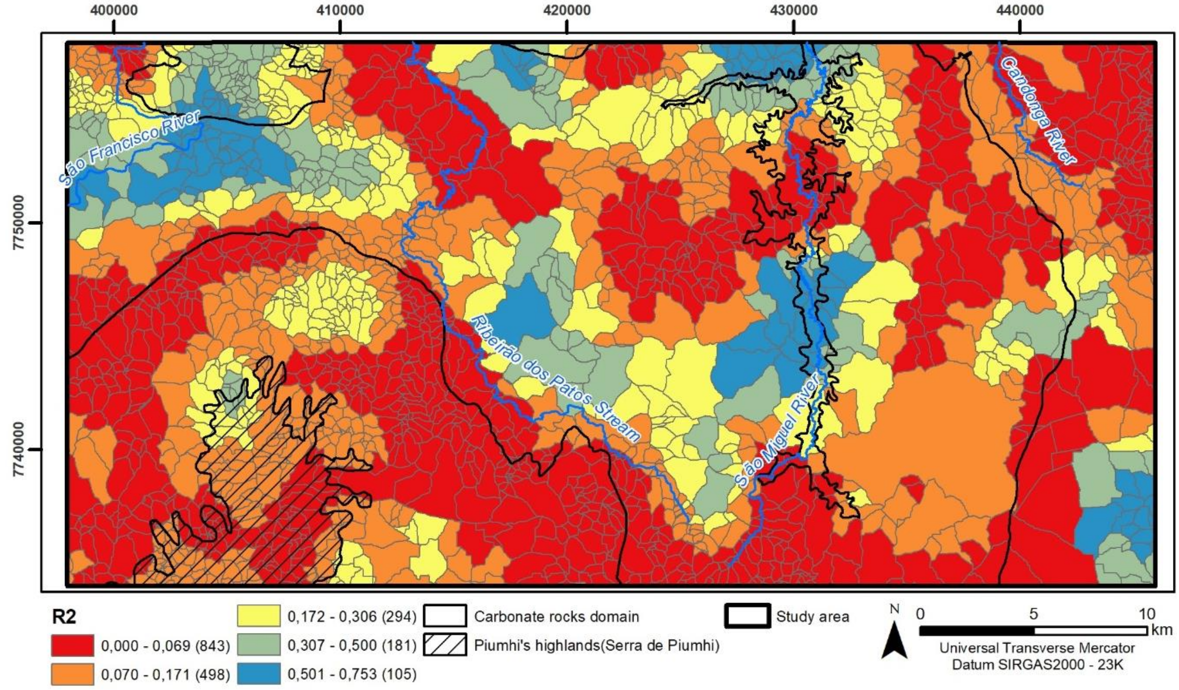
Source: The authors (2018).

Figure 9 – Graph plotting the residuals.



Source: The authors (2018).

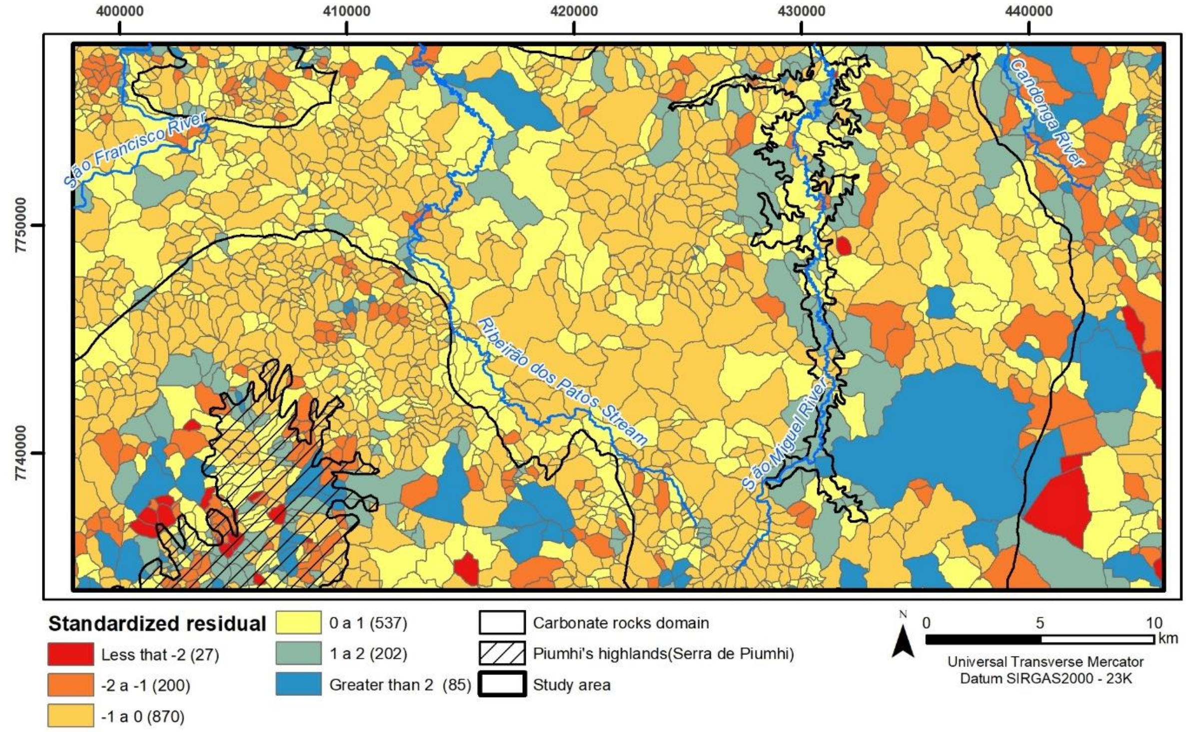
Figure 10 – Spatialization of the Local R^2 of the GWR model of the Arcos-Pains-Doresópolis Karstic Region.



Source: The authors (2018).

In general, it can be inferred that the variation in the GRDI influences the region's geodiversity but cannot explain the model completely. The local R^2 reached a satisfactory level of prediction (above 0.5) in only 5.5% of the basins. Upon visualizing Figure 11, which corresponds to spatialization of the scores of standardized residuals, we can ascertain the discrepancy in the adjustments and, thus, analyze the effectiveness of the model.

Figure 11 – Spatialization of the Standardized Residual of the GWR model of the Arcos-Pains-Doresópolis Karstic Region.



Source: The authors (2018).

The results indicate that 73.24% of the basins have residuals with a standard deviation between -1 and 1, which can be considered acceptable. The basins with much higher geodiversity than the adjustment of predicted Y (14.94%), that is, greater than expected, are found spread across both the existing systems (karstic and non-karstic).

It is supposed that these areas are characterized by variables that are inversely related to high GRDI values, such as alluvial deposits, dolines, and lentic environments (lagoons).

The basins characterized by lower-than-expected residuals (11.82%) are found in scattered groupings, in which the eastern and southern/southwestern portions can be highlighted. In the first portion, the vast majority of the basins have low or very low GRDI. Considering the result of the model, it is supposed that these areas have practically insignificant geodiversity. On the other hand, the basins of the second portion should be analyzed in isolation, given that their GRDI values are considerable.

FINAL CONSIDERATIONS

In this study, it is evident that there are possibilities and advantages to using spatial statistical models in analyses involving abiotic variables, especially when applied to well-defined spatial units. The application of Local Moran's I enabled a better compression of the behavior of the variables by statistically showing the spatial patterns, offering additional information to the regional analyses. The products also demonstrate certain positive local correlations between the variables, being in accordance with the hypothesis presented in the study.

In relation to the Geographically Weighted Regression, the generated data enable isolated analyses, in addition to the identification of similar local behaviors, which resulted in regional groupings. As Lobo et al. (2015) mention, the method makes it possible to compare different regression models, which enables better adjustment of the observed data. As a result, the model generated statistical data, including the local regression index (R^2) and the standardized residual, which reduced the subjectivity of the visual interpretations.

In relation to the hypothesis presented here, it can be observed that the Global Relief Dissection Index cannot explain the behavior of the geodiversity in the study area. It can be inferred that in most basins there are more important variables interfering in the relationship. However, the use of the GRDI is valid in geodiversity research aimed at traditional tropical environments, since the index indicates processes of dissection through pluvial erosion, considering the volume and kinetic energy of the water. It is emphasized that the equation of Serrano and Ruiz-Flanõ (2007) was developed based on non-tropical regions, which may justify the greater influence of the rugosity on the development of geodiversity and the better results than those presented here.

Since the study area is mostly composed of karstic environments, exokarst features and natural cavities were considered in the model, which, in turn, are intrinsically linked to the structure and composition of the carbonate rocks. Furthermore, the karstification process depends on situations that are inversely proportional to the supposition of this article: dependence on smoothed relief for the accumulation and infiltration of water, as Pellitero (2012) explains. Exokarst microfeatures can be found on rugged relief; however, they are associated with outcrops already inserted in the calculation. In this case, the insertion of these variables may lead to overvaluation of the outcrop regions.

It is important to emphasize that this quantification methodology may omit the geodiversity in karstic environments, as it equates cavities of different degrees of relevance and does not consider the geodiversity of the endokarst. Therefore, the use of this methodology does not exclude the need for qualitative analyses and fieldwork.

Another important factor is the quality of the cartographic data regarding its scale of detail. Probably, the use of more refined digital models of terrain (better spatial resolution), in addition to the other variables, could present results more consistent with the hypothesis.

In summary, the rugosity variable acts on the equation as a factor of "cause", providing high geodiversity where there is greater variation in the relief. However, it can generate overvaluation or undervaluation in certain regions, which would probably occur if used in this study. From the practical point of view, it can be said that the use of the coefficient is valid in indirect methodologies (without the use of already mapped variables) and in exploratory research, to quantify unknown regions, especially on less-detailed scales.

REFERENCES

ALMEIDA F. F. M. O cráton do São Francisco. **Revista Brasileira de Geociências**,v. 7: p. 285-295, 1977. https://doi.org/10.25249/0375-7536.1977349364

ANSELIN, L. Local indicators of spatial association - LISA. Geographical Analysis v.27, 1995. Available: http://www.dpi.inpe.br/gilberto/livro/analise/cap5-areas.pdf. Accessed on: Jul. 10, 2018.

BENITO-CALVO, AFONSO et al. Assessing regional geodiversity: the Iberian Peninsula. Earth Surface Processes and Landforms, Burgos, Espanha, n. 34, p. 1433-1445, abr. 2009. https://doi.org/10.1002/esp.1840

BRILHA, J. Inventory and Quantitative Assessment of Geosite and Geodiversity Sites: a Review. **Geoheritage**, n. 2, v. 8, p. 119-134, 2016. https://doi.org/10.1007/s12371-014-0139-3

GILBERT, J.; DANIELPOL, D. L.; Stanford, J. A. **Groundwater Ecology**, v. 1. Academic Press Limited, San Diego, California, p.571, 1994.

GRAY, M. Geodiversity: valuing and conserving abiotic nature. Chichester: Ed. Wiley Blackwell, 2004.

HACK, J. T. Stream-profile analysis and stream-gradient index. **Journal of Research of the United States Geological Survey**, v. 1, n. 4, p. 421-429, 1973.

HJORT, J.; LUOTO, M. Geodiversity of high-latitude landscapes in northern Finland. Elsevier. **Geomorphology**, Oslo, Finlandia, n. 115, p. 109-116, feb. 2010. https://doi.org/10.1016/j.geomorph.2009.09.039

HORTON, R.E. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. **Bulletin of the Geological Society of America Bull**, n.56, p. 275-370, mar. 1945. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

KOT, R. A comparison of results from geomorphological diversity evaluation methods in the Polish Lowland (Toruń Basin and Chełmno Lakeland). Geografisk Tidsskrift-Danish. **Journal of Geography**, v. 118, n. 1, p. 17-35, 2018. https://doi.org/10.1080/00167223.2017.1343673

LOBO, C.; FONSECA; FERREIRA D.; GARCIA, R. A. Verticalização e permeabilização do solo urbano nos setores censitários de Belo Horizonte/MG. **Revista Brasileira de Estudos Urbanos e Regionais**. Recife, v.17, p. 215-228, dez. 2015. http://dx.doi.org/10.22296/2317-1529.2015v17n3p215

LOVELOCK, J. E. Gaia as seen through the atmosphere. **Atmospheric Environment**. 1972. https://doi.org/10.1016/0004-6981(72)90076-5

MADALOSSO, A.; VERONESEV, V. Considerações sobre a estratigrafia das rochas carbonatadas do Grupo Bambuí na região de Arcos, Pains e Lagoa da Prata, MG. **Congresso Brasileiro de Geologia**, Recife, v. 2, n. 30, p. 635-648, jan. 1978.

MAGALHÃES, P. M. Análise estrutural qualitativa das rochas do Grupo Bambuí na porção sudoeste da Bacia do São Francisco. Ouro Preto, p. 1-100 (Tese de Mestrado – Departamento de Geologia da Escola de Minas / Universidade Federal de Ouro Preto, 1989.

MARTINS, T. Mapeamento geomorfológico da folha piumhi, Minas Gerais. 2013. 157 p. Dissertação (Programa de Pós-Graduação em Geografia) - Instituto de Geografia, Universidade Federal de Uberlândia, Uberlândia, 2013. https://doi.org/10.14393/ufu.di.2013.200

MELELLI, L.; VERGARI, F.; LIUCCI, L.; DEL MONTE, M. Geomorphodiversity index: Quantifying the diversity of landforms and physical landscape, **Science of The Total Environment**. 2017. https://doi.org/10.1016/j.scitotenv.2017.01.101

MENEGASSE L. N., GONÇALVES J. M., FANTINEL L. M. 2002. Disponibilidades Hídricas na Província Cárstica de Arcos-Pains-Doresópolis, Alto São Francisco, Minas Gerais, Brasil. **Revista Águas Subterrâneas**, 16: 1-19, 2002. https://doi.org/10.14295/ras.v16i1.1297

PELLITERO, R. O. Geomorfología, paleoambiente cuaternario y geodiversidad en el Macizo de Fuentes Carrionas-Montaña Palentina. Tese de Doutorado, Departamento de Geografia, Universidade de Valladolid, p. 1085, 2012. https://doi.org/10.35376/10324/2495

PEREIRA, E. O.; RUCHKYS, U.; PELLITERO, R. Modelagem da Geodiversidade na Área de Proteção Ambiental Sul da Região Metropolitana de Belo Horizonte MG. **Geonomos**, v. 21, p. 97-101, 2013. https://doi.org/10.18285/geonomos.v21i2.277

PEREIRA E. O.; RUCHKYS, U. A. Quantificação e análise da geodiversidade aplicada ao geoturismo na área de proteção ambiental sul da região metropolitana de Belo Horizonte, Minas Gerais. **Ra'e Ga**, Curitiba, v.37, p.207 - 226, 2016. http://dx.doi.org/10.5380/raega.v37i0.41642

RUBAN, D. A. Geodiversity as a precious national resource: A note on the role of geoparks. **Resources Policy**, Elsevier, v. 53, pages 103-108, 2017. https://doi.org/10.1016/j.resourpol.2017.06.007

RUBAN, D. A.; Yashalova, N. N. Geodiversity meanings in global geoparks: an empirical study. **Environmental Earth Sciences**, v. 77, n. 22, p. 1-8, 2018. https://doi.org/10.1007/s12665-018-7962-9

RUCHKYS, U. A.; CASTRO, P. T. A.; SANTOS, D. J.; BITTENCOURT, J. S. R. Patrimônio em Geossistemas Ferruginosos: Potencial de Uso para o Geoturismo. **Revista Latino-Americana de Estudos em Cultura e Sociedade Revista Latinoamericana de Estudios en Cultura y Sociedad** | Latin American Journal of Studies in Culture and Society, Rio Grande do Sul v. 4, n. 2, 2018. https://doi.org/10.23899/relacult.v4i2.902

SAMPAIO, T. V. M. Parâmetros morfométricos para melhoria da acurácia do mapeamento da rede de drenagem: uma proposta baseada na análise da Bacia Hidrográfica do Rio Benevente –ES. Tese de Doutorado. IGC/UFMG. Belo Horizonte, 2008.

SENA, I. C. Modelagem do potencial geoturístico do Parque Estadual do Sumidouro. 2015. 115 f. Dissertação (Mestrado em Análise e Modelagem de Sistemas Ambientais) - Departamento de Cartografia do Instituto de Geociências, Universidade Federal de Minas Gerais, Belo Horizonte, 2015.

SENA, I.; AZEVEDO, U.; TRAVASSOS, L. E. Geotourism Potential in Karst Geosystems: An example from the Lund Warming Ramsar Site, Minas Gerais, Brazil. **Catena**, 2022. https://doi.org/10.1016/j.catena.2021.105717

SERRANO, E. C.; RUIZ FLAÑO, P. Geodiversidad: Concepto, Evaluación y Aplicación Territorial. El Caso De Tiermes (Caracena). **Boletín de la A.G.E**. n. 45, p. 79-98, 2007.

SERVIÇO GEOLÓGICO DO BRASIL – CPRM. Geologia da folha Piumhi. Brasília, 2008.

SILVA, A. B. Hidrogeologia de Meios Cársticos. Universidade Federal de Minas Gerais, Belo Horizonte,1998.

SILVA, M.L.N., DO NASCIMENTO, M.A.L.; MANSUR, K.L. Quantitative Assessments of Geodiversity in the Area of the Seridó Geopark Project, Northeast Brazil: Grid and Centroid Analysis. **Geoheritage**, 2019. Available: https://link.springer.com/article/10.1007/s12371-019-00368-z. Acessed on: Jun. 10, 2020.

SOCIEDADE EXCURSIONISTA ESPELEOLÓGICA - SEE. **Projeto Arcos Pains Espeleologia** - PROAPE. Área Cárstica de Pains. MPF/Ibama/FEAM/UFOP/FEOP/SEE. DEGEO/EM/UFOP. Ouro Preto, p 549, ago. 2012.

SOUZA, F. E.; FONSECA, B.; COELHO, F. Compartimentação do relevo baseada em parâmetros morfométricos: uma proposta de índice global de dissecação do relevo. I **Congresso Nacional de Geografia Física**, Campinas, v.1, p. 1-12, jul. 2017. https://doi.org/10.20396/sbgfa.v1i2017.2085

TEIXEIRA P. C. D.; DIAS M. S. Levantamento espeleológicos da região cárstica de Arcos, Pains, Doresópolis, Córrego Fundo e Iguatama. **Congresso Brasileiro de Espeleologia**, 27, Januária MG. Anais: 193-199, 2003.

TRAVASSOS, L. E. P. Princípios de Carstologia e Geomorfologia Cárstica. **ICMBio**, Brasília, 2019.

USGS – UNITED STATES GEOLOGICAL SURVEY. Shuttle Radar Topography Mission. Earth Explorer, 2018. Available: https://earthexplorer.usgs.gov/. Accessed on: Jul. 10, 2018.

ZWOLIŃSKI Z. B.; GUDOWICZ J. Geomorphometric analysis of morphoclimatic zones on the Earth. In: Jasiewicz J, 2015. Available: https://geomorphometry.org/wp. Accessed on: Nov. 15, 2022.

AUTHORS CONTRIBUTION

Fabiano Érico Vieira de Souza conceived the study, collected and analyzed the data and wrote the text. Úrsula de Azevedo Ruchkysa, Carlos Lobo and Bráulio Magalhães Fonseca analyzed the data and revised the text.