Geoheritage (2022) 14:92
https://doi.org/10.1007/s12371-022-00724-6

ORIGINAL ARTICLE

A Speleological Relevance Assessment Protocol Based on the Geodiversity of Natural Underground Cavities in Different Lithotypes in Brazil

Laís Luana Massuqueto[1,2,4] · Henrique Simão Pontes[1,2,4] · Luiz Alberto Fernandes[3,4]

Received: 16 September 2021 / Accepted: 1 August 2022

Abstract
An assessment protocol of speleological relevance for natural underground cavities in different Brazilian lithotypes is presented here based on geodiversity elements. The protocol, whose development is based on geoconservation guidelines, aims to contribute to better national speleological legislation regarding determination of speleological relevance. For this purpose, four elements of geodiversity present in natural cavities are considered: their set of geological features (geoforms), their development patterns (shape), dimensions, and hydrological elements. In order that the protocol can be applied in a judicious way, nine analytical parameters are conceptualized here with their weights and contributions numerically defined. The protocol should not, however, be seen as definitive, but a proposal subject to review and update.

Keywords Caves · Inventory · Quantitative assessment · Geoconservation · Speleological law

Introduction

In the definition adopted by the International Union of Speleology (IUS) and the most internationally used one (Piló and Auler 2013), a cave consists of a natural opening in the rock below the surface of the terrain, large enough for human visitation. In Brazilian law, a cave corresponds to "natural underground cavity, any and all underground space accessible by humans, with or without an identified opening, popularly known as cave, grotto, hanging wall, burrow, abyss, pit or hole including the environment, mineral and water content, fauna, flora and rocky body where they are inserted, as long as formed by natural processes, regardless of their dimensions or type of embedding rock" (Brasil 2008).

✉ Laís Luana Massuqueto
lais.massuqueto@gmail.com

1 Grupo Universitário de Pesquisas Espeleológicas (GUPE), Ponta Grossa, Paraná, Brazil

2 Departamento de Geociências da Universidade Estadual de Ponta Grossa (UEPG), Ponta Grossa, Paraná, Brazil

3 Programa de Pós-Graduação em Geologia da Universidade Federal do Paraná (UFPR), Curitiba, Paraná, Brazil

4 Grupo de Pesquisa, CNPq Geoconservação e Patrimônio Geológico, Curitiba, Paraná, Brazil

According to Auler and Piló (2019), caves result from different processes acting on different lithotypes, with large morphological variability. The same authors point out that the cavities can be *primary*, when developed concurrently with the rocks in which they occur, or *secondary*, when subsequently generated, being classified according to their exogenous or endogenous forming agents.

In Brazil, 22,244 underground cavities are inventoried according to statistical reports from the National Register of Speleological Information (*Cadastro Nacional de Informações Espeleológicas*) (CANIE 2021) compiled by the National Cave Research and Conservation Center of the Chico Mendes Institute for Biodiversity Conservation (ICMBio). Of these, 98.9% were developed in carbonate (68.5%), ferriferous (19.5%), siliciclastic (9.9%), and granitic (1%) rocks.

In order to protect such speleological heritage, Decree 99.556/1990, the main Brazilian speleological legal framework, states that caves in Brazilian territory must be protected for purposes of technical-scientific studies and speleological, ethnic-cultural, touristic, recreational, and educational activities (Brasil 1990).

Still regarding legislation, Decree 6.640/2008 and its Normative Instruction 2/2017 (the latter into force after revocation of Normative Instruction 2/2009) substantially modified Decree 99.556/1990 by standardizing the use, suppression, and conservation of Brazilian natural underground cavities according to their degree of speleological relevance (maximum, high, medium, and low). Only caves of maximum relevance have their integrity protected by law. However, such a standardization is a main target of criticism by researchers and members of the speleological community as no underground cavity could be suppressed before its establishment in 2008.

In Brazil, the federal government is responsible for the national assets based on concrete conservation measures while ensuring economic development conditions for cave-bearing regions, always with a view to environmental sustainability (Ganem 2009). Thus, according to that author, establishing the legal status of an underground cavity as national property implies restrictions on property rights, the use of such environments requiring previous environmental licensing studies.

That said, if in theory Decree 6.640/2008 lists a series of characteristics and attributes to be taken into account for purposes of environmental licensing, in practice flaws and gaps are present in its normative regulations. As they address suppression of natural underground cavities of high, medium, and low relevance, these legal devices should not present gaps or margins for subjectivity that would turn such sites irreversibly susceptible to negative impacts.

The speleological relevance of a site must be categorized based on several biological, ecological, geological, paleontological, hydrological, scenic, historical-cultural, and socioeconomic aspects representative of their notoriety, uniqueness, expressiveness, representativeness, and significance, which conveys ecological, scientific, and cultural values to be preserved or compensated elements (Berbert-Born 2010).

However, the assessment protocol enshrined in the Brazilian legislation underestimates geodiversity regarding the relevance of caves in speleological environmental licensing. Lithological variety is responsible for a large underground geodiversity, which includes common or rare, larger, or smaller features formed by distinct and specific genetic processes in response to rock differentiation.

Since the Brazilian speleological legislation itself provides for constant updates of the assessment methods that are applied to speleological relevance, an assessment protocol is presented here including geoconservation guidelines for natural underground cavities in different lithotypes. The protocol, which is based on the assessment of geodiversity, aims to improve the national speleological legislation. Four aspects of underground geodiversity are considered in determining their relevance. Biological, archaeological, paleontological, and cultural aspects were purposely left out since the protocol refers to geodiversity issues.

Methods

Based on geodiversity inventory and assessment methods proposed for natural cavities and surface environments, the present study starts with a critical analysis and possible adaptations of models such as those presented by García-Cortés et al. (2000), Dias (2003), Gray (2004; 2005), Brilha (2005), Pereira (2006), White and Mitchell (2006), Harley et al. (2011), García-Cortés et al. (2012; 2014), Lobo and Boggiani, (2013), Oliveira-Galvão and Costa-Neto (2013), Hjort et al. (2015), Brilha (2016), GUPE (2017), and Pontes et al. (2018). The protocol also employs, in a critical and reconstructive manner, the standard for assessing the speleological relevance of caves in Appendix II of Normative Instruction 02 of 08/30/2017 from the Brazilian Ministry of the Environment (*Ministério do Meio Ambiente*) (MMA 2017).

According to the nomenclature used in the speleological relevance assessment protocol presented here, *aspects* are the components of the underground geodiversity, which include development pattern (shape) and dimensions, geological features, and hydrological elements of cavities. *Components* are aspect elements such as the geological features (ducts, alveoli, speleothems, and already mentioned ones) and hydrological elements (water courses, drips, accumulations); *attributes* correspond to the particularities of each component (scientific value, dimensions, rarity, etc.) chosen for assessment; *parameters* are standards and criteria by which attributes are assessed (high, medium, low, common, unusual, etc.); *weights* are numerical values ranging from 0 to 4 points assigned to the parameters. Finally, *contribution* refers to the percent contribution of each weight to the final relevance value, which only applies to geodiversity aspects in the final relevance score of the cavity.

The criteria to defining the attributes evaluating parameters must be defined based on critical discussions among the researchers who are applying the protocol. With this, we seek to avoid problems, such as not assigning scientific value to a particular place due to the lack of studies, because the absence of research, by itself, does not mean low scientific importance.

The protocol presented here was developed based on the study of caves in carbonate, siliciclastic, granitic, and ferriferous rocks. Of the Brazilian underground cavities, 98.9% are in rocks of these four types. The studied caves correspond, therefore, to a relevant geodiversity sampling of the national speleological context.

Characterization forms for the geological features in the studied caves were submitted to assessment and contribution by speleologists from all over Brazil, including 36 researchers, 27 speleology groups, and 22 speleological licensing companies. The knowledge contributed by the national speleological community supports the selection of the aspects and components of underground geodiversity that are relevant to the assessment of speleological relevance of Brazilian natural cavities.

Results and Discussion

Aspects of Underground Geodiversity and the Attributes by which Their Speleological Relevance Is Assessed

Natural underground cavities show peculiarities that are typical of the different lithotypes in which they develop. For this reason, four aspects are considered for determining the degree of speleological relevance. These aspects are described below, together with their assessment attributes and procedures.

Geological Features

Identification and detailed characterization of underground geological features found in caves makes permits to derive important information about these environments, such as speleogenesis, hydrogeological dynamics, evolution of the landscapes in which cavities develop, and stratigraphic aspects of the surrounding rocks.

In order to determine the speleological relevance of an underground cavity, it is essential that a previous inventory of its geological features be carried out. This includes detailed surveying not only of galleries, halls, and passages, but also of small corners and recesses as these protected areas may host unique features (Box 1).

From previous information, bibliographic research and responses to semi-open qualification forms sent to speleologists, 23 types of geological features were identified in Brazilian caves. However, after further field research in four study areas, the total list of feature types has been expanded.

The inventoried features correspond to 30 components distributed among four groups: speleothems, speleogens/weathering features, geological structures, and clastic deposits. Features are classified as primary or secondary according to their temporal relations with the rock substrate. Geological structures are mostly primary, i.e., generated concurrently with the host rock, including stratigraphy, contacts, ichnofossils, and fossils (which may also be of secondary origin). Speleothems, different types of speleogens, tectonic structures, and slickensides are examples of secondary features.

Known the 30 different geodiversity components, identification and listing of the geological features present are the first steps toward assessing the speleological relevance of an underground cavity. With these initial elements, nine attributes are assessed according to the parameters presented in Table 1. These parameters, which are mathematical and represent the scale of magnitude or presence/absence of each component, define the attributes by which the degree of importance of each feature is determined. A detailed characterization of the attributes involved in the assessment protocol is presented below.

Box 1 Classification of the geological features found in Brazilian caves.

Group	Component
Speleothems	Secondary mineral deposits
Speleogens/weathering features	Dissolution conducts (*canaliculi*)
	Dissolution domes (bell-holes, out-lets)
	Domes (out-lets)
	Equilibrium chimneys (out-lets)
	Cave skylights
	Alveoli (*tafoni*/honeycomb)
	Ceiling vents (meanders, half-tubes)
	Wall vents (half-tube)
	Scallops
	Feeders
	Incrustations
	Anastomosis
	Vertical grooves (whale bristles)
	Pendants
	Pillars
	Landings
	Pots
	Boxworks
	Phantomized/arenized rock (phantomization, alterite)
	Exfoliation
	Paleo-level
Geological structures	Culverts
	Faults/fractures
	Slickensides
	Stratigraphical aspects
	Contacts
	Ichnofossils
	Fossils*
	Enclaves
Clastic deposits	Consolidated or unconsolidated detrital deposits
Primary features*	Secondary features*

Scientific Value

Geological features of scientific value found in natural underground cavities are also of intrinsic educational value. Understanding these important paleoenvironmental records possibilitates to know, interpret, and reconstruct the evolutionary history of underground or surface environments in which they developed. Features recognized as being of scientific value are those that best represent a particular material and/or characteristic (rock, mineral, sediment) or geological process and that are preferably in good preservation conditions.

In assessing the scientific value of an underground feature by using the protocol adapted from Brilha (2016), representativeness (the ability to better illustrate unique geological characteristics or processes), reference (stratigraphic, mineralogical, paleoenvironmental, paleoclimatic), degree of scientific knowledge (studies published on the theme emphasizing the importance of the feature), diversity (presence of different geological components of scientific interest), didactic relevance, and, finally, integrity (degree of preservation) are highlighted.

Rarity

Rare features are those of almost single occurrence. As geodiversity features can be uncommon in certain lithotypes, greater weight is attributed to the type of rock in which the geoform developed. Another factor totally related to rarity, especially in the case of speleothems, is the mineral composition. There are situations in which secondary mineral deposits correspond to infrequent or even absent mineral forms in the surrounding rock.

It should be stressed that the rarity of a feature manifests itself in varying degrees. When the feature is unique, no other specimen exists in the same geological context or even in different lithotypes. Atypical features are those that are difficult to find in a given lithology. When features of the same type are present in relatively insufficient numbers, they are said to be scarce. The state of preservation of a feature can also influence the assessment of the rarity attribute since the more preserved from natural or anthropic processes, the greater its importance.

Model Features

A feature capable of serving as an example or reference in the interpretation of speleogenetic processes, underground dynamics, or even general traits of the embedding rocks is known as a model feature. Such features generally constitute important paleoenvironmental records that also assist in the understanding, interpretation, and reconstruction of the evolutionary history of surface environments.

Features such as those resulting from upward flow constitute morphological groups because they are formed over the same period of time by the action of the same genetic process (Klimchouk 2007, Klimchouk and Ford 2009). Such situations involve association of geological features and should be considered when evaluating this attribute.

The degree of preservation is an important valuation factor because a feature must be in good observation conditions to be considered as a model. Thus, features damaged by weathering or anthropic action may cease to be illustrative of their formative processes. From an educational point of view, model features are didactic and necessarily of scientific value.

Association with Other Elements

In order to identify geosystemic, ecosystemic, and other situations related to archaeological, historical, and cultural contexts, direct association among a feature and biological, hydrographic, or climatic elements that are internal or external to the cave environment is considered an assessment attribute in the protocol discussed here.

Some speleothems may show evidence of microbial metabolic mediation in their mineral precipitation. Association among speleothems and paleoclimatic indicators is another common situation that should be highlighted. Geological features in archaeological sites constituting lithic workshops and surfaces with rock inscriptions are examples of such associations.

Number

Number refers to the extent to which instances of a given geological feature occupy an underground cavity. In order for this attribute to be evaluated, the magnitude of accumulation and the spatial distribution of the geoform must be known.

Dimensions

Dimensions refer to the proportions of magnitude of a feature, which can be measured in terms of length, width, height, diameter, perimeter, area, horizontal projection, linear development, gaps, volume, or mass. Dimensions is another attribute whose assessment must consider the type of embedding rock, even in unusual situations such as those of lithotypes less subject to the development of caves, or those with rare development of the analyzed feature. The extension of the studied area (including situations of geographic isolation) must also be taken into account.

Composition

Composition refers specifically to the type of rock in which the feature developed. In speleothems, not only the type of rock, but also the mineral constitution of the feature must be evaluated. Composition should be categorized as common or unusual, infrequent situations being considered the more relevant ones.

As constitution is a determining factor to the feature's rarity and dimensions, the speleological relevance of compositional elements must be assessed considering these attributes.

Oddity

Oddity refers to features that differ from what is commonly expected. This attribute must be inferred based on the shape and visual aspect of the feature. In the assessment of oddity, situations commonly known in to be present in the lithotype (and area) under study must be considered, together with the element's composition and rarity.

Spatialization

Evaluated by its distribution relative to the total extension of the cave, a feature is categorized as being of *pervasive* spatialization when it is distributed across all galleries and halls. The feature is *dispersed* when it occurs over specific areas of the cave, and it is *restricted* when it occurs in a specific area.

It is important to emphasize that spatialization itself does not relate to the number of occurrences of a feature. Spatialization thus differentiates between geoforms of marked or reduced presence that occur concentrated or scattered across the cave environment. The more widely distributed a feature is, the greater the relevance assigned to it.

Assessment of the Geological Features Aspect

After detailed cave recognition, nine attributes must be assessed for each geological feature found according to the parameters and weights that are shown in Table 1. The individual relevance of each feature corresponds to the general sum of values for each attribute. This being done, the relevance of the geoform can be categorized according to the reference values in Table 2.

As mentioned above, a total of 30 geological features can be assessed individually, with a maximum value of 27 points

Table 1 Attributes, parameters, and weights in the assessment of geological features in natural underground cavities

Attribute	Parameter	Criteria	Weight	Results
Scientific value	High	When there are many important scientific publications or, in case of publications absence, when a group of experts define its importance, based on representativeness, diversity, didactic relevance, and integrity	3	
	Medium	When there are at last one scientific publication or, in case of publications absence, when a group of experts define its importance, based on representativeness, diversity, didactic relevance, and integrity	2	
	Low	When there are no scientific publications, provided that this classification is consensual among a group of experts	1	
Rarity	Present	When the occurrence is unique or uncommon	3	
	Absent	When the occurrence is common and frequent	0	
Model feature	High	Is the best example or reference in the interpretation of processes, dynamics, or products	3	
	Medium	Is a good example or reference in the interpretation of processes, dynamics, or products, but the state of conservation is not good	2	
	Low	Is not the best example or reference in the interpretation of processes, dynamics, or products, provided that this classification is consensual among a group of experts	1	
Association with other elements	Present	Is associated with other elements	3	
	Absent	No association with other elements	0	
Number	High	Presents several occurrences of the geological feature	3	
	Medium	Presents some occurrences of the geological feature	2	
	Low	Presents few occurrences of the geological feature	1	
Dimension	Large	Present large dimension considering the type of embedding rock and unusual situations	3	
	Medium	Present medium dimension considering the type of embedding rock and unusual situations	2	
	Small	Present small dimension considering the type of embedding rock and unusual situations	1	
Composition	Distinct	The existence of a certain geological feature in this rocky substrate or with this mineral composition is considered unusual or rare	3	
	Common	This composition is often found elsewhere	0	
Oddity	Yes	A different shape and/or visual aspect of the geological feature is present	3	
	No	The shape and/or visual aspect of the geological feature is common	0	
Spatialization	Pervasive	Is widely distributed throughout the cave	3	
	Irregular	Occurs sparsely	2	
	Restrict	Only occurs at a single point	1	
Individual relevance (Sum)				

Table 2 Reference values for determining the individual relevance of a geological feature

Score	Relevance
> 24 points	Maximum
16 to 23 points	High
8 to 15 points	Medium
0 to 7 points	Low

being assigned to each of them according to the total sum of values in Table 1. In order to have the final set of reference values for relevance assessment (Table 3), the numerical range of each class of relevance has to be calculated based on the number of features identified in the cave according to Eq. (1).

$$
\begin{aligned}
VRi &= \frac{NFi \times Vm}{Cr} \\
VRi &= \frac{NFi \times 27}{4} \\
VRi &= \frac{30 \times 27}{4} \\
VRi &= \frac{810}{4} \\
VRi &= 202{,}5
\end{aligned}
\tag{1}
$$

In which:

VRi is the reference value for the interval,

NFi is the number of identified features,

Vm is the maximum total sum of the individual relevance values for the geological feature (27 points), and.

Cr is the number of relevance categories (4: maximum, high, medium, and low).

Thus, in a hypothetical situation in which occurrences of the 30 different feature types listed were identified in the same cave, the total number of features would be multiplied by 27 (the maximum score of individual relevance). The final result would correspond to a maximum of 810 points. As relevance is categorized into four levels (maximum, high, medium, and low), the reference interval between each level would be obtained by dividing the maximum score (810) by 4, the result being rounded down (relevance < 0.5) or up (relevance ≥ 0.5) to the nearest integer.

Table 3 Reference values for determining the relevance of geological features in caves, applied to a hypothetical case in which all 30 known geoforms are to be classified

Score	Relevance
> 612 points	Maximum
408 to 611 points	High
204 to 407 points	Medium
0 to 203 points	Low

Shape (Development Pattern) of a Natural Underground Cavity

The pattern of development of a cave is directly related to the planimetric layout of its ducts, passages, and halls. The longitudinal profile and the cross-section of the galleries are also characteristics to be considered.

Regarding shape, six attributes must be evaluated according to the parameters presented in Table 4, which represent a scale of magnitude, presence, or absence. The attributes of morphological assessment (development pattern) of underground cavities are described in detail below.

Scientific Value

In order to assess the scientific value of a speleological shape (development pattern), the same principles applied to the scientific valuation of geological features must be taken into account. Elements such as representativeness, reference, scientific knowledge, diversity, didactic relevance, and integrity must be considered when assessing this attribute (Brilha 2016).

The development pattern is useful in interpreting speleogenetic processes and the evolution of landforms. The forms that best represent the geological processes are considered of scientific value. The combined set of caves, with their shapes and arrangement configuring a karst system, also should be considered relevant.

Rarity

Rare development patterns are those uncommonly found in cave halls. According to Auler and Piló (2019), the different planimetric patterns of underground cavities (dendritic, reticular, anastomotic, ramiform, or spongiform) and the different shapes revealed in cross-sections and longitudinal profiles of cave halls must be analyzed. As with the rarity of a geological feature, this attribute must be evaluated considering mainly the type of rock into which the cave developed.

Development Pattern Model

Development patterns that are able to serve as illustrative examples or references in the interpretation of speleogenetic processes or evolutionary dynamics of underground cavities are referred to as *model development patterns*. Such elements are generally of educational, didactic, or scientific value. Given that certain patterns of development can be rare in some lithotypes, the assessment of this attribute must consider the type of rock in which the cavity developed.

Association with Other Elements

Situations in which the shape of the cavity is directly related to biological, hydrographic, climatic, or other internal or external aspects are assessed by the attribute *association with other elements*. Like in caves whose galleries have been opened or expanded for mining, historical and cultural components must be taken into account.

Composition

The composition of a feature refers specifically to the type of rock in which the cavity developed. Like geological features, composition is classified as common or unusual, with greater relevance being attributed to infrequent situations. Contrary to the case of iron formations, for example, spongiform morphometric patterns are uncommon in granite, quartzite, gneiss, or sandstone.

Oddity

Oddity refers to cases in which the characteristics determined by the development pattern of the cave differ from what is normally expected. In evaluating the relevance of a cavity, its morphometric pattern peculiarities as distinguished from what is observed cavities in the same type of rock in the study area must be taken into account. For example, ducts and groundwater galleries with rounded cross-sections, which are uncommon in granitic rocks, may constitute an oddity situation in a given cavity.

Relevance of the Shape Aspect (Development Pattern) in Natural Underground Cavities

Only after speleological mapping can a natural underground cavity have the relevance of its development patterns assessed based on the attributes, parameters, and weights shown in Table 4.

Table 4 Attributes, parameters, and weights in the assessment of shape (development pattern) relevance in natural underground cavities

Attribute	Parameter	Criteria	Weight	Results
Scientific value	High	When there are many important scientific publications or, in case of publications absence, when a group of experts define its importance, based on representativeness, diversity, didactic relevance, and integrity	3	
	Medium	When there are at last one scientific publication or, in case of publications absence, when a group of experts define its importance, based on representativeness, diversity, didactic relevance, and integrity	2	
	Low	When there are no scientific publications, provided that this classification is consensual among a group of experts	1	
Rarity	Present	When the occurrence is unique or uncommon considering mainly the type of rock into which the cave developed	3	
	Absent	When the occurrence is common and frequent considering mainly the type of rock into which the cave developed	0	
Development pattern model	High	Is the best example or reference in the interpretation of speleogenetic processes or evolutionary dynamics of underground cavities	3	
	Medium	Is a good example or reference in the interpretation of speleogenetic processes or evolutionary dynamics of underground cavities	2	
	Low	Is not the best example or reference in the interpretation of speleogenetic processes or evolutionary dynamics of underground cavities, provided that this classification is consensual among a group of experts	1	
Association with other elements	Present	Is associated with biological, hydrographic, climatic, or other internal or external aspects	3	
	Absent	No association with other elements	0	
Composition	Distinct	The type of rock in which the cave developed is considered unusual or rare	3	
	Common	The type of rock in which the cave developed is considered common	0	
Oddity	Yes	A different shape and/or visual aspect of the cave development pattern is present	3	
	No	The shape and/or visual aspect of the cave development pattern is common	0	
Form (development pattern) relevance (Sum)				

Once the relevance value of each shape attribute has been determined and summed, the speleological relevance of the cave's development pattern is determined based on the elements presented in Table 5.

Dimensions of a Natural Underground Cavity

This aspect is directly related to the extension of the cave (galleries, halls, entrance, chasms). It should be noted that small dimensions do not imply low relevance. For this reason, in addition to the dimensions attribute, composition and rarity are evaluated following the specifications presented below.

Composition

Composition refers to the type of rock in which the cavity developed. As in the case of geodiversity features, composition is distinguished between common and unusual, with low-frequency situations being assigned higher relevance scores.

Extension

Extension refers to the magnitude proportions of a natural underground cavity, which are established in terms of length, width, height, diameter, perimeter, area, horizontal projection, linear development, topographic gaps, and volume. Extension is another attribute that must be evaluated together with the type of embedding rock, taking also into account unusual situations such as lithotypes that are less likely to occur in natural cavities and the study area covered (including geographic isolation situations).

Table 5 Reference values in the shape (development pattern) relevance assessment of a cave

Score	Relevance
> 15 points	Maximum
10 to 14 points	High
5 to 9 points	Medium
0 to 4 points	Low

Rarity

Considering mainly the cavity's lithotype, rare situations are those in which the dimensions of the cavity (linear development, topographical gap, volume, etc.) are uncommon and stand out from the surroundings in the same geological unit.

Relevance of the Extension Aspect of a Natural Underground Cavity

As in the assessment of development patterns, establishing the relevance of an underground natural cavity extension based on the attributes, parameters and weights in Table 6 depends on previous speleological mapping.

Once determined and summed up the relevance scores for the different assessment attributes, the relevance of the extension of the cave is determined from the score ranges in Table 7.

Hydrological Elements

The hydrological elements of a natural underground cavity include its natural water courses, accumulations and/or barriers, infiltration processes, dripping, and falls (perennial, intermittent, or ephemeral). The three attributes to be assessed in determining the relevance of hydrological elements in natural cavities are detailed below.

Table 6 Reference values for determining the relevance of each extension attribute in natural underground cavities

Attribute	Parameter	Criteria	Weight	Results
Rarity	Present	When the dimensions are unique or uncommon considering mainly the type of rock into which the cave developed	3	
	Absent	When the dimensions are common and frequent considering mainly the type of rock into which the cave developed	0	
Extension	Large	Has large dimensions considering its geological context and unusual situations	3	
	Medium	Has medium dimensions considering its geological context and unusual situations	2	
	Small	Has small dimensions considering its geological context and unusual situations	1	
Composition	Distinct	The type of rock in which the cave developed is considered unusual or rare	3	
	Common	The type of rock in which the cave developed is considered common	0	
Relevance of cave dimensions (Sum)				

Table 7 Reference values for determining the relevance of the extension of a natural underground cavity

Score	Relevance
9 points	Maximum
6 to 8 points	High
3 to 5 points	Medium
0 to 2 points	Low

Extension

Extension refers to the proportions of magnitude of the hydrological elements of a natural underground cavity, which can be measured in terms of length, width, height, diameter, perimeter, area, horizontal projection, linear development, topographic gap, volume, or flow. Regarding hydrological elements, analysis of the extension attribute must follow the principle of proportionality, considering also the extension of the cavity and the type of rock in which it developed.

Number

In determining the number of instances of hydrological elements present in a natural cavity (lakes, rivers, waterfalls, rapids, drips etc.), the magnitude of accumulation must be taken into account regardless of spatial distribution, because the objective is to quantify the different types of hydrological elements, regardless of their dimensions or distribution in the cave.

Spatialization

Hydrological elements have their spatial distribution assessed in relation to the total extension of the cavity as *pervasive*, when they are present in all galleries and halls; *irregular*, when they are spread over specific areas; or *restricted*, when they only occur in a specific area of the underground environment. It is important to stress that this attribute does not relate to the number of occurrences.

Relevance of the Hydrological Elements Aspect

After thorough surveying of the underground cavity, three hydrological attributes are assessed in terms of relevance according to the parameters and weights presented in Table 8. The individual relevance of a hydrological element is given by the sum of values determined for each attribute. Subsequently, the individual relevance of the hydrological element is determined from the reference values presented in Table 9.

As there are three types of hydrological elements to be evaluated, the sum of individual relevance values is used for the final assessment of this aspect of geodiversity according to the reference values shown in Table 10.

Final Relevance Assessment of Underground Geodiversity

Once individual relevance scores of the different geodiversity aspects are determined, the final relevance score is obtained by applying the reference values presented in

Table 9 Reference values for determining the individual relevance of hydrological elements in underground cavities

Score	Relevance
9 points	Maximum
6 to 8 points	High
3 to 5 points	Medium
0 to 2 points	Low

Table 8 Reference values for determining the relevance attributes of hydrological elements in underground cavities

Attribute	Parameter	Criteria	Weight	Results
Extension	Large	Has large extension of hydrological elements considering the principle of proportionality, based on the extension of the cavity and the type of rock in which it developed	3	
	Medium	Has medium extension of hydrological elements considering the principle of proportionality, based on the extension of the cavity and the type of rock in which it developed	2	
	Small	Has small extension of hydrological elements considering the principle of proportionality, based on the extension of the cavity and the type of rock in which it developed	1	
Number	High	Presents several occurrences of the hydrological elements	3	
	Medium	Presents some occurrences of the hydrological elements	2	
	Low	Presents few occurrences of the hydrological elements	1	
Spatialization	Pervasive	Is widely distributed throughout the cave	3	
	Irregular	Occurs sparsely	2	
	Restrict	Only occurs at a single point	1	
Individual relevance of the geodiversity feature (Sum)				

Table 10 Reference values for determining the final relevance of hydrological elements in underground cavities

Score	Relevance
> 23 points	Maximum
16 to 22 points	High
8 to 15 points	Medium
0 to 7 points	Low

Table 12 Reference values for the final relevance of geodiversity aspects of an underground cavity

Score	Relevance
76 to 100 points	Maximum
51 to 75 points	High
26 to 50 points	Medium
0 to 25 points	Low

Table 11. Partial results are obtained by multiplying the weight attributed to each aspect by the respective contribution value.

The final relevance score is obtained from the average of partial results. The final result is then categorized according to the intervals shown in Table 12 to establish the relevance of geodiversity aspects as maximum, high, medium, or low. The contribution of geodiversity (60% for geological features, 10% for dimensions; 10% for shape/pattern of development and 20% for hydrological aspects) is mathematically determined from the proportions of occurrence among the different elements of each aspect.

Geological features involve 30 components. Hydrological elements involve three components. Shape (development pattern) and dimensions involve one component each. In total, 35 components are considered. Calculated the mathematical proportions among elements and their contributions, it turns out that geological features contribute 85.71% of the total score, while shape (development pattern) and dimensions contribute 2.86% each. Hydrological elements account for 8.57% of the total.

Table 11 Reference values for the relevance of geodiversity aspects in underground cavities

Geodiversity aspect	Parameter	Weight	Contribution	Result
Features	Maximum	4	60%	
	High	3		
	Medium	2		
	Low	1		
Extension	Maximum	4	10%	
	High	3		
	Medium	2		
	Low	1		
Shape (development pattern)	Maximum	4	10%	
	High	3		
	Medium	2		
	Low	1		
Hydrogeological aspects	Maximum	4	20%	
	High	3		
	Medium	2		
	Low	1		
Relevance of geodiversity aspects (Sum)				

However, due to the low final scores obtained from the occurrence proportions (number of components/contribution), a direct qualitative correction was applied to the contribution values in order to highlight the contributions of shape (development pattern), dimensions, and hydrological elements. These aspects are important in the assessment of underground geodiversity, a correction of values being necessary to prevent disproportionate contributions from directly influencing final scores of speleological relevance.

Conclusions

Defining a geodiversity assessment protocol is inherently complex. Initially, the difficulty lies in establishing the level of importance of each geodiversity element based on numerical values. Also, many geoscientists do not consider relating numerical values to the relevance of natural heritage as the ideal option, mainly due to the subjectivity that is inherent to this type of analysis. However, qualitative assessments can lead to subjective results. A researcher can be influenced by the object of analysis itself and by various surrounding phenomena and processes, which degrades interpretative and evaluative impartiality.

However, since geodiversity also represents an economic value that is essential to human needs (such as energy, iron, steel, lime, cement, and sand, among others), natural underground cavities constitute assets involved in the exploitation of natural resources. This impacts such environments even to the point of complete suppression. Demands related to human development will not cease to exist since the demand for natural resources is continuous. In this context, a protocol for the assessment of natural elements is necessary by which the most relevant areas to be protected can be selected.

As the Brazilian speleological legislation provides for constant updates of the speleological relevance assessment methods, this article presents a protocol based on a set of criteria and formal concepts to be observed in the assessment of relevance for natural underground cavities in terms of geodiversity. The main purposes of this protocol are to present geoconservation guidelines, to reduce subjectivity in the assessment of relevance, and to be a protocol that comprehensively contemplates natural underground cavity geodiversity.

Subjectivity is inherent to any and all forms of natural heritage assessment. Four cave geodiversity aspects are assessed: geological features (30 currently known geoforms), shape (development pattern), dimensions, and hydrological elements (water courses, lakes, waterfalls, infiltration/dripping). Inventory and geodiversity analysis must be carried out by a team of researchers. Critical discussion of results brings different readings and interpretations that consequently lead to lesser degrees of subjectivity in the final scores of relevance of the underground cavities.

For this manuscript, examples were intentionally not presented for the chosen parameters, as it is understood that the team of researchers who apply this method of evaluation must know the lithological context in which the underground cavity is inserted, including other cavities in addition to the one being evaluated. Therefore, the evaluator will have a comparative context to more securely define the evaluation parameters (such as high, medium, low, common, distinct, small, medium, and large, among others) and their respective weights.

The assessment protocol discussed here can serve several purposes: environmental licensing, selection of high conservation value areas, support for the creation of protected areas, management of touristic value cavities, and different types of land zoning and management. In addition, it also provides a type of underground geodiversity assessment that might be applied to caves in various regions of the world.

The results achieved could support proposals for updating the Brazilian speleological legislation in terms of how it categorizes speleological relevance. However, it is essential that the protocol discussed here undergo critical analysis by researchers, especially geoscientists. It is expected that the protocol will also undergo constant review and updating in order to follow the advances in knowledge on the topic, thus aiming to reduce as much as possible the errors and gaps that are common in this type of analysis.

It is important to mention that the recent Federal Decree 10.935, of January 12, 2022, revoked Federal Decree 99.556/1990, which includes Federal Decree 6.640/2008 and its normative instruction 2/2017. This is a setback to the issue of protection of Brazilian speleological heritage since extremely relevant caves, for example, could be destroyed. However, an action in the Federal Supreme Court regarding this change in legislation resulted in the temporary loss of the effects of Federal Decree 10.935/2022 and, until a decision to the contrary, Federal Decree 99.556/1990 remains in force.

Acknowledgements The first author thanks the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES) for a Doctoral scholarship.

Declarations

Conflict of interest The authors declare no competing interests.

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