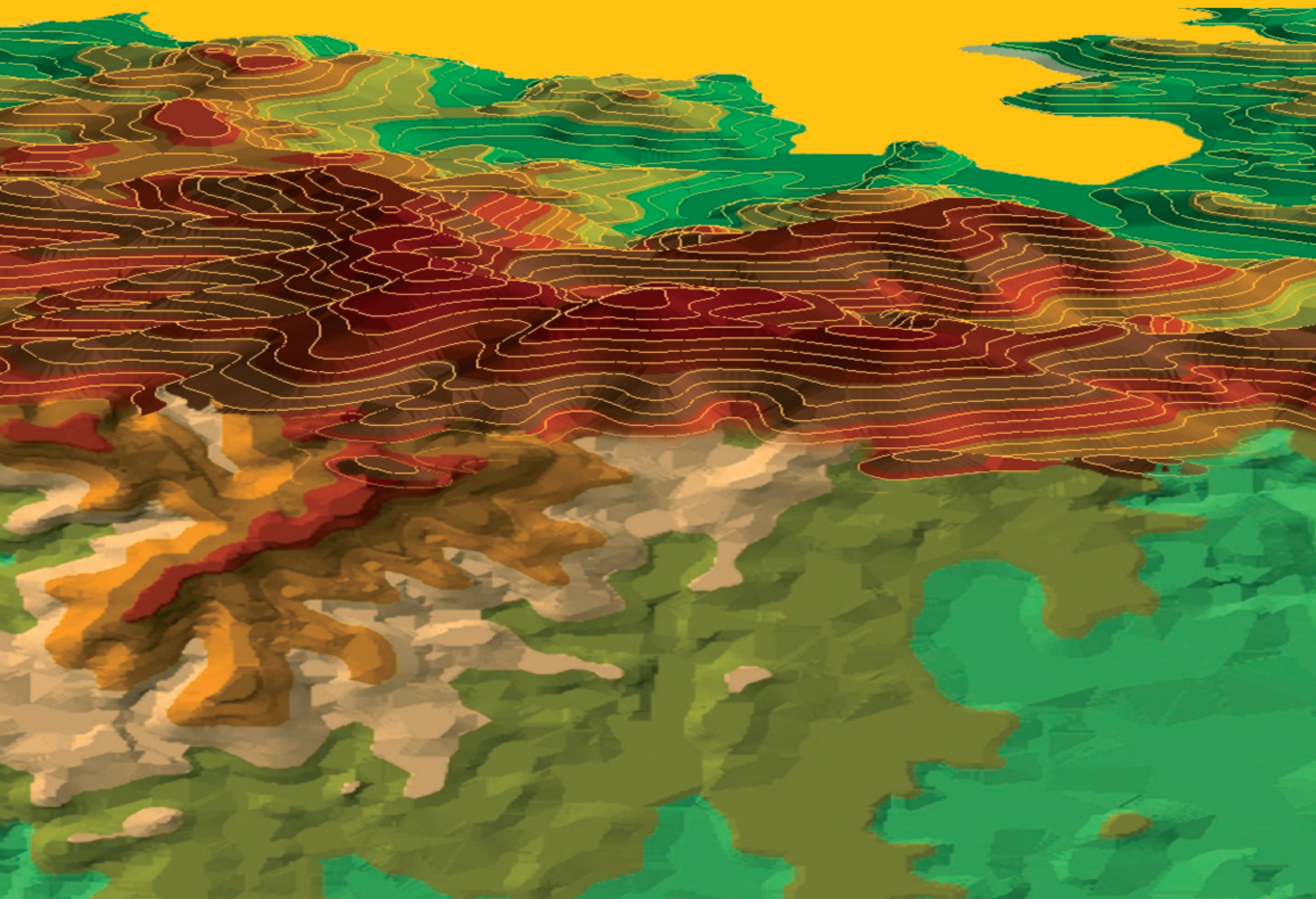
Vol. 33/2025

No. 1

# MORAVIAN GEOGRAPHICAL REPORTS



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# Geodiversity and geoheritage: Bridging science, conservation, and development




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**ISSN 2199-6202 (Online)**

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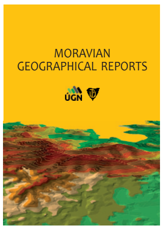


MORAVIAN GEOGRAPHICAL REPORTS

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

journal homepage: www.geonika.cz/mgr.html

doi: https://doi.org/10.2478/mgr-2025-0001

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# New horizons in geodiversity and geoheritage research: Bridging science, conservation, and development

Lucie Kubalíková [a*], Vittoria Vandelli [b], Márton Pál [c]

## Abstract

Geodiversity and geoheritage research has gained increasing prominence in natural and social sciences, reflecting their critical role in nature conservation, regional development, geosystem services, and environmental change. Given the inter- and transdisciplinary character of the geodiversity and geoheritage studies, a notable shift from the basic mapping, description and assessment of particular geosites to more advanced and sophisticated methods and approaches is evident during last years. Emerging research themes include quantitative analyses of geodiversity-biodiversity relationships, the dynamics of geomorphosites, innovative degradation risk assessment methodologies tailored to varying conditions, geotourism assessments in specific areas, and the application of geodiversity concepts in environmental policy and management. Additionally, integrating GIS and IT tools has enhanced the evaluation of geodiversity elements in landscape structures and ecosystem services. This article provides a brief reflection on the new directions and methods in geodiversity and geoheritage research and serves as an introduction to the Special Issue of Moravian Geographical Reports on 'Geodiversity and Geoheritage: Bridging Science, Conservation, and Development'. Generally, it can be stated that the papers included in this special issue reflect the necessity of interdisciplinary approaches to address contemporary challenges in geodiversity and geoheritage conservation and management.

**Keywords:** Geoheritage, risk assessment, geotourism, nature conservation

**Article history:** Received 2 December 2024, Accepted 28 February 2025, Published 31 March 2025

## 1. Introduction

In recent decades, the research on geodiversity and geoheritage has been acquiring increasing attention within both the natural sciences and humanities. These research topics are closely linked to the nature conservation practices, geographical mapping, regional development, geosystem services, environmental change and many other issues, which make them inter- and transdisciplinary (Reynard & Brilha, 2018; Gray, 2021, 2024; Gray et al., 2023; Matthews et al., 2024).

Geographical aspects of geodiversity and geoheritage have been studied since the time of emerging of this topics, however, there is a notable shift from the basic mapping, description and assessment studies (for review, see Mucivuna et al., 2019) to more specific aspects of research and more advanced and sophisticated methods and approaches, such as e.g., risk assessment (García-Ortiz et al., 2014; Selmi et al., 2022; Kubalíková & Balková, 2023), dynamics of the geodiversity and geoheritage (Bratton et al., 2013; Bussard & Giacome, 2021; Kubalíková, 2024), geosystem services (García, 2019; Fox et al., 2020; Gray et al., 2023; Van Ree et al., 2024), spatial-temporal changes (Pál & Albert, 2021, Portal et al., 2024), links between geodiversity, geoheritage and environmental change (Pelfini & Bollati, 2014; Schrodt et al., 2019, 2024; Gordon et al., 2022; Migoń, 2024; Negri et al., 2024), the role of geodiversity and geoheritage in sustainable development (Stewart & Gill, 2017; Gupta et al., 2024; Li et al., 2024; Matthews et al., 2024) or interconnecting geodiversity, culture and cultural landscape (Gordon, 2018; Reynard & Giusti, 2018; Pijet-Migoń & Migoń, 2022; Kubalíková & Coratza, 2023). Examining the geographical aspects also allows us to analyse geodiversity in a quantitative way in relation to biodiversity and land cover, which can be used in almost all above-mentioned issues.

This article provides a brief reflection on the new directions and methods in geodiversity and geoheritage research and serves as an introduction to the Special Issue of Moravian Geographical Reports on 'Geodiversity and Geoheritage: Bridging Science, Conservation, and Development'.

## 2. Traditional and emerging topics in geodiversity and geoheritage research

Although the concepts of geodiversity and geoheritage have been introduced in 1990s (Gray, 2013), the proper methods for identifying, mapping or describing and assessing particular sites of Earth Science interest are much older. Originally, these methods were related to nature conservation and practical protection of particular sites (Burek & Prosser, 2008). Already in 19$^{th}$ century, the conservation of abiotic nature started to be done by declaring specific sites as protected (e.g., rock outcrops, specific landforms,

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caves, hydrogeological phenomena, old quarries and others). Later, systematic inventories have been elaborated (on local, regional and national level) and preliminary assessment of the sites' values have been applied.

Today, identifying, inventorying and mapping the sites of Earth Science interest represent a basic tool for further geoconservation or geotourism activities, management and development (Brilha, 2016), accompanied by various assessment methods that have been intensively developed since 2000s (Mucivuna et al., 2019). These methods are focused on scientific and added (ecological, cultural, aesthetic) values of particular sites and according to the main purposes, they are accompanied by the evaluation of the geoconservation needs, potential for geotourism development, or proposals for sustainable management of the sites. These methods are widespread and used in various conditions, very often they serve for authorities in protected areas or geoparks. In this aspect, the majority of applied methods is based on the already existing approaches or replicating the old and verified methods.

Regarding the spatial aspect, there is a shift from site-oriented research to a more complex approach. The geosite (or geodiversity site) is still in the centre of attention, but methodological approaches covering larger areas or reflecting the complexity of geosystems are developing, including quantitative methods using GIS tools (Pereira et al., 2013; Zwoliński et al., 2018; Pál & Albert, 2021) or ecosystem/geosystem services concept (Gordon & Barron, 2012; Gray, 2013; Van Ree et al., 2017, 2024; Frisk et al., 2022; Gray et al., 2023).

Despite the fast growth of scientific interest in geodiversity and geoheritage that is also reflected in the rapid increase of number of scientific papers (Kubalíková et al., 2023), there is still a number of issues that are not examined in detail. This is also caused by dynamic changes of environments and natural conditions (mostly due to environmental change), by new tasks and challenges in nature conservation and by changing attitudes of human societies on nature and use of natural resources in general. Thus, research on geoheritage and geodiversity research also reflects these aspects and address new topics and challenges. Some of the new research directions are summarised in the 2023–2027 plan of Geomorphosites Working Group (by International Association of Geomorphologists) that are primarily focused on geomorphological sites, however, they can be extrapolated to all the sites of Earth Science interest and other similar fields of studies (http://www.geomorph.org/geomorphosites-working-group/).

A vibrant topic in the geoheritage community is represented by active processes (Fig. 1). Until now, the active geomorphosites have been treated as specific and did not fit very well into the current assessment methods. However, some criteria related to active processes have been occasionally implemented in some methods (Reynard et al., 2016; Selmi et al., 2022; Kubalíková, 2024). In recent years, active geomorphosites have gained more attention as valuable geotourist and geoeducational resources with a very high geoscientific value. The paper of Bussard et al. in this Special Issue provides a comprehensive overview of the criteria that should be considered when assessing active or dynamic geomorphosites. This criteria analysis is a basis for a complex assessment method and approach that is very useful in both the scientific research and practices related to geoconservation and geotourism.

Other directions in the current geodiversity and especially geoheritage studies are represented by examining the close relationships between geoheritage and tourist use. Numerous assessment methods have been developed for assessing geosites and geomorphosites from the geotourist potential point of view (for an overview, see Štrba et al., 2023). These methods have been usually adapted to particular areas and specific – regional and/or local conditions, including mountain areas (Carrión-Mero et al., 2021; Bollati et al., 2023), coastal areas (Selmi et al., 2022; Morante-Carballo et al., 2023), urban areas (Kubalíková et al., 2021; Vegas & Diez-Herrero, 2021) or arid areas (Sayama, 2024). Very specific areas are represented by greatly vulnerable karst areas, but they are important as tourist destinations, thus very frequently visited and intensively used. In this Special Issue, Antić et al. developed a complex method for assessing the tourist potential of karst caves and apply it to selected caves in Switzerland. The added value of this method is in the inclusion of public preferences and expert evaluation.

As geodiversity and geoheritage are continuously at risk and endangered by numerous threats (Fig. 2), the risk assessment methods and approaches are also gaining more attention: risk assessment is a part of common geosite or geomorphosite methods (Brilha, 2016); however, in recent years, the methods focused directly on threat assessment and risks have been developed (García-Ortiz et al., 2014; Selmi et al., 2022; Kubalíková & Balková, 2023; Vandelli et al., 2024). The risk assessment may differ according to the spatial context (e.g., urban areas, rural areas, coastal or mountain areas), and the character of particular threats also varies (Crofts et al., 2020; Anougmar et al., 2024); thus, the proposed parameters may differ, even though generally, the basic set of criteria used

*Fig. 1: The influence of active geomorphological processes on geoheritage is twofold: on the one hand, they may lead to the degradation of Earth Science phenomena (e.g., erosion may cause the destruction of stratigraphic profile), on the other hand, active processes represent an inseparable element of the geoheritage sites themselves and possess and important scientific value. Rudice-Seč abandoned sandpit (left) and Osypané břehy (right), both situated in South-Eastern Moravia, Czech Republic, and protected as Nature Monuments, are the examples of the sites where natural processes such as fluvial erosion and slope processes represent an integral part of the wider area*
*Photos: L. Kubalíková*

*Fig. 2: Threats to geoheritage may be represented e.g., by overtourism. The outcropping flysch sedimentary rocks in Zumaia (Basque Coast Geopark, Spain) are situated just on the beach which is intensively used by tourists. Photo: L. Kubalíková*

for the risk assessment (degradation risk assessment) remain the same. Anyway, apart from the classical assessment of degradation risk (as reviewed by Vandelli et al., 2024) and eventually SWOT analysis which also contains the identification and analysis of threats (Kubalíková & Kirchner, 2016; Carrión et al., 2018), there are other approaches, represented for example by multicriterial analysis (Ahmadi et al., 2022) or application of risk assessment matrices (Brooks, 2013; Kubalíková & Balková, 2023). The use of these methods is quite common in projects or regional development management, but their use in geodiversity and geoheritage studies has not been so widespread. In this Special Issue, a paper by Kubalíková et al. reflects these issues. It applies a methodological approach for assessing risks and threats in a rural area that may be endangered by overtourism. It also discusses the possibilities of nature conservation that may be useful, but sometimes, they do not meet the needs of a particular site.

A huge emphasis is placed on quantitative methods using advanced computing and GIS tools (Pereira et al., 2013; Zwolinski et al., 2018; Najwer et al., 2022; Zakharovskyi et al., 2023; Pál & Albert, 2023). Initially, this field of research was focused on mapping and GIS analyses and based on that, the sites or areas of high geodiversity have been selected, e.g., to be protected or used for geotourism development (Santos et al., 2017; Rypl et al., 2020; Chrobak et al., 2021; Barančoková et al., 2023). These studies responded on many questions concerning mutual relationships between morphology, lithology and hydrological elements. They have enabled to illustrate how geodiversity influences biodiversity or species richness (Tukiainen et al., 2017, 2023; Crisp et al., 2023; Alahuhta et al., 2024; Toivanen, 2024). Studies dedicated to the mutual relationships between geodiversity elements and landscape structure are relatively sparse but have developed in the last few years (Pătru-Stupariu et al., 2017; Datta, 2022). In this Special Issue, this methodological approach is represented by the paper of Albert and Kraja, who examine the links between geodiversity elements and their influence on landscape structure exemplified on a study area in Albania.

## 3. Bridging nature, science and society

As previously emphasised, the research on geodiversity and geoheritage is highly inter- and transdisciplinary, especially in the last years when developing new methods that enable understanding complex relationships between nature and human society. In many aspects, it also helps to frame the nature conservation activities and sustainable use of the landscape and natural resources. Geodiversity and geoheritage are also reflected in and represent a significant contribution to all the Sustainable Development Goals (Stewart & Gill, 2017; Matthews et al., 2024) that confirms their importance and relevance. All the papers included in this Special Issue also possess these issues and contribute significantly to bridging nature, science and society in many aspects.

The paper of Jonathan Bussard, Andrea Ferrando and Aleksandar Antić focuses on the evaluation of active processes on geomorphosites. Based on a detailed analysis, they present a new approach that may serve not only for scientific assessment of geomorphosites in dynamic zones, but it is also useful in geoconservation management. Through three case studies in the Swiss Alps, their results show that an ideal management practice would be to maintain the natural dynamics and rate of change of geomorphological processes, with exceptions when they have a negative impact on landforms of higher heritage value than the processes, or when they threaten human life or infrastructure. Thus, their method is of high relevance both for preserving natural processes and contributing to quality of life of people residing in specific areas.

Aleksandar Antić, Marc Luetscher, Amandine Perret, Andrea Ferrando and Emmanuel Reynard developed a complex method for assessing the tourist potential of karst caves and apply it to selected caves in Switzerland. Given the fact that show caves are considered a very fragile environments and they are of high geotourism relevance, a need for finding a balanced method for assessing these extraordinary sites of Earth Science interest is very urgent and evident. Combining quantitative and qualitative analyses, including geological, ecological, and cultural factors, their paper offers a comprehensive assessment approach, contributing to a practical methodology for cave management, as well as cave tourism planning with regards to the conservation needs. The study provides insights beyond academia, guiding stakeholders involved in cave tourism development, and striving to balance ecosystem preservation with sustainable economic growth.

The paper by Lucie Kubalíková, Karel Kirchner and Piotr Migoń is focused on new, emerging aspect in geoheritage studies – the evaluation of risks and threats. The application of semi-quantitative assessment methods (degradation risk evaluation and Risk Assessment Matrix) in the Chřiby Mountains (a rural area in Czech Republic that may be endangered by overtourism due to the presence of numerous sandstone crags with high geoheritage values) enabled the ranking of the sites according to the degree of possible deterioration and helped to identify particular threats, which can be considered important when planning and managing the area's natural resources. The recognition of geoheritage values of sandstone crags, along with identifying and evaluating risks and threats, may serve as a basis for effective management and further research. The paper also discusses the possibilities of nature conservation (geoconservation) that may be useful, but sometimes, they do not meet the needs of a particular site and need to be discussed with local stakeholders.

Gáspár Albert and Drisela Kraja examine the links between geodiversity elements and their influence on landscape structure exemplified on a study area in Albania. Using open-source GIS tools, they analyse the diverse geographical features, including coastal, agricultural, urban, riverside, and mountain terrains. Their analyses, conducted at low, medium, and high altitudes, reveal a positive correlation between geodiversity and land cover diversity in lower regions but a negative correlation in higher elevations. The results highlight the importance of taking geodiversity into account in conservation efforts and can provide important support for impact studies to be carried out in the planning phase. Their study can be also considered a basis for identifying potential geotourism hotspots characterised by high geodiversity and to estimate the potential impact of tourism activities on local natural values, considering land cover diversity and connectivity.

Despite its limited extent, this Special Issue shows a diverse range of topics in geodiversity and geoheritage research, introducing new perspectives on well-established research areas and methodological approaches. The published papers illustrate emerging trends and pave the way for future research directions in this area.

*Acknowledgements*

*Lucie Kubalíková was supported by the project 'Dynamic Planet Earth of the Czech Academy of Sciences – Strategy AV21'.*

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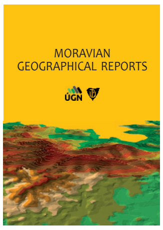
**Please cite this article as:**

Kubalíková, L., Vandelli, V., & Pál, M. (2025). New horizons in geodiversity and geoheritage research: Bridging science, conservation, and development. Moravian Geographical Reports, 33(1), 2–6. https://doi.org/10.2478/mgr-2025-0001




MORAVIAN GEOGRAPHICAL REPORTS

sciendo

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

journal homepage: **www.geonika.cz/mgr.html**

doi: **https://doi.org/10.2478/mgr-2025-0002**

# Heritage recognition of active geomorphological processes: The challenges of geoconservation beyond landforms

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## Abstract

The recognition of geomorphosites as heritage sites is often based on an assessment of their heritage values conducted by scientists, and many methodological proposals have been published in the last two decades to achieve this evaluation. However, the criteria defined in these methods are primarily designed to assess the heritage values of the landforms themselves, focusing mainly on the static aspects of geomorphosites and often overlooking the dynamic processes that are integral to their formation and ongoing evolution. In this article, we define specific criteria for evaluating the heritage values of active processes and discuss four issues related to their protection: (1) defining the functional perimeter, (2) managing natural hazards, (3) determining the relevance of conserving an active geomorphological system in its current state, and (4) deciding whether it is more important to protect the landforms or the processes. Through three case studies in the Swiss Alps, the results show that an ideal management practice would be to maintain the natural dynamics and rate of change of geomorphological processes, with exceptions when they have a negative impact on landforms of higher heritage value than the processes, or when they threaten human life or infrastructure.

**Keywords:** Geoheritage, geomorphology, active processes, assessment methodology, geoconservation

**Article history:** Received 18 July 2024, Accepted 30 November 2024, Published 31 March 2025

## 1. Introduction

The concept of geoconservation (Sharples, 1993; 2002; Burek & Prosser, 2008) refers to the protection of the non-living components of nature, and encompasses the protection of geological features that hold a significant scientific value to Earth sciences. In nature conservation policies, geoconservation is still under-represented in respect to bioconservation (Sharples, 2002; Gray, 2004; 2005; Reynard et al., 2005; Larwood et al., 2013; Crofts, 2018; Brilha et al., 2018), but in the last decades it has grown significantly as a field of research. The term geoheritage refers to all the geological objects that have acquired one or several heritage values. Geoheritage can be *in situ*, i.e. on the original location – in that case, the geoheritage sites are called geosites (Brilha, 2016) – or *ex situ*, e.g., collections in museums, stone heritage in buildings, etc. The geosites whose main interest is linked with geomorphology are called geomorphosites (Panizza, 2001; Reynard & Panizza, 2005; Reynard, 2009).

The recognition of the heritage values of geological objects is the foundation upon which their protection rests. This recognition, sometimes called ‘heritage making’, is a societal process by which a geological object becomes heritage and depends on the values assigned by the different stakeholders over time (Portal, 2010; Reynard et al., 2011; Martin, 2013). Over the years, numerous methodological proposals have been developed to describe and evaluate the heritage values that justify heritage recognition (Brilha, 2018). In the case of geomorphosites, most of the methods distinguish two types of values, suggested by Reynard (2004; 2005): (1) the scientific value, considered as the central value, that reflects the importance of a geomorphological feature from the perspective of Earth sciences; (2) the additional values, such as the cultural value, the ecological value and the aesthetic value, that are linked to or produced by the geomorphological characteristics of the sites and further enhance their heritage value. There is currently no consensus on the best method to be applied (Brilha, 2016; Mucivuna et al., 2019; Németh et al., 2021). But despite the diversity of existing methods for evaluating the heritage values of geomorphological objects, a notable gap remains: the criteria defined in these methods are primarily designed to assess the heritage values of landforms, focussing mainly on the static aspects of geosites and often overlooking the dynamic processes that are integral to their formation and ongoing evolution. Active geomorphological processes are however essential components that distinguish geomorphosites from other types of geosites (Reynard, 2004; 2009; Coratza & Hobléa, 2018). The lack of attention to these processes represents a significant oversight in current geoconservation research and practices.

To address this gap, we propose a new methodology for the assessment of the heritage values of active processes, with the definition of specific criteria to evaluate their scientific, aesthetic, ecological and cultural values. Then, we discuss the implication of protecting geomorphological processes. Protection efforts typically focus on preserving physical features, but when active processes are involved, the dynamics of conservation are questioned on several aspects:

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1. Active processes can act on a wider area than the one included in the perimeter of a geomorphosite; therefore, one should consider the entire area that ensures the functionality of the process;
2. Active processes are often associated with natural hazards – thus, the protection of the process could be in contrast to the objective of reducing natural hazards;
3. Most geomorphological processes evolve over time, both for natural and anthropogenic reasons. This complicates the long-term protection of these processes and questions the relevance of conserving an active geomorphological system in its current state;
4. Active processes could affect the integrity of landforms and reduce their heritage value – so, is it more relevant to protect the landforms or ensure the functionality of the active processes?

The proposed approach is applied to three case studies in the Swiss Alps. The selected sites represent different geomorphological contexts and processes, and illustrate the practical application of our approach, highlighting both its strengths and potential areas for further refinement.

## 2. Conservation of active processes: theoretical framework and challenges

### *2.1 The dynamic dimension of geomorphosites*

Geomorphosites are associated with very heterogeneous temporalities (Bétard et al., 2017; Ben Fraj et al., 2023): age of landforms, duration of formation, speed of morphogenetic processes in the past, present and future, etc. This temporal dimension is very relevant, because dynamic landforms evolve over time, at a rate that is rarely linear (Phillips, 2006). We can classify geomorphosites into three categories based on the activity of the processes involved (Fig. 1): active geomorphosites, passive geomorphosites, and 'evolving passive geomorphosites' (Pelfini & Bollati, 2014). Active geomorphosites are sites where the morphogenetic processes responsible for their formation are currently still active. Passive (or inactive) geomorphosites, in contrast, are those where these morphogenetic processes have ceased (Reynard, 2004), and the landforms are considered as inherited (Thomas, 2016; Coratza et al., 2021). Still, passive geomorphosites can be modified by active processes which are different from the ones that created them – in this case, they are referred to as evolving passive geomorphosites. To avoid confusion, Bussard and Giaccone (2021, p. 386) suggested that active geomorphosites and evolving passive geomorphosites could be called 'dynamic geomorphosites'.

Dynamic geomorphosites are sites where ongoing geomorphological processes are visibly shaping the landscape. These processes may be continuous (e.g., glacial erosion) or discontinuous (e.g., a rockfall) and may vary in frequency and intensity. Processes can also be categorised according to their velocity. Rapid processes (e.g., rockfalls, avalanches) occur over short time scales and can dramatically alter the landscape in an instant. Intermediate processes (e.g., fluvial erosion and deposition) occur over months to years, with periods of acceleration and periods of deceleration. Slower processes (e.g., glacial erosion) can take place over years or decades and are barely noticeable without any means of comparison. A geomorphosite can be considered passive or inactive when the geomorphological processes that shaped it are no longer active, or their activity is so minimal that they do not significantly alter the landscape in the human time scale.

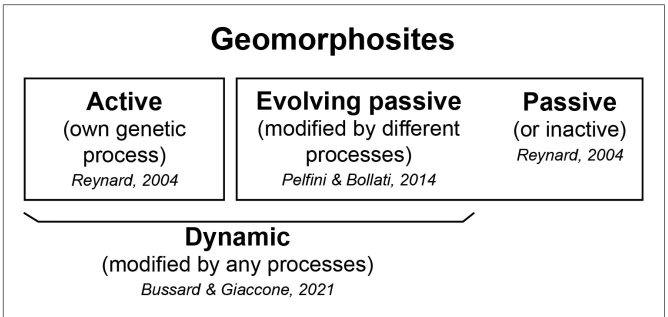



*Fig. 1: Different categories of geomorphosites according to their activity*
*Source: Authors' conceptualisation*

Pelfini and Bollati (2014) underlined three reasons to consider that dynamic geomorphosites are of great interest:

1. Active processes can cause irreversible modifications on existing landforms;
2. They witness the dynamicity of the ongoing land surface processes and landscape evolution; and
3. They can cause natural hazards and risks.

Their ecological value is also significant, as active processes can help to maintain favourable conditions for pioneer species that are adapted to dynamic conditions (Bussard & Giaccone, 2021). Geomorphosites shaped by active processes can also be of great educational interest (Bini, 2009), as they allow us to "understand and visualise geomorphological processes in action; envisage the landscape evolution; highlight their relationship with present societies and their future development" (Reynard & Coratza, 2016, p. 293). However, the heritage recognition of geomorphological processes and the implementation of protection measures raise several issues that we discuss in the following paragraphs.

### *2.2 Geomorphosite perimeter versus functional perimeter*

Geomorphosites are characterised by a striking variety in terms of size and spatial complexity. Spatial classifications of geomorphosites have been proposed by several authors (Grandgirard, 1997; Coratza et al., 2021; Bussard & Reynard, 2022; Santos et al., 2022). For instance, Grandgirard (1997) proposed four categories:

1. single landform;
2. group of landforms, all the same as each other;
3. geomorphological complex, which comprises several different landforms linked by the same main morphogenetic process;
4. geomorphological system, with several different landforms shaped by more than one significant morphogenetic process.

However, the perimeters of geomorphosites are usually delineated around the main features of interest (i.e. landforms), without taking into account the spatial extent of their morphogenetic processes. In fact, in dynamic geomorphosites, the area that is affected by the active morphogenetic processes may be wider than the area included in the perimeter of the geomorphosite itself (Ferrando et al., 2025). For instance, the sediment supply of an alluvial zone can be influenced both by natural processes (e.g., landslides and debris flows feeding sediments to the system) and anthropogenic perturbations (dams and weirs, gravel quarrying on the river bed, etc.) happening upstream of it. Therefore, for dynamic geomorphosites, the strict perimeter should be extended to include the 'functional perimeter' or 'management perimeter', that is, the whole area necessary for the morphogenetic processes to function properly.

### *2.3 Protection of processes versus natural hazards management*

The objective of protecting the heritage values of a process may conflict with the objective of reducing natural hazards. Indeed, active geomorphological processes can be elements of geomorphological risk as they can affect people, structures and human infrastructure – examples are debris flows, avalanches, volcanic eruptions, intense storm surges, floods, etc. This leads to geomorphological risk mitigation and natural hazard management measures. Structural risk mitigation measures, such as coastal defence structures, weirs, dams and dikes along rivers, drainage systems in landslides, avalanche barriers, etc., are generally aimed at attempting to stop, modify or limit the active geomorphological process and its effects on exposed elements. Thus, they represent anthropogenic modifications of the geomorphological process, and affect its integrity and functioning.

### 2.4 Protection of processes in their current state versus in evolution

Geomorphological processes are influenced by numerous endogenous and exogenous factors, resulting in complex interactions that do not follow a straightforward, linear pattern. This complexity gives rise to non-linear dynamics, where cause and effects are not directly proportional. According to Phillips (2006, p. 733), the non-linearity in geomorphological systems can be attributed to several mechanisms, including 'storage effects', where sediments can accumulate and be released at different time, causing delays and discontinuities in sediment mass balances, 'self-reinforcing positive feedbacks', such as karst depressions or nivation hollows, that reinforce themselves by accumulating additional water or snow, and 'multiple modes of adjustment' in response to a single forcing. The presence of these mechanisms means that geomorphological processes show varying degrees of sensitivity to changes in their controlling factors. The degree of response can be highly variable and is often dependent on the specific context.

One significant implication of these non-linear dynamics is the variability in heritage values associated with certain geomorphological processes. In some cases, the current state of these processes is of heritage interest, for example for its present scientific value. Any alteration in this state, such as a reduction in the frequency or intensity of the process induced by natural changes or anthropogenic interventions, could potentially diminish its heritage values. However, in other cases, the non-linear response of geomorphological systems to changes in controlling factors makes their evolution a rich field of study, with a potentially high scientific value and geoeducational potential. For example, glacier geomorphosites evolving due to climate change are widely studied among scientists, but also have a high impact on the general public (Bussard & Reynard, 2023; Bollati et al., 2023).

### 2.5 Protection of processes versus protection of landforms

Geomorphological processes are responsible for the formation and evolution of landforms, including those of heritage interest. These processes, however, also lead to the destruction of geomorphosites, over varying timescales (Reynard, 2009; Komac et al., 2011). This destruction can be rapid or gradual, depending on the nature of the processes involved. Examples of geomorphosites negatively impacted by processes are the Čedca waterfall in Slovenia, which was the highest in the country before it collapsed during two major rockfall events in 2008 (Komac et al., 2011), volcanic events covering or disturbing landforms created by other processes (Reynard, 2009) or runoff erosion on earth pyramids (Bollati et al., 2015) – the latter case is peculiar, because the same process is responsible both for the formation and the degradation of the landforms. Given this dynamic interaction between landforms and geomorphological processes, it is important to determine priorities for protection when a landform and a destructive process are in conflict. This involves weighing up the heritage values of the landforms against those of the natural processes that may threaten their integrity.

## 3. Methodology

We propose to address the research objectives through a methodology in three steps. The first step, described in Section 3.1, aims to assess the heritage values of three selected sites using a 'classical' method and existing criteria, without giving any specific attention to the processes themselves. In a second stage (Section 3.2), we evaluate the heritage values of the process (or processes if several of them are intertwined), using an innovative method and new criteria, including a scaling of the criteria. The third step consists of field observations that provide arguments for discussion of the different issues highlighted in Chapter 2 concerning the protection of geomorphological processes.

### 3.1 Assessment of the heritage values of the sites

An initial assessment of the heritage values of the sites is carried out using an existing methodology developed by Reynard et al. (2016; Tab. 1). The scientific value is defined following four criteria: integrity, rarity, representativeness and paleogeographical interest. The four criteria are assessed quantitatively on a scale of whole numbers from 1 (low value) to 5 (high value). The scientific value is calculated as the sum of these four criteria (without scaling), thus it can range from 4 to 20. Three additional values (the aesthetic value, the ecological value and the cultural value) are described only qualitatively, because of their subjective component, and as it was not feasible, in the context of this research, to perform an exhaustive and robust quantitative assessment. This methodology focuses mainly on the 'site'. It therefore considers both the landforms and the processes that compose the sites, but the primary focus is clearly on the landforms located within the site's perimeter. In addition, there is no explicit mention of the heritage values of the processes; the active or inactive processes are only listed to classify the sites in a morphogenetic category (glacial, periglacial, fluvial, karstic, etc.).

### 3.2 Assessment of the heritage values of the processes

#### 3.2.1 Description of the indicators

The assessment of the heritage values of active geomorphological processes is performed using a slightly different procedure. The starting point is still the method of Reynard et al. (2016), with the assessment of the scientific, aesthetic, ecological and cultural values by means of a series of indicators. However, for each value, new indicators have been introduced (Tab. 2), to take into account the specificities of active processes.

The scientific value is described through four indicators: representativeness, rarity, anthropogenic modifications and maximum intensity. The representativeness is intended in a similar way to what is described in Section 3.1, i.e. focused on the exemplarity of the processes. Rarity takes into account not only how rare the type of process is, but also how rare the process is in terms of intensity and frequency. Anthropogenic modifications is the indicator used to describe the integrity of the process. Anthropogenic action may mitigate the geomorphological processes (e.g., in the case of natural hazard mitigation) but in other cases it can increase their intensity (e.g., anthropised river beds). In any case, the more the process is modified by anthropogenic action, the less its functionality is preserved, and thus the less intact it is. The last indicator is the maximum magnitude of the process; since it is not possible in all cases to see the process unfold at its maximum intensity, this indicator was inferred from the evidence on the ground.

Among the heritage values considered, the aesthetic value is the one with the strongest subjective component (Regolini-Bissig, 2010). In different assessment methods, various authors have proposed quasi-objective indicators for the assessment of the aesthetic value (e.g., Pralong, 2005; Coratza et al., 2012; Reynard et al., 2016). These include panoramic quality, number of viewpoints, colour contrast, vertical development, etc., which, however, clearly refer to landforms.

Assessing the aesthetic value of geomorphological processes poses more problems, for two main reasons. First, the processes are not always easily visible – and when they are not visible, they can't always be easily grasped, especially by non-experts. Second, the aesthetic evaluation of the processes cannot be separated from their effects on the population. Spectacular but potentially destructive processes, such as landslides and debris flows, are perceived negatively (Morino et al., 2022), whereas equally spectacular but non-destructive processes, such as glacial erosion, are perceived more positively. Moreover, this perception may vary considerably between experts and non-experts, and in different social contexts. Thus, for the assessment of the aesthetic value, we tentatively propose two main indicators: 'visibility' and 'aesthetic appreciation'.

The visibility of a process in itself is not that easy to define. Our proposal is to assess it with three sub-indicators: (1) the impact on the landscape of the process, which permits linking the active process to the presence of more or less impressive landforms, (2) the frequency of the process, which goes from episodic on a pluri-annual basis to continuous, and (3) its velocity. The more a process is frequent and has high velocity, the more it is visible.

The second main indicator is the aesthetic perception of the process that can go from negative or neutral to positive. Aesthetic perception is subjective and can be very diverse. The ideal procedure would be to assess it from the perspective of different groups of people (experts, visitors, local inhabitants, managers), by means of extensive surveys, but that would be out of scope for the present research. Therefore, for this work, the aesthetic appreciation has been assessed from the point of view of the authors as experts in the field.

The ecological value is assessed by means of two indicators (following Bussard & Giaccone, 2021): (1) the variety of plant and animal species induced or influenced by the geomorphological processes, and (2) the rarity of those species. Finally, to assess the cultural value, we used a series of indicators inspired by the categories identified by Pijet-Migoń and Migoń (2022) at the interface between cultural heritage and geoheritage. The definition of the criteria is also inspired by the terminology used by UNESCO to define the six cultural criteria of the World Heritage Convention (UNESCO World Heritage Convention, 2023). In addition, we have included the category of natural hazards, not for their (generally negative) impact on cultural heritage, but from the point of view of risk perception and management (Morino et al., 2022).

### *3.2.2 Quantitative assessment and scaling*

The assessment model for the heritage values of geomorphological processes consists of four main groups of indicators: Scientific value (SV), Aesthetic value (AV), Ecological value (EV) and Cultural value (CV). All indicators have their own sub-indicators that are given values (grades) in the range from 1 to 5 (Tab. 2). In total, the scientific value has four sub-indicators, the aesthetic value has two sub-indicators (with the sub-indicator "Visibility" being divided into three additional sub-indicators), the ecological value is also divided into two sub-indicators, while the cultural value is divided into six sub-indicators. Therefore, the model has a total of 14 sub-indicators, which serve to evaluate active geomorphological processes.

Given that each group of indicators consists of sub-indicators, equations 1, 2, 3 and 4 can be written as follows:

$$SV = {}_{i}, \text{ where } 1 \le SISVi \le 5 \quad (1)$$

$$AV = {}_{p}, \text{ where } 1 \le SIAVp \le 5 \quad (2)$$

$$EV = {}_{e}, \text{ where } 1 \le SIEVe \le 5 \quad (3)$$

$$CV = {}_{j}, \text{ where } 1 \le SICVj \le 5 \quad (4)$$

SISVi represents four sub-indicators of the scientific value (i = 1–4); SIAVp represents two sub-indicators of the aesthetic value (p = 1,2); SIEVe represents two sub-indicators of the ecological value (e = 1,2) and $SICV_j$ represents six sub-indicators

| Value | Indicators | Description | Scores | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 |
| Scientific value | Integrity | State of conservation of the site | The integrity of the site is not preserved | Landforms are poorly conserved, with major degradation | Landforms are partly conserved with moderate degradation | Landforms are well conserved with minor degradation | The site is integer |
| | Representativeness | Concerns the site's exemplarity. Used in respect to a reference space | Very low | Low | Moderate | High | Utmost |
| | Rareness | Concerns the rarity of the site with respect to a reference space | Not rare | Local occurrence | Regional occurrence | National occurrence | International occurrence |
| | Paleogeographical interest | Importance of the site for the Earth or climate history | Very low | Low | Moderate | High | Utmost |
| Aesthetic value | a. View points<br>b. Contrasts, vertical development and space structuration | Concerns the scenic beauty of the site | The aesthetic value was qualitatively assessed | | | | |
| Ecological value | a. Ecological impact<br>b. Protected site | Concerns the influence of the site on local ecological communities | The ecological value was qualitatively assessed | | | | |
| Cultural value | a. Religious importance<br>b. Historical importance<br>c. Artistic and literary importance<br>d. Geohistorical importance<br>e. Economic importance | Concerns the impact of the site in local culture | The cultural value was qualitatively assessed | | | | |

*Tab. 1: Assessment model for the heritage values of geomorphosites, with indicators and their description*
*Source: Authors' modification after Reynard et al. (2016)*

of the cultural value (j = 1–6). The numerical scores assigned to each sub-indicator range from 1 (lowest value) to 5 (highest value).

The assessment process consists of two main stages. In the first stage, authors assess and assign scores to the selected active geomorphological processes. The second stage includes experts' evaluation in which they provide importance factors (Tomić & Božić, 2014) for each sub-indicator in the assessment model. The importance factors are average scores from surveys conducted with the experts, each representing the collective assessment of a sub-indicator's significance.

The surveys were conducted online, between June and July 2024. The participants were experts in the field of Geomorphology. In total, 50 experts participated in the survey. The experts were selected through the Web of Science platform, using specific keywords. The following search criteria were used: geoheritage

| **Indicators** | **Sub-indicators** | | **Description** | **Scores** | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 |
| Scientific value | Representativeness | | Degree to which the geomorphological process(es) exemplifies typical characteristics and dynamics of its type | Very low | Low | Moderate | High | Utmost |
| | Rarity | | Rarity of the geomorphological process(es), of its frequency or its intensity | Not rare | Local occurrence | Regional occurrence | National occurrence | International occurrence |
| | Anthropogenic modifications | | Extent to which human activities have modified the natural geomorphological process(es) | Utmost | High | Moderate | Low | None |
| | Maximum intensity | | The maximum intensity of the geomorphological process(es), which has been observed on the field or deduced by the geomorphological context | Minor intensity | Small intensity | Medium intensity | Large intensity | Extreme intensity |
| Aesthetic value | Visibility | Impact on the landscape | How much the landscape is impacted by the process(es) | Barely detectable | Requires effort to observe | Noticeable without too much effort | Stands out in the landscape | Dominates the landscape |
| | | Frequency | The frequency of the geomorphological process(es) | Episodic process on a pluri-annual basis | Episodic process on an annual basis | Episodic process on a seasonal basis | Episodic process on a weekly or monthly basis | Continuous process |
| | | Velocity | The velocity of the geomorphological process(es) | Very low velocity | Low velocity | Average velocity | High velocity | Immediate process |
| | Aesthetic appreciation | | The aesthetic perception of the process(es) by different people (experts/visitors/locals/managers) | Negative or neutral perception | – | Positive perception | – | Outstandingly positive perception |
| Ecological value | Biodiversity | | Variety of plants or animals within the area whose presence is induced or influenced by the geomorphological process(es) | None/Minimal variety of plants or animals | – | Moderate variety of plants or animals | – | High variety of plants or animals |
| | Rarity of species | | Presence of rare plant or animal species induced or influenced by the geomorphological process(es) | Few to no rare species induced or influenced by the geomorphological process | – | Moderate presence of rare species induced or influenced by the geomorphological process | – | High or exceptional presence of rare species induced or influenced by the geomorphological process |
| Cultural value | Geohistorical importance | | Significance of the geomorphological process(es) in contributing to the development of Earth sciences | No contribution to Earth Sciences | Minimal contribution to Earth Sciences | Moderate contribution to Earth Sciences | Significant contribution to Earth Sciences | Exceptional contribution to Earth Sciences |
| | Built heritage | | Association of the geomorphological process(es) with an outstanding example of a type of building or architectural ensemble illustrating one or more significant periods in human history | None | Limited | Moderate | Significant | Exceptional |
| | Symbolic, historic or religious significance | | Association of the geomorphological process(es) with events, living traditions, ideas, beliefs or historical facts | None | Limited | Moderate | Significant | Exceptional |
| | Art and literature | | Association of the geomorphological process(es) with artistic or literary works | None | Limited | Moderate | Significant | Exceptional |
| | Cultural landscape | | Impact of the geomorphological process(es) on the morphology of a landscape marked by interactions between humans and their natural environment | None | Limited | Moderate | Significant | Exceptional |
| | Natural hazards perception and management | | Role of the geomorphological process(es) in the perception and management of natural hazards | No role | Minimal role | Moderate role | Significant role | Crucial role |

*Tab. 2: Assessment model of active geomorphological processes, with indicators and their description. Assigned scores range from 1 (lowest value) to 5 (highest value)*
*Source: Authors' conceptualisation*

(Topic) or geosites (Topic) or geomorphosites (Topic) or geodiversity (Topic) or active geomorphology (Topic) or geomorphological process (Topic) or active landforms (Topic) or geoconservation (Topic) and 2024 or 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 (Publication Years).

The scores given by the authors are then weighted, by multiplying them with the importance factors established by the surveyed experts. Thus, the final ratings incorporate both the authors' evaluations and the experts' input from the field of Geomorphology.

### 3.3 Analysis of issues related to geoconservation

The analysis of management issues for the three case studies is site-specific and based on geomorphological evidence. A detailed geomorphological analysis was carried out, by means of field observations on both the perimeter of the geomorphosite and the surrounding geomorphological context. The goal of the geomorphological field observations was to analyse in detail the theoretical issues outlined in Sections 2.1 to 2.5, with particular emphasis on delineating the 'functional perimeter' of the geomorphosite.

Delineating the functional perimeter requires identifying the currently active processes that affect the geomorphosite and determining their spatial extent (Ferrando et al., 2025). The main issue in defining this functional perimeter is the time scale of the active processes. Given the various temporalities of the morphogenetic processes, considering different time scales could possibly give different functional perimeters. However, this could be misleading for the purpose of geoconservation. In this study, we considered only the processes that can significantly affect the geomorphosite on a human time scale (~100 years), in terms of both landform evolution and the preservation of functional processes. The human time scale was chosen because slower processes are barely perceptible.

## 4. Study sites

In order to apply and test the methodological proposal, we selected three different geomorphosites characterised by the presence of active geomorphological processes. These three sites, namely the Mont Miné glacial system, the Euseigne earth pyramids and the Illgraben torrential system, are located in the Swiss Alps (Fig. 2). Two of them – the Illgraben torrential system and the Euseigne pyramids – are officialy recognised as geosites, as they are part of the Federal Inventory of Swiss Geotopes (https://s.geo.admin.ch/ànczlj6ukwmmb). The Mont Miné glacial system is not officially recognised but has been considered as a geosite in previous works addressing the geomorphosite inventory of the Val d'Hérens (Grangier, 2013; Reynard et al., 2016).

The three sites represent *a priori* three different situations. As a geomorphological system, the Mont Miné site (1, Fig. 2) is characterised by a combination of several processes and landforms. The Euseigne site (2, Fig. 2) is composed of one type of landform (earth pyramids), whose heritage values have already been recognised in previous studies. The Illgraben site (3, Fig. 2) has one main process (torrential activity) and is known for its high frequency of debris flows. The three sites therefore illustrate distinct contexts where assessment and management issues are not necessarily the same.

### 4.1 Mont Miné glacial system

The Mont Miné glacial system (Fig. 3 and 6A) is located on the highest part of the Ferpècle valley, one of the upper branches of the Hérens valley. The geomorphosite includes the Mont Miné glacier and its proglacial area, delimited by the moraines of the Little Ice Age (LIA, 1860 AD). The glacier's accumulation zone is a vast plateau located between the Dents des Bouquetins (3,838 m a. s. l.) and the Tête Blanche (3,711 m a. s. l.). The glacial tongue is divided in two parts: the upper part flows north for about 4 km, then terminates with a high serac above a vertical rock step at 2,800 m of elevation; the lower part is disconnected from the upper one and is mainly fed by ice falls and avalanches. The lower part of the glacial tongue begins at the foot of the rock step, at 2,650 m a. s. l., and flows further down to about 2,100 m a. s. l. The proglacial plain is located at about 1,950 m a. s. l., and it is dammed by a frontal moraine dating from the 1980s. The plain is fed by the Mont Miné stream and another stream coming from the Ferpècle glacier, located in the adjacent valley. Both streams form large fluvioglacial fans when entering the plain. On the west side of the proglacial area, the steep LIA moraines are very well visible and affected by intense gullying and gravitational erosion. The east side is characterised by gentler terrain; here, multiple

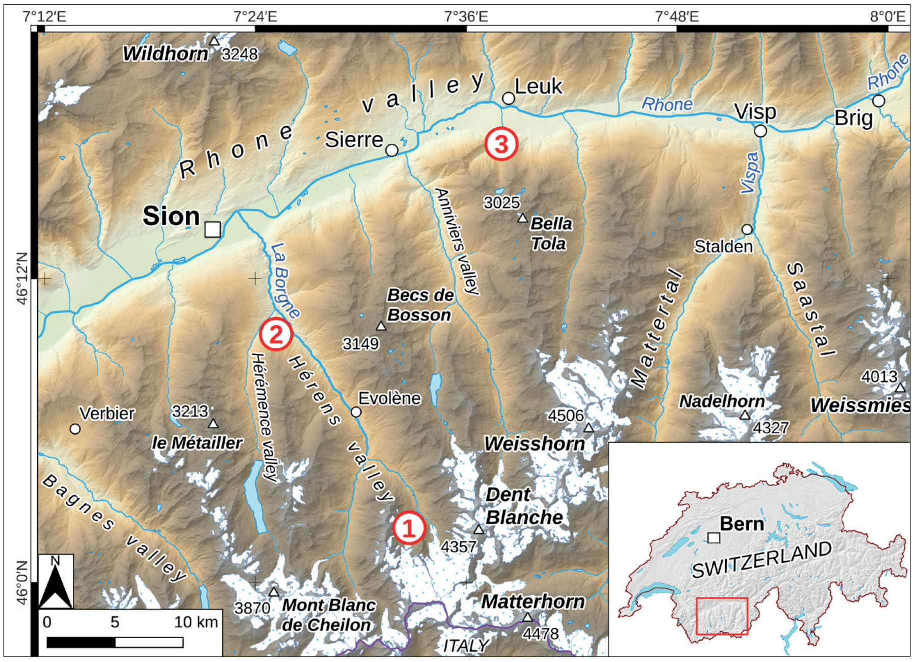



*Fig. 2: Location of the study sites. 1) Mont Miné glacial system; 2) Euseigne earth pyramids; 3) Illgraben torrential system*
*Source: Authors' conceptualisation; Elevation from MDT25 Digital Terrain Model, © swisstopo; other vector data from OpenStreetMap*

moraine ridges can be recognised, along with several outcrops of *roches moutonnées*. The LIA frontal moraine is not well preserved, and it is located at about 1,880 m a. s. l., on the edge of a rock sill. The Borgne de Ferpècle river crosses the sill in a deep fluvial gorge, then enters another alluvial zone in the vicinity of les Salays. This alluvial zone was the proglacial area in the LIA.

The main process present in this site is the glacial activity, including glacier movement, melting of the debris-covered tongue, erosion, transport and deposition of sediments by the glacier. The other processes are: (1) fluvio-glacial activity, i.e. transport and deposition of sediments in the alluvial zone; (2) gullying and gravitational activity, acting mainly on unconsolidated morainic deposits (Curry et al., 2005); (3) torrential activity and avalanches in the lateral zones, contributing to the sediment supply to the system. Both the Mont Miné glacier and the Ferpècle glacier are currently in rapid retreat due to climate change – with the Ferpècle glacier retreating faster due to unfavourable topographic and aspect conditions. Until the 1950s the two glaciers merged into one single glacial tongue at the current proglacial plain (Mariétan, 1952; Bezinge & Kunz, 2001). The steady retreat has been interrupted only in the late 1980s, when the Mont Miné glacier advanced again in the proglacial plain, building a push moraine in the process (Bezinge & Kunz, 2001; Lambiel, 2021).

The lower part of the proglacial area has been slightly impacted by anthropogenic action. Some small weirs are present along the river just downstream of the proglacial plain. In the lower part of the site there is a dam, built to collect water for the Grande Dixence hydropower system – and, in the surroundings, there are excavation works, currently covered by vegetation.

### 4.2 Euseigne earth pyramids

The Euseigne pyramids (Fig. 4 and 6B) are located near the eponymous village in the lower Hérens valley, and are among the most notorious geomorphosites in the valley and in the entire Valais canton (Bollati et al., 2017; Keller et al., 2019; Santos et al., 2019; Reynard, 2020; Reynard et al., 2021). They are included in the Swiss federal inventory of geosites (Reynard et al., 2012). This site consists of a dozen hoodoos, reaching heights up to 10–15 m, topped by gneiss and serpentinite boulders with diameters up to several metres. The earth pyramids are carved in Lateglacial morainic deposits, left by a glacier flowing out of the Hérémence valley (Bollati et al., 2015; Lambiel, 2021). The morainic deposits rest on older glaciolacustrine sediments, with 20° dip towards the Borgne river. Those sediments are the remnants of the so-called 'Hérens lake', formed because the main Rhone glacier dammed the deglaciated lower part of the Hérens valley (Rumeling stage, early Lateglacial; Coutterand, 2012). The alternation of glaciolacustrine and morainic sediments testifies subsequent phases of retreat and advance of the glaciers in the valley (Sartori & Epard, 2011).

The Euseigne moraine is currently shaped by gullying and runoff erosion, which have carved pyramid-like landforms. Badlands and incipient pyramids can be observed north-east of

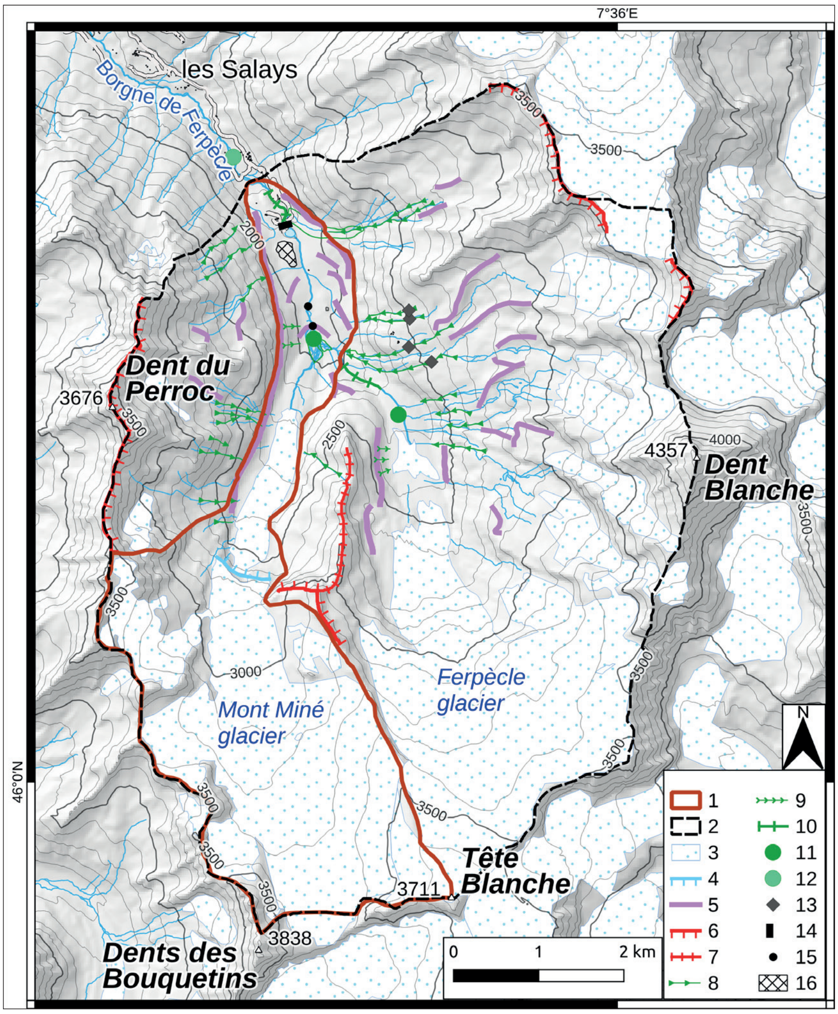



Fig. 3: Geomorphological sketch of the Mont Miné glacial system. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Glacier; 4) Serac subject to ice falls; 5) Moraine ridge; 6) Rock scarp; 7) Rock ridge; 8) Stream with torrential activity; 9) Gully; 10) Fluvial gorge; 11) Active proglacial plain; 12) LIA proglacial plain; 13) Water intake; 14) Dam; 15) Weir; 16) Excavations and embankments
Source: Authors' conceptualisation; Elevation from MDT25 Digital Terrain Model, © swisstopo; Geomorphological elements vector data: own contribution; other vector data from OpenStreetMap

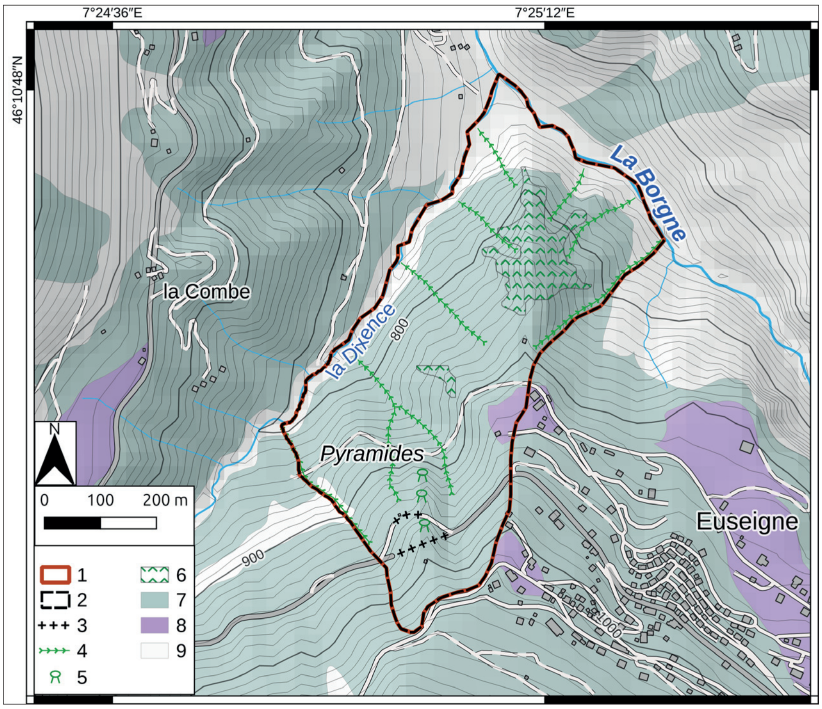



*Fig. 4: Geomorphological sketch for the Euseigne earth pyramids. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Road tunnel; 4) Gully; 5) Earth pyramids; 6) Area affected by denudation and gullying; 7) Morainic deposits; 8) Glaciolacustrine and fluvioglacial deposits; 9) Other superficial deposits or bedrock. Source: Authors' conceptualisation; Elevation from MDT25 Digital Terrain Model, © swisstopo; Geomorphological elements vector data: own contribution; other vector data from OpenStreetMap*

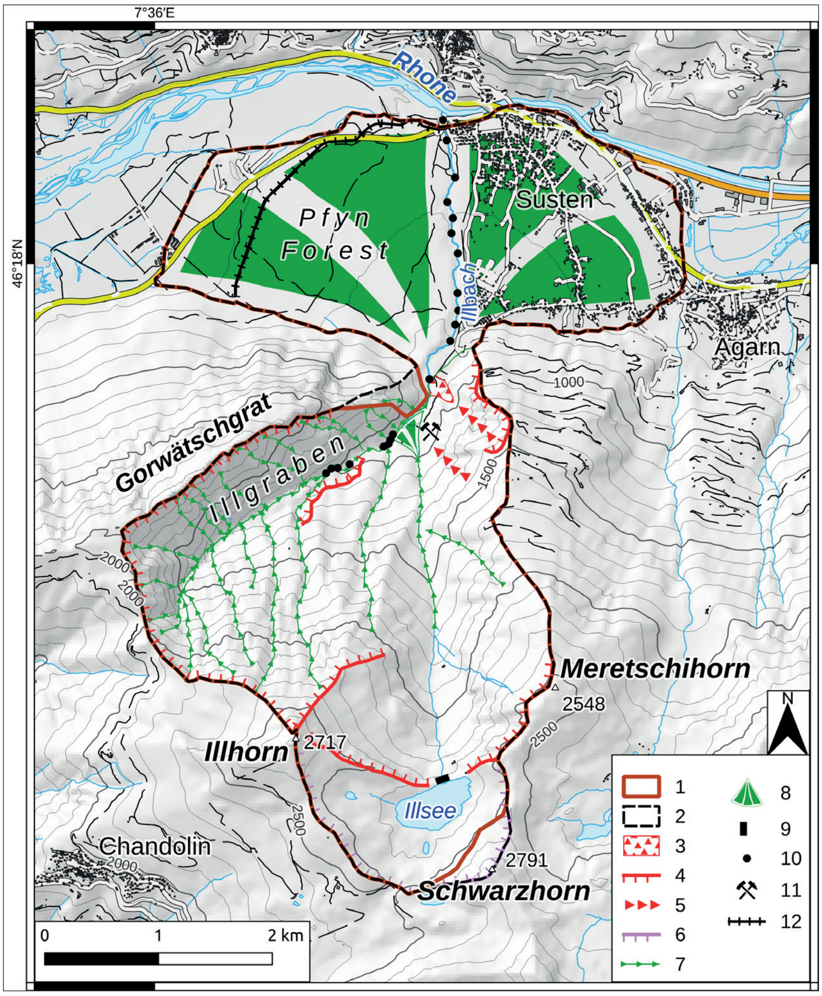



*Fig. 5: Geomorphological sketch of the Illgraben torrential system. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Debris avalanche deposit; 4) Rock scarp; 5) Debris avalanche channel; 6) Glacial cirque; 7) Stream with torrential activity; 8) Debris flow fan; 9) Dam; 10) Retention dam; 11) Quarry; 12) Artificial canal. Source: Authors' conceptualisation; Elevation from MDT25 Digital Terrain Model, © swisstopo; Geomorphological elements vector data: own contribution; other vector data from OpenStreetMap*

the pyramids, near the confluence of the Borgne and Dixence rivers. More recently, the Euseigne pyramids have been affected by human action. The old cantonal road to Euseigne passed through the pyramids with a short tunnel, built in 1947. In 2023, a new tunnel was built further away from the pyramids, and the old one is now used only by pedestrians and cyclists.

### *4.3 Illgraben torrential system*

The Illgraben torrential system (Fig. 5, 6C and 6D) is located on the southern side of the Rhone valley, near the village of Susten (Leuk, Valais). This site is included in the Swiss federal inventory of geosites (Reynard et al., 2012; Najwer et al., 2023). The catchment covers 9.5 km$^2$ and is delimited by the Gorwätschgrat on the NW, by the Illhorn (2,717 m a. s. l.), the Schwarzhorn (2,791 m a. s. l.) and the Meretschihorn (2,548 m a. s. l.) on the S. It consists of two sub-catchments: the main Illgraben channel, flowing with SW–NE orientation between the Gorwätschgrat and the N face of the Illhorn, and the Illbach stream, which flows from S to N. The torrential system terminates with a fan among the largest in the Rhone valley, with a radius of 2 km, a surface of 7.5 km$^2$ and about 250 m of elevation difference between the apex and the base. The eastern half of the fan is partly occupied by the village of Susten, and partly by agricultural fields. The western half is covered by the Pfyn pine forest, which is included in the eponymous regional nature park and nature reserve.

The Illgraben is known for its activity, with 2 to 7 debris flows per year (McArdell & Sartori, 2021). This dynamicity is favoured by the geological settings, with very deformed rocks (quartzites on the S side, carbonate and gypsum rocks on the N) further dissected by numerous faults belonging to the Rhone-Simplon


*Fig. 6: Illustration of the three study sites: A) Mont Miné glacial system, with (1) Mont Miné glacier front in June 2024, (2) Ferpècle glacier, (3) the Little Ice Age moraines, (4) the alluvial zone at the confluence of Mont Miné and Ferpècle streams and (5) the departure sectors of avalanches, lateral streams and debris flows; B) Euseigne Pyramids, with the old tunnel built in 1947; C) Debris flow channel of the Illgraben torrential system viewed from the hanging bridge; D) (1) Illgraben torrential catchment, (2) the debris flow channel (in green) crossed by a hanging bridge and (3) the alluvial fan*
*Photos: J. Bussard (A+D), A. Ferrando (B+C), 2024*

regional fault system (Campani et al., 2010). Because of its activity, the Illgraben has been widely studied in terms of sediment transfer, gravitational phenomena and debris flow dynamics (e.g., Schlunegger et al., 2009; Berger et al., 2011; Bennet et al., 2013; Belli et al., 2022; Meyrat et al., 2022). The main active processes found in this site are therefore the debris flows, in combination with the gravitational processes affecting the catchment part, and the torrential activity (outside debris flows), including runoff, erosion, transport and deposition of sediments. Several debris retention dams were built along the main channel to control sediment transfer, starting in the late 1960s (Lichtenhahn, 1971). From 2000 onwards, monitoring stations are present in several spots of the main channel, and in 2009 an early warning system was put in place to alert the population in case of hazardous events (Badoux et al., 2009). A hanging bridge built in 2005 above the Illbach at the apex of the alluvial fan allows visitors to have a closer look at the debris flow channel.

## 5. Results

### 5.1 Heritage values of the sites

The scientific value of the study sites varies from 12 (on a scale from 4 to 20) for the Illgraben torrential system to 17 for the Mont Miné glacial system (Tab. 3), and the additional values, assessed qualitatively, are described in Table 4. All three sites are very representative, while the other criteria are more contrasted. The only human impact that diminishes the integrity of the Mont Miné glacial system is the presence of small dams in the sandur. This site is not particularly rare at the scale of the Swiss Alps, but has very high paleogeographical interest, thanks to the visible succession of morainic ridges that documents the glacier retreat from the end of the LIA until today. The Euseigne pyramids are also of high paleogeographical interest, as they are carved into moraine deposits that are evidence of a Lateglacial stage, and are rare at the scale of the Swiss Alps. However, the construction of a road tunnel into the pyramids and the concrete reinforcement of some pillars for security issues reduce significatively the integrity of this site. In addition, the integrity of the moraine deposits is lowered by the natural erosion that shapes the pyramids. The integrity of the Illgraben torrential system is also impacted by the river management infrastructure, and by the occupation of half of the alluvial fan by the village of Susten and agricultural fields. Torrential systems are not rare in the region, but the size of Illgraben is uncommon.

| | G1 | G2 | G3 |
|---|---|---|---|
| Integrity | 4 | 3 | 3 |
| Rarity | 3 | 4 | 3 |
| Representativeness | 5 | 5 | 5 |
| Paleogeographical interest | 5 | 4 | 1 |
| Scientific value | 17 | 16 | 12 |

*Tab. 3: Assessment of the scientific value of the study sites. G1 – Mont Miné glacial system; G2 – Euseigne earth pyramids; G3 – Illgraben torrential system*
*Source: Authors' conceptualisation*

### 5.2 Heritage value of the processes

#### 5.2.1 Scientific value

The scientific value of the processes (Tab. 5) present in the Illgraben torrential system (debris flow, torrential activity, gravitational activity) is the highest of the three study sites, thanks to the high frequency and intensity of debris flows. It is also very representative of these types of processes. The scientific value is slightly reduced by the anthropogenic interventions (weirs, dikes) in the stream channel. The processes of the Mont Miné glacial system (glacial activity, fluvio-glacial activity, gullying and gravitational activity, torrential activity, and avalanches) are also very representative of an alpine glacial system, and they are almost untouched by human infrastructure, with the exception of the small dams which accelerate sedimentation in the alluvial zone. However, these processes are not rare, although they are continuous and quite intense. The scientific value of the processes involved in the Euseigne pyramids (gullying, runoff erosion) is much lower, because they have a low intensity, they are not rare and not very representative. As some pillars are reinforced with concrete for security reasons, the processes are slightly reduced by anthropic intervention.

#### 5.2.2 Additional values

The scores assigned to the indicators for the additional values are shown in Table 5. The intertwined processes of the Mont Miné glacial system have the highest aesthetic value among the three case studies, due to their utmost visibility and aesthetic appreciation. The active geomorphological system has indeed a major impact on the landscape, and the main active processes range from continuous but slow (glacial action) to episodic but rapid (landslides, avalanches etc.). The aesthetic value is also quite high for the Illgraben torrential system, as the process is very visible due to its impact on the landscape and its high velocity. In this case, the aesthetic appreciation is positive from the point of view of the authors, but, given the destructive potential of the process, it could change from the perspective of different social groups. At the Euseigne pyramids, the main active process (i.e. runoff erosion) stands out in the landscape because of the impressive landforms, is quite frequent, but has a very low velocity, so that it has an average visibility. The aesthetic appreciation of the process is also low, as the scenic beauty of the site is related to the landforms, not to the process itself.

The ecological value of the Euseigne pyramids and the Illgraben torrential system is negligible. Only the Mont Miné glacial system obtains a higher score thanks to its high biodiversity – the whole vegetation succession, from pioneer species to larch forest, is visible on the site, and the presence of these diverse ecosystems and species is mostly related to the high activity of the system and its evolution due to climate change.

| | G1 | G2 | G3 |
|---|---|---|---|
| Aesthetic value | High. The landscape is very contrasted in terms of colours and topography | High. The shape of the pyramids is very differentiated compared to its immediate environment | The debris flow channel, as seen from the hanging bridge, is impressive, as well as the whole landscape seen from a distance. The upper catchment is not visible from most of the lower part of the site |
| Ecological value | The ecological succession due to glacier retreat and the presence of pioneer species linked to perturbances are worth mentioning | – | A pine forest, rare in the Rhone valley, exists on the alluvial fan (nature reserve) |
| Cultural value | Depicted in painting from the 1830s (see Bezinge & Kunz, 2001) | The earth pyramids are present in the literature, art and history of tourism | – |

*Tab. 4: Qualitative assessment of the additional values of the sites. G1 – Mont Miné glacial system; G2 – Euseigne earth pyramids; G3 – Illgraben torrential system*
*Source: Authors' conceptualisation*

| Indicators | Sub-indicators | | Initial scores G1 | G2 | G3 | Im | Final scores G1 | G2 | G3 |
|---|---|---|---|---|---|---|---|---|---|
| Scientific value | Representativeness | | 5 | 3 | 5 | **0.88** | 4.40 | 2.64 | 4.40 |
| | Rarity | | 3 | 2 | 5 | **0.79** | 2.37 | 1.58 | 3.95 |
| | Anthropogenic modifications | | 4 | 4 | 3 | **0.84** | 3.36 | 3.36 | 2.52 |
| | Maximum intensity | | 4 | 1 | 4 | **0.78** | 3.12 | 0.78 | 3.12 |
| | **Total** | | **16** | **10** | **17** | | **13.25** | **8.36** | **13.99** |
| Aesthetic value | Visibility | Impact on the landscape | 5 | 4 | 5 | **0.78** | 3.90 | 3.12 | 3.90 |
| | | Frequency | 5 | 4 | 3 | **0.78** | 3.90 | 3.12 | 2.34 |
| | | Velocity | 3 | 1 | 5 | **0.78** | 2.34 | 0.78 | 3.90 |
| | Aesthetic appreciation | | 5 | 1 | 3 | **0.66** | 3.30 | 0.66 | 1.98 |
| | **Total** | | **18** | **10** | **16** | | **13.44** | **7.68** | **12.12** |
| Ecological value | Biodiversity | | 5 | 1 | 1 | **0.64** | 3.20 | 0.64 | 0.64 |
| | Rarity of species | | 1 | 1 | 1 | **0.61** | 0.61 | 0.61 | 0.61 |
| | **Total** | | **6** | **2** | **2** | | **3.81** | **1.25** | **1.25** |
| Cultural values | Geohistorical importance | | 2 | 2 | 5 | **0.83** | 1.66 | 1.66 | 4.15 |
| | Built heritage | | 1 | 2 | 1 | **0.66** | 0.66 | 1.32 | 0.66 |
| | Symbolic, historic or religious significance | | 3 | 1 | 2 | **0.69** | 2.07 | 0.69 | 1.38 |
| | Art and literature | | 3 | 1 | 2 | **0.62** | 1.86 | 0.62 | 1.24 |
| | Cultural landscape | | 1 | 1 | 1 | **0.76** | 0.76 | 0.76 | 0.76 |
| | Natural hazards | | 1 | 2 | 4 | **0.84** | 0.84 | 1.68 | 3.36 |
| | **Total** | | **11** | **9** | **15** | | **7.85** | **6.73** | **11.55** |

*Tab. 5: Model scaling for active geomorphological processes. G1 – Mont Miné glacial system; G2 – Euseigne earth pyramids; G3 – Illgraben torrential system*
*Source: Authors' conceptualisation*

The cultural value of the processes is low to average for each of the three sites. The Mont Miné glacial system has some symbolic importance, because retreating glaciers are a very visible symbol of the current climate warming. It is also of average importance for art, as it has been depicted in paintings from the 19$^{th}$ century (Bezinge & Kunz, 2001), and was the setting for a performance art exhibition in 2022 (Ablations: Mont Miné by Sarah Casey). The Illgraben torrential system is of great geohistorical importance, as it is one of the best known and most studied torrential systems in the Alps. This site also has a cultural value related to the management of natural hazards, because of the presence of structures (dikes and weirs) and a monitoring system aimed at reducing the geomorphological risk (see also chapter 6.2 for further discussion). Finally, in the case of the Euseigne pyramids, the active process has very low cultural value – the cultural heritage of the site is mainly linked to the landforms.

### 5.2.3 Importance factors analysis

The aim of the survey research was to determine the views of experts in the field of geomorphology on the significance and importance of the sub-indicators within the model. In total, 50 experts participated in the survey, with 82% being males. The age groups were quite evenly present, with the highest in number being the age group above 55 years (28%). Additionally, the location of the participants included Europe, North and South America, Oceania, as well as Asia and Africa. However, most participants are from Europe (54%). As for the educational level, 88% of the participants hold a PhD, while 12% hold an MSc degree.

The obtained data indicate different levels of importance that determine the final results (Fig. 7). Within the scope of scientific values, the highest importance from the survey was assigned to the representativeness of active geomorphological processes (0.88). Also, the sub-indicator related to anthropogenic modifications was evaluated with high scores (0.84). Slightly lower average scores were assigned to the sub-indicators of rarity (0.79) and maximum intensity (0.78). Within aesthetic values, visibility received a higher rating (0.78) than aesthetic appreciation (0.66). Furthermore, within ecological values, the sub-indicator ratings are similar. However, the biodiversity sub-indicator has a slightly higher score (0.64) than the rarity of species (0.61). Cultural values indicate a significant difference between the sub-indicators in terms of importance. In the questionnaire, the experts singled out geohistorical importance (0.83) and natural hazard (0.84) as the most important sub-indicators, while they singled out built heritage (0.66) and art and literature (0.62) as the least important.

The survey data shows that experts prioritise certain sub-indicators similarly across scientific and cultural values. For instance, the highest scores for representativeness of active geomorphological processes and anthropogenic modifications in the scientific value match closely with geohistorical importance and natural hazard in the cultural value. This similarity suggests a strong emphasis on both natural and human-influenced processes in both categories. Moreover, within the scientific value, the lowest scores are for rarity and maximum intensity, which are still relatively high compared to the lowest in other categories. For the aesthetic value, aesthetic appreciation scores much lower compared to visibility, indicating less emphasis on subjective beauty of the geomorphological processes. The lowest scores for the sub-indicators within cultural values are built heritage and art and literature, both significantly lower than the highest in this

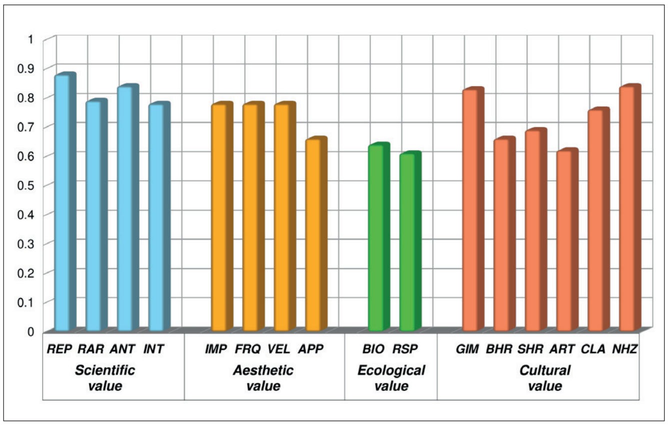



*Fig. 7: Importance factors for each indicator, used for the weighting of the scores. Notes: REP = Representativeness; RAR = Rarity; ANT = Anthropogenic modifications; INT = Maximum intensity; IMP = Impact on the landscape; FRQ = Frequency; VEL = Velocity; APP = Aesthetic appreciation; BIO = Biodiversity; RSP = Rarity of species; GIM = Geohistorical importance; BHR = Built heritage; SHR = Symbolic, historic or religious significance; ART = Art and literature; CLA = Cultural landscape; NHZ = Natural hazards*
*Source: Authors' conceptualisation*

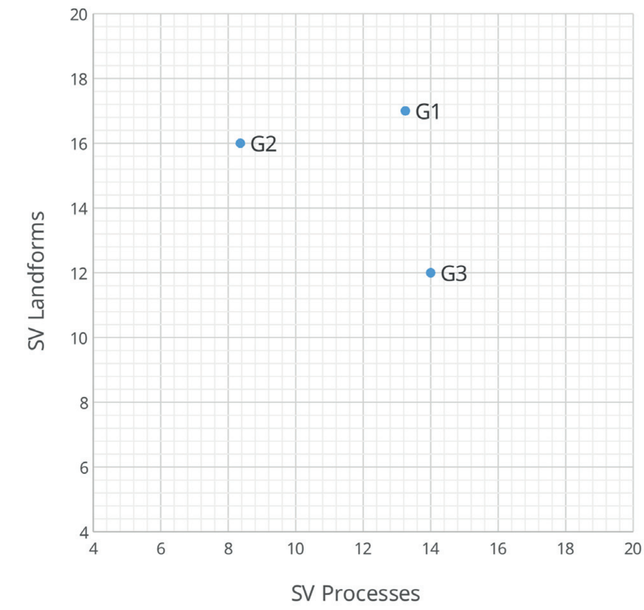
group, which are geohistorical importance and natural hazards. It is evident that the scientific value maintains a relatively high importance and cultural values show the greatest variability. Conversely, aesthetic and ecological values have received lower scores for importance. This comparison highlights that the top priorities in scientific and cultural values align closely, while aesthetic and ecological values represent secondary priorities.

## 6. Discussion

### *6.1 Assessment of the heritage values*

Assessing the heritage values of geomorphological processes presents similar methodological challenges to those encountered in evaluating the heritage values of landforms or geosites. While the criteria for assessing the scientific value are clear and straightforward for geomorphologists, evaluating additional values is more complex and often less precise. This complexity arises from two main issues: first, the interdisciplinary nature of ecological and cultural values requires expertise beyond the scope of the authors of this study. Second, aesthetic value is inherently subjective and should be assessed from multiple perspectives, including experts, visitors, locals, and managers. Although we attempted to enhance objectivity by defining sub-criteria for each additional value, certain aspects remain difficult to evaluate without further literature review or input from other disciplines. We therefore believe that the results obtained for the scientific value of active processes are robust and objective, but those obtained for the additional values could still be debated or consolidated.

Based on our assessment, we created comparative data modelling in which we presented the final results for the scientific value of landforms and of active geomorphological processes. The values of the assessed landforms and processes are presented in a matrix on the x and y axis (Fig. 8), where there is a clear visualisation of their relationship. The Mont Miné glacial system scored the highest, with a landform value of 17 and a process value of 13.25. The very significant paleogeographical interest of the inherited glacial landforms explains why, in that case, the scientific value of the landforms is slightly higher than the one of the processes. Euseigne earth pyramids, with a landform value of 16 and a process value of 8.36, are notable for their unique formations, but the runoff erosion process is much less significant. Illgraben torrential system, scoring a landform value of 12 and a process value of 14, is important for its active debris flow process, despite having a slightly lower landform value. Overall, the Mont Miné glacial system stands out for its balanced and high values in both categories, while Euseigne pyramids contribute mainly through their distinct landforms and Illgraben mainly through its active geomorphological processes.




| Geosites | SV Processes ∑ | SV Landforms ∑ |
|---|---|---|
| Mt. Miné glacial system (G1) | 13.25 | 17 |
| Euseigne pyramids (G2) | 8.36 | 16 |
| Illgraben torrential system (G3) | 14 | 12 |

*Fig. 8: Comparison of the total scientific value of processes and landforms for the three study sites*
*Source: Authors' conceptualisation*

### *6.2 Issues related to geoconservation*

The analysis of the heritage values of geomorphological processes and landforms across three case studies bring up some important points of discussion (see Sections 2.1 to 2.5). These include: i) the extent of the functional perimeter with respect to the perimeter of the geomorphosite; ii) the significance of the active processes at each site in relation to the public perception of natural hazards and their management; iii) the relevance of conserving the geomorphological system in its current state; and iv) the need to prioritise the conservation of either landforms or processes. In the following paragraphs these points are discussed in detail through the examples of Mont Miné, Euseigne pyramids, and Illgraben.

The perimeter of the Mont Miné geomorphosite includes the glacier and its proglacial area, enclosed within the moraines of the LIA (*sensu* Bollati et al., 2023; Fig. 3). However, the proglacial stream of the nearby Ferpècle glacier also flows into the same proglacial plain, influencing its morphogenetic dynamics. Sediment transfer in the geomorphological system also occurs along the lateral slopes (e.g., debris flows, landslides, avalanches, glacial action in the lateral cirques, nival and periglacial processes, etc.). Therefore, the functional perimeter is much larger than the geomorphosite perimeter, encompassing the entire catchment area upstream of the LIA frontal moraine. To effectively protect the processes occurring in this site, conservation efforts should consider the broader functional perimeter rather than just the perimeter of the geomorphosite.

The Mont Miné site exemplifies a geomorphological system responding to changes in controlling factors, such as glacier retreat due to climate change. The evolution of the geomorphological system is rapid, shifting from glacial activity to a range of para- and periglacial processes linked to postglacial readjustment. Therefore, because of the glacial retreat, the heritage values depend less and less on the glacier itself and its dynamics, and more and more on these post-glacial processes (Bussard & Reynard, 2023). Some landforms of particular paleogeographic interest, such as the LIA moraines, are evolving rapidly due to gullying and landslides. Over the coming decades, the proglacial plain will be colonised by vegetation, and the glacier will continue to recede. Here, the evolution of the processes and the temporality of the changes themselves have a high heritage value, as they provide insights into the complex interactions between active processes and their response to climate change (Migoń, 2024). For these reasons, it is not relevant to protect the geomorphological system and its landforms in its current configuration – even without taking into account the technical feasibility of such a geoconservation effort.

The Euseigne pyramids geomorphosite encompasses not only the pyramids structures themselves, but also a large part of the outcrops of Lateglacial deposits, extending down to the confluence of the Borgne and Dixence rivers (Fig. 4). Unlike Mont Miné, the area is not significantly impacted by processes from the outside, at least at the time scale of this study, although lateral erosion by the Dixence and Borgne rivers could affect it over a much longer term. Therefore, the functional perimeter coincides with the perimeter of the geomorphosite. Here, the active process that carved the pyramids is also responsible for their degradation and eventual destruction. However, the heritage value primarily lies in the landforms' scientific, aesthetic and cultural values, and not in ongoing processes. Consequently, it is more appropriate in this case to focus on conserving the landforms rather than the processes. On the site of the Euseigne pyramids, the main element of geomorphological risk is gravitational phenomena (ranging from small mudflows to the collapse of boulders) that could affect the old asphalt road and the tunnel crossing the pyramids. For this reason, the pyramids above the old tunnel were reinforced with concrete, and in 2023, a new road tunnel was constructed further uphill to improve safety.

In the Illgraben torrential system, the perimeter of the geomorphosite already includes the entire catchment area (Fig. 5), matching the functional perimeter. Here, the heritage values lie primarily in the active processes, which actively contribute to the development of present landforms rather than degrading them. Therefore, protecting these active processes would not have a negative impact on the integrity of the landforms.

Among the three sites, the Illgraben torrential system is the most relevant to the issue of natural hazards, as it is very active and many human elements are involved – the village of Susten, the hamlets of Pletschen and Feithieren, all located on the E side of the debris flow fan, and the cantonal road that goes from Sion to Brig (Fig. 5). Structural measures include dikes and numerous retention dams along the torrential stream. These structures do not affect the activity of the process, but rather control its intensity: they limit the solid transport of debris flows and prevent the active channel from migrating along the surface of the alluvial fan. The current situation represents a compromise between the preservation of the activity of the main process and the mitigation of the geomorphological risk associated with it. Thus, it could be relevant to conserve the whole geomorphological system in its current state.

On the other hand, the presence of such an active, studied and monitored torrential system is of fundamental importance for the understanding of this type of phenomenon, for testing natural hazard mitigation measures, and for enhancing the risk awareness of the local population. In that sense, dynamic geomorphosites can be useful in increasing public perception of natural hazards and geomorphological risk. The memory of significant geomorphological events, and the memory of the associated risk, can positively influence the development of local communities, for example by discouraging rebuilding structures in areas previously affected by floods, debris flows or avalanches. Disaster sites provide indeed opportunities to better understand exposure to natural hazards (Coratza & De Waele, 2012; Guilbaud et al., 2021) and the functioning of geomorphological processes (Migoń & Pijet-Migoń, 2019). Conversely, erasing evidence of geomorphological risk may have the opposite effect (Cashman & Cronin, 2008; James-Williamson et al., 2024). When material evidence of such events is removed, especially for less intense disasters, it may indeed negatively impact the public perception of the natural phenomenon and the awareness of risk exposure (Migoń & Pijet-Migoń, 2019; James-Williamson et al., 2024). In the Illgraben torrential system, the impacts of debris flows is clearly visible from different viewpoints on the active channel. It therefore has a high potential for raising public awareness of natural hazards.

## 7. Conclusion

Despite the methodological limitations in assessing of the additional values (aesthetic, ecological and cultural values) of landforms and processes with a sufficient degree of objectivity and expertise, our results provide new insights that enhance the scientific debate around the heritage recognition of active geomorphological systems and that could be beneficial for management practices. First, the case studies clearly indicate that the heritage values of active processes can be higher than those of landforms, especially when a process is particularly representative or rare (also in terms of frequency or intensity), and when simultaneously the associated landforms do not hold significant scientific value. Conversely, landforms can also have a higher scientific value than the processes. Therefore, protection measures should prioritise either the processes or the landforms based on their respective heritage values. Second, we noted that protecting an active geomorphological process is complex, as these processes can be the cause of natural hazards, and may have functional perimeters that extend far beyond the perimeter of the site itself. In addition, protecting a geomorphological process in its current state may be impossible, as many of them depend on external factors, such as climate conditions or meteorological events, which are not controllable by humans, at least at a local scale. Third, our study of a glacial system reveals that the ongoing evolution of the geomorphological system itself, including both landforms and processes in evolution, has a significant heritage value. In this case, protecting the processes in their current state may be counterproductive, as it could reduce the overall heritage values of the site. Therefore, an ideal management practice would be to maintain the natural dynamics and rate of change of geomorphological processes, with exceptions when they have a negative impact on landforms that have a higher heritage value than the processes or when they threaten the infrastructure or human life.

**Acknowledgments**

*The authors would like to address their thanks to Lucie Kubalíková, Márton Pál and Vittoria Vandelli for the edition of this special issue. The fieldwork was supported by the Institute of Geography and Sustainability of the University of Lausanne.*

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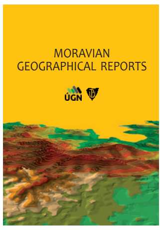
**Please cite this article as:**

Bussard, J., Ferrando, A., & Antić, A. (2025). Heritage recognition of active geomorphological processes: The challenges of geoconservation beyond landforms. Moravian Geographical Reports, 33(1), 7–21. https://doi.org/10.2478/mgr-2025-0002




MORAVIAN GEOGRAPHICAL REPORTS

sciendo

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

journal homepage: **www.geonika.cz/mgr.html**

doi: **https://doi.org/10.2478/mgr-2025-0003**

# Cave tourism in Switzerland: The assessment and implications for subterranean geoheritage sustainability

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## Abstract

This study explores the significance of show caves as subterranean geoheritage sites, focusing on their potential for sustainable cave tourism. The primary objective is to comprehensively assess caves, considering speleological, infrastructure, and tourist values, while developing sustainable tourism strategies. For this, a novel methodology was created that involves literature review, field surveys, assessments and stakeholder consultations, which is applied in the evaluation of nine show caves in Switzerland. By addressing potential challenges and negative impacts, we analyze current tourism development and propose mitigation strategies. Combining quantitative and qualitative analyses, including geological, ecological, and cultural factors, the study offers a comprehensive evaluation, contributing a practical methodology for cave management, as well as cave tourism planning. The findings provide insights beyond academia, guiding stakeholders involved in cave tourism development, and striving to balance ecosystem preservation with sustainable economic growth.

**Keywords:** Show caves, cave tourism, geoheritage, geointerpretation, geoconservation

**Article history:** Received 1 July 2024, Accepted 10 December 2024, Published 31 March 2025

## 1. Introduction

Switzerland, with its diverse geological and geomorphological terrains (Reynard, 2021), is home to numerous karst features that cover roughly 7,900 km$^2$ of the land surface, which corresponds to 19% of the country's surface (Wildberger & Preiswerk, 1997) in four main areas: Jura Mountains, Prealps, Northern Alps (Helvetic Alps) and South Alpine Alps (Austroalpine) (Fig. 1). As for the speleological geoheritage, the Swiss Cave Register includes around 11,500 cave entrances, with a total of 1,200 km of explored underground passage. Cave density varies widely, depending on temperature, flora, and rock suitability and caves are mostly concentrated at Alpine timberline (Wildberger & Preiswerk, 1997).

Effective management and conservation of geoheritage depend on systematic geosite assessments. These procedures are crucial tools for determining values of geological features and landscapes. Moreover, they can enable the identification of scientific, educational, aesthetic, and ecological factors, as well as an understanding of the threats for the assessed sites. The use of standardized methodologies and quantitative frameworks, such as the Geosite Assessment Model (GAM) and its modifications, these evaluations provide the basis for comparing sites and prioritizing them for protection and sustainable development. Geosite assessments are particularly significant in promoting geoheritage conservation as they contribute to the decision-making processes. Furthermore, these evaluations also contribute to the public appreciation of geoheritage by highlighting its intrinsic and cultural importance, thus enhancing geotourism potential.

In the context of caves, geosite assessments are vital for balancing tourism development with the delicate preservation needs of subterranean environments, which are often highly vulnerable to anthropogenic impacts. Incorporating geosite assessment results in broader conservation frameworks supports the establishment of long-term strategies for sustainable use and the mitigation of potential conflicts between development and preservation.

The aim of this paper is to present a comprehensive evaluation of show caves in Switzerland, analyzing their scientific, educational, aesthetic, and protective values, and proposing practical strategies for sustainable cave tourism development while addressing potential challenges and negative impacts. The paper focuses on eight show caves (Tab. 1 and Fig. 1) accessible to visitors without specialized knowledge or equipment; for this reason, renowned caves like Hölloch, known for adventurous tours, are excluded from the analysis. With the development and implementation of a new model for evaluating show caves, the focus is placed on speleological, infrastructure and tourist values of show caves.

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The purpose of these indicators is to show the current state and perspectives of development and protection, as well as the establishment of sustainable development strategies with the aim of continuous (geo)ethical-responsible behavior towards speleological geoheritage.

## 2. Theoretical background

Caves, as subterranean geological formations, hold scientific, cultural, and environmental significance. Show caves stand out as unique destinations that provide visitors with an opportunity to explore geological processes, appreciate their aesthetic beauty, and recognize their ecological importance. A show cave, as defined by the International Show Cave Association, is a "naturally occurring subsurface cavity intentionally opened to the public for guided tours" (see www.i-s-c-a.org). In addition, according to Chiarini et al. (2022), show caves are characterized by an entrance fee, guide service and an existing system of paths, stairs, walkways (or boats) and lighting systems to facilitate visits. These caves are distinguished by their accessibility, requiring no specialized equipment or expert guides for exploration, making them suitable for the general public. However, research regarding cave tourism is quite scarce. Researchers have mainly focused on the motivation, characteristics and preferences of tourists during visits (Kim et al., 2008; Allan, 2011; Garofano & Govoni, 2012; Allan, 2014; Hurtado et al., 2014; Shavanddasht et al., 2017; Antić et al., 2022). To date, there has been limited research on establishing the balance between protecting the underground environment, while promoting tourism development within it. For example, Woo and Kim (2018) investigated the possibilities of developing cave tourism activities with appropriate protection and conservation measures of underground ecosystems. Their inventory and model allow them to assess caves for their suitability for tourism development. However, the findings indicate that no cave in South Korea meets the criteria of their tourism affirmation model. This shows that evaluating the suitability for a cave to be arranged for tourism visits is a complex task that requires the engagement of dedicated multidisciplinary teams.

The speleological geoheritage, including both natural and anthropogenic values within caves, represents a valuable resource in the evolution of geotourism and the establishment of cave tourism as a distinct domain (Dowling, 2013; Donato et al., 2014; Tičar et al., 2018; Tessema et al., 2021; Jaya et al., 2022). Similar to other forms of nature-based tourism, cave tourism confronts multifaceted challenges associated with environmental preservation. Particularly within cave environments, the underground karst ecosystem faces substantial threats during tourist development (Nicod, 1998; Gauchon et al., 2006; Duval, 2008; Nehme et al., 2012; Telbisz & Mari, 2020). Adequate conservation of underground karst landforms requires cave management organizations to follow geoethical principles and implement sustainable strategies aimed at preserving the integrity of speleological geoheritage (Antić et al., 2020). Given the vulnerable nature of underground karst

| Show Caves | Municipality/Canton | Length of tourist pathways (m) | Total length (m) | Altitude (m) | First opened for visitors |
|---|---|---|---|---|---|
| Vallorbe | Vallorbe/Vaud | ~2,000 | ~6,000 | 814 | 1974 |
| Réclère | Réclère/Jura | 1,500 | 300 | 679 | 1890 |
| Beatenberg (St. Beatus) | Beatenberg/Bern | 1,000 | 12,106 | 704 | 1903 |
| Höllgrotten | Menzingen/Zug | ~750[a] | ~750[a] | 534 | 1887 |
| St-Léonard | St-Léonard/Valais | 260[b] | 300 | 523 | 1949 |
| Grotte aux Fées (St-Maurice) | St-Maurice/Valais | ~1,000 | 3,630 | 532 | 1863 |
| Col des Roches | Le Locle/Neuchâtel | ~500 | 862 | 916 | 1988 |
| Kristallhöhle | Oberriet/St. Gallen | 128 | 367 | 645 | 1935 |

*Tab. 1: Show caves investigated in this study*
*Notes: ~ approximately; [a]total length within the upper and lower cave; [b]length of the boat ride on the underground lake*
*Source: https://www.showcaves.com/english/ch/index.html*

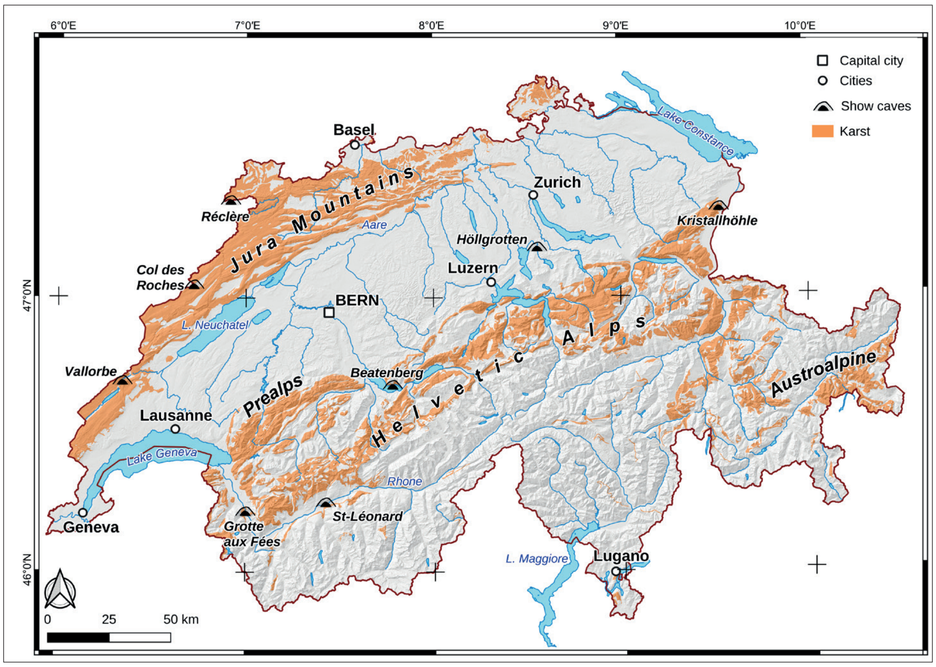


*Fig. 1: Locations of the assessed show caves and karst distribution in Switzerland*
*Source: Authors' elaboration*

formations, including their geomorphological structure, hydrological characteristics, biospeleology, and speleoclimatic properties, the protection and the ethical conduct of human activities within these environments present a complex set of challenges that are essential for sustaining the speleological ecosystem (Buchanan et al., 2022; Chiarini et al., 2022).

The growing interest in cave tourism presents opportunities for economic development while posing challenges such as overexploitation and environmental degradation. Consequently, the sustainable development of cave tourism is of great concern, necessitating strategic planning, adept management, and conservation endeavors. Numerous negative consequences can impact the underground ecosystem of caves. Primarily, the act of arranging the cave for tourist visits has the potential to be harmful to the cave ecosystem. Especially if the management decides to change the geomorphological structure of the cave. The construction material used when equipping the cave for tourist visits can be very detrimental, especially if organic material is introduced which can increase the concentration of $CO_2$ (Cigna, 2019). The increase in speleoclimatic parameters such as temperature and carbon dioxide occur due to the presence of a larger number of people (Lobo et al., 2013), while the most dangerous anthropogenic factor for damaging underground ecosystems is artificial lighting (Cigna, 2016; Cigna, 2019; Baquedano Estévez et al., 2019; Mulec, 2019; Piano et al., 2021; Popović et al., 2023; Addesso et al., 2023). During the installation of lighting in caves, lampenflora (autotrophic lifeforms) develop, which can create irreversible harmful microbiological processes and disturb the speleological ecosystem (Baquedano Estévez et al., 2019). Moreover, the presence of lampenflora has a negative effect on prehistoric cave paintings, which was one of the reasons why Lascaux cave was closed to the public in 1963 (Bastian & Alabouvette, 2009). Also, unlike the Lascaux Cave which was accessible to tourists for several decades before it was closed to visitors, the Grotte Chauvet in France has been inaccessible to tourists since its discovery in 1994. This decision is precisely the result of earlier experiences that confirmed the existence of negative consequences of tourism for the priceless cultural value of cave paintings (Bourges et al., 2014). In addition to the cultural value of cave paintings, valuable contribution of caves is also reflected in the understanding of paleoclimate and environmental dynamics in which natural processes took place (Hennig et al., 1983; Vaks et al., 2003; Harmon et al., 2004; White, 2007; Lachniet, 2009; Fairchild & Baker, 2012; Wong & Breecker, 2015). Speleothems represent a crucial resource for paleoclimatic reconstructions and it is necessary to approach these researches with the maximum geoethical code of conduct that will follow the most modern and responsible approach to speleothem sampling (Gillieson et al., 2022). The results of these researches can be of great importance for geotourism interpretation because these data can be used as indicators of tourist attractiveness. Paleoclimatic interpretation is not a rare occurrence in cave tourism destinations, and it is necessary to make maximum use of the available knowledge that can potentially enrich and brand the image of the destination (Columbu et al., 2021). Therefore, it is evident that management operations must include a series of strategies with the goal of establishing sustainable activities for the development of this type of tourism, which is certainly not easy to manage.

## 3. Materials and methods

### 3.1 Study sites

Situated in the continuation of the scenic Joux valley (Reynard & Schoeneich, 2021), the Vallorbe cave (Figs. 2a, 2b) is the resurgence of the Orbe River, which drains the Joux valley and whose underground flow is linked to the Vallorbe-Pontarlier strike-slip fault (Aubert, 1958); it is the biggest karstic spring in the Swiss Jura (Audétat & Heiss, 2002) and is included in the list of Swiss geosites (Site no. 145; Reynard et al., 2012). The exploration of this unique karst system commenced in 1893, and its doors were opened to the public in 1974 (Wildberger & Preiswerk, 1997). The Vallorbe cave offers an enriching visit facilitated by an audioguide app, accessible in three languages (French, German and English) through the app store. Guided tours, available by appointment, provide a more in-depth understanding of the geological features. This arrangement allows visitors to either explore the scientific aspects of the caves independently or choose a guided experience led by knowledgeable experts, ensuring a comprehensive study of the cave's attributes. Furthermore, the Vallorbe cave reveals an underground landscape shaped by extensive geological processes. The visit encompasses diverse speleothems, including stalactites, stalagmites, and underwater concretions. Noteworthy features include the Cathedral Chamber, which is a 35-meter-high chamber that is illuminated for visitor experience.

Réclère cave (Figs. 2c, 2d), discovered in the late 19$^{th}$ century and operational for tourism since 1890, is a significant geosite in Canton Jura (Swiss geosite no. 133; Reynard et al., 2012), rich with bat colonies (Theubet, 2013). In the immediate vicinity of the show cave there is a Prehistoric Park, that includes an outdoor trail featuring life-sized dinosaur replicas. Réclère cave is limited to one large room (60 × 145 m) and its topographical development does not exceed 300 m (Gigon & Wenger, 1986). However, the

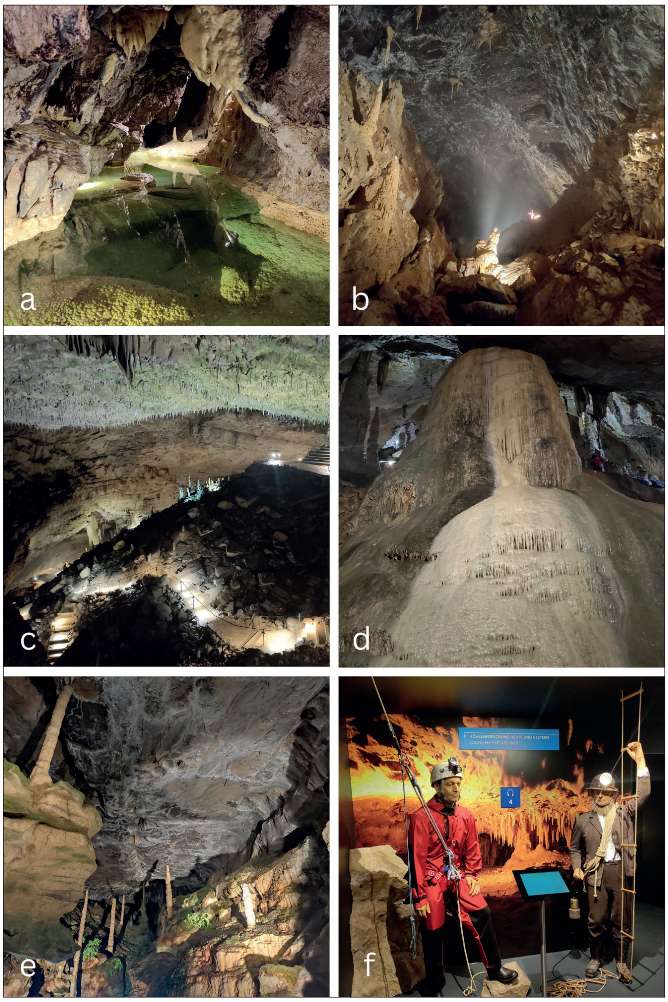


*Fig. 2: Investigated show caves: Vallorbe cave (a) Emarald lake; b) Cathedral Chamber); Réclère cave (c) Main chamber; d) stalagmite Dome); Beatenberg cave (e) stalagmites at the end of the tourist trail; f) Speleology museum in Beatenberg)*
*Photos: A. Antić*

tourist route is longer (1,500 m) because it leads through the cave, exhibiting stalagmites and stalactites with notable features. Key formations include the Pagoda, recognized for its elegance, and the Dome, distinguished as Switzerland's largest stalagmite, which is 15 meters in high (Pfendler et al., 2018).

Beatenberg (St. Beatus) cave (Figs. 2e, 2f), ranked among the top 15 largest caves in Switzerland, is an integral part of the Siebenhengste-Hohgant region's rich surface and underground karstic geoheritage (Häuselmann, 2021; Swiss geosite no. 127; Reynard et al., 2012). The cave system offers unique insights into its formation, historical significance, and the intriguing legend that gave it its name. Beatenberg cave, encompassing a length of 12,106 m, presents an intricate river cave system with numerous ponds, lakes, and waterfalls. Formed in limestone, the cave exhibits notable dripstone formations, including stalactites and stalagmites. Of particular interest is the cave's connection to the regional karst system, with the Siebenhengste-Hohgant being the most extensive cave network (Häuselmann, 2021). While Beatenberg cave is the fifteenth longest in Switzerland, its unique geological features distinguish it as a higher level of karstification (Häuselmann, 2002; Häuselmann, 2021). Accessible to the public through guided tours, Beatenberg cave offers 60-minute exploration along well-lit paths. Particularly visible and accessible, the site has been known since ancient times. The story of Saint-Béat, which refers to a legendary figure from the 1$^{st}$ century, adds a historical dimension to the site. Additionally, a cave museum provides insights into geological context, cave surveying, local lore, and legends, making the Beatenberg cave a comprehensive subject for scientific exploration and appreciation.

The Höllgrotten (Figs. 3a, 3b), situated in Menzingen, present a unique geological site characterized by its young geological age. Around 18,000 years ago, during the Late Glacial (Schlüchter et al., 2021), glacial rivers in the Ägeri Valley formed the Lorze ravine. Groundwater emerged as springs, depositing calcium carbonate and creating a massive spring tufa between 8,500 and 5,500 years ago. As the tufa impeded water flow, the Lorze undercut its base, leading to the formation of dripstone caves (Wyssling & Eikenberg, 2000; Jeannin, 2016; see https://www.hoellgrotten.ch/en/caves.html). Open to the public since 1887, the Höllgrotten offer a self-guided tour. The path winds through narrow passages and chambers rich with various speleothems, providing an immersive experience. The comprehensive tour, spanning approximately 45 minutes, encompasses geological features such as the Sea Grotto, Sky Grotto, Fairy Grotto, Coral Gorge, and the Magic Castle. The journey involves a forest ascent to the entrance, leading through distinct sections within the cave complex, including an outdoor path to the lower cave.

The St-Léonard cave (Figs. 3c, 3d), situated in Valais, features a significant underground lake within a gypsum cave, making it the largest in Europe. It is inscribed in the list of Swiss geosites (Site no. 152; Reynard et al., 2012). Discovered in 1943 (Pittard & Della Santa, 1943), its exploration and subsequent commercialization in 1949 have made it a popular tourist attraction (Pralong, 2006). The cave's geological framework involves several different rock formations, very deformed and tectonized due to the Alpine orogeny. Boats, guided by knowledgeable staff, navigate the underground lake, allowing visitors to appreciate the rich geology. The cave is well-illuminated for safety and aesthetic purposes. Various legends and myths surround the cave, adding cultural and historical dimensions to the tour. The visit features a small museum and events such as musical concerts and wine tasting. The cave underwent extensive renovations in 2003, ensuring safety and continued accessibility.

The St-Maurice cave (*Grotte aux Fées*; Mariétan, 1936), located near St-Maurice town in Valais (Figs. 3e, 3f), holds historical significance as the country's first tourist cave open to the public. The cave's rich history, from legends of fairies to its integration into military fortifications, adds to its allure (Beerli et al., 1999; see https://www.grotteauxfees.ch). The geological history involves the presence of anhydrite and limestone formations, with the cave's discovery dating back to Roman times. Unique features include fairy well and legends of magical encounters within the cave. Beyond its natural allure, the cave played a role in military fortifications, connecting Fort du Scex and Fort de Cindey. The cave's educational trail and cultural legends add depth to the visitor experience, highlighting the intricate relationship between geological phenomena and human narratives (Beerli et al., 1999).

Col-des-Roches (*Moulins souterrains du Col-des-Roches*; Swiss Geosite no. 136; Reynard et al., 2012), is a natural cave system that was anthropogenetically impacted by generations of millers (Gonseth et al., 2002; Pancza, 2001). The milling history indicates an innovative use of hydraulic energy in a cave environment in the Locle valley, Neuchâtel (Figs. 4c, 4d). Initially established by three millers and later expanded by Jonas Sandoz in 1660, the underground mills evolved into a complex system with five hydraulic wheels. Later repurposed as a border slaughterhouse in 1898, the site faced environmental challenges, leading to its closure in 1966. Restoration efforts, initiated in 1973, transformed the site into a museum, gaining public interest (Garin, 1985; Schoellammer, 1997). Since its opening to the public after extensive restoration efforts, the Moulins Souterrains du Col-des-Roches have become a unique tourist destination (Pancza, 2001). The

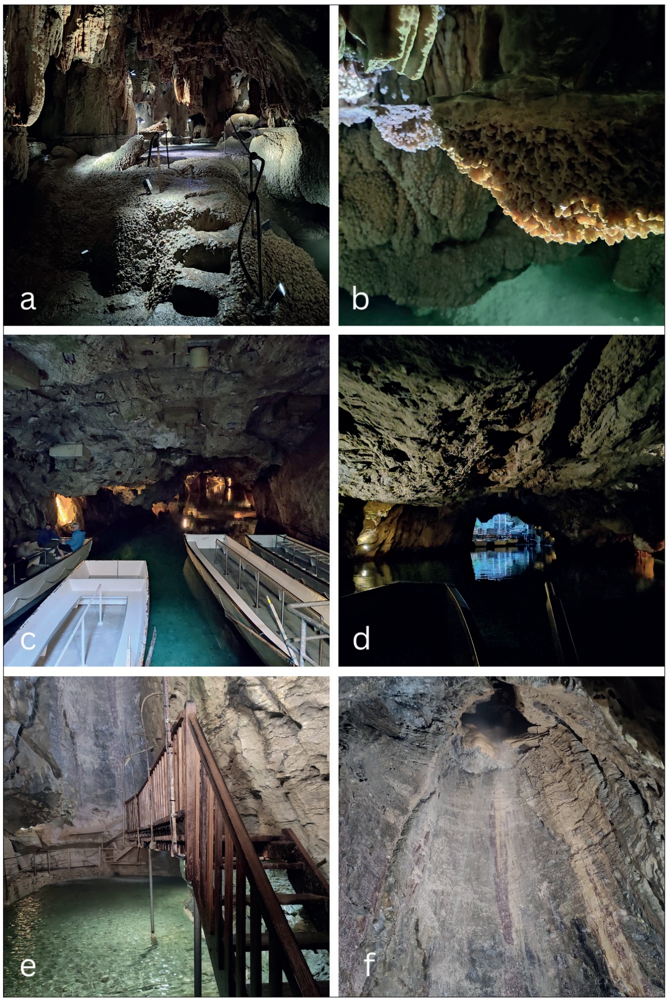


*Fig. 3: Investigated show caves: Höllgrotten cave (a) main path in the lower section of the cave; b) stalactites in the upper section of the cave); St-Léonard cave (c) boats; d) the underground lake); St-Maurice cave (e) lake at the end of the tourist trail; f) cave waterfall)*
*Photos: A. Antić*

tourism office of Neuchâtel established a branch on-site in 2004, and in 2007, a hydraulic circuit was implemented, enabling the operational demonstration of the installations. Regularly organized events and temporary exhibitions further enrich the visitor experience, providing insights into the innovative use of hydraulic energy in this historic underground setting.

The Kristallhöhle cave (Figs. 4e, 4f), situated in the St. Gallen Rhine Valley, was discovered in 1682, notable for its abundance of calcite crystals. Initially described by Johann Jakob Scheuchzer in 1702, the cave gained literary recognition and mineralogical importance. Exploitation for mineral extraction, particularly during World War I, led to substantial crystal loss. However, subsequent discoveries in 1934, spearheaded by Jakob Gyr, unveiled extensive cave passages. Following renovations in 1935, the cave became a show cave, with subsequent renovations in 1987 and 1999. The cave's unique geological features include large calcite crystals, in the form of stalactites and stalagmites, and an interesting false floor formation. The cave features a main passage of 367 meters, with the first 128 meters developed for visitors. The cave river runs alongside the tour path (Heierli, 2001; see https://www.kristallhoehle.ch). Since its opening as a show cave in 1935, Kristallhöhle cave has attracted visitors with its impressive crystal treasures and geological formations. Renovations in 1987 and 1999 enhanced the visitor experience, with improvements such as widened pathways, improved trails, educational exhibits, and the installation of a showcase with cave artifacts.

### *3.2 Methodology*

This paper aims to determine the significance of the investigated show caves in terms of speleological, infrastructural and touristic value. Employing a suitable assessment model is crucial for devising a strategy that balances the preservation of the subterranean geoheritage with economic and tourist considerations. The methodology employed in this study draws upon established and successful assessment models previously utilized in geosite evaluations (Zouros, 2005; Reynard et al., 2007; Vujičić et al., 2011; Cigna & Pani, 2013; Tomić & Božić, 2014; Brilha, 2018; Tomić & Košić, 2020). The Extended Show Cave Assessment Model (E-SCAM), which was used in this paper, represents a new version of SCAM (Antić et al., 2022), consisting of three groups of indicators: speleological value (SV), infrastructure value (IV) and touristic value (TV). All indicators have their own sub-indicators that are given values (grades) from 1 to 5 (Tab. 2 and Appendix 1). The division into speleological, infrastructure and tourist values was made with the aim of specifying indicators related to show caves, their protection and tourist exploitation. Speleological value consists of three groups of sub-indicators. These are: scientific-educational value (VSE), landscape and aesthetic value (VSA) and protection (VPr). In total, speleological value includes 12 sub-indicators (Tab. 2). Furthermore, infrastructural and tourist sub-indicators are not divided into groups. Instead, the infrastructure indicator includes 5 sub-indicators, while tourist indicator includes 21 sub-indicators (Tab. 2).

Thus, we can define the E-SCAM model according to the following equation (1):

$$\text{E-SCAM} = SV + IV + TV$$

where SV, IV and TV are symbols for speleological, infrastructure and tourist values. As speleological value consists of three groups of sub-indicators, we can derive the following equation (2):

$$SV = VSE + VSA + VPr$$


*Fig. 4: Investigated show caves: Col des Roches cave (a) main chamber; b) tourist trail); Kristallhöhle (c) main tourist trail; d) crystals) Photos: A. Antić*

Given that each group of indicators consists of sub-indicators, equations (3), (4), and (5) can be written as follows:

$$SV = VSE + VSA + VPr = \sum_{i=1}^{12} SISV_i, \text{ where } 1 \leq SISV_i \leq 5$$

$$IV = \sum_{e=1}^{5} SIIV_e, \text{ where } 1 \leq SIIV_e \leq 5$$

$$TV = \sum_{j=1}^{21} SITV_j, \text{ where } 1 \leq SITV_j \leq 5$$

Here, $SISV_i$ represents 12 sub-indicators of speleological values ($i = 1, \dots, 12$); $SIIV_e$ represents 5 sub-indicators of infrastructure values ($e = 1, \dots, 5$) and $SITV_j$ represents 21 sub-indicators of touristic values ($j = 1, \dots, 21$). The numerical scores assigned to each sub-indicator range from 1 (lowest value) to 5 (highest value).

The assessment process comprises two distinct stages. In the initial phase, experts evaluate and provide importance factors (Tomić & Božić, 2014) for each sub-indicator within the assessment model. The importance factors are average scores given by experts (1–5) in surveys. Each sub-indicator has its own importance factor, representing the experts' collective assessment of its significance within our model. For SV, the importance factor has already been determined in a previous study (Antić et al., 2022). Thus, the assessment of SV in this paper excluded the first stage of the assessment process, since we used the importance factors of SV from the previous study. Subsequently, in the second stage, authors assessed and assigned scores to the show caves in Switzerland.

| Indicators | | Sub-indicators | Description |
|---|---|---|---|
| Speleological value (SV) | Scientific and educational value (VSE) | Geological interpretation (SISV1) | Possibilities of interpretation of geological and geomorphological processes, phenomena and forms |
| | | Archeological interpretation (SISV2) | Existence and degree of interpretation of material culture of archeological heritage |
| | | Paleontological interpretation (SISV3) | Possibilities of interpretation of paleontological heritage |
| | | Interpretation of the subterranean fauna (SISV4) | Existence and degree of interpretation of the subterranean fauna |
| | Aesthetic value (VSA) | Chambers (SISV5) | Number of halls within the caves |
| | | Speleothems (SISV6) | Quantity and variety of speleothems |
| | | Presence of groundwater (SISV7) | Permanent and/or seasonal rivers, lakes and waterfalls |
| | | Surrounding landscapes (SISV8) | Quality of the surrounding landscape, presence of water and vegetation, absence of artificial damage, proximity to urban areas, etc. |
| | Protection (VPr) | Level of protection (SISV9) | Caves protected by local, regional, national or international institutions |
| | | Disruption of the ecosystem (SISV10) | Quality of the cave ecosystem |
| | | Protection of the subterranean fauna (SISV11) | Degree of protection of the subterranean fauna |
| | | Vulnerability (SISV12) | Level of cave vulnerability/susceptibility to natural or anthropogenic damage |
| Infrastructure value (IV) | | Pathways (SIIV1) | Environmental sustainability of the building material used for pathways |
| | | Handrails (SIIV2) | Environmental sustainability of the building material used for handrails |
| | | Transportation (SIIV3) | Environmental sustainability of various transportation systems |
| | | Gates (SIIV4) | Environmental sustainability of cave gating |
| | | Source of artificial light (SIIV5) | A type of light source in the tourist part of the cave |
| Tourist value (TV) | | Accessibility (SITV1) | Possibilities of access to the cave |
| | | Length of pedestrian track (SITV2) | Length of the tourist trail |
| | | Tourist lighting in the cave (SITV3) | Distance from cave walls and speleothems |
| | | Maintenance of the cave and additional contents (SITV4) | The condition of the tourist infrastructure (if any) – well-maintained and marked trails, signage, rest areas, toilets and the general arrangement and cleanliness of the cave |
| | | Way of movement of tourists through the cave (SITV5) | Ways of movement and means of transport for transporting tourists inside the caves |
| | | Number of visually attractive locations (SITV6) | Places where most visitors take photos and where the guide stops the group and performs the process of tourist interpretation |
| | | Additional natural values (SITV7) | Number of additional natural values within a radius of 5 km (including other caves) |
| | | Additional anthropogenic values (SITV8) | Number of additional anthropogenic values in a radius of 5 km |
| | | Proximity to emissive centers (SITV9) | Proximity to emissive centers |
| | | Proximity to tourist centers (SITV10) | Proximity to tourist centers |
| | | Proximity to visitor centers (SITV11) | Proximity to visitor centers related to the caves |
| | | Proximity to important roads and public transportation facilities (SITV12) | Proximity to important roads and public transportation facilities |
| | | Promotion (SITV13) | Promotional activities by competent tourist organizations |
| | | Number of visitors (SITV14) | Annual number of visitors |
| | | Number of organized group visits (SITV15) | Annual number of organized visits |
| | | Interpretive boards and content (SITV16) | Interpretive characteristics of textual and graphic material, quality, size and fit into the environment and type of interpretative means |
| | | Tourist infrastructure (SITV17) | Level of additional infrastructure for visitors (parking, footpaths, rest areas, waste bins, toilets, etc.). |
| | | Guide service (SITV18) | If any, level of expertise, knowledge of foreign languages, interpretation skills, etc. or availability of audio guides in multiple languages. |
| | | Accommodation facilities (SITV19) | Accommodation services near the caves |
| | | Restaurant services (SITV20) | Restaurant services near the caves |
| | | Rules of conduct (SITV21) | Whether information about the code of conduct is provided and in what way |

*Tab. 2: Structure of the Extended Show Cave Assessment Model (E-SCAM)*
*Source: Authors' conceptualization based on Vujičić et al. (2011); Cigna and Pani (2013); Tomić and Božić (2014); Antić et al. (2022)*

To calculate the final ratings for the investigated show caves in this paper, the authors' ratings were multiplied by the previously established importance factors determined by experts. Therefore, the final ratings incorporates both the authors' opinions and the input from experts in the fields of speleology, cave climate, show cave infrastructure and tourism.

This approach was chosen to gain a more detailed and expert-driven understanding of the significance of show cave tourism values. The study culminates in two matrices: the Speleological-Tourist Value (SV-TV) matrix, and the Infrastructure-Tourist Value (IV-TV) matrix. These matrices compare the speleological and infrastructure values of show caves with their corresponding tourist values. In addition to incorporating infrastructure values into the model, the determination of the importance factor of E-SCAM for tourist values was based on a survey of experts in the tourism field, rather than relying on tourists' surveys conducted within the show caves (as was done in SCAM, Antić et al., 2022). The results of this methodology should provide insights into the current state of the evaluated show caves concerning their speleological and tourist values. While the importance factor for speleological values has been determined in the previous study (Antić et al., 2022), the importance factors of infrastructure and tourist values are defined as (Equations 6 and 7):

$$\text{Im (IV)} = \frac{\sum_{i=1}^{i} \text{Iv}_i}{I}$$

$$\text{Im (TV)} = \frac{\sum_{t=1}^{t} \text{Iv}_t}{T}$$

In this context, $\text{Iv}_i$ represents the assessment, a numeric score allocated by experts to sub-indicators concerning infrastructure values, with $I$ signifying the total number of experts. Also, $\text{Iv}_t$ stands for the evaluation, a numerical value contributed by each expert for sub-indicators associated with tourist values, while $T$ represents the overall number of experts. It's worth noting that the importance factor can assume scores ranging from 1 to 5.

Finally, the E-SCAM equation (8 and 9) with the importance factor is defined and shown in the following form:

$$\text{IV} = \sum_{e=1}^{n} \text{Im}_e \times \text{IV}_e$$

$$\text{TV} = \sum_{j=1}^{n} \text{Im}_j \times \text{TV}_j$$

The maximum attainable scores for SV, IV, and TV are determined based on the comprehensive scoring system employed in the assessment method. For SV, with its 12 sub-indicators, the maximum score per cave is 300, calculated by multiplying the highest possible score (5) given by authors and the highest potential importance factor (5), resulting in a cumulative impact of 25 for each sub-indicator. The infrastructure value (IV), comprised of 5 sub-indicators, yields a maximum score of 125 and the tourist value (TV), encompassing 21 sub-indicators, has a maximum score of 525 for each sub-indicator.

These maximum scores reflect the cumulative impact of all sub-indicators within each category, providing a standardized and transparent framework for evaluating the multidimensional values associated with show caves. The approach ensures that each sub-indicator is considered in proportion to its perceived importance, as assessed through expert surveys. This methodology facilitates meaningful comparisons between different caves, offering an understanding of their diverse values. Moreover, these maximum scores serve as benchmarks, allowing for precise measurement and analysis of the overall significance of each show cave in terms of speleological infrastructure, and tourist values. This standardized framework enhances the reliability of the assessment and provides valuable insights for scientific analysis and informed management considerations within the context of cave conservation and utilization.

Data collection was conducted digitally, through online surveys, between November and December 2023. The participants were experts in the field of caves/geosciences and tourism/geotourism/cave tourism. Since the study involved the compilation and distribution of two different surveys, it was necessary to compile two different databases in order to select the experts for the surveys. For the first survey related to the environmental sustainability of the infrastructure in show caves the following research interest was searched: cave infrastructure, show caves, tourist caves, lampenflora in caves, biofilm in caves and cave disturbance. The second survey is related to the tourist value of show caves, thus, the following research interest was searched: geosites, geoheritage, geotourism, speleotourism, cave tourism and nature-based tourism. Table 3 presents the socio-demographic data collected from 104 participants.

## 4. Results

### *4.1 Importance Factor Analysis*

The following analysis includes the findings obtained from two surveys conducted among experts in the fields of cave sciences and tourism, aimed at quantifying the importance factors associated with Infrastructure, and Tourist values. The term 'importance factor' in the context of this assessment method refers to an average numerical rating assigned by experts to each sub-indicator within the model. It serves as a quantifiable measure of the perceived significance of a specific aspect related to cave tourism.

The experts' assessments provide valuable insights into the priorities and considerations among the E-SCAM sub-indicators. The sub-indicators with higher average scores reflect a consensus among experts on the importance of these factors for the

| Surveys | Gender (%) | | Age (%) | | Location (%) | | Education Level (%) | |
|---|---|---|---|---|---|---|---|---|
| Infrastructure values (N=35) | Female | 34.2 | 18–25 | 0.0 | Switzerland | 5.7 | BSc | 2.8 |
| | Male | 65.8 | 26–35 | 14.2 | Europe | 68.5 | MSc | 5.9 |
| | | | 36–45 | 34.2 | North/South America | 17.4 | PhD | 88.5 |
| | | | 46–55 | 17.1 | Africa | 2.8 | Professional Diploma | 2.8 |
| | | | >55 | 34.5 | Asia | 2.8 | | |
| | | | | | Oceania | 2.8 | | |
| Tourist values (N=69) | Female | 39.1 | 18–25 | 0.0 | Switzerland | 11.5 | BSc | 1.6 |
| | Male | 60.9 | 26–35 | 24.6 | Europe | 55.0 | MSc | 15.9 |
| | | | 36–45 | 36.2 | North/South America | 13.0 | PhD | 79.7 |
| | | | 46–55 | 24.6 | Africa | 2.8 | Professional Diploma | 2.8 |
| | | | >55 | 14.6 | Asia | 13.0 | | |
| | | | | | Oceania | 4.7 | | |

*Tab. 3: Sample characteristics (N = 150)*
*Source: Authors' survey*

assessment of cave tourism. For instance, geological interpretation (SISV1), archeological interpretation (SISV2), and paleontological interpretation (SISV3) received high scores (Tab. 4), indicating that experts recognize the significance of understanding the geological and cultural history of caves for effective tourism management. This suggests a strong emphasis on educational and interpretive aspects, aligning with a trend in responsible tourism where visitors seek meaningful and educational experiences. Additionally, factors related to environmental preservation and conservation, such as the level of protection (SISV9), disruption of the ecosystem (SISV10), protection of subterranean fauna (SISV11), and vulnerability (SISV12), also received high scores (Tab. 4). This indicates the experts' collective emphasis on maintaining the ecological balance and protecting the natural and cultural heritage associated with cave environments. On the other hand, indicators related to visitor experience, safety, and infrastructure, such as interpretive boards and content (SITV16), tourist infrastructure (SITV17), and guide service (SITV18), also received relatively high scores. This highlights the importance of providing visitors with a safe, enjoyable, and informative experience, balancing conservation efforts with the need to accommodate and educate tourists responsibly.

The sub-indicators with lower average scores in the experts' assessments provide valuable insights into areas which are perceived with lesser priority and importance in the evaluation of show caves. For instance, proximity to emissive centers (SITV9) and proximity to tourist centers (SITV10) received lower scores, indicating a potential divergence in expert opinions on the significance of these factors for show cave tourism assessment. This suggests that, while experts prioritize geological, archeological, and ecological considerations, factors related to the proximity of tourist and emissive centers may be perceived as less critical in the overall assessment. Similarly, sub-indicators such as proximity to visitor centers (SITV11), proximity to important roads and public transportation facilities (SITV12), number of visitors (SITV14), and number of organized group visits (SITV15) received comparatively lower scores. The lower scores on accommodation facilities (SITV19) and restaurant services (SITV20) also point out to the fact that experts are not prioritizing on-site complementary services as highly as other aspects of cave tourism. Nevertheless, given the recognized significance of conservation in the assessment, it can be concluded that experts most strongly emphasize the importance of managerial efforts to address visitor numbers and their impact on cave ecosystems.

## 4.2 E-SCAM Assessment

### 4.2.1 Speleological Value

The assessments of geological interpretation vary among the explored show caves. Vallorbe, Réclère, Beatenberg, Höllgrotten and St-Léonard received the highest scores (5), which indicated that the management ensured understandable explanations of geological processes, with an adequate educational experience. Col des Roches received a score of 4, indicating appropriate accessibility to the knowledge about geological processes, however, not at the same level as previously mentioned caves. Kristalhöhle received a moderate score of 3, suggesting adequate but less engaging explanations. Grotte aux Fées (St-Maurice) encounters challenges with a score of 2, indicating a limited attempt at explaining geological processes. In terms of archeological interpretation, most caves received the lowest score (1), indicating an absence of material culture related to speleo-archeological heritage. Beatenberg stands as an exception, earning a score of 4 due to the presence of St. Beatus's legend and grave, showcasing the potential for on-site historical interpretation. As for the paleontological interpretation scores, Réclère and Vallorbe lead with higher scores. Réclère cave is located right next to the Prehistoric park with many educational factors regarding paleontological heritage from the Jura mountains. In Vallorbe there is a medium value of interpretation, including mention and visualization, showcasing a 30,000-year-old bear skeleton. Beatenberg, Höllgrotten, St-Léonard, Grotte aux Fées, Col des Roches, and Kristallhöhle all receive a score of 1, indicating a lack of paleontological interpretation. Cave fauna interpretation for all show caves, except St-Léonard lake, receive the lowest score (1), emphasizing a missed opportunity to educate visitors about subterranean ecosystems. St-Léonard, hosting artificially introduced cave fish, serves as an exception with a score of 4. Overall, the findings point to the fact that there is a potential for enriching the interpretive value of the assessed show caves, particularly for the archeological, paleontological, and cave fauna sub-indicators.

The assessment of chambers in caves showed diverse spatial configurations, which can be significant for tourism experiences. Vallorbe and Beatenberg are assessed with the highest scores due to the extensive networks with numerous chambers within these show caves. Show caves with fewer chambers, such as St-Léonard, provide focused itineraries, that can be meaningful for visitors that seek shorter stays in the subterranean environment. The evaluation of speleothems among the explored caves indicates diverse formations, which are often in the focus of marketing strategies for cave tourism. Vallorbe and Réclère received the highest scores (5) for the diversity, quality and quantity of speleothems. The well-preserved speleothem formations in Vallorbe highly contribute to visual aesthetics in the subterranean environment, appealing to tourists with and without any knowledge regarding speleothem preservation. Réclère hosts the largest stalagmite in Switzerland, adding an important and representative feature to its diverse geological display. Beatenberg and Col des Roches both received scores of 3, indicating a medium amount and good diversity of speleothems, enhancing the overall subterranean experience for tourists. Grotte aux Fées and Kristallhöhle include a smaller amount and medium diversity of speleothems, thus, receiving a score of 2. However, it is notable that in Kristallhöhle there are speleothems that are less common. St-Léonard has a more limited representation, receiving a score of 1. In addition, all show caves include unique water features that enhance the subterranean experience. Tourism operators can use this to attract visitors and researchers interested in both geological and hydrogeological aspects. Furthermore, the surrounding landscapes are highly rated for all show caves. Vallorbe, Réclère, Beatenberg, Höllgrotten, and Kristallhöhle all received a score of 5, indicating the presence of attractive relief and well-preserved natural vegetation. This analysis underscores Switzerland's commitment to maintaining ecological vitality, enriching the visitor experience in these distinct subterranean environments. The elevated scores for show caves in proximity to urban areas, like St-Léonard, Grotte aux Fées, and Col des Roches, signal the need for the integration of these show caves with urban landscapes. This can be used for diverse visitor interests, ranging from nature enthusiasts to those seeking more urban subterranean exploration.

As for the cave protection statuses, all show caves are protected on a cantonal-level, indicating regional recognition for their conservation. Despite not having federal (national) or international protection, such as UNESCO coverage, the cantonal-level recognition highlights the most important efforts to protect these subterranean ecosystems, contributing to their long-term preservation. However, Vallorbe, Réclère, Beatenberg, St-Léonard and Col des Roches have been recognized and listed in the non-official Swiss Inventory of Geosites, carried out by scientific experts (Reynard et al., 2012). For this reason, these show caves received higher score (4), while others received the score of 3. With further tourism utilization of caves, it might be crucial to recognize caves as geoheritage sites of national importance in order to maximize their long-term conservation.

| Indicators | | Sub-indicators | Scores | | | | | | | | Im | Total values | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 | SC7 | SC8 | | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 | SC7 | SC8 |
| Speleological value (SV) | Scientific and educational value (VSE) | Geological interpretation (SISV1) | 5 | 5 | 5 | 5 | 5 | 2 | 4 | 3 | 4.69 | 23.45 | 23.45 | 23.45 | 23.45 | 23.45 | 9.38 | 18.76 | 14.07 |
| | | Archeological interpretation (SISV2) | 1 | 1 | 4 | 1 | 1 | 1 | 1 | 1 | 4.27 | 4.27 | 4.27 | 17.08 | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 |
| | | Paleontological interpretation (SISV3) | 4 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 4.16 | 16.64 | 20.80 | 4.16 | 4.16 | 4.16 | 4.16 | 4.16 | 4.16 |
| | | Interpretation of the subterranean fauna (SISV4) | 1 | 1 | 1 | 1 | 4 | 1 | 1 | 1 | 3.80 | 3.80 | 3.80 | 3.80 | 3.80 | 15.20 | 3.80 | 3.80 | 3.80 |
| | Aesthetic value (VSA) | Chambers (SISV5) | 5 | 2 | 5 | 3 | 2 | 3 | 4 | 1 | 3.55 | 17.75 | 7.10 | 17.75 | 10.65 | 7.10 | 10.65 | 14.20 | 3.55 |
| | | Speleothems (SISV6) | 5 | 5 | 3 | 4 | 1 | 2 | 3 | 2 | 4.19 | 20.95 | 20.95 | 12.57 | 16.76 | 4.19 | 8.38 | 12.57 | 8.38 |
| | | Presence of groundwater (SISV7) | 5 | 3 | 5 | 5 | 5 | 5 | 5 | 5 | 4.13 | 20.65 | 12.39 | 20.65 | 20.65 | 20.65 | 20.65 | 20.65 | 20.65 |
| | | Surrounding landscapes (SISV8) | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 4.11 | 20.55 | 20.55 | 20.55 | 20.55 | 16.44 | 16.44 | 16.44 | 20.55 |
| | Protection (VPr) | Level of protection (SISV9) | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 3 | 4.33 | 17.32 | 17.32 | 17.32 | 12.99 | 17.32 | 12.99 | 17.32 | 12.99 |
| | | Disruption of the ecosystem (SISV10) | 4 | 4 | 3 | 3 | 4 | 1 | 3 | 3 | 4.33 | 17.32 | 17.32 | 12.99 | 12.99 | 17.32 | 4.33 | 12.99 | 12.99 |
| | | Protection of the subterranean fauna (SISV11) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4.13 | 4.13 | 4.13 | 4.13 | 4.13 | 4.13 | 4.13 | 4.13 | 4.13 |
| | | Vulnerability (SISV12) | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4.41 | 13.23 | 13.23 | 13.23 | 13.23 | 13.23 | 13.23 | 13.23 | 13.23 |
| Infrastructure value (IV) | | Pathways (SIIV1) | 4 | 4 | 4 | 4 | 5 | 2 | 2 | 3 | 4.22 | 16.88 | 16.88 | 16.88 | 16.88 | 21.10 | 8.44 | 8.44 | 12.66 |
| | | Handrails (SIIV2) | 5 | 5 | 5 | 4 | 5 | 2 | 5 | 4 | 4.02 | 20.10 | 20.10 | 20.10 | 16.08 | 20.10 | 8.04 | 20.10 | 16.08 |
| | | Transportation (SIIV3) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3.97 | 19.85 | 19.85 | 19.85 | 19.85 | 19.85 | 19.85 | 19.85 | 19.85 |
| | | Gates (SIIV4) | 3 | 3 | 5 | 3 | 5 | 5 | 3 | 3 | 4.20 | 12.60 | 12.60 | 21.00 | 12.60 | 21.00 | 21.00 | 12.60 | 12.60 |
| | | Source of artificial light (SIIV5) | 4 | 4 | 4 | 3 | 4 | 2 | 4 | 3 | 4.62 | 18.48 | 18.48 | 18.48 | 13.86 | 18.48 | 9.24 | 18.48 | 13.86 |
| Tourist value (TV) | | Accessibility (SITV1) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4.34 | 21.70 | 21.70 | 21.70 | 21.70 | 21.70 | 21.70 | 21.70 | 21.70 |
| | | Length of pedestrian track (SITV2) | 4 | 4 | 3 | 3 | 2 | 3 | 3 | 1 | 3.65 | 14.60 | 14.60 | 10.95 | 10.95 | 7.30 | 10.95 | 10.95 | 3.65 |
| | | Tourist lighting in the cave (SITV3) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3.82 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 |
| | | Maintenance of the cave and additional contents (SITV4) | 5 | 5 | 5 | 5 | 5 | 3 | 5 | 5 | 4.30 | 21.50 | 21.50 | 21.50 | 21.50 | 21.50 | 12.90 | 21.50 | 21.50 |
| | | Way of movement of tourists through the cave (SITV5) | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 3.76 | 3.76 | 3.76 | 3.76 | 3.76 | 11.28 | 3.76 | 3.76 | 3.76 |
| | | Number of visually attractive locations (SITV6) | 5 | 5 | 4 | 4 | 2 | 2 | 5 | 2 | 3.98 | 19.90 | 19.90 | 15.92 | 15.92 | 7.96 | 7.96 | 19.90 | 7.96 |
| | | Additional natural values (SITV7) | 5 | 2 | 5 | 5 | 4 | 4 | 3 | 1 | 3.72 | 18.60 | 7.44 | 18.60 | 18.60 | 14.78 | 14.78 | 11.16 | 3.72 |
| | | Additional anthropogenic values (SITV8) | 5 | 3 | 5 | 5 | 2 | 5 | 5 | 3 | 3.43 | 17.15 | 10.29 | 17.15 | 17.15 | 6.86 | 17.15 | 17.15 | 10.29 |
| | | Proximity to emissive centers (SITV9) | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 2.98 | 8.94 | 11.92 | 11.92 | 11.92 | 11.92 | 11.92 | 8.94 | 8.94 |
| | | Proximity to tourist centers (SITV10) | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3.28 | 9.84 | 13.12 | 13.12 | 13.12 | 13.12 | 13.12 | 9.84 | 9.84 |
| | | Proximity to visitor centers (SITV11) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3.55 | 17.75 | 17.75 | 17.75 | 17.75 | 17.75 | 17.75 | 17.75 | 17.75 |
| | | Proximity to important roads and public transportation facilities (SITV12) | 4 | 2 | 5 | 3 | 5 | 4 | 5 | 3 | 3.42 | 13.68 | 6.84 | 17.10 | 10.26 | 17.10 | 13.68 | 17.10 | 10.26 |
| | | Promotion (SITV13) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3.81 | 15.24 | 15.24 | 15.24 | 15.24 | 15.24 | 15.24 | 15.24 | 11.43 |
| | | Number of visitors (SITV14) | 5 | 4 | 5 | 4 | 5 | 3 | 4 | 3 | 3.40 | 17.00 | 13.60 | 17.00 | 13.60 | 17.00 | 10.20 | 13.60 | 10.20 |
| | | Number of organized group visits (SITV15) | 5 | 4 | 5 | 4 | 5 | 3 | 4 | 3 | 3.37 | 16.85 | 13.48 | 16.85 | 13.48 | 16.85 | 10.11 | 13.48 | 10.11 |
| | | Interpretive boards and content (SITV16) | 5 | 5 | 5 | 5 | 5 | 3 | 5 | 3 | 4.01 | 20.05 | 20.05 | 20.05 | 20.05 | 20.05 | 12.03 | 20.05 | 12.03 |
| | | Tourist infrastructure (SITV17) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4.20 | 21.00 | 21.00 | 21.00 | 21.00 | 21.00 | 21.00 | 21.00 | 21.00 |
| | | Guide service (SITV18) | 5 | 5 | 4 | 4 | 5 | 3 | 4 | 5 | 4.13 | 20.65 | 20.65 | 16.52 | 16.52 | 20.65 | 12.39 | 16.52 | 20.65 |
| | | Accommodation facilities (SITV19) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3.07 | 15.35 | 15.35 | 15.35 | 15.35 | 15.35 | 15.35 | 15.35 | 15.35 |
| | | Restaurant services (SITV20) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3.13 | 15.65 | 15.65 | 15.65 | 15.65 | 15.65 | 15.65 | 15.65 | 15.65 |
| | | Rules of conduct (SITV21) | 5 | 3 | 5 | 5 | 1 | 1 | 1 | 1 | 3.94 | 19.70 | 11.82 | 19.70 | 19.70 | 3.94 | 3.94 | 3.94 | 3.94 |

*Tab. 4: Sub-indicator values given by the authors for each analyzed show cave, importance factor values (Im) given by experts (SV, MV, IV and TV) for each sub-indicator and the total value of each sub-indicator in the E-SCAM model*
*Notes: SC1 – Vallorbe; SC2 – Réclère; SC3 – Beatenberg; SC4 – Höllgrotten; SC5 – St-Léonard; SC6 – Grotte aux Fées; SC7 – Col des Roches; SC8 – Kristallhöhle)*
*Source: Authors' elaboration*

Moreover, the assessment of ecosystem disruption in the explored show caves provides valuable insights into the overall quality of the cave ecosystems. Vallorbe and Réclère both received a score of 4, acknowledging minor damage primarily attributed to construction works related to tourist cave adaptation. The use of light and materials in these caves has been managed carefully, resulting in a solid condition for the ecosystem. Beatenberg received a score of 3, indicating moderate damage due to the presence of lampenflora and graffiti. Similarly, Höllgrotten, St-Léonard, Col des Roches, and Kristallhöhle all received scores of 3, with lampenflora being a notable factor contributing to moderate disruption. Grotte aux Fées stands out with a score of 1, indicating significant damage, with the highest amount of lampenflora in Switzerland. This cave has experienced severe disturbances, making it a crucial site for targeted conservation efforts. Furthermore, the uniform vulnerability score of 3 across all assessed caves indicates a medium level of susceptibility to both natural and human-induced activities. This classification highlights that while the caves possess a level of resilience, they are not immune to potential threats and disturbances.

#### *4.2.2 Infrastructure Values*

The evaluation of pathways, focusing on the environmental sustainability of the building materials, includes a range of approaches among the assessed show caves. Notably, St-Léonard stands out with a highest score of 5, due to the absence of pathways as visitors visit the cave by boat on the underground lake. The management structures of Vallorbe, Réclère, Beatenberg and Höllgrotten demonstrates a commitment to safety and sustainability, which is why they are assigned with the score of 4, indicating the presence of safe and environmentally sustainable pathways with minimal impact on the ecosystem. In addition, Grotte aux Fées and Col des Roches both have large amounts of wood materials in their pathways. According to Chiarini et al. (2022), organic materials are considered hazardous and unsustainable for cave environments and that is why these show caves received lower scores (2). Kristallhöhle received a score of 3, indicating pathways that are safe and environmentally sustainable. However, in certain locations, the pathway is inadequately positioned, given that some of the speleothems were altered to accommodate the placement of iron materials for the tourist trail. As for the handrails, Vallorbe, Réclère, Beatenberg, St-Léonard and Col des Roches all include safe and environmentally sustainable handrail materials (mainly stainless steel), which is why they were assigned with the highest scores (5). Höllgrotten and Kristallhöhle, while still ensuring safety, exhibit handrails that are not in the best condition, thus receiving scores of 4. In Grotte aux Fées there are less sustainable handrails, resulting in a score of 2. Furthermore, all assessed show caves uniformly receive a top score of 5 for the transportation sub-indicator, indicating highly safe and sustainable practices with no negative impact on the subterranean ecosystems. Transportation is only required in St-Léonard cave. However, the boat ride on the cave lake is safe and environmentally sustainable. All other show caves are entirely walkable. This managerial performance underscores a shared commitment among these show cave management structures to prioritize low-impact transportation methods.

The assessments of environmental sustainability regarding cave gating shows variable practices, with most show caves practicing moderate level of sustainable gating, thus receiving a score of 3. This indicates the presence of gates that completely seal the cave but maintain safety standards. Vallorbe, Réclère, Höllgrotten, Col des Roches, and Kristallhöhle all fall into this category, with the gates effectively ensuring safety but potentially impacting natural cave ventilation. Beatenberg, Grotte aux Fées, and St-Léonard, however, practice a more environmentally approach, which is why they are assigned with the top scores of 5. In the cases for these show caves, the gates are not completely sealed, which preserves ventilation while maintaining safety standards. Additionally, proper gating practices are important for bat populations. Mainly due to habitat protection and safe access for the bats, while also reducing disturbances that could impact reproduction.

The examination of artificial light sources in the assessed show caves reveals diverse practices. Vallorbe, Réclère, Beatenberg, St-Léonard, Col des Roches, and Kristallhöhle all received scores of 4, indicating the adoption of safe and sustainable lighting systems with minimal impact on the cave environments. Particularly noteworthy is the proactive approach demonstrated by St-Léonard, Beatenberg, and Réclère in addressing historical concerns by replacing older, higher-temperature lights with more sustainable alternatives (LED lighting systems). This managerial commitment reflects an awareness of past environmental impacts and a dedication to the principles of responsible cave tourism. However, Grotte aux Fées received a score of 2, indicating a less sustainable lighting system, which is responsible for the large amount of lampenflora that is present in this show cave. Numerous scholars (Cigna & Forti, 2013; Cigna, 2016; Novas et al., 2017; Constantin et al., 2021; Piano et al., 2021; Piano et al., 2024) have emphasized the critical need to adopt eco-speleo-friendly lighting technologies to address past impacts and advance sustainable practices in cave tourism. This is why urgent measures need to be implemented in order to achieve inhibition of lampenflora growth in these environments.

#### *4.2.3 Tourist Values*

The assessment regarding accessing show caves in Switzerland uniformly indicates a high degree of easy access for visitors. All show caves received the highest score of 5, which means that there are well-established transportation networks in place, allowing visitors to reach these destinations conveniently. Also, public transport in Switzerland is recognized for its efficiency, providing an ideal travel experience for both individual and group tourists (Buehler et al., 2019). For all show caves it is possible to access the destination by car, bus, or a short walk from parking areas. Therefore, assigned high scores indicate an existing managerial commitment to enhancing the visitor experience and promoting inclusive tourism. As for the length of pedestrian tracks within the show caves, Vallorbe, Réclère, Beatenberg, and Höllgrotten, each received a score of 4, indicating a presence of trails ranging from 1,001 to 2,000 m, providing visitors with a substantial subterranean exploration. Beatenberg, Grotte aux Fées, Col des Roches, and Réclère, received a score of 3, indicating the presence of trails spanning from 501 to 1,000 m, thus, ensuring a moderate-length visit. Kristallhöhle received the score of 1, which indicates the presence of trails up to 200 m, providing shorter experience for visitors. The advantage of existing variations in trail lengths is their suitability for diverse visitor preferences, accommodating both those seeking a comprehensive exploration of extensive cave systems and those seeking a shorter, more focused subterranean visit. The assessment of tourist lighting for all show caves indicates high values, which reflects adequate illumination for visitors, including safety and the possibility of clear observation of intricate speleothems and unique features. High scores are also given to the maintenance of tourist infrastructure for the explored show caves. Vallorbe, Réclère, Beatenberg, Höllgrotten, St-Léonard, Col des Roches, and Kristallhöhle each received a top score of 5, highlighting the excellent condition of trails, signage, rest areas, toilets, and overall cleanliness. Thus, the management of these show caves provides visitors with a well-organized experience, emphasizing the importance of maintaining high standards for both safety and aesthetics. Grotte aux Fées received a score of 3, due to the presence of wooden boards on the ground and a large amount of lampenflora, indicating a lower level of maintenance compared to the other show caves.

The assessment of additional natural values within a 5 km radius shows diverse surroundings of the explored show caves in Switzerland. Vallorbe received the highest score (5), due to its proximity to a smaller cave (Grotte aux Fées de Vallorbe), Orbe River, and waterfalls, as well as Joux and Brenet lakes. Réclère was assigned with a score of 2, having in its proximity only a small religious cave, while Beatenberg received a highest score (5), due to the proximity of St. Beatus waterfall, Lake Thun, and numerous lakeside beaches and parks. Höllgrotten also received the highest score (5) because of the proximity to Zug Lake, Ägeri Lake, and various rivers and waterfalls. Due to a more limited additional natural sites, St-Léonard received a score of 4. These sites include the Rhone River and three smaller lakes, as well as the proximity to the Pfyn-Finges Regional Natural Park. Grotte aux Fées also received the score 4 and its sites include the Rhone River, Caillettes glacier mill, Vièze and Trient gorges and Pissevache waterfall. Col des Roches received a score of 3, due to its proximity to only two additional natural sites, which are Rançonnière and Doubs waterfalls. Kristallhöhle received the lowest rating (1). This show cave is situated near the Wichenstein Nature Reserve; however, there are no additional natural sites in its proximity.

Moreover, the assessment of additional anthropogenic values in the vicinity of the show caves showed a presence of very rich cultural and historical landmarks that are crucial as complementary elements for tourists. Vallorbe received the highest score (5) due to its proximity to numerous anthropogenic tourist sites, such as Juraparc (animal park), Iron and Railway museum, Viaduc du Day and Pré-Giroud Military Fort (Army museum). Réclère received a score of 3, due to its proximity to two sites, which are: the Prehistoric Park and Château de Montjoie-le-Château. Beatenberg received the highest score due to its proximity to several cultural tourist sites, including Interlaken international tourist resort, Festung Waldbrand museum, Ruine Weissenau and Burgruine Unspunnen. Höllgrotten received the highest score due to its proximity to Lorzentobelbrücken bridge, Ruine Wildenburg, Prehistory museum in Zug, as well as other cultural attractions in Zug. St-Maurice also received the highest score (5) due to its cultural and historical surroundings, which include Theban Legion heritage and Notre-Dame-du-Scex chapel, as well as the Salt Mines of Bex. Cultural and historical values are also high for the Col des Roches show cave, due to its proximity to the Watch museum and Art museum in Le Locle (UNESCO World Heritage site), but also due to the history of the cave and its immediate surroundings that concern milling tradition. St-Léonard and Kristallhöhle all received lower scores. Nevertheless, such rich cultural and historical attractions in the proximity of the show caves allows tourists to prolong their stays in the region, thus stimulating local economies through increased tourism expenditure.

The proximity of emissive and tourist centers to the assessed show caves plays a crucial role in facilitating accessibility and visitation. All show caves received scores of 3 or 4, indicating that major population centers, such as Lausanne, Interlaken, Zug, Sion, Martigny, Chur, Neuchâtel, La Chaux-de-Fonds, Delémont, and St. Gallen, are within a convenient range of 5 to 50 km. Most of the investigated show caves are located in important regional tourist destinations in Switzerland: Vaud Jura (Vallorbe), Neuchâtel Mountains (Col-des-Roches), Jura (Réclère), Valais (St-Léonard, St-Maurice), Bernese Oberland (Beatenberg), Central Switzerland (Höllgrotten) and Säntis Region (Kristallhölle), which ensure a large number of potential visitors. Also, all show caves feature small or large visitor centers with souvenir shops, that offer a diverse range of merchandise, mostly related to cave-themed items.

The proximity of all show caves to key national road networks enables easy access by car. However, our assessment is also focused on sustainable transportation systems which are possible via public transportation facilities. For this sub-indicator Beatenberg, St-Léonard and Col des Roches received the highest scores (5), because the distance from the nearest public transportation station to these show caves is less than 500 m. Vallorbe and Grotte aux Fées received the score of 4, because the nearest station is located less than 1 km from the show cave. Other show caves received lower scores, due to the fact that the nearest stations are located more than 1 km away from the show caves. In case of Réclère, the nearest station is located more than 2 km away and that is why this show cave received the lowest score (1) for this sub-indicator.

The promotional activities for the assessed show caves on both national and cantonal levels indicate their significance in Switzerland's tourism landscape. While Vallorbe, Réclère, Beatenberg, Höllgrotten, St-Léonard, Grotte aux Fées and Col des Roches benefit from national exposure through Swiss Tourism – the national organization for tourism promotion – official website (see https://www.myswitzerland.com/en-ch/destinations/nature/caves-and-grottos/), Kristallhöhle stands out as an exception, being promoted primarily on a cantonal level. Furthermore, the sub-indicator for onsite interpretive boards was generally assessed with high scores, ranging from 3 to 5. Most destinations have the inclusion of interpretative material in three languages – English, German, and French, which reflects a managerial dedication to accommodating diverse audiences, enhancing the accessibility of educational content. Vallorbe, Réclère, Beatenberg, and Höllgrotten particularly stand out for high quality panels, that offer in-depth information on karst landscapes, cave formations, and related geological phenomena. This managerial approach of multilingual and comprehensive interpretative content enhances the educational value of the cave visits among tourists with varied linguistic and knowledge backgrounds.

The sub-indicators related to the proximity of accommodation and restaurant services within a 5 km radius are assessed with the highest scores (5) for all show caves. This ensures convenience for visitors and contributes to the economic sustainability and attractiveness of these destinations. Additionally, the availability of restaurants provides convenience for visitors to save time and be close to the show caves during their visit. The sub-indicator regarding guide services includes varying degrees of quality. Réclère, St-Léonard, and Kristallhöhle have mandatory in-person guidance, which ensures quality interpretative efforts. Thus, these show caves received the highest scores (5). In Vallorbe, advanced booking for in-person guides is necessary. However, in addition to available audio guides, it is possible to download a free Vallorbe app for the tour, which enhances the interpretation and visit. Due to this innovative approach, Vallorbe also received the highest score for guide services (5). Beatenberg, Höllgrotten, and Col des Roches also offer advanced booking for in-person guides and an audio guide, which is why they all received a score of 4. The visit to Grotte aux Fées includes guidebooks for interpretation and guide service only per request, indicating the need for improvement by potentially introducing audio guides, mobile apps and other ways for enhancing the visitor experience.

The evaluation of rules of conduct inside the show caves reveals a range of approaches. Vallorbe, Beatenberg, and Höllgrotten received the highest score (5), due to comprehensive information provided visually in multiple languages with continuous monitoring of visitor behavior. This geoethical approach indicates a proactive managerial commitment to both visitor safety and environmental conservation. Réclère received a score of 3, as the information is provided only through visual images, that offer guidance without any linguistic support. This approach focuses on universality, but it may benefit from additional linguistic inclusivity. St-Léonard, Grotte aux Fées, Col des Roches, and Kristallhöhle all received a score of 1, indicating limited or no provision of information about the code of conduct. Informing visitors about the rules of conduct within show caves aligns with the broader goal of implementing responsible tourism practices. For this reason, show cave management for caves with lower scores should consider improving this factor.

### 4.3 E-SCAM Matrices

In this section, we analyze the two matrices – Tourist-Speleological (TV-SV), and Tourist-Infrastructure (TV-IV). These matrices (Tab. 5; Figs. 5 and 6) collectively contribute to a thorough understanding of the cave tourism dynamics in Switzerland. The TV-SV matrix shows the balance between geological significance and tourist attraction, highlighting areas for interpretative improvements and conservation efforts. The TV-IV matrix explores the correlation between infrastructure environmental sustainability that is utilized for the overall visitor experience. This triadic approach represents a holistic analysis and allows for stakeholders and decision makers to focus on specific strengths and weaknesses in each aspect of the E-SCAM indicators.

In the TV-SV matrix (Fig. 5), Vallorbe, Réclère, and Beatenberg are positioned in the field 33. Their position reflects the presence of high speleological and tourist values, with limited need for urgent cave management improvements. Höllgrotten is positioned close to the border of fields 23 and 33, indicating high tourist values but moderate speleological values. This suggests the presence of a certain imbalance and a need for enhanced efforts in speleological interpretation and preservation of the subterranean ecosystem. St-Léonard and Col des Roches, are both positioned in the field 23, indicating moderate speleological values and high tourist values. Similarly as Höllgrotten, these show caves should have higher speleological values through enhanced interpretation and protection. Grotte aux Fées is also positioned in the field 23, but much closer to the field 22, which indicates the presence of lower tourist values in comparison with previously mentioned show caves. Moreover, these show caves also possess low speleological values, that require improvements in interpretation, maintenance, and managerial aspects. This is especially the case with Grotte aux Fées, where large amounts of lampenflora remain neglected. Kristallhöhle is positioned in the field 22, displaying the lowest tourist values and with considerable potential for improvements in promotional strategies, geological interpretation, and overall visitor experience in order to elevate its position in the matrix.

The analysis of the TV-IV matrix (Fig. 6) focuses on the environmental sustainability of infrastructure and building materials that were implemented for cave tourism utilization. Vallorbe, Réclère, Beatenberg, Höllgrotten, and St-Léonard are positioned in the field 33, which is characterized by high tourist values and high infrastructure values. Therefore, the management of these show caves is succeeding in attracting tourists, while maintaining a commitment to sustainable infrastructure development. Beatenberg stands out within this matrix, due to its utmost infrastructure values. These values include sustainable cave gating method, distinguishing it from conventional 'sealed'

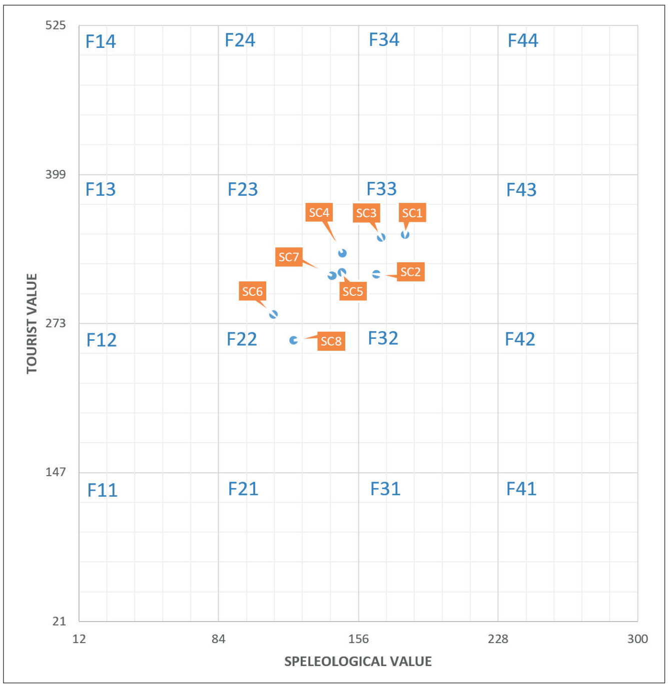


*Fig. 5: TV-SV matrix*
*Source: Authors' elaboration*

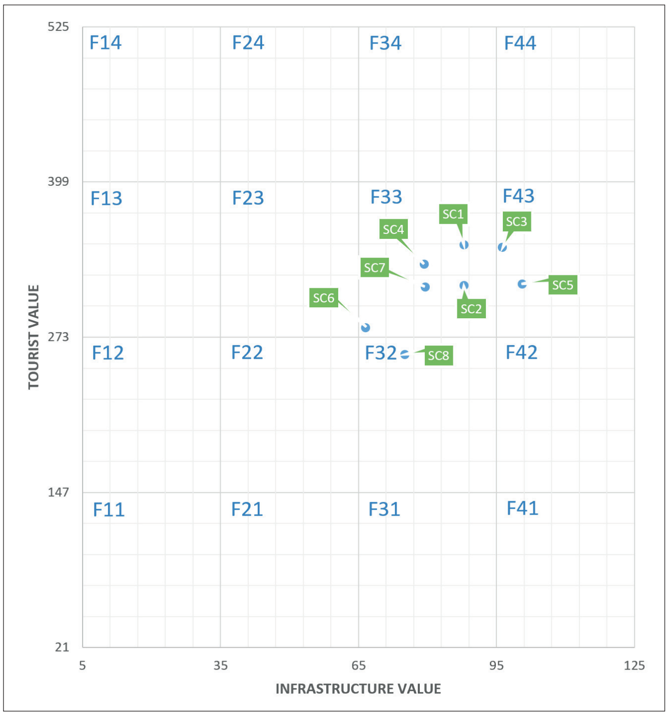


*Fig. 6: TV-IV matrix*
*Source: Authors' elaboration*

| Show cave | Values ∑ | | | Matrix | |
|---|---|---|---|---|---|
| | Speleological | Infrastructure | Tourist | Field in TV-SV | Field in TV-IV |
| Vallorbe (SC1) | 180.06 | 87.91 | 348.01 | F33 | F33 |
| Réclère (SC2) | 165.31 | 87.91 | 314.76 | F33 | F33 |
| Beatenberg (SC3) | 167.68 | 96.31 | 345.93 | F33 | F43 |
| Höllgrotten (SC4) | 147.63 | 79.27 | 332.32 | F23 | F33 |
| St-Léonard (SC5) | 147.46 | 100.53 | 316.10 | F23 | F43 |
| Grotte aux Fées (St-Maurice) (SC6) | 112.41 | 66.57 | 280.68 | F23 | F33 |
| Col des Roches (SC7) | 142.52 | 79.47 | 313.68 | F23 | F33 |
| Kristallhöhle (SC8) | 122.77 | 75.05 | 258.83 | F22 | F32 |

*Tab. 5: Overall results of the E-SCAM for the assessed show caves*
*Source: Authors' calculations*

caves, handrails completely made of stainless steel, as well as the absence of organic materials. St-Léonard does not include conventional infrastructure (tourist trails, handrails, staircases etc.), as visitors are visiting the cave with boats and the cave is illuminated with low-temperature lights, that are not causing major damage to the ecosystem. Thus, this show cave holds the utmost infrastructure values due to its unconventional infrastructure. Grotte aux Fées, and Col des Roches are positioned in the field 33, indicating moderate tourist values and moderately high infrastructure values. Despite moderate tourist values, the management structures of these show caves are generally focused on sustainable infrastructure. However, Grotte aux Fées faces challenges, due to its position near the border with the field 23. Since this show cave includes the highest lampenflora damage and wooden boards for walking in some areas, the need for sustainable infrastructure management is high and it requires urgent action. When compared to Grotte aux Fées and Col des Roches have much better positions within the field 33. Both show caves stand out with higher infrastructure values. Nevertheless, in Col des Roches there are also significant amounts of lampenflora and organic building materials, thus, a more balanced infrastructure development is required. Kristallhöhle is positioned in the field 32, displaying moderate tourist values and moderate infrastructure values, slightly higher than Grotte aux Fées.

## 5. Discussion, synthesis and recommendations

### 5.1 Assessment and modeling comparisons

Previous research in the field of cave tourism was mainly focused on the application of the M-GAM (Modified Geosite Assessment Model) methodological approach in the evaluation of caves for the needs of tourism development. Given that M-GAM was also used for the evaluation of other geosites recognized as geotourism potential, the applicability of this model has multiple significance. M-GAM consists of 'Main' and 'Additional' values and as such includes a wide range of geosite indicators. However, in order to interpret the complex problems of tourism in caves, it was necessary to create detailed evaluation analyzes that provide insight into the specificity of cave tourism. For this reason, a specialized model was created for the evaluation of show caves that provides insight into the specific context of the relationship between caves and tourism. This model was named SCAM (Show Cave Assessment Model) and was applied for the first time for the evaluation of show caves in Serbia. With this methodological approach, insight was gained into speleological and tourist values, as well as into the dynamism of their relationship in the analyzed destinations.

The model that was created and implemented in this study is an extension of the SCAM model in which, in addition to speleological and touristic values, infrastructure values are also added. Therefore, with this modeling, the complexity and problems of cave tourism were additionally analyzed in a way that corresponds to the current challenges and problems at the destinations.

Given that the numerical structure and statistical analysis is different for all three mentioned models, it is impossible to perform an adequate comparative analysis. However, Table 6 indicates the differences of all three models, as well as their contributions to knowledge about the problems of interaction between tourism and caves.

### 5.2 Strategic frameworks

The results of the evaluation indicate a range of strengths and weaknesses among the evaluated cave tourism destinations. Given the vulnerability of these sites, it is essential not only to identify their strengths and weaknesses but also to conduct a thorough situational analysis. To ensure the long-term sustainability of cave management, it is crucial to implement actionable strategies that enhance education, protection, and promotion. This chapter focuses on presenting practical recommendations and solutions for cave management structures, as well as providing guidance for decision-makers. Addressing these challenges requires a comprehensive strategy to optimize the management of these unique environments.

- Enhancing Educational Interpretation: Educational content at geologically significant sites that are accessible to tourists are crucial factors for the visitor's experience. Given that the caves include a wide range of multidisciplinary scientific-educational potentials and values, the level of interpretive possibilities is high. Although geological interpretations are well-organized, there are certain areas of improvement which can enhance the educational programs. In particular, at Beatenberg cave, the integration of historical elements like the St. Beatus legend could be expanded to further highlight the cave's cultural and historical importance. Other show caves could also use this approach by weaving in stories of early human

| Models | Indicators/Sub-indicators | Score Assessment |
|---|---|---|
| M-GAM (2014)[a] | Main value (Scientific/educational, Scenic/Aesthetic and Protection) – 12 sub-indicators<br>Additional value (Functional and Tourist values) – 15 sub-indicators | **First phase:** Calculating importance factors for all sub-indicators via survey with tourists for both groups of indicators (main and additional values)<br>**Second phase:** Authors insert the scores for the selected sites<br>**Third phase:** Sum up the scores and present the final results in one matrix with x (main values) and y (additional values) axis |
| SCAM (2022)[b] | Speleological value (Scientific/educational, Scenic/Aesthetic and Protection) – 15 sub-indicators<br>Tourist value – 21 sub-indicators | **First phase:** Calculating importance factors for all sub-indicators via survey with experts in the field of Geosciences for speleological values<br>**Second phase:** Calculating importance factors for all sub-indicators via survey with tourists for tourist values<br>**Third phase:** Authors insert the scores for the selected sites.<br>**Fourth phase:** Sum up the scores and present the final results in one matrix with x (speleological values) and y (tourist values) axis |
| E-SCAM | Speleological value (Scientific/educational, Scenic/Aesthetic and Protection) – 12 sub-indicators<br>Infrastructure value – 5 sub-indicators<br>Tourist value – 21 sub-indicators | **First phase*:** Calculating importance factors for all sub-indicators via survey with experts in the field of Geosciences for speleological values<br>**Second phase:** Calculating importance factors for all sub-indicators via survey with experts in the field of Geosciences for infrastructure values<br>**Third phase:** Calculating importance factors for all sub-indicators via survey with experts in the field of Tourism (Geotourism/Cave Tourism/Nature-Based Tourism) for tourist values<br>**Fourth phase:** Authors insert the scores for the selected sites<br>**Fifth phase:** Sum up the scores and present the final results in 2 matrices: 1) SV-TVand 2) IV-TV |

*Tab. 6: Comparison of different modelling approaches for cave tourism assessments. Notes: *The phase was skipped due to the existing data from Antić et al. (2022); [a]Albania (Braholli et al., 2023); Slovenia (Tičar et al., 2018); Iran (Tomić et al., 2021); India (Mahato & Jana, 2021); Indonesia (Reinhart et al., 2023); Serbia (Tomić et al., 2019); Hungary (Pál & Albert, 2018); [b]Serbia (Antić et al., 2022)*
*Source: Authors' elaboration based on referenced studies*

activity in the region. Vallorbe and Réclère, with their rich prehistoric findings, are particularly well-suited to emphasize paleontological discoveries and ancient life in their educational offerings. Additionally, show caves like St-Léonard, home to unique fauna, can offer visitors insight into subterranean ecosystems, showcasing the importance of biodiversity and conservation. This can be enhanced through interactive exhibits, multilingual panels, and well-trained guides.

- Implementing Environmentally-Sustainable Infrastructure: Environmental sustainability is essential for effective cave management, and some show caves are already making progress in minimizing their environmental impact. However, enhancements are still needed, particularly regarding the materials used for pathways, handrails, and lighting. Caves like Vallorbe, Réclère, and St-Léonard are excellent examples, utilizing stainless steel handrails and eco-friendly materials for their pathways. In contrast, Grotte aux Fées and Col des Roches could benefit from moving away from organic wood to more sustainable and durable alternatives. The adoption of LED lighting in caves like St-Léonard, Beatenberg, and Réclère has demonstrated its effectiveness in reducing environmental issues. However, Grotte aux Fées, which relies on outdated lighting systems, should prioritize switching to LED technology to mitigate problems like lampenflora growth. Implementing sustainable materials and energy-efficient lighting should be the norm for all show caves, with regular maintenance to ensure these improvements are sustained over time.
- Visitor Engagement and Sustainable Cave Tourism: Achieving an optimal balance between visitor experience and environmental protection in show caves requires the integration of accessibility with sustainable management practices. All of the assessed show caves are efficiently linked to public transportation networks. However, opportunities exist to further enhance visitor engagement through advanced technological solutions. Expanding the use of digital tools, such as Vallorbe's self-guided tour app, can facilitate personalized exploration while delivering in-depth educational content on geological, ecological, and historical features. These digital platforms also hold potential for reinforcing responsible tourism practices by promoting sustainability guidelines. Targeted sustainability campaigns, emphasizing the preservation of these vulnerable environments, would advance both conservation goals and visitor awareness.
- Strengthening Conservation Efforts: While all assessed show caves benefit from cantonal protection, achieving federal or international conservation status would significantly enhance preservation efforts. Caves such as Grotte aux Fées, which have suffered ecological disturbances, require targeted conservation initiatives to mitigate further environmental degradation. Current gating practices vary, with some utilizing partially sealed gates that maintain proper ventilation while safeguarding the cave ecosystems. Adopting these environmentally sensitive gating solutions for all sites would enhance ecological integrity.
- Community Engagement for Conservation: Establishing collaborative partnerships with local communities to actively involve them in decision making processes and conservation efforts. This includes offering local products, traditional performances, and culinary experiences at the show cave destinations. Some examples of good practice can be seen among the UNESCO Global Geoparks (Farsani et al., 2011; Rodrigues et al., 2021), where geoheritage sites serve as places for promoting local culture and as socio-economic boosters. This strategy is important for all the assessed show caves, due to the significance of community engagement for nature conservation and tourism activities.

## 6. Conclusion

This study evaluated eight show caves in Switzerland. A comprehensive analysis of their scientific, educational, aesthetic, and conservation values was conducted using the Extended Show Cave Assessment Model (E-SCAM). The research identified key strengths and weaknesses regarding speleological, infrastructure, and tourist values. The imbalance between environmental sustainability and tourism utilization is most pronounced in caves with lower infrastructure scores, emphasizing the need for targeted improvements. Recognizing the speleological importance of show caves as geoheritage sites could elevate their status, as seen with Vallorbe, Réclère, and Beatenberg, which have the potential to achieve higher speleological rankings. Grotte aux Fées, currently limited by inadequate infrastructure, requires immediate intervention to restore sustainable environmental conditions and strengthen its position as a geoheritage attraction. These findings underscore the necessity of implementing strategic frameworks that integrate cave conservation efforts, infrastructure development, enhanced interpretation, and community engagement. Addressing anthropogenic impacts is critical, as the data reveals a growing concern for ecological preservation. With the utilization of geoethically responsible management practices, these vulnerable karst environments can have a higher conservation value, which is crucial for the future generation of local communities, researchers, stakeholders and tourists.

While this study provides valuable insights into the current state of show caves in Switzerland, it also highlights the need for further research on carrying capacities and long-term conservation strategies. Such studies are essential for understanding and mitigating the impacts of tourism, ensuring the preservation of caves and their ecosystems over time. Furthermore, the assessment reflects the current state of the caves, but long-term monitoring is necessary to account for changes in infrastructure, tourism activities, and environmental conditions over time. Nevertheless, the newly developed methodological approach presented here can serve as a foundation for broader applications in sustainable cave tourism management across similar karst environments globally.

### Acknowledgement

*Dr. Aleksandar Antić would like to acknowledge the Federal Government of Switzerland for providing postdoctoral funding for this research in the form of a scholarship (Swiss Government Excellence Scholarships – SBFI). He also expresses his gratitude to the University of Lausanne for providing all the resources and for hosting his postdoctoral project at the Institute of Geography and Sustainability in Bramois (Sion).*

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**Please cite this article as:**

Antić, A., Luetscher, M., Perret, A., Ferrando, A., & Reynard, E. (2025). Cave tourism in Switzerland: The assessment and implications for subterranean geoheritage sustainability. Moravian Geographical Reports, 33(1), 22–39. https://doi.org/10.2478/mgr-2025-0003

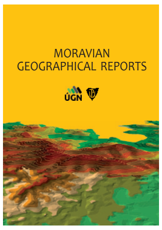
# Appendices

*Appendix 1. Ratings of the E-SCAM model*
*Source: Authors' conceptualization based on Vujičić et al. (2011); Cigna and Pani (2013); Tomić and Božić (2014); Antić et al. (2022)*

| Indicators | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| SV | $SISV_1$ | None: No attempt at explaining geological processes or significance to the general public | Limited: Basic attempt at explaining geological processes, but challenging for individuals without a geological background to comprehend fully | Moderate: Adequate explanation of the geological process with some difficulty for those without a geological background, yet not engaging enough for the average visitor | Considerable: Clear and engaging explanation of the geological process that is accessible and comprehensible to the average visitor, providing a considerable level of depth and detail | Extensive: Engaging and easily understandable explanation of the geological process, catering to the interest and understanding of the average visitor, while incorporating a sufficient level of depth to convey the geological significance effectively |
| | $SISV_2$ | None | The presence of archeological heritage, without tourist interpretation | Low interpretive value (only mention) | Medium value of interpretation (mention and visualization) | High value of interpretation (mention and visualization of several cultural epochs) |
| | $SISV_3$ | None | The presence of paleontological heritage, without tourist interpretation | Low interpretive value (only mention) | Medium value of interpretation (mention and visualization) | High value of interpretation (mention and visualization with the possibility of reconstruction of paleoecological conditions) |
| | $SISV_4$ | None or no attempt at explaining the subterranean fauna to the general public | Limited: Basic attempt at explaining the subterranean fauna, but challenging for individuals without a biological background to comprehend fully | Moderate: Adequate explanation of the subterranean fauna with some difficulty for those without a biological background, yet not engaging enough for the average visitor | Considerable: Clear and engaging explanation of the subterranean fauna that is accessible and comprehensible to the average visitor, providing a considerable level of depth and detail | Extensive: Engaging and easily understandable explanation of the subterranean fauna, catering to the interest and understanding of the average visitor, while incorporating a sufficient level of depth to convey the cave fauna significance effectively |
| | $SISV_5$ | None | 1 | 2–3 | 4–5 | More than 5 |
| | $SISV_6$ | Small amount and poor diversity of speleothems | Small amount and medium diversity of speleothems | Medium amount and poor/medium diversity of speleothems | A large quantity and rich diversity of speleothems | A large amount and unique diversity of speleothems |
| | $SISV_7$ | None | – | Constant and/or seasonal flows, water inlets and cave ice | – | Constant and/or seasonal streams, water inlets, cave ice, lakes and/or waterfalls |
| | $SISV_8$ | Unattractive relief and devastated natural vegetation under anthropogenic influence | Attractive relief and devastated natural vegetation under anthropogenic influence | Unattractive relief and preserved natural vegetation | Attractive relief and preserved natural vegetation | Attractive relief and preserved natural vegetation with the application of protection and conservation measures |
| | $SISV_9$ | None | Local protection (local community or show cave management) | Regional protection | National protection | International protection |
| | $SISV_{10}$ | Severe and irreversible damage – ecosystem has suffered irreversible harm, with a substantial loss of biodiversity, habitat degradation, and significant disturbances to key ecological processes | Significant damage – ecosystem has experienced substantial harm, leading to a notable decline in biodiversity, considerable habitat degradation, and significant disturbances to critical ecological processes | Moderate damage – ecosystem has undergone moderate harm, resulting in a noticeable reduction in biodiversity, moderate habitat degradation, and disturbances to some ecological processes | Minor damage – ecosystem has incurred minor harm, with a slight decrease in biodiversity, minimal habitat degradation, and minor disruptions to specific ecological processes | No damage – ecosystem remains largely undisturbed, with no significant impact on biodiversity, minimal to no habitat degradation, and no disruption to ecological processes |
| | $SISV_{11}$ | None | – | Some species are protected | – | All species are protected |
| | $SISV_{12}$ | No possibility of 'recovery' (with possibility of total loss) | High (can be damaged easily) | Medium (can be damaged by natural or human activities) | Low (can only be damaged by human activities) | Very low (it cannot be seriously damaged) |

*Appendix 1 - continued*

| Indicators | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| IV | $SIIV_1$ | Unsafe and poorly maintained pathways | Pathways with some safety features but lacking environmental sustainability | Adequately safe and somewhat environmentally sustainable pathways | Safe and environmentally sustainable pathways with minimal impact on the ecosystem | Highly safe and environmentally sustainable pathways with no negative impact on the ecosystem |
| | $SIIV_2$ | No handrails or unsafe handrails | Handrails with limited safety features and environmental sustainability | Handrails that provide some safety and environmental sustainability | Safe and environmentally sustainable handrails with minimal impact on the ecosystem | Highly safe and environmentally sustainable handrails with no negative impact on the ecosystem |
| | $SIIV_3$ | Unsustainable and polluting modes of transportation | Transportation with limited safety features and environmental sustainability | Adequately safe and somewhat environmentally sustainable transportation | Safe and environmentally sustainable transportation with minimal impact on the ecosystem | Highly safe and environmentally sustainable transportation with no negative impact on the ecosystem / or no transportation |
| | $SIIV_4$ | Gates that harm the ecosystem and are unsafe | Gates with limited safety features and environmental sustainability | Gates that provide some safety and environmental sustainability | Safe and environmentally sustainable gates with minimal impact on the ecosystem | Highly safe and environmentally sustainable gates with no negative impact on the ecosystem |
| | $SIIV_5$ | Unsustainable and polluting light systems | Light systems with limited safety features and environmental sustainability | Adequately safe and somewhat environmentally sustainable light systems | Safe and environmentally sustainable light systems with minimal impact on the ecosystem | Highly safe and environmentally sustainable light systems with no negative impact on the ecosystem |
| TV | $SITV_1$ | Inaccessible | Low (only on foot with special equipment and expert guides) | Medium (by bicycle and other similar means of transport) | High (by car) | Highest (by bus) |
| | $SITV_2$ | Up to 200 m | 201–500 m | 501–1,000 m | 1,001–2,000 m | More than 2,000 m |
| | $SITV_3$ | No artificial light | No direct light, not near the cave walls | Direct light, but not near the cave walls | No direct light, near the cave walls | Direct light near the cave walls |
| | $SITV_4$ | Low | – | Medium | – | High |
| | $SITV_5$ | Only walking | – | Use of boats, elevators, trains and other means of transportation in the cave | – | A combination of multiple modes of movement/transportation in the cave |
| | $SITV_6$ | None | 1 | 2–3 | 4–6 | More than 6 |
| | $SITV_7$ | None | 1 | 2–3 | 4–6 | More than 6 |
| | $SITV_8$ | None | 1 | 2–3 | 4–6 | More than 6 |
| | $SITV_9$ | More than 100 km | 100–50 km | 50–25 km | 25–5 km | Less than 5 km |
| | $SITV_{10}$ | More than 100 km | 100–50 km | 50–25 km | 25–5 km | Less than 5 km |
| | $SITV_{11}$ | None | 50–20 km | 20–5 km | 5–1 km | Local area |
| | $SITV_{12}$ | None | 10 or more km away from important road networks with public transportation facilities located more than 2 km from the cave | Less than 10 km away from important road networks with public transportation facilities located 1 to 2 km from the cave | Less than 10 km away from important road networks with public transportation facilities located 0.5 to 1 km from the cave | Less than 10 km away from important road networks with public transportation facilities located less than 500 m from the cave |
| | $SITV_{13}$ | None | Local tourist organization | Regional tourist organization | National tourist organization | International tourist organization |
| | $SITV_{14}$ | None | Low (less than 5,000) | Medium (from 5,001 to 10,000) | High (from 10,001 to 100,000) | Utmost (more than 100,000) |
| | $SITV_{15}$ | None | Less than 12 per year | From 12 to 24 per year | From 24 to 48 per year | More than 48 per year |
| | $SITV_{16}$ | None | Low quality | Medium quality | High quality | Utmost quality |
| | $SITV_{17}$ | None | Low level | Medium level | High level | Utmost level |
| | $SITV_{18}$ | None | Low quality | Medium quality | High quality | Utmost quality |
| | $SITV_{19}$ | More than 50 km | 25–50 km | 10–25 km | 5–10 km | Less than 5 km |
| | $SITV_{20}$ | More than 25 km | 10–25 km | 10–5 km | 1–5 km | Less than 1 km |
| | $SITV_{21}$ | None | Information provided only verbally | Information provided only visually in the local language | Information provided visually in multiple languages | Information provided visually in multiple languages with continuous monitoring of visitor behavior |




MORAVIAN GEOGRAPHICAL REPORTS

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

journal homepage: **www.geonika.cz/mgr.html**

doi: **https://doi.org/10.2478/mgr-2025-0004**

# Geoheritage values and threats related to sandstone crags of the Chřiby ridge (Moravian Carpathians, Czech Republic)

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## Abstract

Rock landforms provide non-invasive, easy insights into the distant geological past, and they reflect landform evolution and processes shaping the earth surface in the past and present. Moreover, rock landforms, especially crags and tors, have a high geoheritage relevance. The territory of the Czech Republic shows many diverse examples of crags and tors, especially in sandstone areas. However, while the Bohemian Cretaceous areas have been examined in detail, the sandstone crags in Moravian Flysch Carpathians have been given only limited attention. The paper is focused on the sandstone crags in the Chřiby Mountains being explored from two main perspectives: identification of the crags as geoheritage elements and their assessment in terms of threats and degradation risk. The application of semi-quantitative assessment methods (degradation risk evaluation and Risk Assessment Matrix) enabled the ranking of the sites according to the degree of possible deterioration and helped to identify particular threats, which can be considered important when planning and managing the area's natural resources. The recognition of geoheritage values of sandstone crags, along with identifying and evaluating risks and threats, may serve as a basis for effective management and further research.

**Keywords:** Sandstone crags, geoheritage, Chřiby, degradation risk, threats to geodiversity

**Article history:** Received 9 October 2024, Accepted 10 February 2025, Published 31 March 2025

## 1. Introduction

Rock landforms, understood as topographic elements built of exposed solid rock (Migoń et al., 2017; Migoń, 2022), occur in a large variety of sizes, shapes, and origins. Depending on bedrock properties and climatic conditions favouring (or not) the development of thick soils and vegetation spread, rock landforms may be abundant, even dominant, or rare within a given area. Thus, they may exist in extensive clusters (e.g., rock cities) or as continuous outcrops many kilometres long (e.g., rock escarpments), whereas elsewhere they occur in isolation, separated by tracts of regolith-covered terrain. In the latter cases, rock landforms generated particular curiosity as natural features difficult to explain and hence, were often associated with myths and legends (Vitaliano, 1968; Piccardi & Masse, 2007; Kirchner & Kubalíková, 2015; Khoshraftar & Torabi Farsani, 2019; Telecka, 2024). With the advent of modern tourism, rock landforms began to be appreciated for their scenic values (Gordon, 2012; Reynard & Giusti, 2018) and became popular tourist destinations as 'wonders of nature'.

The realisation of their geoheritage values is of more recent date, and so is the awareness that they also face various threats and require conservation efforts, as other components of nature do (Gray, 2013; García-Ortiz et al., 2014; Crofts et al., 2020; Selmi et al., 2022; Kubalíková, 2024). The core scientific values of rock landforms are twofold. First, they provide non-invasive (as opposed to quarries), easy insights into the distant geological past, into the times when a given rock complex came into being. The larger the rock landform, the more insightful this view could be, as one can examine the continuity and variability of sedimentary structures, lithological changes, or the pattern of tectonic structures. Therefore, rock landforms are highly valued by geologists, especially in areas where outcrops are rare. Second, rock landforms are the subject of geomorphological studies. Being an outcome of differential denudation and erosion, they inform us about geological controls in landform evolution and processes shaping the earth surface in the past and present. Examined in the context of the geomorphological setting and cover deposits in the vicinity, they become vital sources of information about mechanisms and pathways of landform development (Linton, 1955; Cunningham, 1965; Thomas, 1965; Gerrard, 1988; André, 2004; Michniewicz, 2019). Most recently, cosmogenic exposure dating performed on rock landforms helps constrain lowering the timing of surface lowering (Phillips et al., 2006; Raab et al., 2021, 2024; Máčka et al., 2023). Therefore, rock landforms, especially crags and tors, are increasingly presented within the geoheritage framework (Washington & Wray, 2011; Kubalíková & Kirchner, 2016; Rypl et al., 2019; Duszyński & Migoń, 2022).

Among the most scenic rock landforms are those built of sandstone (Mainguet, 1972; Härtel et al., 2007; Young et al., 2009; Adamovič et al., 2006, 2010; Twidale, 2010) and the territory of the Czech Republic shows many and diverse examples. Some are of international significance, for instance, the rock cities in

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northern Bohemia, which are the core value of the Bohemian Paradise UNESCO Global Geopark (Adamovič et al., 2006; Mertlík & Adamovič, 2016). This paper focuses on the isolated ridge of Chřiby in the Flysch Carpathians, which stands out in terms of the number and diversity of sandstone rock landforms, referred to as crags. Crags are understood as natural, rugged outcrops of bedrock protruding from ridge tops and regolith-covered slopes, which emerged due to selective weathering and mass wasting. Moreover, most of these landforms are easily accessible, located not far from public roads and along waymarked hiking trails or next to these. This easy access is a significant factor for geoconservation, contributing to the growing human impact associated with multiple uses. Crags in Chřiby also have various cultural associations, so their value is not limited to the scientific one, but the added cultural value becomes important and is explored separately in a geomythological context (Kubalíková et al., 2025).

This paper examines sandstone crags in the Chřiby ridge from two main perspectives. First, we aim to present a selection of the most representative crags from a scientific point of view, mainly emphasising their geomorphological diversity. Thus, we identify the crags as geoheritage/geodiversity elements. Second, the crags are assessed in terms of threats and degradation risk, which will be done semi-quantitatively. This paper is a region-specific study that fills a gap in regional knowledge but is also of broader relevance for at least two reasons. First, crags are not endemic to the Chřiby area but are a repetitive theme for the entire Flysch Carpathians (Alexandrowicz, 1978, 2008; Kubalíková & Kirchner, 2016; Welc & Miśkiewicz, 2020; Bayrak & Heneralova, 2024). Therefore, this study provides a reference for an area that is hardly accounted for and will inform any future range-wide reviews focused on rock landforms. Second, crags are popular places to visit wherever they occur and hence, their use generates various conservation challenges, especially if the crags are, for some reason, particularly vulnerable to human impact (Migoń, 2022). Thus, our approach through the lens of degradation risk assessment may be inspirational for similar studies elsewhere.

## 2. Theoretical Background

Given their scientific but also scenic values, selected sandstone crags may be considered an important part of the geoheritage of a given area. The concept of geoheritage is based on the definition of natural heritage, which was presented already in 1972 (UNESCO, 1972), and later, the concept of geoheritage was developed by Dixon (1996) and Sharples (2002). Currently, geoheritage is respected as a full-value part of natural heritage and is examined from different points of view (Reynard & Brilha, 2018; Kubalíková et al., 2023 and references herein). Although on an international level, it is not so strongly represented as biodiversity values, considerable efforts to raise its status have been recently undertaken, e.g., within special commissions of the International Union for Conservation of Nature (IUCN) or the International Union of Geological Sciences (IUGS) and as other initiatives (ProGEO, Global Geoparks Network, working groups within the International Association of Geomorphologists (IAG)).

Sandstone crags, as an important part of geoheritage, may be considered geosites, defined as portions of the geosphere that present particular importance for the comprehension of Earth history (Reynard, 2004). Thus, geosites are associated with value, which is primarily scientific (Brilha, 2016). However, these scientific values are of different kinds. In some studies, the focus is on sedimentary structures exposed in crags, with little consideration of processes that have led to the emergence of the crag so that they become essentially sites of geological interest. In this study, we primarily analyse the crags as landform elements, and hence, the specific term 'geomorphosite' may be used to emphasise the focus on crags' geomorphology. It was also argued that the values of geological and geomorphological objects may reside in their cultural/historical, aesthetic and/or social/economic attributes, being related to the diversity of human perception or exploitation (Panizza, 2001; Bussard & Reynard, 2022).

However, despite their apparent values and existing and established legal protection, there is still a range of possible threats (both natural and anthropogenic) that may affect these valuable sites. In the last years, the topics of vulnerability and resilience of geoheritage have been discussed in numerous papers from different points of view – climatic change, urban pressure, and tourist and recreational use (Prosser et al., 2006; Ruban, 2010; García-Ortiz et al., 2014; Fuertes-Gutiérez et al., 2016; Wignall et al., 2018; Vereb et al., 2020; Crofts et al., 2020; Németh et al., 2021; Selmi et al., 2022; Kubalíková & Balková, 2023). The overview of the methods is presented by Vandelli et al. (2024). Crofts et al. (2020) presented 11 types of threats associated with 1) Urbanisation and construction, 2) Mining and mineral extraction, 3) Changes in land use and management, 4) Coastal protection and river management and engineering, 5) Offshore activities, 6) Recreation and geotourism, 7) Climate change, 8) Sea-level rise, 9) Restoration of pits and quarries, 10) Stabilisation of rock faces, 11) Irresponsible fossil and mineral collecting and rock coring. Further types of threats include the lack of state or regional financial support for management, vandalism, vegetation overgrowth, social pressure regarding the use of the sites, confusion in protection measures, or indifference to geoheritage (Górska-Zabielska et al., 2020; Kubalíková et al., 2021; Selmi et al., 2022; Kubalíková & Balková, 2023; Kubalíková, 2024).

Within the concepts of geosites/geomorphosites, the assessment of vulnerability, risks and threats is usually included in the general assessment methods that have been continuously developed during last decades (for a recent overview, see Mucivuna et al., 2019). Generally, there are two main ways how to assess the threats and risks at a site:

1. Degradation risk assessment, which is based on the set of criteria used for geosite/geomorphosite assessment (Brilha, 2016; Reynard et al., 2016) – this method has been developed and applied, among others, for geosites in Malta (Selmi et al., 2022), Brazil (Rabelo et al., 2023), Romania (Papp, 2023), and Czech Republic (Kubalíková & Balková, 2023);
2. application of Risk Assessment Matrix (or concepts of probability and impact), where every threat is considered (Brooks, 2013; Gordon et al., 2022; Kubalíková & Balková, 2023; Kubalíková, 2024). The effective evaluation, classification and prioritisation of risks, threats and conflicts of interest followed by the design of adequate management proposals (e.g., monitoring, strengthening legal protection or community participation) can contribute to the balance of all needs and demands at a site or within an area (Gordon et al., 2021, 2022; Selmi et al., 2022; Kubalíková et al., 2022; Ruban et al., 2022; Papp, 2023; Kubalíková, 2024).

Up to now, only a limited number of studies have explored the geoheritage values of sandstone rock landforms in the Czech Flysch Carpathians and associated geoconservation issues. The scientific significance of selected crags may be inferred from geomorphological studies emphasising periglacial inheritance (Czudek et al., 1961; Kirchner et al., 1996; Křížek, 2001; Bubík et al., 2004; Stráník et al., 2021) and genetic relationships with landsliding and deep-seated slope gravitational deformations, including the formation of non-karstic caves (Kirchner, 2004; Lenart et al., 2014; Lenart, 2015; Břežný et al., 2021). Adamovič et al. (2010) included a few sandstone crags, including examples from the Chřiby area, in their site-by-site presentation of sandstone landforms in the Czech Republic. Further examples from this region can be found in geomorphological regionalisation by Demek and Mackovčin (2015) and in regional inventories of protected areas and geological sites at the Zlín district level (Mackovčin & Sedláček, 2002; Mackovčin, 2007; Hrabec et al., 2017; Šnajdara et al., 2021). Numerous crags and other rock landforms were also presented within regional popular science literature (Baščan et al., 2003a, 2003b, 2003c, 2004, 2005; Žižlavský et al., 2019, 2020; Žižlavský, 2021).

Studies focused explicitly on geoheritage issues are even fewer. Kubalíková and Kirchner (2016) examined a few representative geomorphosites in the Vizovická vrchovina Highland, including crags and tors, and argued for their suitability for geotourism, although threats related to excessive use, particularly by climbers, have also been noted. Pánek and Lenart (2016) presented several geomorphological sites in Beskydy Mountains and mentioned their geocultural value and tourist aspects of the area. Studies from the adjacent Polish Flysch Carpathians are also relevant to the subject. The first papers arguing for the scientific value of crags and the need of their legal protection date back to the 1930s (Klimaszewski, 1932; Świdziński, 1932), whereas comprehensive, detailed presentations including geological and geomorphological characteristics were offered by Alexandrowicz (1970, 1978, 1987, 1989), Alexandrowicz and Pawlikowski (1982), Alexandrowicz et al. (2014). In the last two decades a series of papers explored sandstone crags in the context of their attractiveness for geotourism (e.g., Alexandrowicz, 2008; Welc & Miśkiewicz, 2019, 2020).

## 3. Methods

The first procedural step is the identification of crag sites, which could be considered most representative of the area and would have the most evident geoheritage value. Among the factors and properties taken into account were dimensions, shape, relief complexity, topographic setting and related distinctiveness in the landscape, and the presence of weathering features. Cultural associations were considered of secondary importance. An underlying assumption was that crag localities that are more extensive (longer and/or higher), more complex and distinctive are more valuable from the geoheritage standpoint than minor outcrops lacking any special features. Based on the literature review and fieldwork, 10 crag localities have been selected for more detailed analysis. They have been described qualitatively in terms of the properties listed above and then assessed regarding the degradation risk.

In the assessment of threats and risks at a particular crag locality, a set of criteria proposed by Brilha (2016), Selmi et al. (2022) and Kubalíková and Balková (2023) is used (Tab. 1). However, some criteria have been modified to better account for the local conditions, whereas others have been excluded (e.g., density of population, because the value is practically the same for all the sites). Based on Selmi et al. (2022), the degree of risk degradation was established on a numerical scale (Tab. 2).

The degradation risk assessment was accompanied by a Risk assessment matrix where the most relevant threats were evaluated. The Risk assessment matrix is a simple tool for risk evaluation originally used in project planning, but very useful in nature conservation studies as well (Brooks, 2013; Kubalíková, 2024). For every identified threat, a probability and impact are determined on a scale of 1 to 5 (for a detailed explication see Kubalíková & Balková, 2023). The multiplication then shows the total risk: minor, moderate, major, and severe (Fig. 1). Based on this complex assessment, proposals for further management are discussed.

## 4. Study area

The study area, Chřiby Mountains, is situated in south-eastern Moravia (south-eastern part of the Czech Republic) between the municipalities of Koryčany, Staré Město and Otrokovice (Fig. 2). The Chřiby Mts. correspond to an eponymous geomorphological unit which is oriented from southwest to northeast. They are about 35 km long, up to 10 km wide, and cover an area of about 335 $km^2$. The highest peak, Brdo, reaches 587 m a. s. l. Etymologically, the toponym ‘Chřiby’ may refer to the Slavic word that means ‘hills’; however, this is just one of several hypotheses.

### *4.1 Geology*

The area is formed by Upper Cretaceous to Oligocene flysch sediments (sandstones, claystones and siltstones) belonging to the Magura Flysch and the subordinate Rača Unit, Soláň Formation (Czech Geological Survey, 2024a). Within this formation, several facies and members can be distinguished, with the Lukov Beds and Ráztoky Beds being the most relevant for the study area. The Lukov Beds (Upper Palaeocene), which are from 200 to 800 m thick, represent the so-called ‘wild flysch’ deposited from dense turbidity currents in the upper parts of submarine deltaic cones. They are characterised by the predominance of coarse arkosic sandstones, which are very resistant, forming distinctive narrow ridges and elevations with crags (e.g., Budačina, Komínky, Kozel). The Ráztoky Beds (up to 1,200 m thick) are of Upper Cretaceous (Campanian–Maastrichtian) to Palaeocene age and are represented by moderately rhythmic flysch with claystone interbeds and sandstones. These sedimentary rocks are less resistant and usually form the slopes. The valleys and depressions are usually excavated in less resistant Paleogene claystones and filled with Quaternary hillslope sediments.

### *4.2 Geomorphology*

The Chřiby Mts. (Fig. 3) belong to the geomorphological region of the Central Moravian Carpathians and the geomorphological subprovince of the Outer Western Carpathians. They are characterised by rugged relief arising from erosional response to intensive neotectonic uplift, the occurrence of relatively narrow and structurally controlled ridges, deep valleys, and bear evidence of intensive periglacial processes which occurred during the Pleistocene (Demek & Mackovčin, 2015). Numerous rock outcrops are affected by weathering, producing abundant honeycombs, tafoni, ledges, fissure caves and other micro- and mesoforms, making the area very valuable from the geoheritage point of view. Due to the regional geomorphological and hydrogeological situation, the area is susceptible to landsliding and other slope processes (Czech Geological Survey, 2024b; Krejčí et al., 2023).

### *4.3 Historical and cultural aspects related to geodiversity*

The area has been settled since prehistoric times, as confirmed by archaeological evidence from the Upper Palaeolithic (Aurignacian culture findings in the northeastern part of the study area, approx. 20,000–40,000 BP). An important settlement phase is also represented by the Eneolithic period (Bronze Age), approx. 3,000 BP, proved by findings of the Lusatian Culture, e.g., fortifications on the Brdo Hill (Baščan et al., 2003a; Hrubý, 1961).

In the 6$^{th}$ century, Slavs came to this area, as evidenced by a considerable number of archaeological findings. In the 9$^{th}$ century, the Great Moravia Empire influenced this area considerably as the settlement of Staré Město, one of its important centres, was situated nearby. Numerous archaeological structures of Slavic tumuli (e.g., Tabarky) or fortresses, e.g., St. Kliment (Baščan et al., 2005; Hrubý, 1961), come from this period.

In the Middle Ages, several castles were founded on distinctive terrain elevations, some among natural outcrops and crags, e.g., Střílky, Cimburk, Buchlov. Also, in the 12$^{th}$ century, a Cistercian monastery was founded in Velehrad, a site that, in oral tradition, is connected with the centre of Great Moravia. In the 14$^{th}$ century, the Augustinian monastery and provostry on St. Kliment Hill were established, but later, they were destroyed during the Hussite

| Criterion | Description | Scoring |
|---|---|---|
| Integrity | Related to the present status and conditions of the geosite or geodiversity site. The better the conditions are, the lower the risks that can occur. | 0 – excellent conditions;<br>0.25 – good conditions;<br>0.5 – medium, average conditions;<br>0.75 – bad conditions, but with a possibility to recover;<br>1 – bad conditions; site is damaged |
| Accessibility /availability of parking | Possibility of how to reach the site. The closer the parking, the higher risk can occur due to more frequent visits. The scoring and distances may be adjusted according to local conditions (e.g., proximity of cities, character of surrounding landscape). | 0 – parking place situated at a distance more than 5 km from a site;<br>0.25 – 2–5 km;<br>0.5 – 1–2 km;<br>0.75 – 0.2–1 km;<br>1 – parking place situated at a distance less than 200 m from the site |
| Accessibility/availability of public transport | Possibility of how to reach the site. The closer the stop of public transport, the higher risk can occur due to more frequent visits. The scoring and distances may be adjusted according to local conditions (e.g., proximity of cities, character of surrounding landscape). | 0 – bus/train stop situated at a distance more than 5 km from a site;<br>0.25 – 2–5 km;<br>0.5 – 1–2 km;<br>0.75 – 0.2–1 km;<br>1 – bus/train stop situated at a distance of less than 200 m from the site |
| Presence of accompanying tourist infrastructure | Position of the site near the well-marked and easily accessible paths, overall attractiveness of the site's surroundings. | 0 – the site is situated near marked paths, not accompanied by tourist infrastructure;<br>0.5 – the site is well accessible, some basic infrastructures are in proximity (e.g., shelters, educational paths);<br>1 – the site is well accessible and situated near other sites of interest (e.g., cultural assets, shelters, refreshments…) |
| Management on site | Existence of strategic document that deals with site management (care plans, set of recommendations…). If any documents exist, it can be assumed that they can prevent the site from deterioration. | 0 – existing care plan where geodiversity is a subject of protection and taken into account within site management;<br>0.5 – existing care plan, but only focused on species and ecosystem; geodiversity is not a subject of protection, but it is treated as a part of the ecosystem;<br>1 – recommendations for management, but on a very general level, e.g., Set of recommendations for a Special Area of Conservation (EVL) or no recommendation (not in our study area) |
| Legal protection | Legislative tools applied to a site. The stronger legislative protection, the lower the risk that can occur. In this method, the criterion is adapted to reflect the Czech environmental legislation (Act No. 114/1992 Coll.) but may be adjusted to local conditions. | 0 – Category National Natural Monument/Reserve (or site declared as protected on a national level);<br>0.25 – Category Natural Monument/Reserve (or site declared as protected on a regional level);<br>0.5 – Category Important Landscape Element or Special Area of Conservation (or site declared as protected on municipal level);<br>0.75 – Included in the database or list of geological localities of a National Geological Survey, ongoing monitoring of the site, but no legal protection;<br>1 – No legal protection, not in the database or list of geological localities |
| Proximity to areas/activities with the potential to cause degradation | The lower the distance, the higher the risk can occur (e.g., proximity to roads, cities, municipalities, big camping places, recreational areas, factories and other possible disturbing activities). | 0 – Site located less than 1 km from a potential degrading area/activity;<br>0.5 – Site located within 0.5–1 km distance from a potential degrading area/activity;<br>1 – Site located less than 0.5 km from a potential degrading area/activity |
| Current use of the site | A number of different uses (hiking, climbing, mineral and rock collecting, etc.). The higher the number of various site uses, the higher risk can occur. | 0 – 1 possible activity;<br>0.5 – 2 different activities;<br>1 – 3 and more different activities |
| Visitation (public influx) | Number of visitors. The higher the number of visitors, the higher the risk that can occur. Based on expert estimation as it is not possible to count the visitors exactly. | 0 – low number of visitors;<br>0.5 – medium number of visitors;<br>1 – high number of visitors, causing problems |
| Use limitations | Limits of the use related to the possibility of access and safety. The easier the access to the site (no need for permissions, no obstacles), the higher the risk to a site that can occur. It also refers to the presence of fences or other types of physical protection of the site. | 0 – The use is restricted due to difficult terrain, safety issues or the necessity to obtain the permission;<br>0.5 – The site can be used after overcoming limitations (legal, permissions, safety, etc.);<br>1 – The site has no limitations to be used by wide public, no obstacles, no fences or physical barriers |

*Tab. 1: Degradation risk assessment*
*Source: Authors' conceptualisation based on García-Ortiz et al. (2014); Brilha (2016); Selmi et al. (2022); Kubalíková and Balková (2023)*

| Total Score on Degradation Risk | Risk Level |
|---|---|
| 0.00–2.25 | low |
| 2.50–4.75 | medium |
| 5.00–7.75 | high |
| 8.00–10.00 | very high |

*Tab. 2: Classification of the degradation risk level of geosites*
*Source: Authors' conceptualisation adjusted from Selmi et al. (2022)*

| PROBABILITY | Very low | Low | Medium | High | Very high |
|---|---|---|---|---|---|
| Highly probable | 5 Moderate | 10 Major | 15 Major | 20 Severe | 25 Severe |
| Probable | 4 Moderate | 8 Moderate | 12 Major | 16 Major | 20 Severe |
| Possible | 3 Minor | 6 Moderate | 9 Moderate | 12 Major | 15 Major |
| Unlikely | 2 Minor | 4 Moderate | 6 Moderate | 8 Moderate | 10 Major |
| Rare | 1 Minor | 2 Minor | 3 Minor | 4 Moderate | 5 Moderate |
| | IMPACT | | | | |

*Fig. 1: Risk assessment matrix*
*Source: Adapted from Leveson (2011)*

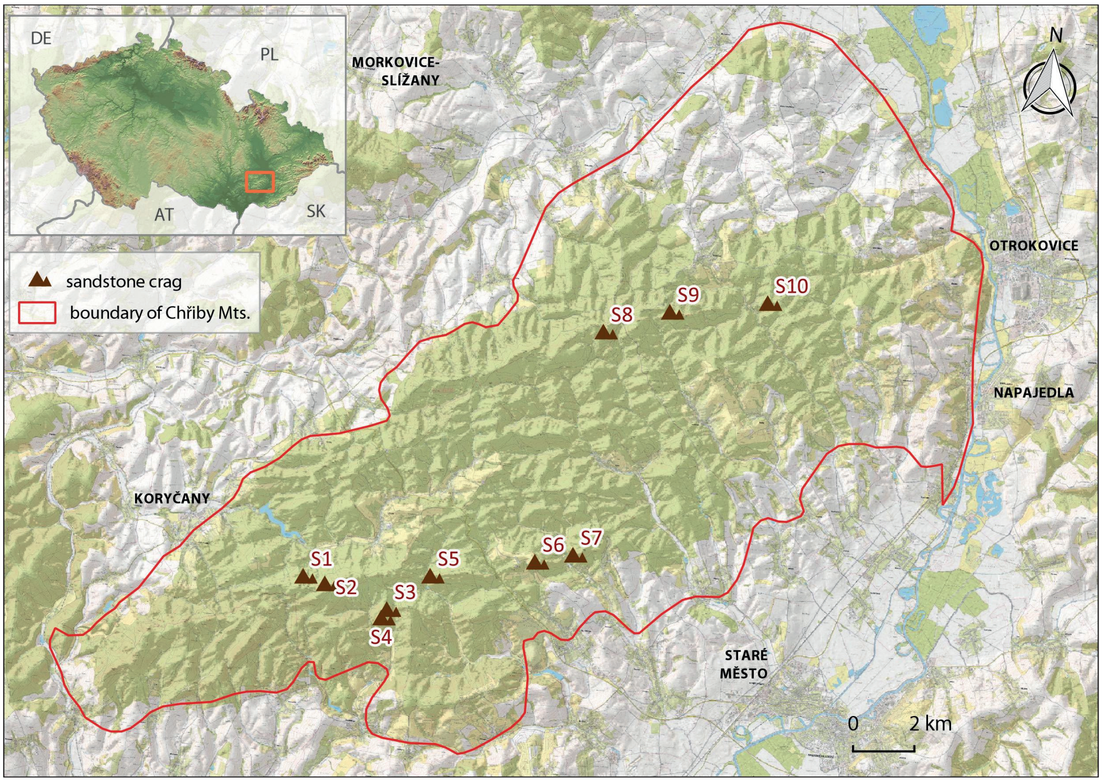


*Fig. 2: Chřiby Mts. and their position within the Czech Republic. Sandstone crags: S1 Kozel, S2 Kazatelna, S3 Osvětimanské skály, S4 Trpasličí město, S5 Zbořené zámky, S6 Barborka, S7 Břestecká skála, S8 Jeřabčina, S9 Komínky, S10 Budačina*
*Source: Basic topographic map of the Czech Republic 1:10,000, Czech Office for Surveying, Mapping and Cadastre*

*Fig. 3: The panoramic view of the southern part of the Chřiby Mountains, including the main landscape dominants (landmarks) of the study area. From left to right: Holý kopec (548 m a. s. l.), Buchlov (509 m a. s. l., with a castle on the top), Barborka (510 m a. s. l., also called Modla) and Komínek Hill (456 m a. s. l.)*
*Photo: L. Kubalíková*

Wars. All these geocultural sites are closely related to the myths and legends and represent an important part of local identity (Psotová, 2015; Daníčková & Bajer, 2019; Baščan et al., 2003a, 2003b, 2003c, 2004, 2005).

Regarding the use of natural resources, sandstone has long been extracted in the study area, as testified by numerous remnants of old quarries (e.g., Vraní lom near Koryčany, an abandoned sandstone quarry in Stupava). The local stone was used primarily to build the above-mentioned castles and fortifications. In the northern part of the area, several small limestone quarries near the village of Cetechovice used to operate. The material extracted was widely used as a decorative stone ('Cetechovice marble') on sacral monuments in the towns of Uherské Hradiště, Křtiny and Brno (Mrázek, 1993; Rybařík, 1994).

### 4.4 Nature conservation, current use of the area, risks and threats to geodiversity

The Chřiby Mts. are protected as a Nature Park (since 1991, according to the Act No. 114/1992 Coll.) and as a Special Area of Conservation (according to the Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora). There is a considerable number of small-scale protected sites – 6 Nature Reserves and 23 Nature Monuments. The scientific importance of Chřiby is not limited to geomorphological values. However, the area is also significant for biological reasons, and some protected species have their northernmost extent here, e.g., *Cordulegaster heros* (Holuša & Holušová, 2022). Despite its natural values, the area is not protected in any higher category (National Nature Reserve/Monument), and there is no large-scale area of special territorial protection (Nature Conservation Agency, 2024). Currently, the area is used mainly for tourism and recreation, thanks to easy access from regional centres around the cities of Brno and Zlín. Tourist infrastructure is good thanks to the dense network of tourist trails and numerous accommodation facilities (Bajer et al., 2018). The crags are often used for climbing (Association for climbing of the Czech Republic, 2024; Kohn & Bajer, 2015).

## 5. Results

### 5.1 Description of the crags and their geoheritage value

Based on the detailed fieldwork and comparison with literature and other resources (Adamovič et al., 2010; Czech Geological Survey, 2024c; Nature Conservation Agency, 2024), 10 crags have been described and documented (Figs. 4, 5, 6). The results of the identification and description of representative sandstone crags, emphasising their geoheritage and geocultural values, are presented below.

#### S1 Kozel

Kozel ('Goat') is a solitary sandstone rock tower rising from a moderately inclined upper slope (Fig. 4A). It is shaped as a narrow rock wall, up to 22 m in height, 18 m long, but only 6 m wide. The ground plan reflects the presence of two joint sets perpendicular to each other, whereas slightly inclined bedding planes are exposed in rock faces, facilitating selective weathering (Fig. 6A). Rows of arcades and cavernous features are ubiquitous, whereas a large recess is present along a more porous conglomeratic layer, approximately halfway up the height of the crag. In the vicinity of Kozel, numerous low outcrops (up to 2–2.5 m in height) and detached boulders are present, some hosting small weathering pits and tubes.

Kozel has been a traditional climbing and tourist destination since the 19$^{th}$ century. Thanks to its shape, the crag is associated with several legends. It is said to be a petrified devil who wanted to thwart the construction of a chapel planned by a local hermit.

The area near the crag is cleared of trees, so the crag itself is clearly visible. A marked trail runs next to it and the rock is currently heavily used by climbers. It is listed as a Nature Monument, but on-site interpretation is currently missing.

#### S2 Kazatelna

Kazatelna ('Pulpit') is a lone tower-like sandstone outcrop rising from the upper slope, close to the flattened crest (Fig. 4B). It is distinctively asymmetric, only 2.5 m on the upslope side, but 8–9 m in height on the downslope one. Vertical rock surfaces are irregular as an effect of selective weathering, but well-developed cavernous features are missing. The crag was anthropogenically modified: steps were cut in the rock to reach the top surface, and an iron cross was erected on the top. Next to Kazatelna, a similar but much lower asymmetric sandstone outcrop (2.5 m in height) is present.


*Fig. 4: General view of sandstone crags: A – Kozel, B – Kazatelna, C – Osvětimanské skály, D – Trpasličí město, E – Zbořené zámky*
*Photos: L. Kubalíková (A, E) and P. Migoń (B, C, D)*


*Fig. 5: General view of sandstone crags: A – Barborka, B – Břestecká skála, C – Jeřabčina, D – Komínky, E – Budačina*
*Photos: P. Migoń*

Geocultural connections are represented by popular histories about the Byzantine Christian theologians and missionaries Cyril and Methodius (known as Apostles to the Slavs) who preached here and converted pagans to Christianity. According to other, more recent popular histories, Jan Amos Komenský (Comenius), a famous Moravian philosopher and pedagogue, stopped here to preach and then went into exile, never to return. The crag is located next to a popular hiking trail and is listed as a nature monument.

***S3 Osvětimanské skály***

A small rock city, consisting of seven larger sandstone outcrops, numerous smaller ones, and detached boulders, in places piled one upon another, crowns the top of a low elevation (Fig. 4C). It is approximately 40 × 40 m, with the height up to 10 m. The ground plan of the rock city shows adjustment to two main joint directions, N–S and W–E, whereas the shapes of the outcrops in detail reflect selective weathering along moderately inclined (approximately 40°) bedding planes. Arcades, honeycombs and small tafoni, up to 0.5 m across, are common. A remnant boulder on top of one of the outcrops seems to be turning into a balanced rock due to enhanced weathering at the base. A space between the eastern and western outcrops is partially filled with large sandstone boulders, apparently products of in situ disintegration rather than fall from the adjacent outcrops.

Osvětimanské skály are also called 'Devil's rocks' thanks to the existence of numerous legends related to the site that should have served as a gateway to the hell from where the devils came out and punished bad people. Several decades ago, a small tramp settlement was founded here. The site is used by climbers and described in climber literature. The Osvětimanské skály rock city is located away from marked hiking trails and, hence, is not well known and less visited. However, access is easy along forest paths, and the crags are visible from quite a distance, thanks to the open forest. No special protection is enforced, and no interpretative facilities exist.

***S4 Trpasličí město***

The locality, whose name translates as 'Dwarfs town', consists of two crags on top of a low, flattened elevation, some 40 m from each other (Fig. 4D). The one in the northwest resembles a cube and is 2.5 m in height, with a few minor outcrops and boulders in the immediate vicinity. The southeastern one is asymmetric, only 2 m in height towards the hilltop, but up to 8 m in height towards the slope. Its upper surface is nearly flat and approximately 7 m across. A distinctive feature of both crags is the extreme development of cavernous features along horizontal bedding planes. The hollows of different shapes (hemispherical, oval, horizontal slots) coalesce and penetrate deeply into the outcrops, locally piercing them through (Fig. 6B). In the SE crag, the length of a horizontal slot through the entire rock is up to 7 m. In the distance of 150 m to the south, at the slope break, two more crags are located, known as Dvě hlavy ('Two heads'). From the downslope side, they are up to 7 m high. A feature of interest is the basal recess due to enhanced weathering of a conglomeratic inlier.

No marked trail goes to the crags, although the site is easily accessible along unmarked forest paths. No special protection is enforced, and no interpretative facilities exist.

### *S5 Zbořené zámky*

The asymmetrical rocky ridge called Zbořené zámky ('Demolished (or collapsed) castles'), also known as Cvičitelská skála ('Exercise/Trainer Rock'), is a continuation of one of the main ridges in Chřiby – Holý Kopec (Fig. 4E). The top part reaches 375 m a. s. l. The southern face of the rocky ridge is formed by an inclined plate, about 8 m high, whereas the northern face is a nearly vertical cliff with basal overhangs, approximately 20 m high. The length of the crag is approximately 25 m. The rock ridge continues on the opposite slope, and it is possible that the Dlouhá řeka Brook cut through the originally compact (integral) ridge. The alternation of sandstone and conglomerate beds is reflected in variable resistance to weathering, the conglomerates being more prone to cavernous weathering. It is particularly effective along the bedding planes, which are well visible on the northern face of the ridge.

Thanks to its massiveness, visual similarity to a building (also called 'Stone chalet') or castle ruins, and traces of quarrying leaving the partially worked blocks of rock behind, the site is connected with several legends. According to popular histories, since the Great Moravian period, there used to be a space where people could spend the night and later, the site served as a shelter for bandits. The sandstone was exploited until the beginnings of the 20$^{th}$ century. On the nearby Holý kopec Hill, there used to be a large Slavic settlement, whose ditches and mounds are visible until now.

The site is a part of the Maršava Nature Monument. Although there is a marked cyclo-path in the Dlouhá řeka Valley, the site is not easily accessible for ordinary tourists. It is mainly used by climbers who come by a narrow path leading to the steep slope. Many climbing routes have been designated; there are also traces of fireplaces.

### *S6 Barborka*

The name refers to a large group of sandstone outcrops (Fig. 5A) within the steep southern slope of Barborka Hill (510 m), extending over an area of 250 × 70 m. It consists of ten individual crags, mainly in the shape of asymmetric towers rising from the slope and subvertical rock slabs. The height of individual outcrops reaches 20 m on the downslope side but only a few metres on the upslope side. The south-facing rock surfaces are inclined rather than vertical, adjusted to the steep dip of sandstone strata to the south. Cavernous weathering is ubiquitous along bedding planes, whereas conglomeratic inliers are locally preferentially weathered into slots and tunnels. Basal overhangs and narrow slots due to gravitational displacements are further features of interest.

On the top of the hill, the baroque St. Barbora Chapel, dating back to the 17$^{th}$ century, is situated. It served as a family tomb and pilgrimage site. However, traces of human settlements are much older. Archaeological research confirmed the Eneolithic age of ceramics. Later, a Halstatt Age (Lower Iron Age) settlement was located here, with mounds and ditches still visible. From the Late La Tène Age (European Iron Age culture), there is evidence of a settlement, which, according to folk tradition, was a sacred site and a cult place. There were intentions to build a monastery here during the Late Middle Ages, but the idea was abandoned. Some crags are modified by quarrying (stone was used for building St. Barbora Chapel).

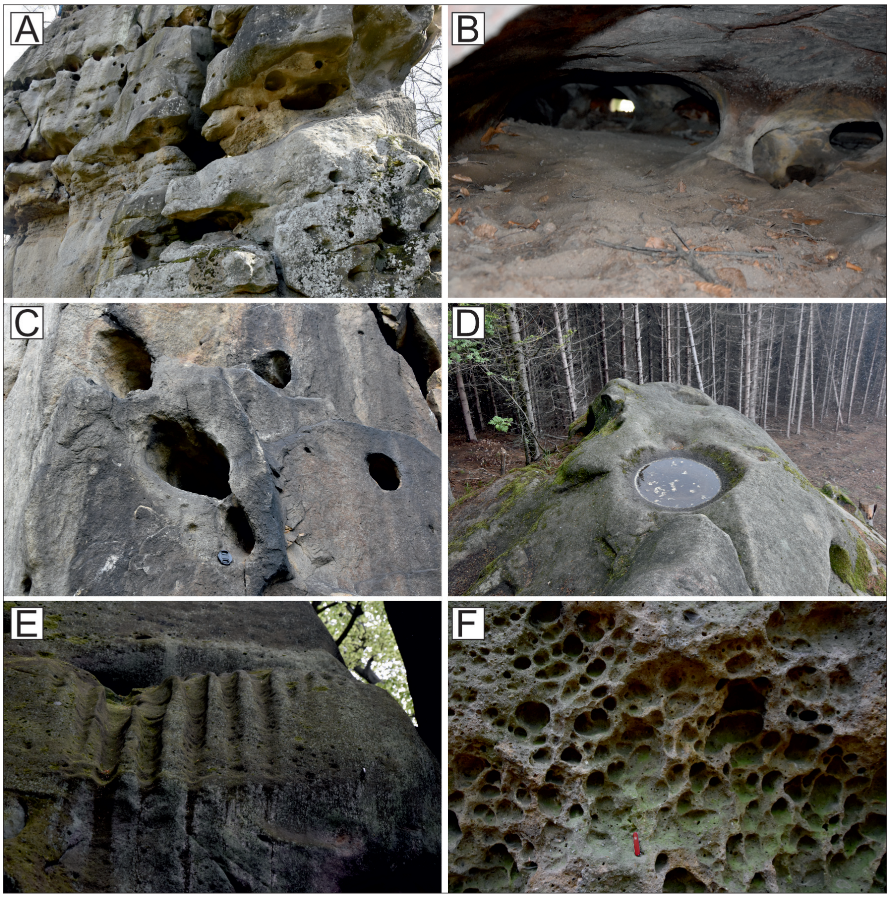


*Fig. 6: Diversity of weathering features on crag surfaces in Chřiby. A – selective weathering along bedding planes (Kozel), B – tube through an entire crag (Trpasličí město), C – tafoni, probably after complete dissolution of carbonate concretions (Břestecká skála), D – weathering pit (Jeřabčina), E - karren (Komínky), F – honeycombs (Budačina)*
*Photos: P. Migoń*

Despite its proximity to important historical sites and a marked trail nearby, the locality is not easily accessible for ordinary tourists. This is because of the very steep slope, the absence of clearly marked paths, and dense forest. Crags are visible neither from the trail nor from the viewing point next to the hilltop chapel. However, it is known among climbers, and many climbing routes have been designated. The entire slope is under protection as a Nature Monument.

#### S7 Břestecká skála

Břestecká skála is a complex outcrop, partly natural and partly of anthropic origin, located on the sloping ridge (Fig. 5B). The upper part is natural and consists of a series of inclined rock walls, towers and spurs, as well as minor steps and low angular outcrops within a less inclined section of the slope. The shapes of outcrops reflect a steep dip (50° and more) of sandstone beds to the south, whereas ubiquitous cavernous weathering develops along inclined bedding planes. Some caverns are remarkably smooth and regular, genetically linked with the dissolution of carbonate concretions (Fig. 6C). Thin (~1 m) conglomeratic beds are apparently less resistant than sandstone and have been weathered to narrow clefts and abri. In the lower part, natural outcrops have been undercut by now abandoned quarries, and it is difficult to identify the boundary between natural and anthropic features. The height of natural outcrops is up to 10 m, whereas the cumulative height of quarry walls is even higher.

In the surroundings, the traces of Neolithic settlement have been found. There are some old quarries and an old scout log cabin in the nearby valley. The top of the crag is easily accessible along a marked trail, but the most interesting parts below are more difficult to reach (no signage, unstable sloping surfaces). Likewise, no waymarked route goes to the old quarries. The locality is used by climbers, and a number of routes have been designated. The entire slope, from the highest crags to the valley floor, is protected as a nature monument. No educational facilities are available; only brief information about the site exists near the road (together with the Nature Monument sign).

#### S8 Jeřabčina

Jeřabčina skála is a cluster of sandstone outcrops on the top of an elevation within the main ridge of Chřiby (Fig. 5C). The highest one is an asymmetric, massive tower, rising by only 2 m on the upslope side, but approximately 12 m in height on the downslope side. A large overhang is present at the base. Next to it, on the ridge, are two fins approximately 3 m high, with ubiquitous cavernous weathering. More to the east is a rounded outcrop sloping steeply to the south, with several weathering pits on the upper surface, some periodically filled with rainwater (Fig. 6D), and shallow tafoni on the subvertical walls. Further outcrops and loose boulders occur in between the main crags.

The name 'Jeřabčina' refers to the local word for rowanberry tree (Sorbus). Nearby, a traditional tourist chalet, 'Na Bunči', is situated. A marked trail provides access to the crags. The locality is not under special protection and lacks interpretative facilities.

#### S9 Komínky

The crag crowns an elevation (521 m a. s. l.) in the main ridge of Chřiby. It is a discontinuous rock wall, up to 5 m in height in the central, highest section (Fig. 5D). Because of the steep (~ 50°) dip of sandstone beds to the south, the wall is asymmetric, with overhangs on the northern side. The central section was subject to anthropic modification: a series of rock-cut steps facilitates access to the narrow crest of the crag. To the north of the summit wall, a sandstone cliff that is approximately 15 m long up to 10 m in height exists, rounded in the upper part and undercut by a recess at the base. A feature of special interest is a group of parallel karren, up to 1 m long (Fig. 6E) – generally a rare phenomenon among sandstone outcrops in Chřiby. Further crags are present approximately 200 m to the west of the main elevation, shaped as inclined walls, fins and boulder piles.

Archaeological research confirmed the Halstatt Age of ceramic pieces. According to popular histories, the hill served as a 'fire mountain' where the guards (patrols) would set fires here in case of danger, and the smoke would warn others in the surroundings. Since the $19^{th}$ century, it has been a favourite tourist destination, offering great views of the surrounding landscape. Steps have been carved into the rock and there used to be railings. When the railings were inserted into the rock, there was much smoke, which gave birth to the mystification of the volcanic origin of Komínky (the word can be translated as 'Little chimneys') and the reactivation of a dormant volcano. This popular history is used very often to promote the site. Komínky also served as a border stone (a visible carving H:K) delimiting the Kvasice estate, with further border stones situated on the continuation of the ridge. There is also a memory plaque of scout Emanuel Rupert, who tragically died here in 1998.

A marked trail provides access to the crags, which are also used for climbing and bouldering. The locality is protected as a Nature Monument, and interpretative panels are erected at the crossings of marked trails nearby.

#### S10 Budačina

The name refers to a group of crags which mostly form a discontinuous cliff line a few metres high along the upper slope break (Fig. 5E). However, two isolated rock landforms exist in front of the steep slope, named Velká skála ('Big Rock') and Malá skála ('Little Rock'). The former is particularly impressive, being more than 20 m long and 12 m high, with subvertical rock surfaces all around the perimeter. Its shape reflects geological structure, namely a steep (> 60°) dip of sandstone and conglomerate beds to the south. Variable thickness of beds and preferential weathering along bedding planes produced inclined rock slabs and a jagged outline of the crag, with a distinctive crest in the top part. Another effect of bedding-controlled weathering is a fissure cave that extends approximately 7 m into the crag; it is 1 m wide and 2 m high. Several other widened fissures also developed along subvertical bedding planes and joints. Evidence of cavernous weathering is abundant, mostly as small honeycombs existing in clusters (Fig. 6F). The coalescence of honeycombs gives rise to larger hollows within the rock walls, but deep tafoni are apparently absent.

The site is connected with several legends about famous bandits Ondráš and Juráš, who had their shelter here and kept stolen goods in the fissure cave. There is also a commemorating plaque of Antonín Rozsypal, a founder of Forest settlement for young campers in the nearby valley (Kudlovická dolina).

The crag is easily accessible from a local road nearby (less than 1 km) and located next to a waymarked hiking trail. It is used by rock climbers. Next to the crag an interpretive panel was erected, but information about geology and geomorphology is very limited. The site is protected as a Nature Monument, which extends over a larger section of the slope, covering 8.2 ha in total.

The detailed geomorphological analysis of selected crags allows for the following summary of their geoheritage values (Tab. 3).

### 5.2 Degradation risk assessment

The detailed description and analysis of the specific sites served as a basis for assessing threats and risks. The results of the degradation risk assessment are presented in Table 4.

According to the risk level classification (Tab. 2), most sites (7 sites) fall within the medium risk category, including one nearly at the boundary with low risk. Two sites scored above 5 (S1 Kozel, S8 Jeřabčina), meaning high risk. Only one site falls in the category of low risk.

| Crag | Key geoheritage values |
|---|---|
| Kozel | The highest crag in the area; distinctive shape; good visibility; evidence of rock-controlled selective weathering |
| Kazatelna | Unusual shape; connection with local history |
| Osvětimanské skály | A good example of a rock city, unique in the area |
| Trpasličí město | Unique weathering features (cavernous weathering, long horizontal slots) |
| Zbořené zámky | Complex shape; clear example of bedding control on weathering patterns |
| Barborka | Large complex of rock slabs, towers and spurs; evidence of gravitational displacements |
| Břestecká skála | Distinctive setting on a spur; unusual cavernous weathering; selective weathering of conglomerate beds |
| Jeřabčina | Distinctive cluster of large outcrops; alveolar weathering and weathering pits |
| Komínky | Ridge-top crest (rare in the area); the occurrence of karren and basal recesses; connection with local cultural history |
| Budačina | Large dimensions of the main crag; distinctive shape related to rock structure (steep dip of sandstone beds); fissure cave; ubiquitous cavernous weathering |

*Tab. 3: Key geoheritage values of sandstone crags in the Chřiby area*
*Source: Authors' elaboration*

| Criterion/site | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Integrity | 0.5 | 0.5 | 0.25 | 0.25 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0.25 |
| Accessibility/availability of parking | 0.75 | 0.5 | 0.75 | 0.75 | 0.25 | 0.75 | 0.75 | 0.75 | 0.75 | 0.5 |
| Accessibility/availability of public transport | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.5 | 0 | 0.25 | 0.25 |
| Presence of accompanying tourist infrastructure | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0.5 | 0.5 |
| Management on site | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| Legal protection | 0.25 | 0.25 | 0.5 | 0.5 | 0.25 | 0.25 | 0.25 | 0.5 | 0.25 | 0.25 |
| Proximity to areas/activities with the potential to cause degradation | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.5 | 0 | 0 |
| Current use of the site | 1 | 0 | 1 | 0.5 | 0 | 0 | 0.5 | 0.5 | 0.5 | 1 |
| Visitation (public influx) | 1 | 1 | 0 | 0 | 0 | 0 | 0.5 | 1 | 1 | 0.5 |
| Use limitations | 1 | 1 | 1 | 1 | 0 | 0 | 0.5 | 1 | 0.5 | 1 |
| **Total degradation risk** | **5.75** | **4.5** | **4.75** | **4.25** | **0.75** | **2.75** | **4.5** | **6.75** | **4.25** | **4.25** |

*Tab. 4: Degradation risk assessment for geomorphological sites*
*Source: Authors' elaboration*

The values of total degradation risk differ depending on various aspects. Generally, the sites that are unsafe to visit (no good access path, location within steep unstable slopes) have acquired relatively low scores, so they can be considered facing less risk than sites that are well accessible and safe. The latter, situated near tourist facilities (such as chalets), marked on tourist maps and close to the tourist paths (or on tourist paths), with available parking places nearby and good access by public transport, are more endangered. In some cases, despite existing legal protection, the sites have reached relatively high scores (e.g., S1 Kozel or S2 Kazatelna and S7 Břestecká skála).

Zbořené zámky (S5) is the least endangered site, especially due to its limited accessibility and lower safety. The site is not widely known and, moreover, it is situated in a Nature Monument which should ensure protection and suitable management. Perhaps unexpectedly, the S6 site of Barborka also emerged as being at rather a low risk (the second lowest score). The locality is a well-known and often visited site due to its proximity to Buchlov Castle, easy access to the hilltop, and the presence of a cultural monument. It is also located close to the public road with parking. However, in the assessment exercise, only the south-facing slope with crags was examined, not the adjacent hilltop. The slope, in turn, is not developed for tourism, so crags are not visible and poorly accessible. Safety issues additionally discourage ordinary tourists from exploring the steep slope. The site is used only by climbers and is not recommended for ordinary tourists.

Generally, the most endangered site is S8 Jeřabčina, which is very well accessible and safe to visit but has no legal protection and management plan. Also, the site S1 Kozel has reached quite a high score, especially due to its good accessibility, intensive use, and high visitation. Also, it is one of the best-known sites within the Chřiby Mts., in the proximity of Cimburk castle ruins.

### *5.3 Risk assessment matrix*

The degradation risk assessment is accompanied by evaluating particular threats using the Risk Assessment Matrix. Based on fieldwork, several threats have been identified (Fig. 7) and assessed (Tab. 5).

Table 5 shows the main threats identified for all the sites and their assessment. It can be noted that the intensity of the threat varies depending on the site. Generally, after elaborating the simple average of all the results for particular threats, it appears that the most important threats are represented by Recreation and tourism (18) and Climbing and consequent damage of the crags (15.7). Other threats, such as Natural geomorphological processes (15), Lack of finances (14.7), Vegetation overgrowth (14.5) and Changes in land use (14), can also be considered important. Regarding the 'Emphasising the living nature', it proved to be moderate, reaching an average value of 7.9.

The values of risk intensity for particular sites are presented as an average value of all the particular threats for a single site. According to this method, the most threatened sites are S8 Jeřabčina (15.9) and S1 Kozel (15.4), which corresponds to the final ranking and values of Degradation risk in Table 4. These most endangered sites are followed by S6 Barborka (14.4) and then, with the same value (14.3), S3 Osvětimanské skály, S4 Trpasličí město, and S10 Budačina. S9 Komínky (14) and S2 Kazatelna (13.4) are the less endangered sites. According to this evaluation, the least threatened site is S5 Zbořené zámky, which corresponds with the ranking in Table 4 (Degradation risk assessment).

## 6. Discussion

Based on the results, particular management proposals can be discussed. Given the character and focus of the methodological approaches, these proposals can be focused in two directions:

1. On particular sites – following the results of Degradation risk assessment and also Risk Assessment Matrix, the S1 Kozel and S8 Jeřabčina should gain the priority attention as they have reached the highest score, so they are considered the most important;

| Sites | Threats | Changes in land use (including agriculture, forestry, new cottages, expanding recreational areas, …) | Recreation, tourism (visitors' pressure, – overtourism, littering, vandalism, breaking the rules) | Climbing and consequent damage of the crags | Lack of finances for maintaining the sites and their Earth Sciences phenomena | Emphasising the living nature | Vegetation overgrowth | Natural geomorphological processes (slope processes, erosion, accumulation of debris) | Average risk on specific site |
|---|---|---|---|---|---|---|---|---|---|
| S1 Kozel | prob | 3 | 5 | 5 | 3 | 1 | 2 | 3 | |
| | imp | 5 | 5 | 5 | 5 | 3 | 5 | 5 | |
| | **total** | **15** | **25** | **25** | **15** | **3** | **10** | **15** | **15.4** |
| S2 Kazatelna | prob | 1 | 5 | 4 | 3 | 1 | 2 | 3 | |
| | imp | 5 | 5 | 5 | 5 | 4 | 5 | 5 | |
| | **total** | **5** | **25** | **20** | **15** | **4** | **10** | **15** | **13.4** |
| S3 Osvětimanské s. | prob | 3 | 3 | 4 | 5 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 3 | 3 | 5 | 5 | |
| | **total** | **15** | **15** | **16** | **15** | **9** | **15** | **15** | **14.3** |
| S4 Trpasličí m. | prob | 3 | 3 | 4 | 5 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 3 | 3 | 5 | 5 | |
| | **total** | **15** | **15** | **16** | **15** | **9** | **15** | **15** | **14.3** |
| S5 Zbořené z. | prob | 1 | 1 | 3 | 3 | 3 | 4 | 3 | |
| | imp | 5 | 5 | 4 | 5 | 3 | 5 | 5 | |
| | **total** | **5** | **5** | **12** | **15** | **9** | **20** | **15** | **11.6** |
| S6 Barborka | prob | 4 | 3 | 3 | 3 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 5 | 3 | 5 | 5 | |
| | **total** | **20** | **15** | **12** | **15** | **9** | **15** | **15** | **14.4** |
| S7 Břestecká s. | prob | 3 | 4 | 4 | 3 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 5 | 3 | 5 | 5 | |
| | **total** | **15** | **20** | **16** | **15** | **9** | **15** | **15** | **15.0** |
| S8 Jeřabčina | prob | 4 | 5 | 3 | 5 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 3 | 3 | 5 | 5 | |
| | **total** | **20** | **25** | **12** | **15** | **9** | **15** | **15** | **15.9** |
| S9 Komínky | prob | 3 | 4 | 3 | 3 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 4 | 3 | 5 | 5 | |
| | **total** | **15** | **20** | **12** | **12** | **9** | **15** | **15** | **14.0** |
| S10 Budačina | prob | 3 | 3 | 4 | 3 | 3 | 3 | 3 | |
| | imp | 5 | 5 | 4 | 5 | 3 | 5 | 5 | |
| | **total** | **15** | **15** | **16** | **15** | **9** | **15** | **15** | **14.3** |
| **Intensity of particular threats** | | **14** | **18** | **15.7** | **14.7** | **7.9** | **14.5** | **15** | |

*Tab. 5: Risk Assessment Matrix for the particular sites (prob = probability, imp = impact)*
*Source: Authors' elaboration*

2. On particular threats – following the results of Risk Assessment Matrix, abundant tourist and recreation use of the sites and climbing are the threats that should be addressed with priority when designing the management proposals for a wider area.

Regarding the most endangered sites, in the case of S1 Kozel, legal protection has already been established. Thus, other measures should be applied to avoid future degradation or damage of the Earth Sciences phenomena. Environmental education focused on geoheritage values and the development of geoeducational products that inform about Earth Sciences values of the sites prove to be effective tools (Pijet-Migoń & Migoń, 2019; Bussard & Reynard, 2022; Rodrigues et al., 2023). Also, the education of local residents can be useful (Muzambiq et al., 2021). Lowering the number of visitors by their re-distribution in a wider area could also reduce degradation risk. However, visitors usually tend to visit the 'top' sites within a certain area (S1 Kozel is one of the best-known sites) and rarely miss them (Drápela, 2023), so this proposal may not be so effective. In the case of S8 Jeřabčina, which has no legal protection, it is possible to include the site in the Database of Geological Sites (Czech Geological Survey, 2024c), which would ensure at least regular monitoring. Later, this record can serve as a basis for establishing legal protection, which can contribute to lowering the degradation risk. Although, in some cases, the establishment of legal protection may result in a higher frequency of visits, more often, the attractiveness of a site for visitors is conditioned by other factors, such as visual attractiveness of the locality, access, visit safety, or information availability (Štrba et al., 2020).

The other sites evaluated as less endangered using the Degradation risk methodology should be at least regularly monitored. Generally, this is ensured for legally protected sites, as an existing care plan is updated every 10 years (Nature Conservation Agency, 2024). However, regular monitoring should have a shorter interval as changes can occur rapidly. One of the possibilities of monitoring more frequently is to include particular sites in the local communities' activities or projects, which proved


*Fig. 7: Threats on selected sandstone crags: A – heavy use of the crags by climbers (Kozel), B – significant trail erosion (Komínky), C – various examples of rock defacing from bouldering (traces of magnesium) and making fires (Komínky), D – vegetation overgrowth (Břestecká skála), E – graffiti making (Komínky), F – making fires and camping (Jeřabčina)*
*Photos: P. Migoń (A, B, C, D) and L. Kubalíková (E, F)*

to be an effective tool to raise awareness about geoheritage values or care about the sites (Prosser, 2019). These include such activities as 'Watch over a rock' (Vegas et al., 2018) or participatory mapping of geoheritage (Drápela, 2019; Bollati et al., 2023).

Regarding point 2 (particular threats), the most important issues in the study area are recreation and tourism, followed by climbing and consequent damage to the crags. In both cases, environmental education may help to reduce these threats. Another possibility is to employ 'nature guards', which is quite usual in National Parks and Protected Landscape Areas (González & Martin, 2007). In the case of Chřiby, however, there is no roofing large-scale protected area administration, so the pool of nature guards is complicated to set up or invite to the particular sites.

There is a possibility of enhancing legal protection (from Nature Monuments to National Nature Monuments) or establishing new protected sites. However, as legal instruments of geoconservation are top-down initiatives resulting from political decisions, the local communities may be reluctant to accept that and may consider it useless; thus, it is appropriate to involve local communities in the decision process (Nunes et al., 2022). Moreover, proper legal conservation or protection does not assure that the site will not face any threats and risks (Crofts et al., 2020; Nunes et al., 2022; Kubalíková & Balková, 2023; Kubalíková, 2024). A bottom-up approach to geoheritage care and protection can also be considered. These initiatives can result in a complex involvement of various stakeholders from the area and the creation of a Geodiversity Action Plan, which may contribute to more effective management of geoheritage (Burek, 2012; Ferrero et al., 2012; Dunlop et al., 2018; Kubalíková et al., 2022). The positive effects of community-led conservation and care activities are already proven (Tavares et al., 2015; Gravis et al., 2020; Bollati et al., 2023).

Regarding climbing, which has been identified as one of the main threats, there is a significant difference between particular sites. For example, S1 Kozel is intensively used, and traces of magnesium and other negative consequences can be found on-site (e.g., littering or even vandalism). In contrast, other sites (e.g., S5 Zbořené zámky and S6 Barborka), which are also intensively used and well-known among the climbers' community, are less damaged and endangered. It is probably related to the accessibility of the sites and the individual behaviour of the climbers. Closer communication between the nature conservation authorities and the Association for Climbing of the Czech Republic is desirable in order to minimise the negative influence and can contribute to a better understanding and more respectable use of the sites for climbing and bouldering. Moreover, according to Bollati et al. (2014, 2024), sport climbing is a powerful tool for disseminating complex scientific information (e.g., conditions for rock formation, types of deformation, surface modelling and geological time) and consequent appreciation of geoheritage values.

The topic of natural geomorphological processes and their influence on geo-phenomena may be viewed in two ways. First, if the natural processes damage the Earth Sciences phenomena under protection, they should be somehow treated, e.g., in the case of heavy erosion and intensive slope processes which may damage profile of sediments or important stratigraphic boundaries. This is usually reflected in care plans; however, in some cases, there is an emphasis on living nature management, and abiotic features are considered ‘in good conditions’ (Nature Conservation Agency, 2024). Second and more often, these natural processes are taken as an inseparable part of a particular site (Smith, 2005; Prosser et al., 2006), and such sites should be treated in a complex way as dynamic geomorphosites (Kubalíková, 2024). In the case of specific sites in the study area, most probably there is a very limited possibility to avoid processes such as occasional rock fall, but it is possible to reduce the intensity of other slope processes, such as soil creep or overland flow, e.g., by regulating the number of visitors or by redirecting their movement. This, however, would require some investment into supporting infrastructure and higher financial demands.

## 7. Conclusions

This research was focused on two main points: recognition of sandstone heritage in a less explored terrain of the Chřiby Mountains and evaluation of risks and threats to particular sites (sandstone crags). Based on the literature and map review and using results of detailed fieldwork, 10 sandstone crags have been described and qualitatively evaluated regarding their geoheritage values. The diversity of sandstone geoheritage within selected sites is high, especially when considering mesoforms and microforms (e.g., abundant occurrence of tafoni, honeycombs, or perforations). Based on their geoheritage values, some sites may be proposed for a higher degree of legislative protection, or at least they can be included in the Database of geological localities, ensuring regular monitoring. Nevertheless, further research is needed, focusing, e.g., on micro- and mesoforms inventories, the intensity of natural geomorphological processes, and the genesis of the sandstone crags.

The evaluation of degradation risk and the use of a risk assessment matrix enabled us to rank the sites according to the degree of possible deterioration and helped to identify particular threats, which should be considered as important when planning and managing natural resources of the area. The most important threat is represented by recreation and tourism (and related camping, making fires or littering and vandalism), followed by climbing (and consequent damage of the crags) and natural geomorphological processes. Several management proposals have been discussed, but the application of particular measures to specific sites or practical dealing with particular threats is a subject of further efforts, communication with relevant authorities, and community involvement. Nevertheless, recognising the geoheritage values of sandstone crags and identifying and evaluating possible risks and threats may be considered an important step towards effective management and further research.


### Acknowledgement

*The authors thank František Kuda for preparing a situation map (Fig. 2). The fieldwork of Piotr Migoń was carried out during a research visit to Masaryk University in Brno, supported by the home institution (University of Wrocław) through the Research University – Excellence Initiative programme. Lucie Kubalíková and Karel Kirchner were supported by the project Dynamic Planet Earth of the Czech Academy of Sciences – Strategy AV21.*


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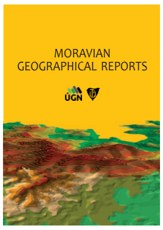
**Please cite this article as:**

Kubalíková, L., Kirchner, K., & Migoń, P. (2025). Geoheritage values and threats related to sandstone crags of the Chřiby ridge (Moravian Carpathians, Czech Republic). Moravian Geographical Reports, 33(1), 40–55. https://doi.org/10.2478/mgr-2025-0004



MORAVIAN GEOGRAPHICAL REPORTS
Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science
journal homepage: www.geonika.cz/mgr.html
doi: https://doi.org/10.2478/mgr-2025-0005

# Geodiversity and land cover diversity from coast to mountains in Northern Albania

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## Abstract

The present study explores the relationship between geodiversity and land cover diversity in northern Albania, near Shkodra, covering approximately 1,400 km$^2$. Using open-source GIS tools, we analyse the diverse geographical features, including coastal, agricultural, urban, riverside, and mountainous terrains. Geodiversity is assessed through geological, soil, morphometric, paleontological, and mineral data, while land cover diversity is determined using Copernicus Global Land Cover 2019 data. Our analyses, conducted at both low and medium altitudes (< 850 m a. s. l.) and high altitudes, reveal a positive correlation between geodiversity and land cover diversity in lower regions but a negative correlation in higher elevations. The connectivity in the study area shows low values in low-altitude areas with high land cover diversity, characterised as cultural landscapes. Our results highlight the importance of taking geodiversity into account in conservation efforts, as areas rich in geodiversity and land cover diversity offer potential for geotourism but also deserve attention due to human activities. Consistent with previous research, our results confirmed that there is a relationship between geodiversity and land cover diversity. However, the negative correlation at high altitudes is a new finding. Overall, our research underscores the intricate interplay between geodiversity, land cover diversity, and connectivity in shaping ecological patterns and emphasises the need for coordinated conservation strategies in diverse landscapes.

**Keywords:** Geodiversity, land cover diversity, geotourism, connectivity, coordinated strategies

**Article history:** Received 24 September 2024, Accepted 7 February 2025, Published 31 March 2025

## 1. Introduction

The evaluation of land cover diversity supports ecological analyses and has long been present in scientific research. Studies typically use indicators such as the Shannon diversity index to measure the diversity of surface vegetation cover within a given unit area (Uuemaa et al., 2009). Although diversity is a scale-dependent measure and the definition of classes is challenging, the classes defining land cover diversity are well defined within the CORINE programme, and the CORINE surface cover map, which is constructed from remotely sensed data and regularly updated, is freely available and allows their analysis using GIS tools (Büttner, 2014).

Vegetation cover is defined as the average leaf area per unit of land area, and different vegetation cover types (such as open or closed forest, shrubland, cropland, etc.) contribute to different land cover types (Martin et al., 2021). The diversity or homogeneity of the vegetation cover has an impact on the fauna and flora that live in it. Different land cover categories mean different habitats. Some organisms prefer homogeneous habitats, others prefer contact zones, and population size is related to habitat size. For groups of organisms, it is important to be able to move between habitats that suit their living conditions, so connectivity of land cover categories is an important measure alongside diversity (Taylor et al., 1993; Debinski & Holt, 2000).

The diversity of vegetation cover and the size of contiguous homogeneous areas are most affected by human expansion. In general, an increase in land cover categories in an area represents an increasing intensification of urbanisation and agriculture, and tends to be more pronounced in the vicinity of inhabited areas (Alados et al., 2004). Although some species are well adapted to human proximity, increasing habitat fragmentation leads to a reduction in the size of populations that prefer homogeneity and become more vulnerable on the long run (Tilman et al., 1994).

Under natural conditions vegetation cover depends on climatic, topographic and soil characteristics (Florinsky & Kuryakova, 1996). It has long been known that climate and altitude are the primary factors influencing vegetation cover, but the relief, slope steepness and soil quality (i.e. the parent rock) also influence the vegetation cover of a given area (Florinsky & Kuryakova, 1996; Cantón et al., 2004). These variables are also being investigated by a relatively new subdiscipline of earth sciences, known as geodiversity studies.

Geodiversity, if assessed in a quantitative way, can usually be interpreted in a similar way to land cover, i.e. as a measure per unit area (e.g., Zwoliński et al., 2018 and references therein). Geodiversity usually includes geomorphological, hydrological, geological and soil diversity (Gray, 2018). Since several of the defining variables are common, it is therefore logical that land cover

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and geodiversity are interrelated and to better understand the nature of the relationship, studies are needed that are sufficiently broad and cover a large enough area to provide statistical evidence of the association observed.

In the present study, the area of Shkodra (Shkodër) municipality in northern Albania is investigated, which has diverse topography and rich of natural values within its boundaries (Fig. 1). With an area of 953.64 km$^2$, Shkodra municipality is relatively large in Albania and one of the richest geosite areas in the country, featuring 25 geo-related and 10 living natural monuments, such as forests and habitats, listed in the national geoportal (State Authority for Geospatial Information – ASIG, 2023). The geosites include mainly caves, glacial lakes, waterfalls, springs, and geomorphological features (canyons, rock formations, glacial features). The area includes Lake Shkodra, the largest in the Balkans, the Adriatic coast and the North Albanian Alps, reaching an altitude of 2,694 m a. s. l. The region also includes three major rivers (Buna, Drini, Kiri), and nature reserves like Albanian Alps National Park formed from the merge of the Theth National Park and the Valbona Valley National Parks in 2022, and the Maranai Park. Situated in the Eastern Alpine Mediterranean Belt, the area has diverse geological formations, including Mesozoic marine sediments (Triassic dolomites, limestones, shales, Jurassic limestone, marl, and Cretaceous carbonates), along with Late Permian and Cenozoic sediments (Meço & Aliaj, 2000).

Focusing on this diverse landscape, the research sought to answer the questions:

1. Can a relationship between geodiversity and vegetation cover diversity be demonstrated in this area?
2. Is the nature of the relationship (if any) linear?
3. Is there a spatial variation?

Since the area under study is already partly protected, and its geoscientific diversity is high, it is very suitable to become a geopark, which would enable the region to exploit the growing tourism in the area in a sustainable way (Dollma, 2019; Serjani, 2020). A previous geodiversity study in the area confirmed this assumption by noting that geodiversity hot-spots in the area coincide with areas already partly exploited for tourism (Kraja & Albert, 2023). Therefore, in the present study, parameters that represent both geotourism and local business aspects (e.g., fossil sites, raw materials) are taken into account. The results are particularly discussed in the light of the ecological implications of the exploitation of high geodiversity sites for geotourism purposes when designing the infrastructure of a possible geopark.

## 2. Theoretical background

The structure of the land cover of an area is a key determinant of biodiversity, and its distinct components, the 'patches', can be considered as elements of the landscape, the spatial characteristics and relationships of which can be studied using landscape metrics (Walz, 2011). The techniques of landscape metrics use indices and primarily measure characteristics of landscape elements such as: composition, configuration (or structure) and function (Lausch et al., 2015). Methods that include remotely sensed data and GIS are the most useful way to determine the composition (e.g., diversity) and structure (e.g., connectivity) of patches of land cover (Herold et al., 2002; Lang & Blaschke, 2007).

Landscape element diversity at this level (i.e. the level of satellite images), although a determinant of biodiversity, does not automatically represent species diversity (Walz, 2011), so no conclusions on biodiversity can be drawn from the analysis of land cover alone. It appears that a close relationship exists between them, although this may change over time. For example,

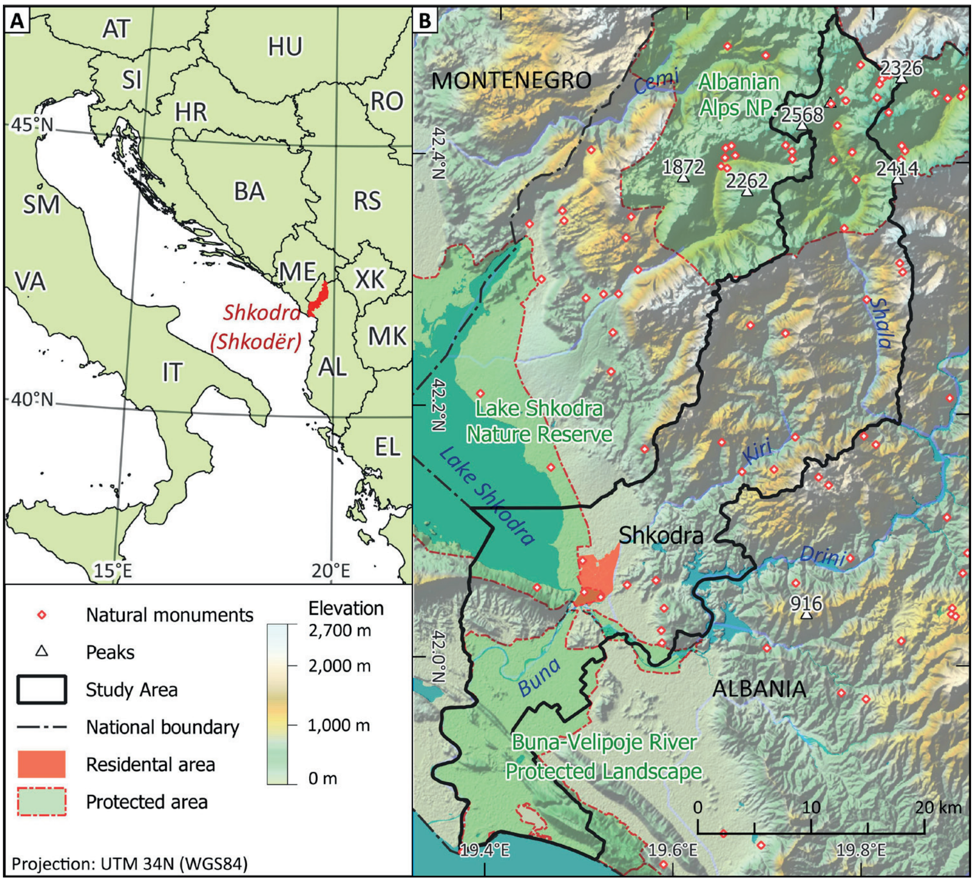


*Fig. 1: Location (A) and geographical settings (B) of the study area*
*Source: Authors' elaboration*

the diversity of land cover leads to an increase in the number of species in the short term, as more habitat types appear in a unit area (e.g., Honnay et al., 2003). However, as diversity increases, the size of habitats decreases, and the same habitat types become more distant from each other, resulting the reduction of species diversity (Debinski & Holt, 2000). Furthermore, anthropogenic impacts may temporarily increase both diversity, but in the longer term lead to a decline in species numbers (Tilman et al., 1994; Martin et al., 2021).

The diversity of vegetation is usually expressed by the Shannon diversity index and the Simpson diversity index (Forman, 1995). The former measures the inequality and richness of the classes under study, while the latter characterises the proportion of dominant categories. The scale of the area under study determines the appropriate distinction to be made between the different vegetation cover groups. For regional and smaller scales, vegetation cover categories are determined based on satellite data. The CORINE Programme (Co-ordination of Information on the Environment), initiated by the European Commission, has developed a well-defined categorisation system over decades of operation (Büttner, 2014; Buchhorn et al., 2020). The processing of multispectral satellite imagery has resulted in the production of free-use land cover maps (European Environment Agency, 2019; Büttner et al., 2021).

Landscape metrics include not only composition (variety of categories, i.e. diversity), but configuration as well. Configuration refers to the geographical distribution of patches. A common metric of configuration is the edge length calculation and the connectivity index. As the diversity of surface cover increases, the length of the edges of individual habitat patches also increases, making communities more vulnerable to expanding species (Saunders et al., 1991). The effects of fragmentation are not the same for all species, but in general, the connections that remain between patches can help link populations and thus reduce vulnerability (Debinski & Holt, 2000; Riitters et al., 2000). Connectivity is the ratio of actual to potential connectivity between habitats of the same type and is a measure of the extent to which organisms have the potential to move between habitats in a way that maintains their preferred living conditions (Taylor et al., 1993; Nikolakaki, 2004). Connectivity is a number between 0 and 1; the closer it is to 1, the more mobility there is for the species living there, i.e. the more homogeneous the area.

While in the case of vegetation cover the categories that form the basis for measuring diversity are well defined, in the case of geodiversity it is more complex and, as a relatively young sub-discipline, there is no consensus on the metrics. The most widely used method for estimating geodiversity is the quantitative approach, which can be quickly implemented using a geographic information system based on maps, surveys or data derived from a geodatabase (Zwoliński et al., 2018). There are two subtypes of this approach, one is map-algebra based and the other is indicator based, and both basic types are common, as well as their combinations (Serrano & Ruiz-Flaño, 2007; Pál & Albert, 2023). Quantitative analysis is achieved by quantifying the elements that play a role in geodiversity and then summarising them over the area under study (e.g., Pereira et al., 2013; Argyriou et al., 2016). The elements of geodiversity are usually derived from the available data: geological diversity is defined by the categories of the geological map, soil diversity by the categories of the soil map and geomorphological diversity by the categories of the geomorphological map. In the case where there is no categorisable map, only point data on geodiversity elements (e.g., cave dataset), diversity is defined by the number of points per unit area (e.g., Stojilković, 2022). Given the large number of methods available, the geodiversity estimate should therefore be chosen primarily on the basis of the basic data available, the size of the study area and the purpose of the study (Zwoliński et al., 2018; Crisp et al., 2021).

For medium and small-scale (i.e. regional) analyses, there are often edited geological, soil and geomorphological maps of the area, as well as a digital terrain model (DEM) that can be used to calculate morphometric indicators. These can be used to calculate geodiversity values along a regular grid using a map-algebraic method. If a geomorphological map is not available, DEM-derived maps of morphological classes can be used, typically based on geomorphons or Topographic Position Index (TPI) classes (Chrobak et al., 2021; Nasiri et al., 2022; Zakharovskyi & Németh, 2022). The hydrographic elements at this scale can also be implemented from a global database (e.g., OpenStreetMap) or derived from the DEM (Pál & Albert, 2021a). By combining maps with specific geodatabases (e.g., karst features cadastre, fossil sites, etc.), the geodiversity calculation can be fine-tuned to a specific theme.

The relationship between geodiversity and vegetation cover has been established by several studies (Jačková & Romportl, 2008; Hjort et al., 2012; Dos Santos et al., 2019). It was concluded that geodiversity underpins biological diversity, as all organisms rely on the abiotic elements of their environment. Consequently, a decline in geodiversity will negatively impact biodiversity. For example, plant species diversity benefits from higher geodiversity, but only in areas away from human influence (Tukiainen et al., 2017). At the regional scale, a positive correlation between geodiversity and land use/cover diversity has been shown (Datta, 2022), but the spatial variability of this relationship has not been investigated to our knowledge.

## 3. Data and methods

### *3.1 Study area*

Albania, located in Southeastern Europe on the Balkan Peninsula, boasts a distinctive and very diverse landscape, shaped by geological activity and the Mediterranean climate. The study area lies in the northern part of the country, where around 80% of the Shkodra region consists of mountainous terrain, including the Albanian Alps (Fig. 1). It is also abundant in water resources, with rivers such as the Drini, Buna, Shala, Kiri, and Cemi, as well as Lake Shkodra, the largest lake in the Balkans. This tectonic-karstic lake spans the border between Albania and Montenegro.

Northern Albania has an exceptionally rich and diverse natural environment, thanks to its varied topography and proximity to the Adriatic Sea. Landscapes from the high mountains to the coast vary considerably in terms of flora, fauna and climate. The climate is characterised by a combination of mediterranean and continental influences, modified by the diversity of topography (Metaj, 2007). The coastal areas are characterised by warm, dry summers and mild, wet winters with 650–1,060 mm/year of precipitation and average annual temperatures of 14–17 °C, while in the mountains the temperature decreases and the precipitation increases with increasing altitude. In the hilly and mountainous areas, the average annual temperature is around 7–11 °C, and the average annual precipitation can reach 2,100–3,100 mm/year (Kopali et al., 2013). However, the effects of climate change are evidenced by an increasing temperature and a decreasing precipitation year on year (Gjoni et al., 2023).

Thanks to the varied climatic conditions, the region has a relatively rich flora (Shuka et al., 2017). The coast is covered with Mediterranean evergreen shrubs and forests, dominated by acorn oaks, olive trees and myrtle. In the lower parts of the mountains, deciduous forests have developed, with beech, oak and ash being the main tree species. In the higher regions, coniferous forests, followed by subalpine and alpine meadows, replace deciduous forests (Fig. 2A).

The landscape has been shaped by human activity for thousands of years (Dyczek et al., 2020). Deforestation, agriculture and urbanisation have resulted in the loss of many natural habitats. Grazing and fires have also contributed to vegetation change, but the higher regions of the area have low population densities and better-preserved natural habitats due to the sparse road network. In order to preserve the natural vegetation cover, increased attention has recently been paid to the creation of national parks and the expansion of protected areas (Fig. 1).

The geological diversity of the region also affects its morphology and soils (Hoxha, 2021), so an overview of the formations and evolutionary history of the area is given in the following. The study area lies at the junction of the Albanides and Dinarides mountain ranges, separated by the Scutari-Pec transverse zone between the High Karst Nappe tectonic unit in the north and the Mirdita ophiolites in the south (Speranza et al., 1995; van Hinsbergen et al., 2020). Its unique geological history is shaped by tectonic activity from the convergence of the African and European plates during the Alpine orogenesis. The Cretaceous and Cenozoic orogenic phases created a stacked nappe structure with folded and thrusted sequences.

The geological formations in the Shkodra region show significant variation in age and type (Fig. 2B). Although Mesozoic carbonates form the bulk material of the Albanian Alps, the oldest sediments date back to the Permian, consisting of fossiliferous limestones, sandstones, conglomerates, and shales. The Lower Triassic features terrigenous-carbonate rocks, while the Middle Triassic marks the development of a carbonate ramp transitioning into a marine basin filled with cherty limestones and tuffaceous sediments (Gaetani et al., 2015). At the beginning of the Late Triassic the carbonate platform sediments of the Adriatic region started to develop (Vlahović et al., 2005; Gawlick & Schlagintweit, 2019). The Jurassic and Cretaceous sequence in the area consists of shallow-marine neritic limestones and pelagic limestones transitioning to deep-marine turbiditic deposits in the Paleogene (Meço & Aliaj, 2000; Robertson & Shallo, 2000). From the Cretaceous period onwards, the Alpine orogenesis has induced a series of nappe thrusts, resulting in a variety of marine- and terrestrial sediments being overthrusted by and folded under the Albanian Alps zone (Meshi et al., 2014). The folded succession includes Cretaceous shallow marine carbonates, evaporites, Paleocene bauxite, and Middle Eocene nummulitic limestones, followed by Oligocene turbidites (Schmitz et al., 2020). East of Shkodra, on the southern side of the Scutari-Pec transform zone, the Mirdita ophiolites expose oceanic crust with volcanic rocks from the Triassic to Late Jurassic (Dilek et al., 2005). Recent tectonic activity, marked by SW–NE shortening and reactivated thrust faults, leads to frequent earthquakes, including the 1905 Shkodra earthquake (magnitude 6.6) (Biermanns et al., 2019).

The geomorphology of the area is mainly the result of tectonic uplift and the action of fluvial waters, and the precursors of the deep river valleys were already formed in the Neogene (Lenaerts et al., 2013). A series of Quaternary glaciations around the Last Glacial Maximum (LGM) produced glacial and periglacial landforms in the area (Milivojević et al., 2008). The border region between northern Albania and Montenegro is covered by Quaternary sediments, creating broad alluvial plains stretching

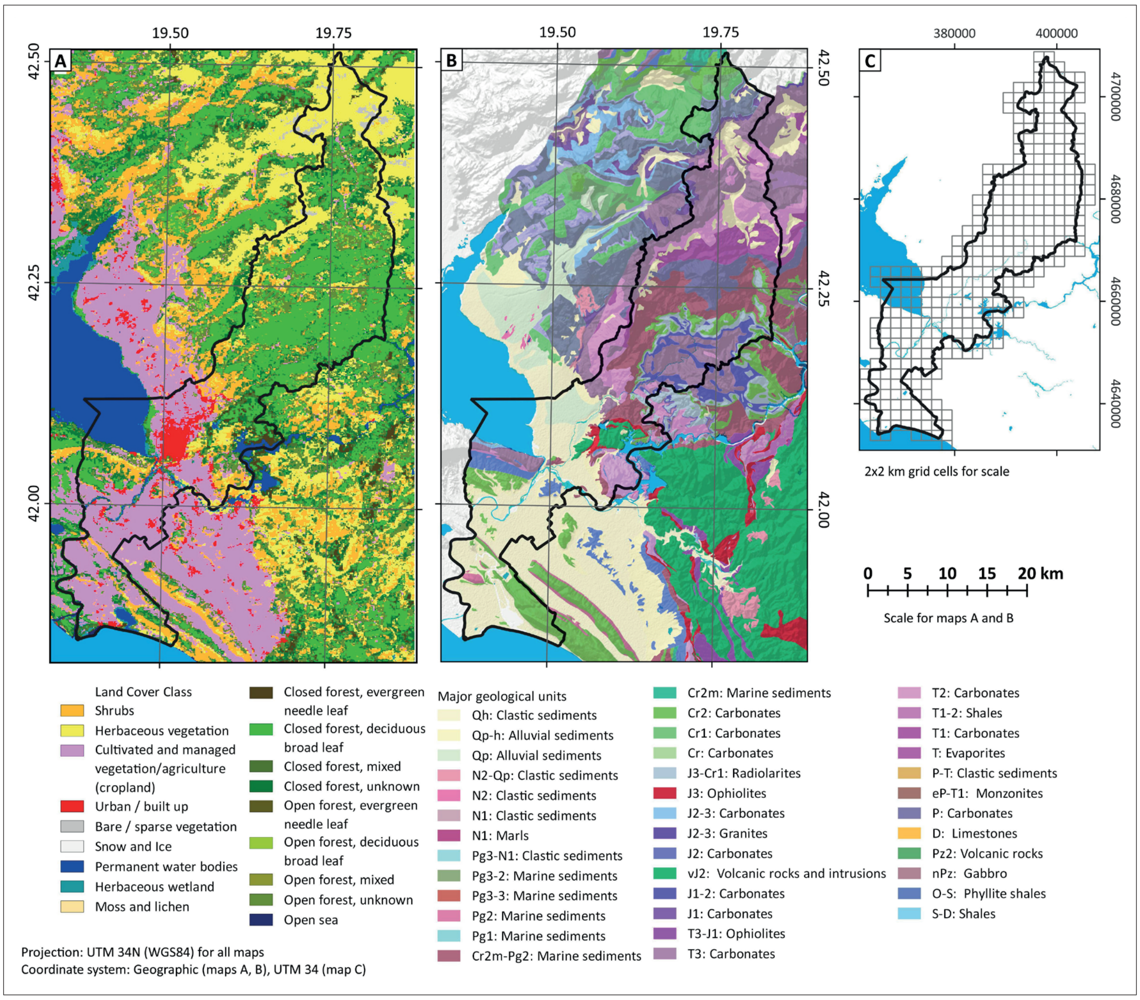


*Fig. 2: Land cover map (A) and geological map (B) of the study area based on the Copernicus Global Land Cover 2019 data for vegetation (Buchhorn et al., 2020), and the geological map of Albania (Xhomo et al., 2002). Adjacent map (C) shows the 2 × 2 km grid resolution*
*Source: Authors' elaboration*

from the city of Shkodra to the coast. This area is dominated by Lake Shkodra, a relatively young freshwater lake, around 6,000 years old, surrounded by marshlands, with evidence of human activity dating back to prehistoric times (Mazzini et al., 2016). On the plains and on the shores of Lake Shkodra, accumulation landforms developed. These were modified by man throughout history to regulate flooding (Hoxha, 2021).

The varied geology, topography and climate of the area around Lake Shkodra and the Albanian Alps has resulted in a wide variety of soils. The soils around Lake Shkodra are mainly alluvial and hygromorphic (wetland) soils and near the Adriatic coastline halomorphic soils are present, which are exposed to saline groundwater (Kraradžić et al., 2020). The alluvial soils are formed by sediments deposited by rivers and the marshy soils are formed by frequent flooding. Throughout the High Karst Nappe of the Dinarides-Albanides mountain ranges the soils were formed by karstification, weathering and erosion. The most common soil types are rendzina, which is a thin layer of humus overlying limestone bedrock, cambic soil types, which is a fertile soil with a deeper layer of humus, and skeletal soils of high mountain areas, which are stony, rocky soils where humus formation is limited (Zdruli, 2005; Kraradžić et al., 2020).

### 3.2 Methodology

To answer the research questions, we calculated and compared diversity indices. For the calculation we used partly open data available online and partly published maps. Due to the size of the study area, the maps were on a medium scale and the indices were calculated on a 2 × 2 km grid, which is a common dimension for regional analyses (Elkaichi et al., 2021; Manosso et al., 2021; Pál & Albert, 2023). The source material was digitised and analysed using QGIS (v.3.24.1) and SAGA (v.9.6.1) open-source geospatial software in UTM34N Cartesian coordinate system (WGS84 datum). In this coordinate system the extent of the area was: 361,500 min. easting; 407,500 max. easting; 4,630,800 min. northing; 4,708,800 max. northing (Fig. 2C). When analysing diversity grids, we display this coordinate system on our maps, where the grid cells can also be used as scales. The analysed area covered 1,464 $km^2$. The analysis was carried out using established methods, which have already been described in the literature review and are further detailed below.

#### 3.2.1 Data

The free-use data included a digital elevation model (DEM) of the area, which was the MERIT (Multi-Error-Removed Improved-Terrain) model (Yamazaki et al., 2017). This model does not include the height of vegetation and built features but has a relatively poor resolution (3 arc second, which corresponds to about 70 × 90 m at this latitude). The resolution was converted to square pixels of 50 m edge length by bicubic interpolation due to the use of a rectangular coordinate system. Also free-use data was the hydrography of the area, which was extracted from the OpenStreetMap database (OSM, 2024). To calculate the geodiversity index, we used the freely available European Geological Data Infrastructure (EGDI) mineral raw material database (EGDI, 2024), which contained five object types for the area as point data: 1) precious minerals, gemstones; 2) metallic minerals; 3) industrial minerals and dimension stones; 4) geological energy sources; 5) mineral waters and springs. For vegetation cover analysis, we used the Copernicus Global Land Cover 2019 data for vegetation with 100 m resolution raster data, which distinguishes 22 land cover types (Buchhorn et al., 2020).

The geological and soil map of the area was not freely available, but published data were obtained. The scale of the geological map was 1:200,000 (Xhomo et al., 2002); the map had to be converted into a vector format, with polygons containing the rock types and characteristic fossils of each geological category as attributes. The soil map was at a scale of 1:250,000 (Zdruli, 2005) and its categories corresponded to the World Reference Base for Soil Resources database (IUSS Working Group, 2006). The maps represented the categories in a generalised way due to their scale.

#### 3.2.2 Calculating the land cover diversity and the connectivity indices

The great variety in the vegetation cover of the area is shown by the fact that in the area of the Shkodra municipality 18 of the 22 possible cover types are found. The 18 categories included 14 vegetation categories, three water surface, and one urban cover category (Fig. 2A). The diversity was expressed using the Shannon diversity index for each 2 × 2 km edge length cell, which were parallel to the coordinate system and covered the entire area of Shkodra municipality. The Shannon Diversity Index is a commonly used metric in ecology and other fields that measures the richness and distribution of a given community (Pielou, 1969). The higher the value of the index, the more diverse the community. The formula for calculating the index is as follows (Shannon, 1948):

$$H = -\sum(p\_i * \ln(p\_i))$$

where *p_i* is the relative abundance of the ith group (i.e. land cover category) in the community. The value of the Shannon diversity index is usually between 0 and ln(S), where *S* is the number of groups. The index is largest when all groups occur with equal frequency.

When comparing the diversity of various communities of different composition, the normalised value is commonly used (Ramezani, 2012). In normalisation, the index value is divided by the maximum possible diversity value, which is usually equal to the natural logarithm of the number of possible groups, but in our case this is not a realistic scenario, as no 2 × 2 km cell contains all the 18 coverage categories. For this reason, the cells were divided into groups by altitude and normalised to these groups. The groups were subdivided along terciles: cells with an average elevation over 850 m (126 cells), cells with an average elevation between 80 and 850 m (115 cells), and cells with an average elevation of less than 80 m (126 cells). Thus, for each cell a value between 0 and 1 was obtained, where 1 represents the maximum diversity.

The calculation was performed on the 100 m resolution raster Copernicus-2019 data by examining the base data pixel-by-pixel in a 20-pixel square kernel, which resulted in a "Shannon index raster" also with 100 m resolution. The values of the resulting raster data layer were further examined within each 2 × 2 km cell and its maximum within a cell was recorded in a geodatabase.

In addition to the Shannon Index, we also calculated the connectivity. Since we did not focus on the migration of specific species or other taxonomic groups in the present study, we used the most general approach to the calculation, which is implemented in the SAGA GIS (Conrad et al., 2015) and was developed as an image processing algorithm (Burger & Burge, 2008). In this sense connectivity is defined as the number of pixel-connections within a search radius where fields of the same type are considered to be neighbours and is used for general analyses of landscape connectivity (e.g., Gupta & Pandey, 2020). Connectivity was calculated by the 'Diversity of Categories' SAGA tool using the same kernel geometry as for the Shannon Index and the queen's case principle was followed without distance weighting, i.e. diagonal pixels were considered to be neighbours in the same way as adjacent pixels. The connectivity index can take values between 0 and 1 and the degree of connectivity varies depending on the value. A higher value indicates a stronger and more extensive connectivity.

#### 3.2.3 Calculating the geodiversity index

The Geodiversity Index aims to represent all geoscientific aspects in a balanced manner, without prioritising any specific geodiversity element (Gray, 2018). To achieve this, we analysed geological, paleontological, pedological (soil), mineral, and geomorphological (hydrological and relief) data for the Shkodra region using a quantitative methodology based on studies by Pereira et al. (2013) and Pál and Albert (2021b). The resulting geodiversity index is calculated from the combined values of the identified sub-indices. Since the five sub-indices have different ranges of values a normalisation of the values was performed in each case. Normalisation is a common operation in the calculation of the components of the geodiversity index, and in almost all cases the aim is to bring the basic data with different variability to the same scale and thus to give them the same weight in the computation (Bétard & Peulvast, 2019; Pál & Albert, 2021b; Carrión-Mero et al., 2022).

The geological sub-index was calculated using the 1:200,000 scale geological map of Albania (Xhomo et al., 2002). This sub-index was derived by counting the number of different lithological and stratigraphic units within each grid cell.

To calculate the palaeontological sub-index, no fossil site database or map was available. However, based on the geological map and the information provided in the explanatory book 'Geology of Albania' by Xhomo et al. (2002), it was possible to determine the number of fossil assemblages present in the various lithological and stratigraphic units depicted on the map. When digitising the map, these were recorded and the number of different fossil groups in each grid cell could be determined, which represents the value of the palaeontological sub-index. The groups cannot be linked to a specific taxonomic level, as the map did not follow this logic. The number of isolated groups was 21, consisting mainly of corals, ammonites, bivalves, and gastropods.

The mineral occurrences sub-index was calculated using European Geological Data Infrastructure (EGDI). For the study area, 12 occurrences or deposits were retrieved, indicating the location of quarrying of building material, ornamental stone and base metals. The sites were concentrated in the coastal region and therefore the diversity index could not be calculated for most of the cells.

The soil sub-index was calculated using a 1:250,000 scale soil map of Albania (Zdruli, 2005) following the same principle as for the geological sub-index, i.e. counting the number of different soil units within each grid cell.

The geomorphological sub-index consists of two components: hydrology and relief, for which sub-indices were calculated separately and then combined to obtain the geomorphological sub-index value using the method of Pál and Albert (2021b). For both components we used the MERIT elevation model and for hydrology we used the OpenStreetMap water course data. For the hydrology sub-index, the Strahler hierarchy level of watercourses (Strahler, 1957) was calculated first, which was done using the SAGA GIS program. The value of the sub-index in each cell is the highest hierarchical level divided by 2, rounded to the nearest integer. Cells with no watercourses were assigned a value of zero, while the index for larger rivers and lakeside areas was 4. For the relief sub-index, the classification method of geomorphological elements developed by Jasiewicz and Stepinski (2013) was used. This algorithm uses line-of-sight to classify relief elements from DEM and classifies cells of the relief model into 10 morphological types. The computation was performed in SAGA GIS using line tracing method from pixels as centre to 8 directions with radius of 500 m. To calculate the value of the sub-index, the diversity of the resulting geomorphic map was examined for the 2 × 2 km cells, where the range of values was 0–10. After calculating the hydrological and relief sub-indices, the next step was to sum them to obtain the geomorphological sub-index.

## 4. Results

The diversity of the study area is illustrated by the compiled maps (Fig. 3), and for comparison purposes, diagrams and tables were prepared. The spatial distribution of land cover diversity and connectivity is shown in Figures 3A and 3B. In the three altitude categories, we also examined these indicators separately to see if any difference in the distribution of diversity values could be observed (Fig. 4). In the low and medium altitude categories and in the regions above 850 m, both the Shannon diversity and the connectivity distribution function showed different patterns, but in the low altitude region, the histograms showed a greater difference than the other two. Here, the mean value of the Shannon diversity index was smaller and showed a larger standard deviation, and the mean value of the connectivity was larger than in the other two cases (Figs. 4A, 4D). In none of these ranges did the phenomena under study show a purely normal distribution, which was confirmed by the Shapiro-Wilk test performed in Excel at the alpha = 0.05 significance level (Shapiro & Wilk, 1965; Zaiontz, 2024). However, in almost all cases the distributions were unimodal, and the histograms were nearly bell-shaped.

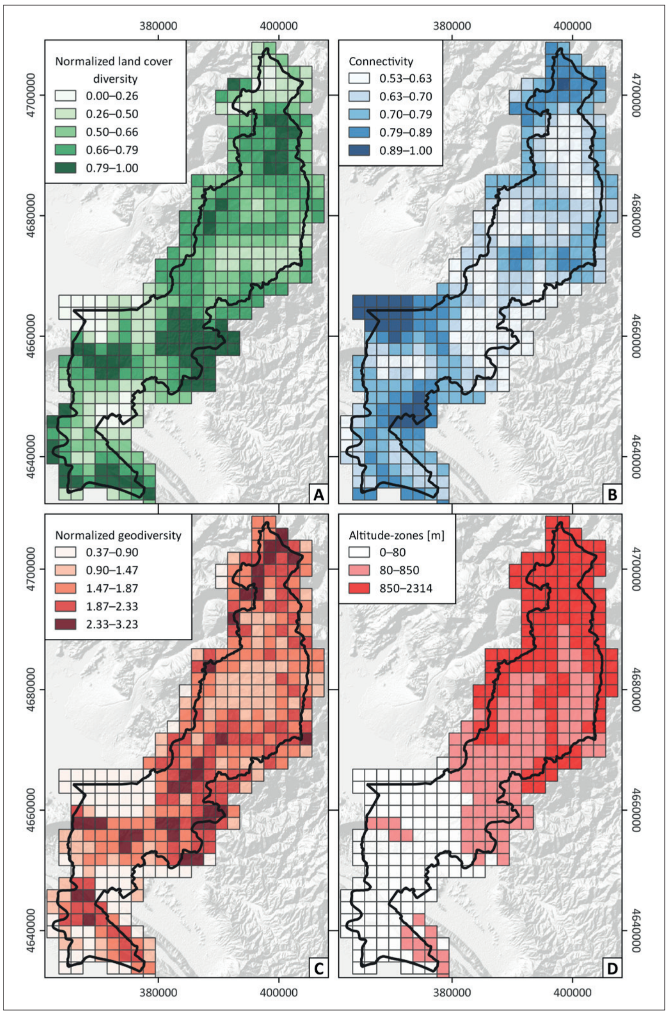


*Fig. 3: Diversity maps of the study area: A) Normalised land cover diversity (Shannon-diversity); B) Connectivity; C) Normalised geodiversity; D) Map of the three height zones*
*Source: Authors' elaboration*

The spatial distribution of geodiversity is shown in Figure 3C. In two of the three altitude ranges, medium and high, the geodiversity index was normally distributed according to both the histogram and the Shapiro-Wilk test. In the low altitude ranges, however, the conditions for a normal distribution (such as unimodality, symmetry and bell curve) were apparently not fulfilled, and the histogram had two distinct peaks (Fig. 4G).

Since most of the phenomena under study were not normally distributed, Pearson correlation tests could not be performed. However, the Spearman rank correlation is also suitable for examining the relationships between variables with a different distribution (Daniel, 1990). The aim of the correlation analysis

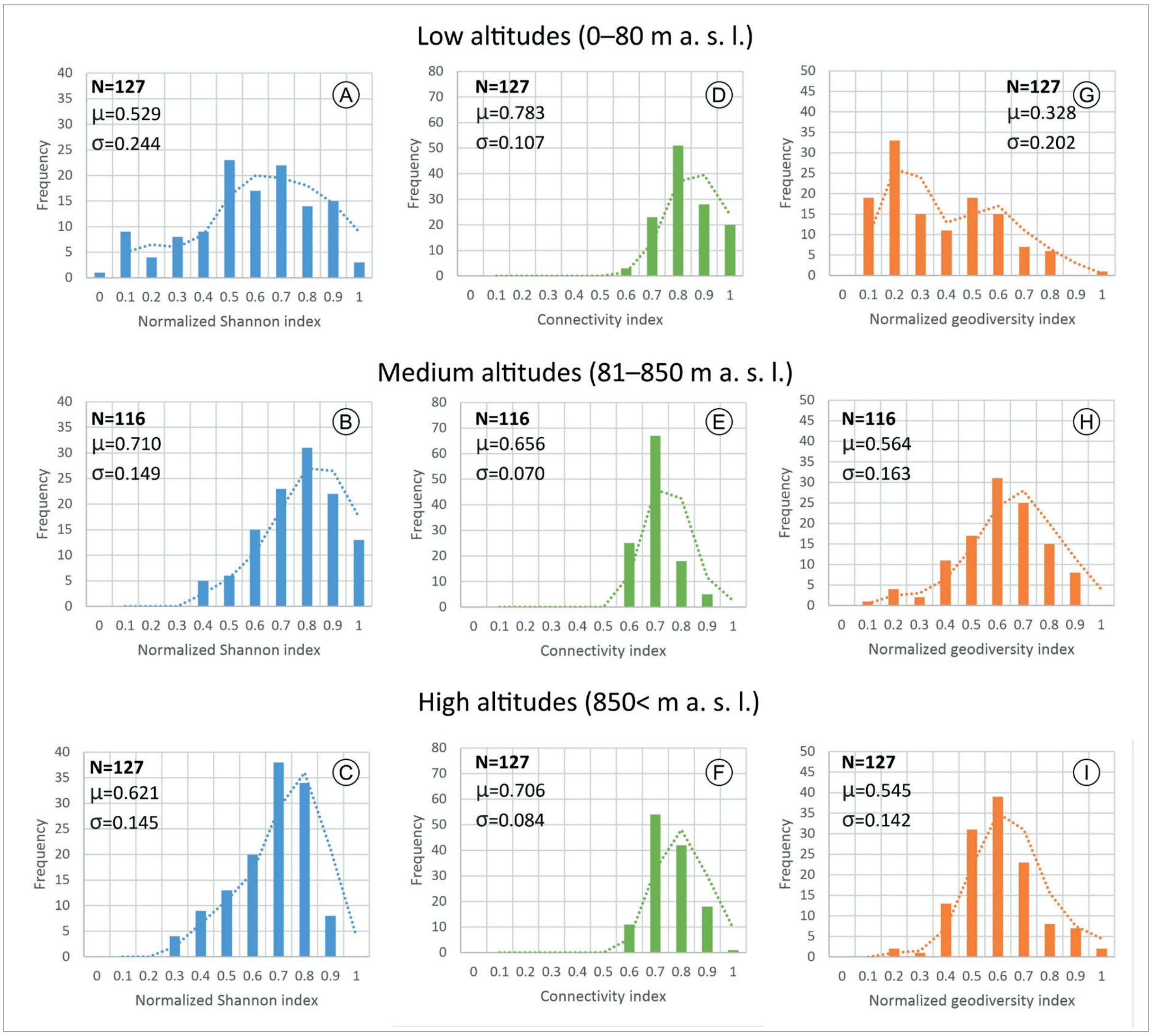


*Fig. 4: Histograms and descriptive statistics (N = sample number, μ = mean, σ = standard deviation) of the examined indices for the three altitude zones: Low (0–80 m a. s. l.), Medium (81–850 m a. s. l.), and High (> 850 m a. s. l.). The dotted lines show the moving average. Panels A, B, C: the frequency distributions of the Normalised Shannon Index (land cover diversity) for Low, Medium, and High altitudes, respectively. Panels D, E, F: the frequency distributions of the Connectivity Index for Low, Medium, and High altitudes, respectively. Panels G, H, I: the frequency distributions of the Normalised Geodiversity Index for Low, Medium, and High altitudes, respectively*
*Source: Authors' calculations and elaboration*

was to analyse the relationships between the three variables under study, but we also included the averaged values of altitude in the cells. In most cases, the correlation indicated a significant relationship between the variables (Tab. 1). For geodiversity and Shannon diversity, and for geodiversity and connectivity, only at medium altitudes was there no significant relationship.

An important result of the correlation analyses is the opposite relationship observed between geodiversity (GD) and Shannon diversity (i.e. land cover diversity = LCD) and between geodiversity and connectivity in low and high-altitude areas. Specifically, at low elevations, GD and LCD move together and connectivity moves opposite. Conversely, in high altitude areas, geodiversity and connectivity move together to a smaller extent, and the higher they are, the lower the LCD. It can also be seen that there is a strong negative correlation between connectivity and LCD at each altitude zone, which is not surprising since the greater the fragmentation of areas, the less the relationship between the same coverage types.

The relationship between elevation and the other variables shows a unique feature in all three cases. Elevation and geodiversity are positively correlated in low and high-altitude areas and negatively correlated in medium altitude areas. Elevation and land cover

| **Low** | **GD** | **Conn.** | **LCD** | **Elev.** |
|---|---|---|---|---|
| GD | 1 | – 0.6326* | 0.6146* | 0.6371* |
| Conn. | | 1 | – 0.8848* | – 0.4446* |
| LCD | | | 1 | 0.268** |
| Elev. | | | | 1 |
| **Medium** | **GD** | **Conn.** | **LCD** | **Elev.** |
| GD | 1 | – 0.048 | 0.1406 | – 0.2765** |
| Conn. | | 1 | – 0.77* | 0.1327 |
| LCD | | | 1 | – 0.4918* |
| Elev. | | | | 1 |
| **High** | **GD** | **Conn.** | **LCD** | **Elev.** |
| GD | 1 | 0.3314* | – 0.2323** | 0.3167* |
| Conn. | | 1 | – 0.8874* | 0.7105* |
| LCD | | | 1 | – 0.5508* |
| Elev. | | | | 1 |

*Tab. 1: Spearman rank correlation matrices of the different variables on the three elevation ranges (low, medium, high)*
*Notes: GD = normalised geodiversity index, Conn. = connectivity index, LCD = normalised Shannon diversity index for land covers, Elev. = average elevations. *Correlations are significant at p < 0.001, **Correlations are significant at p < 0.005*
*Source: Authors' calculations*

diversity show a slight positive correlation in low elevation areas, which turns into a medium and then a medium-strong negative correlation in higher elevation areas. This means that coastal areas tend to have more diverse vegetation cover at higher levels (i.e. hill tops), while valley bottoms tend to have more diverse vegetation cover at the medium and high elevation zones. Finally, elevation and connectivity show a moderately negative correlation in low areas, a strong positive correlation in high areas and no significant relationship in medium elevation areas. This in turn implies that in the coastal areas the contiguous habitats are found at lower levels and in the high elevation areas on ridges and peaks.

In order to better understand the relationship between the geodiversity index and the other indices, the two main sub-indices of the geodiversity index, the geological and the geomorphological sub-indices, were also examined separately using Spearman's rank correlation. The results of the analysis (Tab. 2) show that the geomorphological sub-index plays generally a more dominant role in the relationship between the geodiversity index and the other variables, and this dominance is most pronounced in the high-altitude zone.

## 5. Discussion

In examining the diverse and in many ways outstanding natural assets of the Shkodra region, we sought to answer three main questions. Based on previous literature (e.g., Jačková & Romportl, 2008; Hjort et al., 2012; Dos Santos et al., 2019), a link between geodiversity and land cover diversity was assumed, which was our first research question, and one of our objectives was to confirm this with the analyses. This was successful, as our results also demonstrate a relationship between the two diversity indices. We can therefore say that there is a relationship between the two phenomena, as confirmed by the correlation studies.

### *5.1 Non-linearity of the relation*

The success of the correlation test does not imply a causal relationship between the two phenomena. It is possible that a third factor is causing both phenomena to change simultaneously. This is particularly important in the present case, as we have examined indices that use several factors in their calculation, since it is possible that the factors have different roles (weights) in the correlation.

We have therefore formulated our working hypothesis with greater uncertainty about the linear or non-linear nature of the relationship. Both indices represent complex natural phenomena, which makes it logical to assume that the relationship between the indices cannot be modelled in a linear way. This was partly confirmed by the results, as the distribution of the indices was not unimodal in the low elevation zone and the Shannon diversity index of land cover and connectivity were not normally distributed in either elevation zone.

A linear relation requires that there is a relationship between the variables that can be approximated by a line. The points on the scatter plot then follow a straight line and the correlation test can be performed using Pearson's method. This also requires the variables to be normally distributed (Daniel, 1990), which in this case was only verified by the Shapiro-Wilk test for geodiversity values at medium and high altitudes. However, in these altitude zones, the other two variables (Shannon index and connectivity) were also bell-shaped, if not symmetric. These results suggest that the relationship between the variables cannot be approximated by a linear model in the present case, but that further areas should be investigated to understand whether this is the case in all circumstances, as the varying behaviour of the variables across areas is clearly demonstrated by our results.

### *5.2 The dynamics of the relationship between living and non-living nature*

In a sense, the multi-area analysis was also carried out within the framework of the present research, as the study area was divided into three altitudinal ranges (Fig. 3). The study area was subdivided by altitudinal zones mainly because the composition of vegetation cover is different in the coastal and mountain areas, and nowhere (within the 2 × 2 km cells) does the number of cover categories reach the number of categories found in the whole area, so it was not possible to normalise the Shannon index to the whole area. These areas also have different climatic conditions due to the difference in altitude, which affects the vegetation cover (Kalajnxhiu et al., 2012).

The correlations between the investigated variables in the three areas showed three different dynamics. The tables (Tabs. 1, 2) can be interpreted in many ways and since causality cannot be proven, one can only speculate about the causes of the relationships, but the degree and direction of correlation is informative. The relationship was significant in most cases. The results suggest a complex relationship between geodiversity, land cover diversity, and connectivity. While geodiversity is generally positively correlated with land cover diversity in low elevation zones, this relationship can reverse in higher elevation areas. Conversely, geodiversity is negatively correlated with connectivity in low elevation zones but positively correlated in higher elevation areas. No significant relationship was detected in the medium elevation zones. In the low-altitude zone, the co-variation of geodiversity and land-cover diversity is probably related to the dominance of the cultural landscape in this zone, where agricultural land overlaps with natural habitats in the foothills, and where the extraction of minerals and building stones is most concentrated. In the high zone, however, the human influence is less pronounced, and natural processes (e.g., climate and mountain zonation) are more likely to induce the relationships.

This highlights the importance of interpreting results for specific environments and avoiding generalisations when examining the links between the living environment and geodiversity. In demonstrating the relationship between geodiversity and biodiversity, Hjort et al. (2012) and Tukiainen et al. (2017) have emphasised the boreal environment in their conclusions and have also demonstrated the important role of climate in their research.

| | Low elevation zone | | | Medium elevation zone | | | High elevation zone | | |
|---|---|---|---|---|---|---|---|---|---|
| | LCD | Conn. | Elev. | LCD | Conn. | Elev. | LCD | Conn. | Elev. |
| GD | 0.6146* | – 0.6764* | 0.6371* | 0.1406 | – 0.0475 | – 0.2765** | – 0.2323** | 0.3314* | 0.3167* |
| Geom_si | 0.5546* | – 0.6543* | 0.6480* | 0.3287* | – 0.119 | – 0.4068* | – 0.3489* | 0.3263* | 0.2977* |
| Geol_si | 0.5567* | – 0.5962* | 0.5345* | 0.2886** | – 0.2098 | – 0.2378** | – 0.0419 | 0.0961 | 0.091 |

*Tab. 2: Spearman rank correlations of the normalised geodiversity index (GD), and its geomorphological (Geom_si) and geological subindices (Geol_si) with the normalised Shannon-diversity index of the land cover (LCD), the connectivity index (Conn.) and the average elevations (Elev.) on the three elevation ranges*
*Notes: Red colour: Negative correlation (as one variable increases, the other decreases); Blue colour: Positive correlation (as one variable increases, so does the other). *Correlations are significant at $p < 0.001$, **Correlations are significant at $p < 0.005$*
*Source: Authors' calculations*

Hjort et al. (2012) investigated the effects of several variables (e.g., precipitation, slope angle, elevation), of which elevation was the most relevant in our case due to the much smaller scale. Although there were no large differences in elevation in the area they studied, elevation showed a significant negative correlation with vegetation species diversity.

The results of the present study show that the relationship between land cover diversity and geodiversity was dominated by the morphological component of geodiversity, and that is more pronounced in the high-altitude zone. This could be explained by the fact that, in addition to linear erosion landforms and karstic landforms, glacial landforms also contribute to the geomorphological diversity in this zone. A relationship between land cover diversity and elevation can also be detected. At low altitudes, the diversity of vegetation cover increases with increasing altitude, but this relationship is reversed at medium and high altitudes, and a negative correlation is observed. This negative link is in line with the findings of the study (Hjort et al., 2012) on the relationship between biodiversity and altitude.

### 5.3 Implications for conservation strategies, geotourism, and human activities

Even though the reason for the relationship is not known, the awareness that there is a link between geodiversity and the diversity of living nature places much greater emphasis to the protection of non-living nature. In Albania, geoconservation efforts have included the collection of major geosites/geomorphosites (Serjani et al., 1998; Serjani, 2020) and detailed surveys have already been carried out in some areas (Braholli & Menkshi, 2021; Braholli et al., 2023). Geotourism also fits well into the state's rural development programme launched in 2018, which involves several villages in the study area (Ministres së Bujqësisë dhe Zhvillimit Rural, 2024).

The geodiversity of the study area (canyons, caves, waterfalls) makes it an ideal location for geotourism (Serjani, 2020), and there is already an infrastructure in place, which would be expanded with additional facilities in case the area is declared as a Geopark. Geosites, which are likely to occur in places with higher geodiversity (Pál & Albert, 2021b), are the tourist destinations of a geopark. If a geopark were to be created in the area, in addition to geosites, tourist infrastructure development (parking, buildings, roads, etc.) would also be implemented, especially in the more accessible low and medium elevation zones, which will affect the vegetation cover and its connectivity. The present study has shown that the vegetation cover at high geodiversity areas is already much more fragmented in the low altitude zone, which would be further amplified by such an intervention. In the high-altitude areas, high geodiversity areas are less fragmented and would be less impacted by infrastructure development.

The currently protected areas (Albanian Alps National Park, Shkodra Lake National Reserve, and part of the Buna Velipoje River Protected Landscape area) are typically low Shannon diversity, high connectivity areas. In these areas, infrastructure is therefore already in place in the high geodiversity hot-spot areas, and the chances of vulnerability of the living environment are also lower due to the existing control. Because of this, utilisation of the existing tourism infrastructure in these areas to showcase geodiversity would be most effective. Such geodiversity hot-spots can be found, for example, in the high mountain area of the Albanian Alps National Park and in the morphologically diverse parts of the Buna Velipolje River Protected Landscape. However, human-induced fires, for example, may pose a greater threat to contiguous forests in these regions, especially as the tourist season and the dry season coincide (Milenković et al., 2020).

## 6. Conclusion

Focusing on this diverse landscape, the research has demonstrated that there is a link between geodiversity and vegetation diversity, and found that the nature of the relationship is not linear. The large relief variation and size of the area made it possible to divide it into altitudinal zones and to investigate these indicators and the relationships between them on a zone-by-zone basis. The main result of the study can be derived from this, which to our knowledge has not been shown by other scholars.

We have shown that the relationship between geodiversity (GD) and land cover diversity (LCD) is different in different altitude zones:

- In low, coastal areas (< 80 m a. s. l.), GD and LCD show a strong positive correlation, i.e. the higher the geodiversity, the more fragmented the vegetation cover. This is also associated with a decrease in connectivity. In this zone, it was shown that GD increases with increasing altitude, and that the geomorphological subindex has only a slightly larger role than the geological subindex.
- At intermediate altitudes (between 80 and 850 m a. s. l.), there was no detectable relationship between GD and LCD, but both LCD and GD decreased with increasing altitude and the geomorphological subindex played a much greater role than the geological subindex.
- At high altitudes (above 850 m a. s. l.), there is a negative correlation between GD and LCD, i.e. the higher the geodiversity, the lower the vegetation cover fragmentation; this is associated with an increase in connectivity. In this zone, GD increases with altitude, but only the geomorphological subindex plays a role. LCD decreases with increasing altitude.

Underlying this zonality is, in our opinion, an increasing morphological variability towards the high relief areas, which can be traced back to diverse events in the geological past. Based on the results of the study, the policymakers, conservationists, and land managers of the future geopark in the area can design the geotourism infrastructure taking into account the different dynamics of the relationships between living and non-living natural assets. The potential impacts we have formulated, derived from the identified correlations, are not exhaustive, as this was not the scope of the study. However, our results can provide important support for impact studies to be carried out in the planning phase. This study presents a process for identifying potential geotourism hotspots characterised by high geodiversity and to estimate the potential impact of tourism activities on local natural values, considering land cover diversity and connectivity. However, the data employed are suitable only for broad, regional analyses and are not adequate for detailed assessments of ecotourism and geotourism impacts.

### Acknowledgement

*The authors would like to thank the anonymous reviewers and the associate editors (Lucie Kubalíková, Márton Pál and Vittoria Vandelli) for their constructive feedback on a previous version of this manuscript, which has significantly contributed to its improvement.*

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**Please cite this article as:**

Albert, G., & Kraja, D. (2025). Geodiversity and land cover diversity from coast to mountains in Northern Albania. Moravian Geographical Reports, 33(1), 56–67. https://doi.org/10.2478/mgr-2025-0005

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