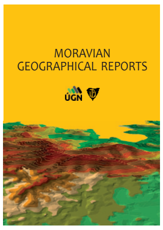

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Heritage recognition of active geomorphological processes: The challenges of geoconservation beyond landforms

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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

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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

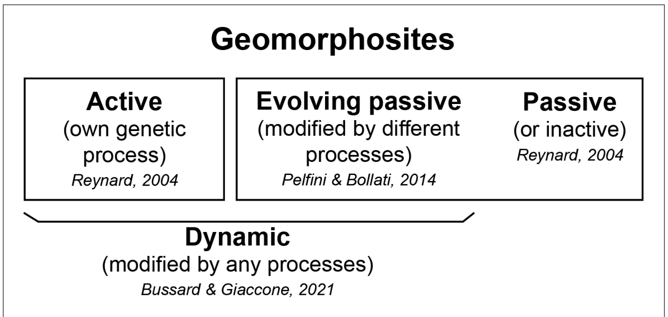


Fig. 1: Different categories of geomorphosites according to their activity
Source: Authors' conceptualisation

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.

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:

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

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

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

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

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 $\mathrm{SICV_j}$ 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 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 b. Protected site	Concerns the influence of the site on local ecological communities	The ecological value was qualitatively assessed				
Cultural value	a. Religious importance b. Historical importance c. Artistic and literary importance d. Geohistorical importance 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/nczlj6ukwmmb). 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

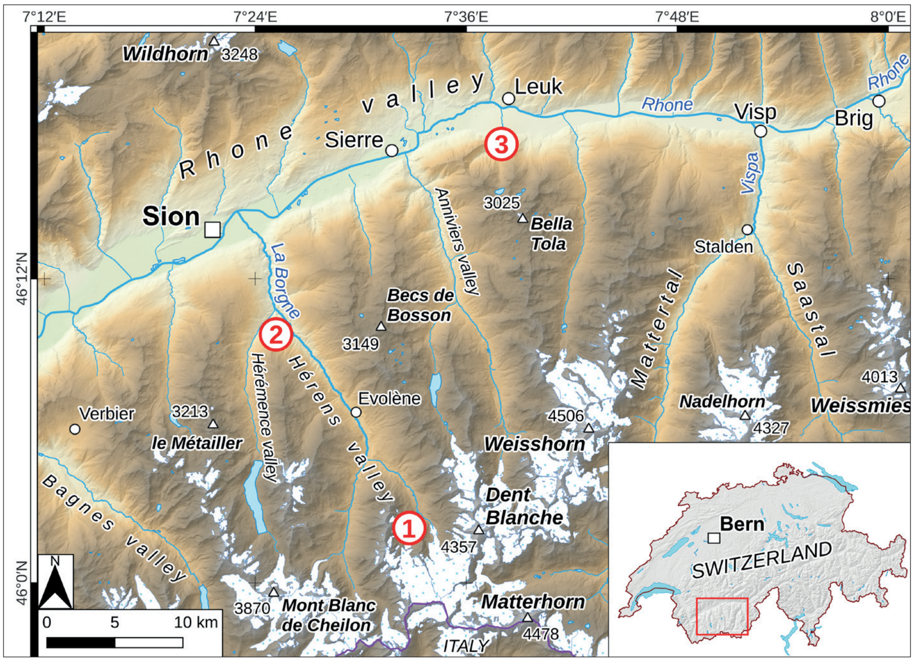


Fig. 2: Location of the study sites. 1) Mont Miné glacial system; 2) Euseigne earth pyramids; 3) Illgraben torrential system
Source: Authors' conceptualisation; Elevation from MDT25 Digital Terrain Model, © swisstopo; other vector data from OpenStreetMap

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

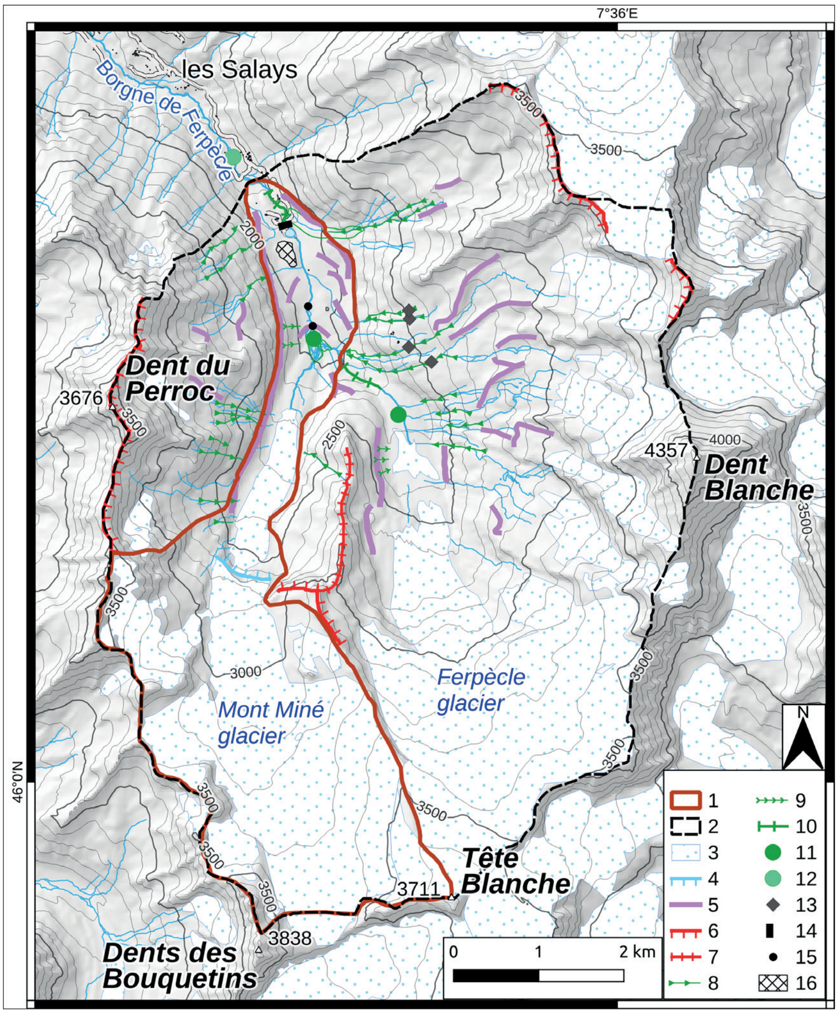


Fig. 3: Geomorphological sketch of the Mont Miné glacial system. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Glacier; 4) Serac subject to ice falls; 5) Moraine ridge; 6) Rock scarp; 7) Rock ridge; 8) Stream with torrential activity; 9) Gully; 10) Fluvial gorge; 11) Active proglacial 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

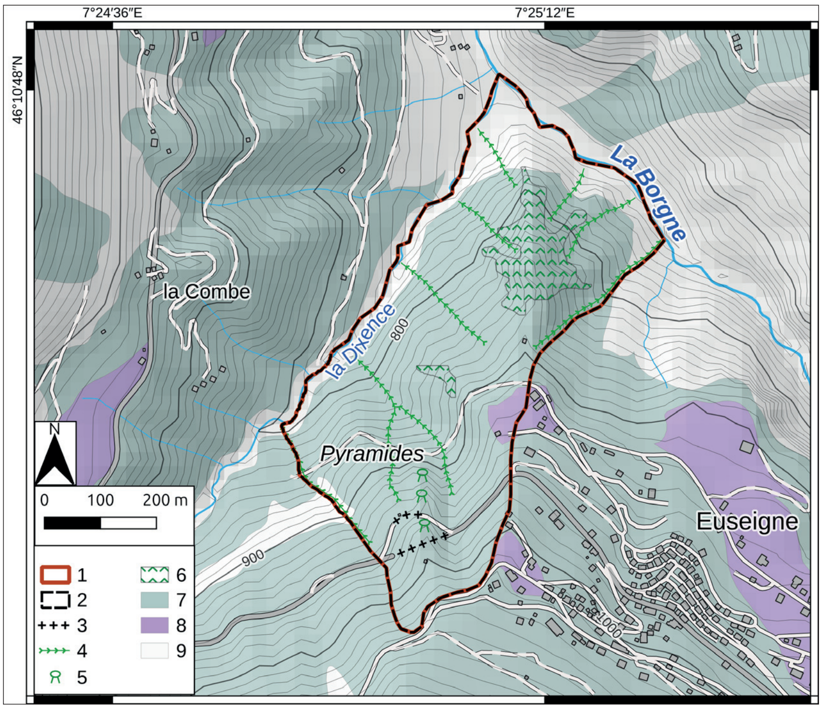


Fig. 4: Geomorphological sketch for the Euseigne earth pyramids. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Road tunnel; 4) Gully; 5) Earth pyramids; 6) Area affected by denudation and gullying; 7) Morainic deposits; 8) Glaciolacustrine and fluvioglacial deposits; 9) Other superficial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

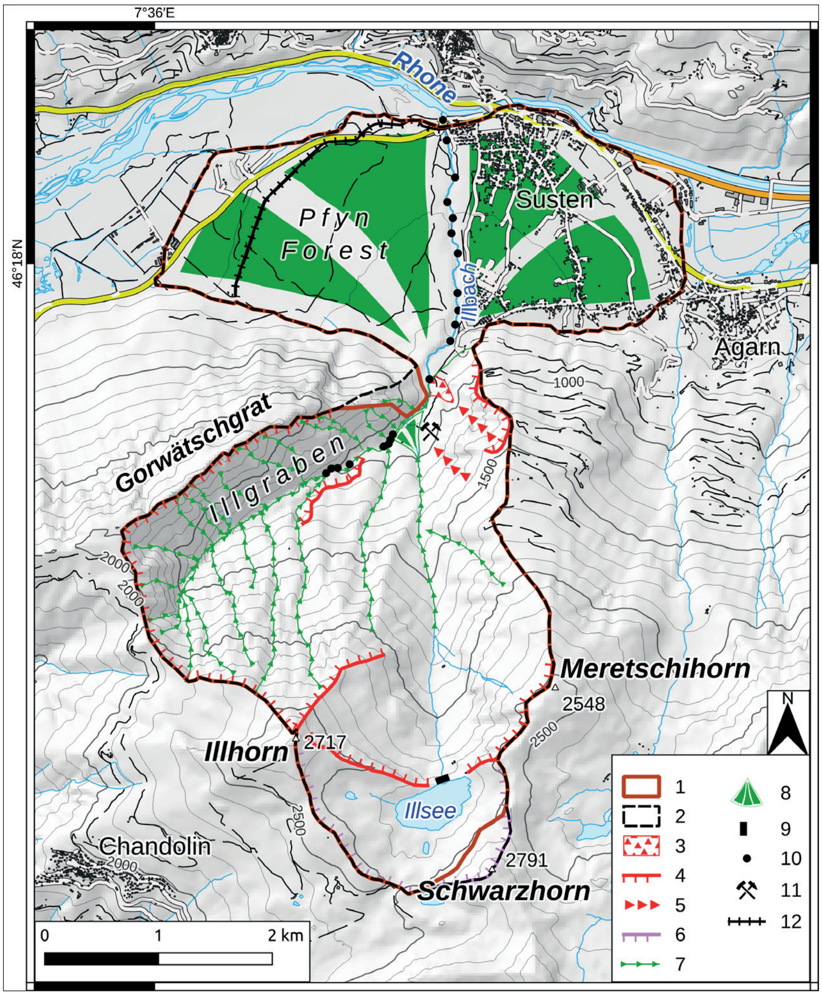


Fig. 5: Geomorphological sketch of the Illgraben torrential system. Notes: 1) Geomorphosite perimeter; 2) Functional perimeter; 3) Debris avalanche deposit; 4) Rock scarp; 5) Debris avalanche channel; 6) Glacial cirque; 7) Stream with torrential activity; 8) Debris flow fan; 9) Dam; 10) Retention dam; 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			Im	Final scores		
			G1	G2	G3		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 19th 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

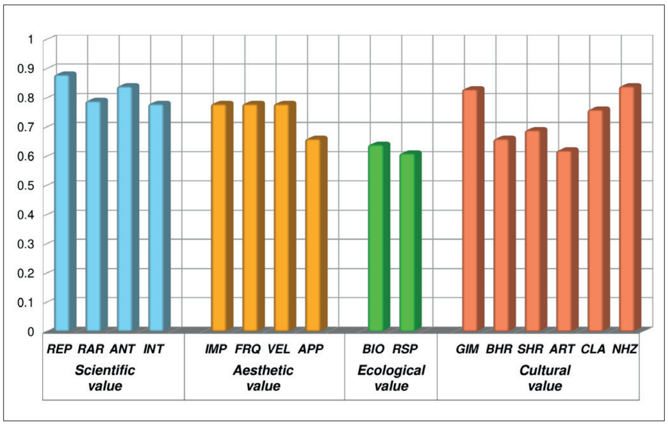


Fig. 7: Importance factors for each indicator, used for the weighting of the scores. Notes: REP = Representativeness; RAR = Rarity; ANT = Anthropogenic modifications; INT = Maximum intensity; IMP = Impact on the landscape; FRQ = Frequency; VEL = Velocity; APP = Aesthetic appreciation; BIO = Biodiversity; 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

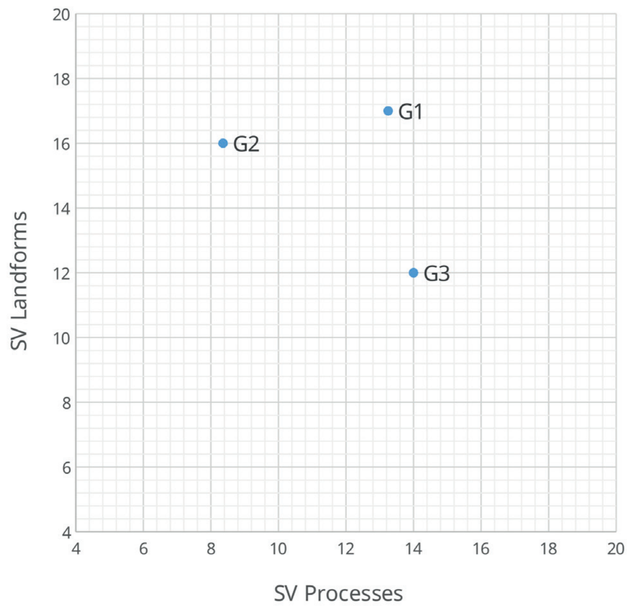
Assessing the heritage values of geomorphological processes presents similar methodological challenges to those encountered in evaluating the heritage values of landforms or geosites. While the criteria for assessing the scientific value are clear and straightforward for geomorphologists, evaluating 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.

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.



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

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.

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