



# The Specificities of Geomorphosites and Their Influence on Assessment Procedures: a Methodological Comparison

Daniel S. Santos<sup>1</sup> · Emmanuel Reynard<sup>2</sup> · Kátia L. Mansur<sup>1</sup> · José C. S. Seoane<sup>1</sup>

Received: 25 March 2019 / Accepted: 20 September 2019 / Published online: 30 October 2019  
© The European Association for Conservation of the Geological Heritage 2019

## Abstract

The growing interest in geoconservation is demonstrated, by among others, the numerous site inventories that have been conducted in different countries. The methodological bases of these inventories are still under development, and several proposals representing significant theoretical and practical advances have been published in recent decades. The methods are designed to match the purpose of the inventory. Geomorphosites are a type of geosite whose specificities are highlighted in the literature: the imbrication of spatial and temporal scales, and the dynamic and aesthetic dimensions. Two other characteristics that are not specific to geomorphosites can also be highlighted: the ecological and cultural values of such sites. The objective of this study was to analyze the influence of these specificities on the assessment procedures used for geomorphosites. Two methods—the Brazilian GEOSSIT method and the Swiss UNIL method—were applied in two completely different geomorphological contexts: a mountain area in the Swiss Alps and a coastal area in Rio de Janeiro, Brazil. Ten sites were selected in each area to be assessed using the two methods, one of which was designed specifically for geomorphosites (UNIL) and the other was designed for any type of geosite (GEOSSIT). The results revealed marked disparities between the two methods and highlighted the influence of the specificities of geomorphosites in all steps of the assessment. These results underline the fact that methods of assessment need to take these characteristics into account to create inventories that will be effective for the conservation, use, and management of geomorphosites.

**Keywords** Geomorphosites · Assessment methods · Geomorphological heritage · Methodological comparison

## Introduction

The last three decades have witnessed growing interest in geodiversity and geological heritage (Reynard and Brilha 2018). Geoconservation has been emerging as a new scientific domain concerned with the conservation and sustainable use of exceptional geodiversity elements (Henriques et al. 2011; Brilha 2017), and more and more geoscientists around the globe are dedicating themselves to the task. These researchers are responsible for significant conceptual and methodological

advances that have been strengthening geoconservation initiatives and highlighting their importance to society.

Geodiversity was defined by Gray (2013) as “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscape.” In other words, the concept of geodiversity comprises the entire diversity of the physical environment of the planet. Building on this concept, Brilha (2018) points out that one of the main challenges facing geoconservation is selecting the elements that should be conserved for the benefit of present and future generations. The answer to this challenge resides in the values that geodiversity elements may possess, which has turned out to be one of the most important topics on the subject: inventories of geodiversity elements presenting one or more value(s) that justify specific treatment.

In response, several countries are conducting national inventories as a basis for implementing geoconservation policies, especially in Europe (Wimbledon and Smith-Meyer

---

✉ Daniel S. Santos  
danielsouza@id.uff.br

<sup>1</sup> Post-Graduation Program in Geology, Department of Geology, Federal University of Rio de Janeiro, 274 Athos da Silveira Ramos Av Rio de Janeiro RJ 21941-916 Brazil

<sup>2</sup> Institute of Geography and Sustainability, University of Lausanne, Lausanne VD Switzerland

2012). The importance of this step is stressed by Lima et al. (2010), who affirm that limited knowledge of our geological heritage and the absence of inventories increase the risk of degradation or even total destruction of important sites. In order to properly address this issue, the inventory must be based on a well-structured methodology able to avoid misjudgments and provide a clear and objective evaluation of each site (Brilha 2016).

Methods for inventorying and evaluating sites have been proposed by several authors (e.g., Bruschi and Cendrero 2005; Coratza and Giusti 2005; Brilha 2005, 2016; Reynard et al. 2007, 2016; Pena dos Reis and Henriques 2009; Pereira and Pereira 2010; Lima et al. 2010; Fassoulas et al. 2012; Kubalíková 2013; Bollati et al. 2017a; Garcia et al. 2018). Some of these methods are specifically focused on the evaluation of geomorphosites (geosites of geomorphological nature, Panizza 2001; Reynard et al. 2009), which can be explained by the fact that most of the first studies on geoheritage were conducted by geomorphologists and physical geographers (Coratza and Hobléa 2018). These studies culminated in the creation of the “Working Group on Geomorphological Sites” in 2001 by the International Association of Geomorphologists (Reynard and Coratza 2013). One of the main objectives of this group was establishing guidelines for inventorying and assessing geomorphological sites, being responsible for significant discussions and advances on the topic (e.g., Piacente and Coratza 2005; Reynard and Panizza 2005; Reynard et al. 2009; Reynard and Coratza 2013; Coratza and Hobléa 2018).

Among all the different types of geological sites (e.g., lithological, stratigraphic, palaeontological, mineralogical, geomorphological), geomorphosites present some peculiarities. According to Reynard (2009), three characteristics make geomorphosites unique: the imbrication of spatial and temporal scales, the dynamic dimension, and the aesthetic dimension. A further characteristic is the fact that most of the geomorphological sites are not limited to scientific values, but have one or more additional values (Reynard 2005), among which the ecological (Bollati et al. 2015, 2018) and the cultural (Panizza and Piacente 2003; Reynard and Giusti 2018) ones are the most important. In fact, this type of site usually associate several heritage values and can be considered as the category of geosites with the broadest set of values (Coratza and Hobléa 2018).

Scale can confer a high degree of complexity on the assessment of geomorphosites, since scale can vary widely both spatially and temporally. Concerning the spatial scale, geomorphosites may be punctual occurrences with only a few square meters, such as small dolines or tafonis; may have aligned forms with several hundred meters, such as meandering rivers; or may consist of great dimension areas, such as mountain massifs or great barrier islands. Besides that, they may consist of a single landform, independently of size, such

as waterfalls or coastal plains, or of groups of landforms (Grandgirard 1999) that form geomorphological landscapes (Reynard 2005), such as glacial valleys. The imbrication of temporal scales is also a factor of complexity because the same site can present landforms developed in past tectonic/climatic conditions at the same time as processes that are underway today (Pelfini and Bollati 2014). This type of situation is common in areas affected by Quaternary glaciations or sea-level oscillations, for instance.

The dynamic dimension concerns the fact that geomorphosites may present ongoing geomorphological processes. Reynard et al. (2009) distinguishes active and passive geomorphosites. Active geomorphosites are those that allow the observation of geomorphological processes that are underway, while passive geomorphosites are remnants of processes that are no longer underway, as they are landforms inherited from past natural conditions. More recently, the term *evolving passive geomorphosite* was proposed by Pelfini and Bollati et al. (2014), to refer to geomorphosites composed of inherited landforms that are currently being modified by active processes different from the processes that originated the form, another example of the imbrication of temporal scales.

Many geomorphosites are also important for their aesthetic value, which is of particular importance for tourism and/or the educational use of the site, since the aesthetic component of a site is what initially attracts people’s attention. Goudie (2002) mentions the importance of the aesthetic component in bringing society closer to geomorphology, since the visual attractiveness of sites can be used to interest the public in understanding the forms and processes that have been structuring landscapes throughout the history of the Earth. Several of the landforms or geomorphological landscapes classified as World Heritage sites were selected based on the “aesthetic criterion” (Migón 2009, 2018). No wonder then that many of the methodological proposals for inventorying and evaluating geomorphosites account for the aesthetic value (e.g., Pralong 2005; Pereira and Pereira 2010; Fassoulas et al. 2012; Reynard et al. 2016; Bollati et al. 2017a).

Reynard and Giusti (2018) emphasized that the links between geodiversity and culture gave rise to new Earth Sciences domains. For instance, Panizza and Piacente (2003) presented the term *cultural geomorphology*, in which geomorphology is considered to be part of the cultural heritage of a territory and the cultural components are analyzed according to the geomorphological context in which they are embedded. Coratza et al. (2016) also stressed the importance of integrating the natural and cultural heritage in a case study in the Maltese Islands, highlighting its contribution to the high touristic value of the area. Cultural assets may be linked to other types of geological elements, but the importance for the geomorphological context is highlighted by the fact that many of these interactions occur at the landscape scale. Iconic landforms are dispersed and known all around the globe (e.g.,

Uluru in Australia; Matterhorn on the border between Switzerland and Italy; the Sugar Loaf mountain in Brazil; the Nile Delta in Egypt; Mount Fuji in Japan). The cultural component can thus also be highlighted as an essential part of the geomorphological heritage and is assessed in many methodological proposals (e.g., Bruschi and Cendrero 2005; Serrano and González-Trueba 2005; Zouros 2007; Kubalíková 2013; Reynard et al. 2016; Bollati et al. 2017a).

Finally, the ecological importance of geomorphosites is also discussed in many studies. Like cultural value, ecological value is not specific to geomorphosites. Hjort et al. (2015) described the relevance of geodiversity in sustaining ecosystems, using several examples of geosites with a significant ecological impact. Many of the examples including caves, cliffs, sand dunes, and waterfalls are geomorphological. The ecological component of landscapes is a discriminating factor for geomorphosite assessment, especially because of the dynamic dimension (Bollati et al. 2015), and several methodological proposals include the ecological value as part of the scientific value of the site (e.g., Pralong 2005; Comanescu et al. 2012; Bollati et al. 2015) or assess it as a separate value (e.g., Zouros 2007; Pereira and Pereira 2010; Kubalíková 2013; Reynard et al. 2016).

Considering the abovementioned specificities of geomorphosites, the objective of this paper is to discuss their influence during the process of assessment. Two methods were applied to two completely different geomorphological contexts: a mountain area in the Canton of Valais, Switzerland, and a coastal area in Rio de Janeiro State, Brazil. To adequately address this question, we chose methods that differ significantly, one focusing specifically on the assessment of geomorphosites (Reynard et al. 2016) and the other designed for use in any geological context: GEOSSIT, which is a Brazilian adaptation of the methods proposed by Brilha (2005, 2016) and García-Cortés and Carcavilla (2009).

## Methodological Procedures

Two inventory and assessment methods were applied in two different areas to investigate the influence of the specificities of geomorphosites on the assessment procedures. One method, GEOSSIT, used by the Geological Survey of Brazil (Portuguese acronym CPRM), focuses on the assessment of geosites and geodiversity sites as a whole; the second is the method developed by the University of Lausanne (UNIL) in Switzerland, first presented in Reynard et al. (2007) with a new version described in Reynard et al. (2016). Although this method can be used with any type of geosite or geodiversity site, it was specifically developed for the assessment of geomorphological sites. Therefore, the present study was based on the application of one method designed for any type of geosite and another designed specifically for geomorphosites.

Both methods include qualitative and quantitative steps, the result being the description of each site and numerical ranking. However, the objective of the present study was not to compare rankings, since this would depend on the specific problems of each method, which were not directly compared. Our main objective was to analyze how the specificities of geomorphosites influence the application of the methods, without considering which method is more or less appropriate.

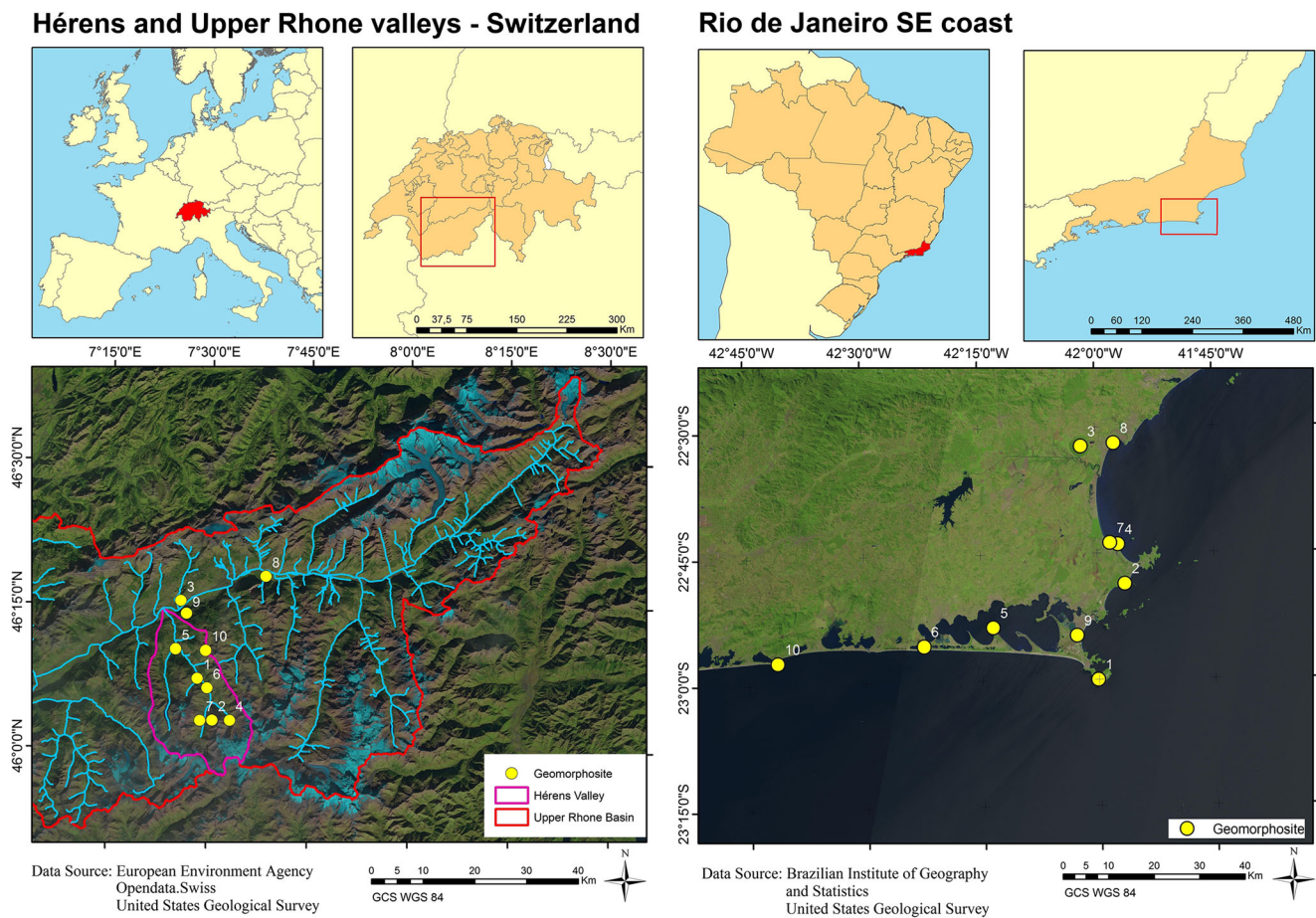
## Study Areas

Two study areas with completely different geomorphological contexts were chosen for the evaluation: a mountain area in the Canton of Valais in Switzerland, and a coastal area in Rio de Janeiro State in Brazil (Fig. 1). Ten sites were selected in each area and an effort was made to cover as many different landforms as possible. The sites present different features, processes and sizes, ranging, for instance, from dolines only a few square meters in size, to large dune fields or glacier forefields more than 5 km<sup>2</sup> in size.

In Switzerland, the sites are located in the Upper Rhone valley and in one of its main secondary catchments, the Hérens valley.

The geomorphology of the Upper Rhone valley is marked by events at different temporal scales, mainly characterized by structural landforms related to the Alpine orogeny and relict landforms related to Quaternary glaciations. Tectonically, it is located between the Helvetic (north) and Penninic (south) tectonic units and its morphology is determined by the Rhone-Simplon fault zone (Hubbard and Mancktelow 1992; Egli and Mancktelow 2013). The Quaternary glaciations were responsible for the well-known U-shape morphology of the valley. During the Last Glacial Maximum in the Northern Hemisphere, around 22,000 years BP, this portion of the Rhone valley was occupied by glaciers reaching altitudes up to 2200 m a.s.l. in Sion (Schlüchter 2009; Becker et al. 2017), which explains why it is so wide. Currently, the valley is characterized by a high rate of urbanization which is having major impacts on its landforms and geomorphological sites (Clivaz and Reynard 2018).

The Hérens valley is one of the main catchments in the Upper Rhone, located in the left side (south) of the Rhone valley (Fig. 1). Lambiel et al. (2015) produced a geomorphological map of the area, describing the main morphogenetic processes and the resulting landforms. The altitude of the valley ranges range between 470 and 4357 m and the geological structure strongly influences the geomorphological context. From north to south, there is a succession of five nappes (Escher et al. 1997; Steck et al. 2001): Siviez-Mischabel, Mont Fort, Tsaté, Cimes Blanches, and Dent Blanche nappes. Lithologies are mainly metamorphic rocks (gneisses, ophiolites, schists), as well as sedimentary and evaporitic rocks (dolomites, coal, gypsum). The glacial history also has



**Fig. 1** Study areas: Hérens and Upper Rhone valleys on the left; Rio de Janeiro SE coast on the right. Sites numbered as in Table 4

a marked influence and there are several geomorphological records of the glacial activity in the area, including during the Little Ice Age, between the fourteenth and nineteenth centuries.

According to the morphogenetic classification of Lambiel et al. (2015), the Hérens valley mainly comprises glacial, periglacial, gravitational, and fluvial landforms. At a more detailed scale, there are also karstic landforms due to the dissolution of gypsum, which are found in a specific area, in the village of Nax and surroundings. Active processes typical of high mountain areas (debris flows, processes related to glacier and permafrost melting) are common, making the valley a laboratory for the investigation of mountain processes related to climate warming. These diverse processes combined with the topographic and geological variety are responsible for the marked geomorphological diversity of the Hérens valley.

Bollati et al. (2016, 2017b) presented the scientific, educational, and touristic importance of the geomorphosite known as Euseigne Pyramids (Fig. 7a), which consists of earth pillars originated from the erosion of glacial deposits. The presence of boulders in the deposits creates conditions where the finer sediments located right under them are protected from water runoff erosion, originating these peculiar formations. The

cited authors also highlight the importance of climatic changes, which can be responsible for enhancing the risks of degradation of this and other geomorphosites.

In Brazil, the sites are located in the region called the coastal lowlands of Rio de Janeiro, on the southeastern coast of the State (Fig. 1). All the chosen sites are located inside the aspiring geopark *Costões e Lagunas* (cliffs and lagoons) of Rio de Janeiro.

Geologically, this area is inserted in the Cabo Frio tectonic domain, which represents the last episode of Gondwana assembly, in a Cambrian-Ordovician thermo-tectonic event called Búzios Orogeny (Schmitt et al. 2004). This unit is mainly characterized by orthogneisses and paragneisses of high metamorphic degree, which can be seen in the typical coastal massifs of the region. The breakup of this palaeocontinent and the Atlantic Ocean opening, between the Upper Jurassic and Lower Cretaceous, was the most important tectonic event for the geomorphological setting of the south and southeastern regions of Brazil, generating several rifting processes and intense alkaline magmatism, responsible for the uplift of the mountain ranges parallel to the coastline (Mantiqueira and Mar) and of the lower coastal massifs (Asmus and Ferrari 1978; Zalán and Oliveira 2005).

While in the Alps the Quaternary was characterized by periods of glaciation and deglaciation, the geomorphological history of the Brazilian coast in the same period was marked by sea-level oscillations, which are directly related to glacial and interglacial phases. Martin et al. (1996) described relative sea-level fluctuations during the Quaternary and their consequences for the development of coastal plains and lagoons of different ages: two periods when the sea level was higher left several geomorphological records: the first in the Pleistocene, 123,000 years BP, when the sea level was around 8 m higher than at present, and the Holocene maximum transgression, 5100 years BP. Castro et al. (2014, 2018) described the relative sea-level variation curve in the region during the Holocene, using a multitude of geological, geomorphological and biological indicators, and estimated the maximum sea level to be about 2.5 to 3 m above the present. These authors named the event the Cabo Frio transgression. Using different methods, Jesus et al. (2017) estimated a transgressive maximum of about 2.4 m above present level 4700 to 4500 years BP for the area.

As can be seen from the above, the study area in Rio de Janeiro is characterized by landforms related to its tectonic history, responsible for the uplift of the coastal massifs, and by landforms related to coastal processes, such as barrier-lagoon systems, wetlands related to colmatation of palaeolagoons, cliffs, dune fields, etc., while taking the strong influence of sea-level fluctuations on all of these landforms into account.

## Inventory and Assessment of Geomorphosites

Many methods have been proposed on how to conduct inventories and site evaluations. Since the objective of this study is not a direct analysis of the methods, but to discuss how the specificities of geomorphosites affect evaluation procedures, we selected two methods: the method used by the Geological Survey of Brazil (CPRM), GEOSSIT, and the method described in Reynard et al. (2016), the UNIL method.

The aim of the GEOSSIT program is to create a national database in which researchers from all around the country can register sites and assess them using the same methodological procedures. GEOSSIT is the biggest Brazilian project for the creation of a national inventory, which is a major challenge due to the continental dimensions of the country (Lima et al. 2010). GEOSSIT can be accessed through the CPRM website (<http://www.cprm.gov.br/geossit/> - in Portuguese).

GEOSSIT was originally based on the methods of Brilha (2005) and García-Cortés and Carcavilla (2009). It was subsequently updated based on proposals made by Brilha (2016), who presented new conceptual definitions and ways to create the inventory and perform the evaluation. GEOSSIT is thus not a new method but is an adaptation of existing methods.

GEOSSIT starts with a general documentation of the site, which is followed by a characterization starting with the

geological contextualization. A specific contextualization exists for palaeontological sites, but it was not used for any of the sites cited in the present work. Following the contextualization, there is the characterization of the interests of the site. All information for these steps are presented in Table 1.

After the characterization, there is a description of the conservation status, in which it is possible to insert information about statutory protection (protected areas), indirect protection (indigenous territory, presence of traditional communities, biosphere reserve, etc.), and characteristics of use and occupation of the territory.

The quantitative evaluation is that proposed by Brilha (2016), with slight modifications. First, the scientific value is assessed under seven criteria. The second part is the assessment of the risk of degradation under five criteria. The final part is the evaluation of educational and touristic potential, under 15 criteria. The score of each parameter ranges from 0 and 4. The total scores ranges from 0 and 400 but to facilitate the comparison of results in this study, we converted the score to a range between 0 and 1. The criteria and weighting are presented in Table 2.

It is important to highlight that key locality is evaluated differently from Brilha (2016). While the author defines parameters related to different geoscientific areas, including geomorphology, GEOSSIT is more restricted to geological and palaeontological indicators, so it is not applicable to geomorphosites, unless they present geological or palaeontological relevance.

The GEOSSIT method quantitatively assesses the scientific value, the potential educational and touristic uses, and the risks of degradation. The scientific value determines the relevance of the site, which may be national or international. At the end of the process, based on the scores reached in the evaluation, a recommendation is made for management, in which sites with high scores but with a high risk of degradation are a priority for conservation, thereby underlining the importance of the quantitative assessment for the management of geosites.

The UNIL method is fully described in Reynard et al. (2016), and although it can be adapted to other contexts, it is focused on the assessment of geomorphosites. It was developed by the University of Lausanne (UNIL) and first presented in Reynard et al. (2007). The original version was subsequently modified based on other proposals (mainly by Serrano and González Trueba 2005; Bruschi and Cendrero 2005; Pereira et al. 2007; Pereira and Pereira 2010).

The UNIL assessment also starts with a documentation of the site but, since it is designed to be used for geomorphological sites, contextualization consists of describing the main characteristics of the site and its morphogenetic history.

The quantitative assessment is divided into two parts: assessment of central value (scientific value), under four criteria—integrity, representativeness, rarity, and palaeogeographic interest; and assessment of additional

**Table 1** Documentation, geological contextualization, and characterization of interests in the GEOSSIT

Documentation	Geological contextualization	Interests
Name	Geological province	Content (petrological, geomorphological, tectonic, hydrological, etc.)
Classification	Age	Associated (archaeological, ecological, historic/cultural, aesthetic and scenic expression)
Localization	Type (metamorphic, plutonic, volcanic, sedimentary)	Use (scientific, educational, touristic, others)
Abstract	Stratigraphy (complex, suite, group)	
Author(s)	Main lithostratigraphic unit Subordinate lithostratigraphic unit Rock types/geological structures Relief forms	

values—ecological (ecological impact and protection of the site); aesthetic (viewpoints, contrast, vertical development and space structure); cultural (religious, historical, artistic and literary, geohistorical, and economic importance). A score between 0 and 1 is given to each parameter and there is no weighting on this method. The values are the result of the arithmetic means of the scores, except for the cultural value, in which the parameter with the higher score represents it.

The third part concerns the use and management characteristics, in which the protection status, damages and threats, visit conditions, and educational potential are characterized. Unlike other proposals (e.g., Serrano and González Trueba 2005; Bruschi and Cendrero 2005; Pereira et al. 2007; Pereira and

Pereira 2010; Brilha 2016), in the UNIL method these characteristics are not evaluated using numerical values, since they are not considered parts of the “quality of the site.”

Finally, the last part is a synthesis of the entire evaluation. We highlight the “management measures proposals,” in which the evaluator can propose protection and promotion measures based on the full assessment. In contrast to GEOSSIT, these suggestions are made by the evaluator and not generated automatically at the end of the assessment.

Beyond some differences in the criteria, three main differences between the methods can be highlighted: first, GEOSSIT quantitatively assesses the scientific value and the educational and touristic potential uses, while the UNIL

**Table 2** Criteria and weighting of the quantitative assessment in GEOSSIT

Scientific value	Risks of degradation	Educational/touristic potential uses
Representativeness (30%)	Possibility of deterioration of geological elements (35%)	Vulnerability (10%)
Key locality (20%)	Proximity to areas/activities with potential to cause degradation (20%)	Accessibility (10%)
Scientific knowledge (5%)	Legal protection (20%)	Use limitations (5%)
Integrity (15%)	Accessibility (15%)	Security (10%)
Geological diversity (5%)	Population density (10%)	Logistics (5%)
Rarity (15%)		Population density (5%)
Use limitations (10%)		Association with other values (5%)
		Scenic beauty (5%*/15%**)
		Uniqueness (5%*/10%**)
		Observation conditions (10%*/5%**)
		Didactic potential (20%*)
		Geological diversity (10%*)
		Divulcation potential (10%**)
		Economic level (5%**)
		Proximity to recreational areas (5%**)

\*For the educational use potential

\*\*For the touristic use potential

method evaluates the scientific, ecological, aesthetic, and cultural values; second, GEOSIT uses weighting to assess the parameters, while the UNIL method does not; and third, the difference in use and management characteristics, such as the risks of degradation, accessibility, vulnerability, etc., which are assessed quantitatively in GEOSIT and qualitatively in the UNIL method.

The classification of geomorphosites proposed by Grandgirard (1999) and Perret (2014) (Fig. 2) was also used to address the scale issue. It consists in classifying the sites according to their type (point, line, or polygon) and according to the complexity of the number of forms and related processes.

The UNIL method also proposes a procedure for the preselection of sites to be considered for the assessment based on spatial and temporal criteria. However, as the aim of the present study was not to conduct an inventory, the sites were selected to cover various types of landforms for the purpose of comparison and the preselection part of the methodology was consequently not used.

## Results

### Geomorphosites and Numerical Rankings

The present study assessed geomorphosites in the two areas: Hérens and Upper Rhone valleys and on the southeastern coast of Rio de Janeiro. The sites were selected to account for the geomorphological diversity of each study area, in an attempt to incorporate as many geomorphological contexts as possible. The geomorphosites selected are listed in Table 3,

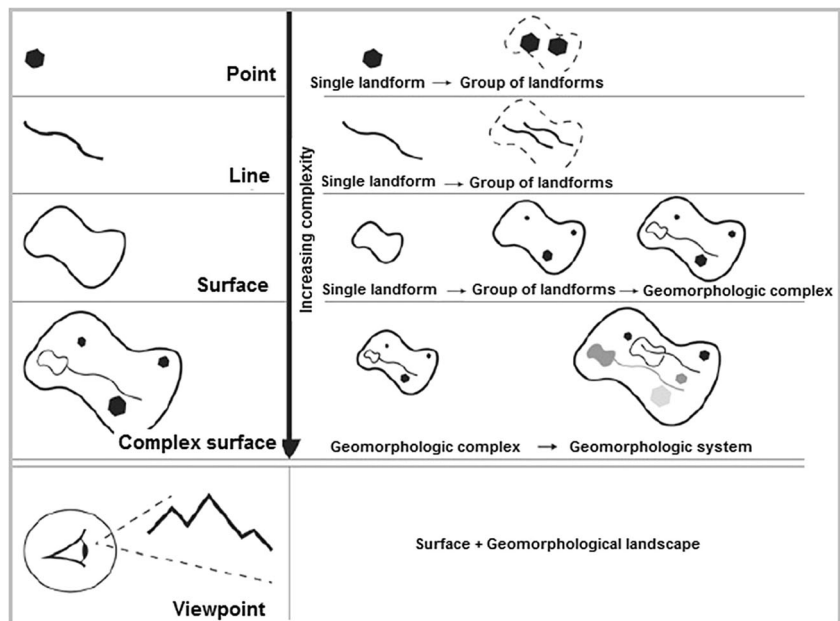
which also lists the diversity of features and processes, along with the different degrees of complexity. Tables 4 and 5 present the numerical rankings provided by each method. They were ranked based on scientific value, with the added values and potential uses used as tie breakers.

In Table 3, the influence of spatial scale is evident in the significant variation in size, from punctual occurrences to more than 17 km<sup>2</sup>; and classification, varying from a single landform to geomorphologic systems, which is directly linked to the degree of complexity of the geomorphosites. The imbrication of temporal scale is highlighted by the large number of sites presenting inherited landforms or even both active and inactive features. It is interesting to note that this fact influences the evaluation of several parameters in both methods, some more obvious, such as palaeogeographic value and others more indirectly, such as rarity and risk of degradation. Therefore, the imbrication of scales influences the entire assessment.

The great majority of sites present active processes, highlighting the dynamic dimension of geomorphosites. It is important to stress that active processes can be responsible for modifications in inherited landforms and may even be responsible for the destruction of other interesting features. They may also represent threats to or may even damage society. This characteristic of geomorphosites also influences many steps of the assessment, including the evaluation of integrity and vulnerability.

The significant differences in the numerical rankings reflect the differences between the two methods, as highlighted in Fig. 3. The scientific value varied widely, calling for analysis of which parameters are mainly responsible for the differences. Beyond these differences, the methods also assess

**Fig. 2** Classification of geomorphosites. Translated from Perret (2014)



**Table 3** List of geomorphosites in the two study areas and their main characteristics

Site	Classification	Geomorphological feature(s)	Process(es)	Area
Hérens and Upper Rhone valleys				
Rock Sill and Anthropogenic Terraces of Flammayen	Geomorphologic system	Rock Sill + anthropogenic terraces	Glacial + anthropogenic – inactive	0.4 km <sup>2</sup>
Tsarminne Glacial System	Geomorphologic system	Moraine deposits + glacier (free and debris-covered) + active rock glacier + torrential system	Glacial + fluvial + torrential + gravitational – active/inactive	0.8 km <sup>2</sup>
St-Léonard Underground Lake	Single landform	Cave in gypsum rock filled by a lake	Karstic – active	6000 m <sup>2</sup>
Ferpècle Glacier Forefield	Geomorphologic system	Glaciers + sandurs + alluvial zone + moraine deposits	Glacial + fluvial – active/inactive	7.3 km <sup>2</sup>
Euseigne Pyramids	Single landform	Moraine deposits forming pyramids	Glacial + erosional – active/inactive	6930 m <sup>2</sup>
Lotrey Terraces	Geomorphologic complex	Uneven fluvial terraces + alluvial zone	Fluvial – active/inactive	0.46 km <sup>2</sup>
Lac Bleu Moraine System	Geomorphologic system	Moraine deposits + moraine dammed lake	Glacial + fluvial – active/inactive	0.06 km <sup>2</sup>
Torrential System of Ilgraben	Single landform	Torrential system + alluvial fan of great magnitude	Torrential – active	7 km <sup>2</sup>
Dolines of Nax	Group of landforms	Dolines in gypsum rocks	Karstic – active	Punctual occurrences
La Maya Summit	Single landform	Alpine summit	Tectonic + erosional – active/inactive	Punctual occurrence
Rio de Janeiro SE coast				
Cabo Frio Island	Geomorphologic system	Island formed by alkaline massif + climbing dunes + anthropogenic deposits ( <i>sambaquis</i> )	Tectonic + aeolian + anthropogenic – active/inactive	6.6 km <sup>2</sup>
José Gonçalves Beach	Geomorphologic complex	Beach + marine terrace	Marine (depositional) – active/inactive	3840 m <sup>2</sup>
São João Hill	Single landform	Alkaline massif	Tectonic + erosional – active/inactive	17.67 km <sup>2</sup>
Pai Vitório Point and Stone Mangrove	Geomorphologic system	Aligned hills + talus deposits	Tectonic + erosional + gravitational – active/inactive	0.15 km <sup>2</sup>
Araruama Lagoon Spits	Group of landforms	Lagoonal spits	Lagoonal (intralagoonal waves) – active	9 km <sup>2</sup>
Vermelha Lagoon	Geomorphologic system	Double barrier-lagoon system + foredunes + anthropogenic landforms ( <i>salinas</i> )	Marine (depositional) + anthropogenic – active/inactive	1.7 km <sup>2</sup>
Cliffs and Palaeocliffs of Rasa Beach	Group of landforms	Active cliffs + inactive cliffs	Marine (erosional) – active/inactive	Punctual occurrences
Tartaruga Beach	Single landform	Beach with high rates of coastal erosion + mitigation structures (riprap)	Marine (erosional) – active	~ 1 km (line)
Dama Branca Dune Field	Geomorphologic complex	Dune field with high diversity of dune types	Aeolian – active	5 km <sup>2</sup>
Ponta Negra Promontory	Single landform	Rock promontory separating large coastal barriers	Tectonic + erosional – active/inactive	1.36 km <sup>2</sup>



**Table 4** Results of quantitative assessment using the GEOSSIT method

Site	Scientific value	Educational use potential	Touristic use potential	Risk of degradation
Hérens and Upper Rhone valleys				
1. Rock Sill and Anthropic Terraces of Flanmayen	0.71	0.63	0.64	0.66
2. Tsarmine Glacial System	0.7	0.6	0.58	0.4
3. St-Léonard Underground Lake	0.65	0.69	0.85	0.88
4. Ferpècle Glacier Forefield	0.65	0.63	0.6	0.63
5. Euseigne Pyramids	0.63	0.71	0.86	0.83
6. Lotrey Terraces	0.63	0.69	0.69	0.74
7. Lac Bleu Morainic System	0.63	0.58	0.59	0.81
8. Torrential System of Illgraben	0.61	0.78	0.71	0.93
9. Dolines of Nax	0.59	0.71	0.69	0.79
10. La Maya Summit	0.46	0.5	0.53	0.36
Rio de Janeiro SE coast				
1. Cabo Frio Island	0.95	0.63	0.7	0.51
2. José Gonçalves Beach	0.88	0.61	0.63	0.39
3. São João Hill	0.83	0.71	0.73	0.49
4. Pai Vitório Point and Stone Mangrove	0.78	0.73	0.71	0.7
5. Araruama Lagoon Spit	0.74	0.59	0.65	0.63
6. Vermelha Lagoon	0.68	0.68	0.7	0.85
7. Cliffs and Palaeocliffs of Rasa Beach	0.68	0.7	0.68	0.64
8. Tartaruga Beach	0.66	0.76	0.65	0.98
9. Dama Branca Dune Field	0.63	0.83	0.75	0.79
10. Ponta Negra Promontory	0.48	0.7	0.68	0.71

**Table 5** Results of quantitative assessment using the UNIL method

Site	Central value	Ecological value	Aesthetic value	Cultural value
Hérens and Upper Rhone valleys				
1. Ferpècle Glacier Forefield	0.81	0.88	1	1
2. Rock Sill and Anthropic Terraces of Flanmayen	0.81	0.75	0.75	1
3. Euseigne Pyramids	0.75	0.5	1	0.5
4. Lac Bleu Morainic System	0.75	0.13	1	0.25
5. Tsarmine Glacial System	0.75	0.13	0.88	0
6. Torrential System of Illgraben	0.69	0.5	1	0.5
7. Lotrey Terraces	0.63	0.75	0.75	0.25
8. La Maya Summit	0.63	0.5	1	0.5
9. Dolines of Nax	0.63	0.25	0.75	0
10. St-Léonard Underground Lake	0.63	0.38	0.25	0.5
Rio de Janeiro SE coast				
1. Vermelha Lagoon	0.94	0.88	0.88	0.75
2. Cliffs and Palaeocliffs of Rasa Beach	0.94	0.13	0.88	0.75
3. Dama Branca Dune Field	0.88	1	1	0.5
4. Cabo Frio Island	0.81	1	1	1
5. Pai Vitório Point and Stone Mangrove	0.75	1	1	0.75
6. Araruama Lagoon Spit	0.75	0.75	0.88	0
7. José Gonçalves Beach	0.75	0.63	0.38	0
8. Tartaruga Beach	0.69	0	0.75	0
9. São João Hill	0.69	0.75	0.88	0.5
10. Ponta Negra Promontory	0.5	0.38	1	0.5

different characteristics. GEOSSIT does not assess the ecological, cultural, and aesthetic values, which only play a small role in the assessment of touristic and educational potential use. On the other hand, the UNIL method does not rank the risk of degradation or the educational and touristic potential, which is provided by GEOSSIT. Since these scores were used as tie breakers, they also influenced the differences in the rankings.

As can be seen in Fig. 3, only three sites occupy the same position in the two rankings. Others, including Lotrey Terraces and Araruama Lagoon Spit, occupy similar positions. However, other sites, such as St-Léonard underground lake and Dama Branca dune field occupy very different positions in the two rankings, so it is important to investigate the parameters used for the evaluation of the sites.

### Scientific Value

The scientific value is the only value that is quantitatively assessed in both methods, thus allowing direct comparison. Table 6 lists the detailed scores for GEOSSIT, and Table 7 lists those for UNIL.

One of the most important issues to be highlighted concerning the GEOSSIT method is the use of the key locality parameter, which corresponds to 20% of the total value. This parameter does not take geomorphological aspects into consideration, only geological and palaeontological aspects. For that reason, the majority of sites did not receive any points. The only exceptions are three sites in Rio de Janeiro, which

are considered key localities for lithological reasons. Due to the great importance of this parameter, these sites occupy the first positions in the GEOSSIT ranking and differ considerably from their ranking using UNIL.

For the UNIL method, the main difference is the assessment of palaeogeographic value, which corresponds to 25% of their total value, since the UNIL method does not give different weights for the parameters. This parameter is also responsible for significant differences in the rankings, since sites with no paleogeographic importance tend to occupy the last positions. All the other parameters assessed with the UNIL method are also assessed by GEOSSIT, so their effect on the difference in rankings was reduced. For the other parameters used in GEOSSIT, the effect was also reduced due to the smaller weight.

### Risk of Degradation

The risk of degradation is taken into account in both methods, but the GEOSSIT assesses it quantitatively, while the UNIL method characterizes its protection status and damages/threats. Consequently, only a qualitative comparison of the results was possible. The quantitative results obtained with GEOSSIT are presented in Fig. 4, which shows that a total of eight sites were classified as facing a high risk of degradation.

The comparison of results revealed some inconsistencies. Most of the sites classified as facing a high risk of degradation were not characterized as such using the UNIL method. In Rio

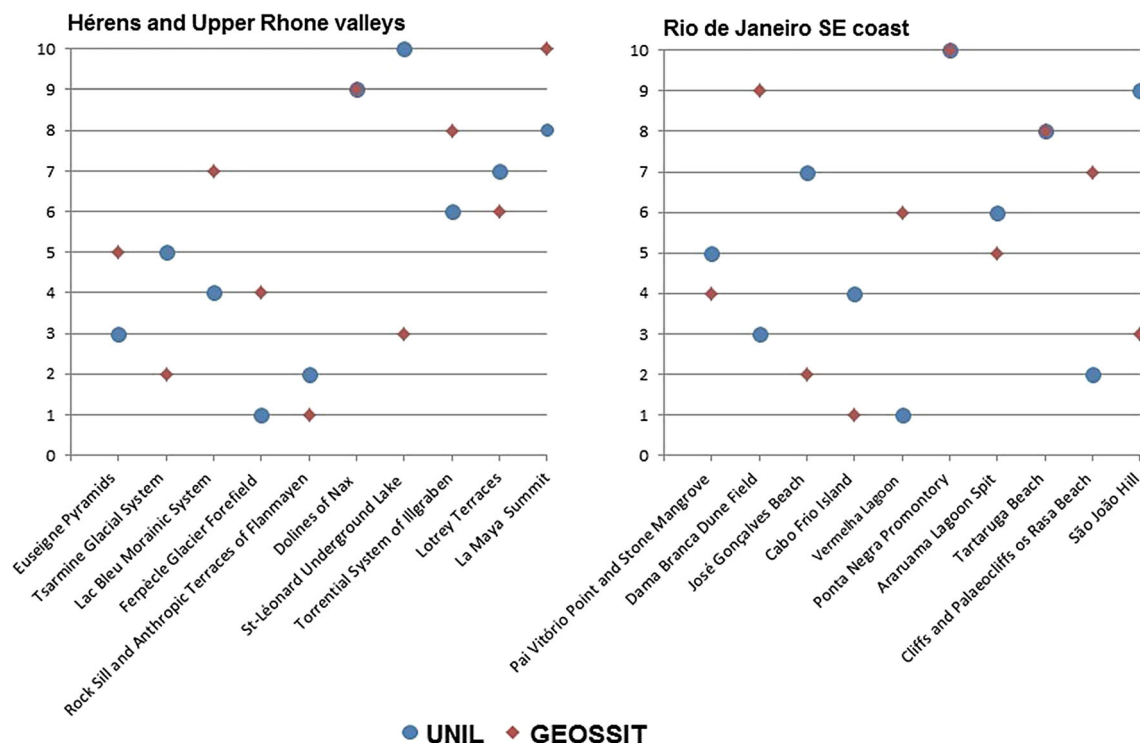


Fig. 3 Position of the geomorphosites in the rankings produced by each method

**Table 6** Assessment of the scientific value using the GEOSSIT

Geomorphosite	Representativeness	Key locality	Scientific knowledge	Integrity	Geological diversity	Rarity	Use limitations	Total
<b>Hérens and Upper Rhone valleys</b>								
Rock Sill and Anthropic Terraces of Flanmayen	4	0	0	4	1	4	4	0.71
Tsarmine Glacial System	4	0	4	4	2	2	4	0.7
St-Léonard Underground Lake	4	0	4	2	2	4	2	0.65
Ferpècle Glacier Forefield	4	0	4	2	4	2	4	0.65
Euseigne Pyramids	4	0	4	2	2	2	4	0.63
Lotrey Terraces	4	0	4	2	2	2	4	0.63
Lac Bleu Morainic System	4	0	4	2	2	2	4	0.63
Torrential System of Illgraben	4	0	4	2	4	1	4	0.61
Dolines of Nax	4	0	0	2	1	4	2	0.59
La Maya Summit	2	0	0	4	2	1	4	0.46
<b>Rio de Janeiro SE coast</b>								
Cabo Frio Island	4	4	4	4	4	4	2	0.95
José Gonçalves Beach	4	4	2	2	2	4	4	0.88
São João Hill	2	4	4	4	2	4	4	0.83
Pai Vitório Point and Stone Mangrove	4	0	2	4	4	4	4	0.78
Araruama Lagoon Spit	4	0	2	4	1	4	4	0.74
Vermelha Lagoon	4	0	4	2	4	4	2	0.68
Cliffs and Palaeocliffs of Rasa Beach	4	0	2	2	2	4	4	0.68
Tartaruga Beach	4	0	2	2	1	4	4	0.66
Dama Branca Dune Field	4	0	4	2	2	2	4	0.63
Ponta Negra Promontory	2	0	4	2	2	2	4	0.48

de Janeiro, for instance, Dama Branca Dune Field is a very large area and the main features of the site are not under threat, especially because they are located inside the Sun Coast State Park. However, because of damage and threats to some portions of the dune field, the whole site was classified as facing a high risk of degradation.

Tartaruga Beach is a particular site where active coastal erosion processes affect urban structures. The main characteristic of this site is the active process, as well as its negative effects on society. This type of situation demands a different approach to risk assessment, since it is the urban structures that are being damaged, not the site itself. An important question to be addressed is how to assess the risk of degradation to a site when the risks threaten society (i.e., the geomorphological processes impose damages and/or threats to surrounding areas)? This peculiarity is directly related to the dynamic dimension of geomorphosites, which is not addressed in the method of quantification used in the GEOSSIT method.

The active processes at sites such as Lotrey Terraces, Ferpècle Glacier Forefield, and Pai Vitório Point and Stone Mangrove have been altered by human interventions, which increase the risk of degradation. However, this was not taken into account using GEOSSIT, so they were classified as Medium risk.

It is also useful to underline the indirect importance of the aesthetic dimension in degradation risk assessment. The Lac Bleu Morainic System, for instance, receives many visitors due to its great scenic beauty, and negative effects have been observed in the form of damage to the terrain caused by people walking off-trail. In such cases, if it was not for the aesthetic value, the risk of degradation would be significantly reduced.

The analysis of the quantitative assessment using GEOSSIT and of the characterization using UNIL revealed that the specificities of geomorphosites strongly influence degradation risk assessment. In some cases, the numerical ranking was not representative of the real situation because these issues were not taken into account. The spatial scale and the dynamic dimension were the two most important specificities, but the results show that the aesthetic dimension may also be an important issue in more specific cases.

### Additional Values and Potential Uses

This part of the analysis was differentiated according to the method. While the GEOSSIT method evaluates the educational and touristic potential uses, the UNIL method assesses the ecological, aesthetic, and cultural values. However, the UNIL method also characterizes the educational and touristic interest and potential of the sites.

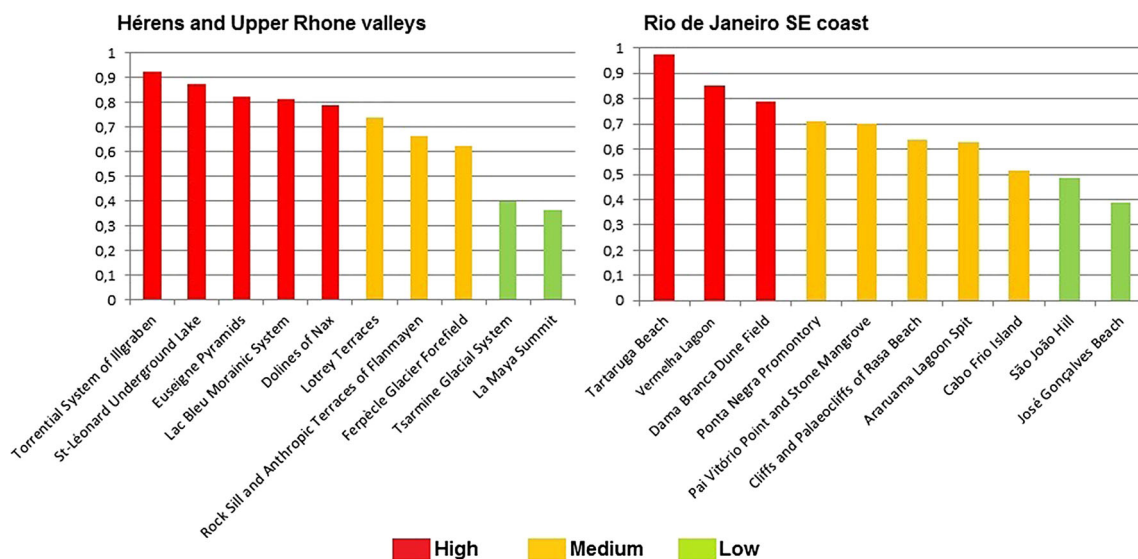
**Table 7** Assessment of scientific value using the UNIL method

Geomorphosite	Integrity	Representativeness	Rarity	Palaeogeographic value	Total
<b>Hérens and Upper Rhone valleys</b>					
Ferpècle Glacier Forefield	0.75	1	0.5	1	0.81
Rock Sill and Anthropic Terraces of Flanmayen	1	0.75	0.75	0.75	0.81
Euseigne Pyramids	0.5	1	0.75	0.75	0.75
Lac Bleu Morainic System	0.5	0.75	0.75	1	0.75
Tsarmine Glacial System	1	1	0.5	0.5	0.75
Torrential System of Illgraben	0.5	1	0.75	0.5	0.69
Lotrey Terraces	0.75	1	0.5	0.5	0.63
La Maya Summit	1	0.75	0.25	0.5	0.63
Dolines of Nax	0.75	0.75	1	0	0.63
St-Léonard Underground Lake	0.5	1	1	0	0.63
<b>Rio de Janeiro SE coast</b>					
Vermelha Lagoon	0.75	1	1	1	0.94
Cliffs and Palaeocliffs of Rasa Beach	0.75	1	1	1	0.94
Dama Branca Dune Field	0.75	1	0.75	1	0.88
Cabo Frio Island	1	1	1	0.25	0.81
Pai Vitório Point and Stone Mangrove	1	1	1	0	0.75
Araruama Lagoon Spit	1	1	1	0	0.75
José Gonçalves Beach	0.5	1	0.75	0.75	0.75
Tartaruga Beach	0.75	1	1	0	0.69
São João Hill	1	1	0.75	0	0.69
Ponta Negra Promontory	0.75	1	0.25	0	0.5

The results for the educational and touristic potential uses obtained with GEOSSIT are presented in Fig. 5. It is interesting to note that, in most cases, the scores for education and tourism were similar, which can be explained by the fact that many parameters are used to assess the two potential uses. It is

also clear that differences among the sites are small, since the ones in last position are not very far from those in first position.

The quantitative results obtained using UNIL method are presented in Fig. 6. Unlike GEOSSIT, major differences can

**Fig. 4** Risks of degradation according to GEOSSIT

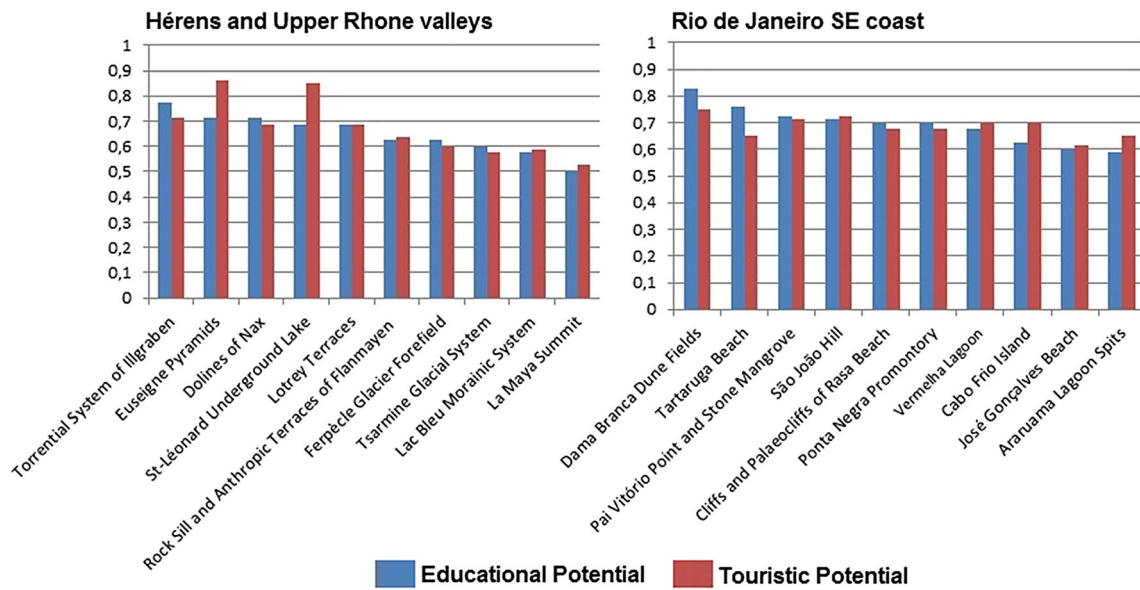


Fig. 5 Educational and touristic potentials using GEOSSIT

be seen in the values assessed. Sites such as Ferpècle Glacier Forefield and Cabo Frio Island present high scores for all values assessed, highlighting the importance of other values in addition to the scientific values. The aesthetic value of the majority of sites was high. Lower values were attributed to José Gonçalves Beach and St-Léonard Underground Lake. The first because the main geomorphological feature is covered by vegetation and the second, because the lake is underground, lacks color contrast and vertical development, which are among the main parameters used by the UNIL method to assess aesthetic value.

By applying both methods, it was possible to achieve numerical rankings for the educational and touristic potential uses and for the ecological, aesthetic, and cultural values. The GEOSSIT method does not ignore the ecological,

cultural, and aesthetic values, as they are parameters for the assessment. Therefore, it means that there is an intrinsic link between these three values and the potential for educational and touristic uses, even though they play a less important role in GEOSSIT than in UNIL. In the UNIL method, the characterization of educational and touristic interests also accounts for ecological, aesthetic, and cultural values.

### Discussion

#### Spatial and Temporal Scale

The imbrication of scales is surely one of the most important factors when dealing with geomorphosites, as it influences all

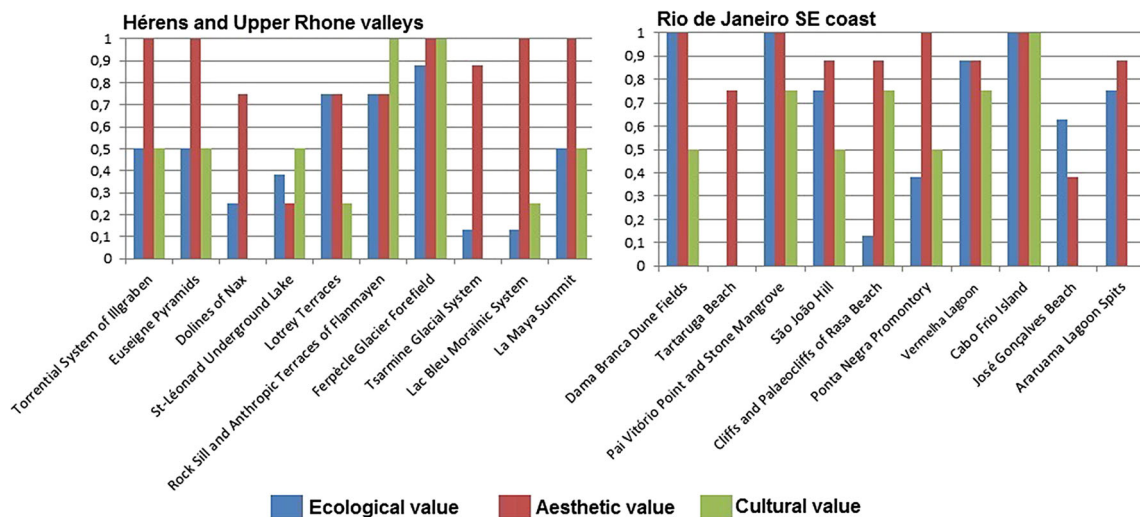


Fig. 6 Additional values using the UNIL method

steps of the assessment. Despite not being applied in this particular study, it is important to underline that the UNIL method includes a selection procedure fully based on the spatial and temporal scales, so the selected sites have to be representative of the geomorphological context of the study area in spatial (rare and representative forms) and temporal (inherited and active forms) terms. As the GEOSSIT was developed for any type of geosite anywhere in Brazil, it does not include a selection process.

While some sites consist of single landform occurrences, others are composed of several different but interconnected landforms, which together form geomorphological systems. This difference directly affects the degree of complexity of the assessment. The temporal scale is also a major factor, since a site may present active landforms or forms that were originated in past climatic and/or tectonic conditions, and as such, are inherited landforms. The degree of complexity can also be heightened by the fact that sites presenting both types of features are common.

Concerning the scientific value, all parameters assessed in both methods (representativeness, integrity, and rarity) are directly linked to the scale. However, two specific parameters are responsible for major differences in the rankings: key locality (GEOSSIT) and palaeogeographic value (UNIL). While key locality, as addressed in GEOSSIT (different from Brilha 2016), cannot be applied in geomorphological contexts, the palaeogeographic value is directly related to the temporal scale. The significant differences in the numerical rankings due to this factor confirm its relevance, since it shows that many sites have a higher scientific value due to aspects related to the morphogenetic history of the study area. For instance, sites such as Ferpècle Glacier Forefield and Cliffs and Palaeocliffs of Rasa Beach rank first with UNIL method due to their palaeogeographic value. However, they do not rank first with GEOSSIT because they are not key localities.

The assessment of risks of degradation was also strongly influenced by the spatial scale. As demonstrated in the quantitative assessment of Dama Branca Dune Field, the dimensions of the site and the diversity of aeolian features led to erroneous results, since the impacts and threats are concentrated in a specific part of the dune field. Therefore, the site's being ranked third does not take into account the fact that most of the site's surface, including the main features (the megaform parabolic dunes), is legally protected. This means that the assessment of risks of degradation must take into account that the imbrication of spatial scales may bring a higher degree of complexity, so the parameters cannot be applicable only to the simplest situations.

Therefore, as an intrinsic characteristic of geomorphosites, the imbrication of spatial and temporal scales must be taken into account in order to avoid mistakes and/or misunderstandings in the assessment procedures. From the selection of sites to the assessment of scientific and additional values, potential

uses, as well as the risk of degradation, the influence of scale is perceivable and can be responsible for disparities in the results, as demonstrated above.

## Dynamic Dimension

Geomorphosites can be highly dynamic, thus allowing observation of ongoing processes. As affirmed by Coratza and Hobléa (2018), the geological heritage is usually static. A rock outcrop presenting specific mineral occurrences, tectonic structures or fossils, for instance, are results of processes that took place in the past. Landforms and landscapes, on the other hand, are subject to change, as they developed over time, but simultaneously present features that originated in past conditions (imbrication of temporal scales).

The scientific value of geomorphosites is usually directly related to the dynamic dimension. The assessment of representativeness, one of the most important parameters in the two methods, is determined through the “capacity” of a site to represent active processes or processes that took place in the past (inherited landforms). The assessment of integrity also includes the dynamic dimension, since not only the forms are evaluated, but also the processes. So, the dynamic dimension is particularly important for the scientific value of geomorphosites because, for instance, if a site is representative of a process and presents good integrity, it can be directly used by geomorphologists for quantitative studies of the process concerned. This is demonstrated on the works of Pelfini and Bollati et al. (2014) and Bollati et al. (2017b) in the Euseigne Pyramids (Fig. 7a), which is a site characterized by a peculiar process of erosion. The cited authors show the importance of the surface processes dynamics for both scientific value and risks of degradation of the site.

The dynamic dimension is also crucial for degradation risk assessment, and its influence is apparent in the quantitative evaluation performed by GEOSSIT. The GEOSSIT method does not account for the fact that the processes underway at some sites have been altered by human intervention, and this was reflected in their ranking. Lotrey Terraces is a good example. The fluvial process in this site was affected by a reduction in flow due to the redistribution of water upstream related to the creation of a hydropower plant. Its impacts can also be observed in the vegetation occupying the alluvial zone, highlighting the importance of the links between geomorphology and biodiversity. Because this type of impact is not taken into account in the GEOSSIT method, the risk of degradation at this site was classified as medium, as it ranked in sixth position.

Another important aspect is that active processes may be responsible for significant modifications or even destruction of a site. Pelfini and Bollati et al. (2014) proposed the term *evolving passive geomorphosite* to describe sites characterized as inherited landforms that are currently being modified by

**Fig. 7** **a** Euseigne Pyramids: example of *evolving passive geomorphosite* (photo: Emmanuel Reynard), **b** Active coastal erosion and damages in Tartaruga Beach (photo: Daniel Santos), **c** Lac Bleu Morainic System (photo: Daniel Santos), and **d** Cabo Frio Island (photo: Daniel Santos) as examples of sites with aesthetic value. **e** Tsarmine Glacial System seen from the Lac Bleu (photo: Daniel Santos), **f** The Stone Mangrove and its unusual substrate (photo: Daniel Santos), **g** The Anthropic Terraces of Flanmayen (photo: Emmanuel Reynard), and **h** Salt production in the Vermelha Lagoon (photo: Daniel Santos) as examples of anthropic landforms



active processes (different from those that generated the landform). This is the case of Euseigne Pyramids (Fig. 7a), which is composed of moraine deposits related to the end of the last glaciation, when the area was occupied by a glacier. With the climate changes after this period and the retreat of the glaciers, the deposits were subjected to weathering and to the erosion processes, responsible for the origin of the peculiar landforms of pyramids that are still active today. Erosion continues to modify the site today and may result in damage or even its total destruction in the future (Bollati et al. 2016, 2017b).

The example of Tartaruga Beach (Fig. 7b) should also be highlighted. This beach is subject to intense coastal erosion, which is also responsible for the destruction of urban infrastructures. Ripraps have been built to prevent further damage, but only to one portion of the beach. Therefore, the active process represented by this site is of great scientific and educational interest. Coratza and De Waele (2012) stressed

the importance of using geomorphosites for the purpose of geoscientific education on the subject of hazards and risks, which is the case of Tartaruga Beach. The quantitative assessment of degradation risks in this site was difficult, since it is a particular case that is not addressed in the GEOSSIT method. The coastal erosion process presents risks for urban structures, which have been already damaged, and there is not exactly a landform to be protected. Therefore, assuming that this type of geomorphosite may represent important values and uses, it would be useful to dispose of a methodological approach that addresses this particular situation.

García-Ortiz et al. (2014) presented a specific method for the assessment of risks of degradation of geosites based on three criteria: sensitivity, fragility, and vulnerability (natural and anthropic). This work was not focused on geomorphosites; however, it takes into account the active process that may affect the fragility and natural vulnerability. It shows that if a method is intended to

embrace any type of geosite, it must address specific issues of the different categories.

### Aesthetic Dimension

The aesthetic dimension of geomorphosites is important in different aspects. Besides being crucial for the touristic potential, the aesthetic aspect attracts the interest and attention of the general public (Goudie 2002) and can be used to improve understanding and promote geoscientific knowledge, thereby enhancing the educational potential of the site. Sites such as the Lac Bleu Morainic System (Fig. 7c) or Cabo Frio Island (Fig. 7d) are easily recognized for their beautiful scenery. In such cases, it may be difficult to argue against the importance of the aesthetic value. Nonetheless, assessing this value can be one of the most difficult due to the high degree of subjectivity.

While the UNIL method evaluates the aesthetic value, the GEOSSIT method, following Brilha (2016), only uses the aesthetic dimension as parameter to assess the educational and touristic potential uses. However, the parameter “scenery,” which corresponds to 5% of the educational value and 15% of the touristic, is evaluated according to tourist campaigns (i.e., if a site is used as tourist destination in campaigns). Therefore, if a site is not a tourist destination, its score will be zero.

The assessment of the aesthetic value is, however, not only an evaluation of “how beautiful” is the site. The presence of good viewpoints or obstacles to the best views of the site is also part of this assessment. For instance, José Gonçalves Beach is a site of great scenery beauty. However, its main geomorphological feature is a marine terrace created during the Holocene when the sea level was higher. Today, the terrace is almost totally covered by vegetation, making observation of the landform extremely difficult. For this reason, the aesthetic value of the site assessed with the UNIL method was low.

In GEOSSIT, the “observation conditions” is also part of the assessment, corresponding to 10% of the educational potential use and 5% of the touristic potential use. Because of this low weighting, sites lacking good viewpoints, which are crucial in particular for educational purposes, may be ranked as high as sites with very good observation conditions. This fact is evident in the GEOSSIT rankings, which do not reveal any significant differences among the sites. Therefore, despite being used as a parameter, the influence of the aesthetic dimension in the GEOSSIT results is limited, and hence this peculiarity of geomorphosites is not well addressed by the GEOSSIT.

Another important discussion concerning the aesthetic dimension is exemplified by sites such as La Maya Summit, which is an alpine peak with a characteristic form, being well remarkable in the landscape. In this case, the assessment of the aesthetic value depends on the viewpoints used to see it, which is also related to the evaluation of accessibility

conditions, one of the parameters used in both methods for the assessment of educational and touristic potentials. It would not make sense to use the site itself as viewpoint, since climbing an alpine peak is not an easy task, may be dangerous and obviously: from the peak, the visitors have an amazing view of many things, except of the site itself. Therefore, it is more useful to select good viewpoints outside the site, allowing an adequate visualization of it. It is important to highlight the fact that some authors consider viewpoints as a category of geosites (e.g., Pereira and Pereira 2010; Fuertes-Gutiérrez and Fernández-Martínez 2012; Rodrigues 2013; Migón and Pijet-Migón 2017) but, in cases like the one described here, the viewpoint should not be considered as a geosite, but as a location to visualize a geosite, being natural or artificial, such as a tower, a building, a parking with a good view, etc.

This leads to another interesting discussion: a geomorphosite can be used as viewpoint to another geomorphosite. From the Lac Bleu Morainic System, for instance, it is possible to see all the features of the Tsarmine Glacial System (Fig. 7e). The latter is a site located in an alpine environment, with quite dangerous active processes and where access is only possible after rather long and exhausting hike. Besides that, due to its spatial scale and complexity, it is hard to visualize all features from the site itself. However, the Lac Bleu Morainic System is located right in front and the access is much easier. Therefore, by using this site as viewpoint, the aesthetic, educational and touristic values of the Tsarmine Glacial System are enhanced at the same time that there is an enhancement of the educational and touristic values of the Lac Bleu Morainic System.

### Ecological Value

Some geomorphosites are highly representative of the relationships between geodiversity and biodiversity (Bétard 2018), for example, Pai Vitório Point and Stone Mangrove (Fig. 7f). This site is divided into two parts, the aligned hills of Pai Vitório Point and the Stone Mangrove, which is a very rare example of mangrove vegetation in a substrate composed of gravel and coarse sand from a talus deposit. The development of this type of vegetation can be explained by geological, geomorphological and hydrological factors. The fresh water necessary for the mangrove comes from aquifers in the sedimentary rocks of the area and is discharged in a coastal area protected from high energy waves. The ecological value of this site is highlighted in Obraczka et al. (2018) and a conservation unit was created to protect the area in December 2018.

In the GEOSSIT method, the ecological value is used to assess the educational and touristic values through the parameter “association with other values,” which corresponds to only 5% of the two values. Therefore, although not totally



disregarded, ecological importance does not appear to be very relevant and does not clearly appear in the results, as it is “mixed” with other possible values. The UNIL method, on the other hand, clearly presents the ecological importance of geomorphosites, assessing it as an additional value. The ecological importance is also taken into account in the characterization of educational and touristic interests.

The importance of ecological value for geomorphosites has been emphasized by several authors. Panizza (2001) includes it as part of scientific value because geomorphological features can provide a habitat for particular species, which may enhance certain aspects of conservation; Bollati et al. (2012) also consider ecological value as part of the scientific value in their assessment procedure, which focuses on the creation of educational itineraries, highlighting the influence of the educational value. Similarly, Pralong (2005) includes the ecological value in his evaluation procedure aimed at the promotion of geotourism. These three examples show how the ecological value can influence aspects related to use and management, such as the need for conservation, educational use, and the promotion of tourism. Therefore, relevant characteristics of the geomorphosite are, from a practical point of view, excluded from the results of the assessment procedures when the ecological value is not a part of it. In the present context of efforts to integrate geodiversity and biodiversity (Matthews 2014), this type of problem should be avoided.

## Cultural Value

The links between culture and geomorphology can be analyzed using different approaches (Reynard and Giusti 2018). One of the most perceptible are anthropic landforms, which can be exemplified by two sites: the Rock Sill and Anthropic Terraces of Flanmayen (Fig. 7g), and the Vermelha Lagoon (Fig. 7h). The first consists of an inherited glacial landform that was historically used for agriculture and is characterized by the man-made terraces constructed for the purpose. The second is a double barrier-lagoon system that was partly transformed into a *Salina* (Portuguese word referring to an area of salt production), that is today considered as a national geomining heritage. Both occupations are related to the geomorphologic and climatic conditions that facilitated the establishment of human activities.

However, anthropic landforms are not the only expression of the links between culture and geomorphology. History, religion, literature, arts, geohistory, and economy are examples of cultural assets that can be directly linked to geomorphology. In this sense, two of the sites assessed here can be highlighted: São João Hill and St-Léonard Underground Lake. The first consists of an alkaline massif that resulted from an important magmatic event that took place in southeastern Brazil. The site has been studied for decades and has made a major contribution to geoscientific knowledge about this type of geological/

geomorphological feature. Its geohistorical importance is part of the cultural value of the site, being also important to highlight that some methods include this parameter as part of the scientific value (e.g., Bollati et al. 2016). The St-Léonard Underground Lake is a cave in gypsum rocks filled by a lake, and is a major tourist attraction. Visitors pay a fee to visit the site and other touristic infrastructures, such as shops and restaurants, are located in the vicinity. In this case, according to the UNIL method, the cultural value of the site is related to its economic importance. Other methods assess the economic value independently from the cultural (e.g., Pralong 2005; Bollati et al. 2016).

As shown by the above examples, cultural value can be approached in different ways, depending on the type of relationship between the geomorphological and the cultural assets. This is a very important topic because it directly affects a site's use and management. Cultural aspects may be part of the promotion of the site for geotouristic use, for instance, or may be a reason to improve protective measures. As the cultural value of a site is part of its intrinsic value, which is important for geomorphological studies, and strongly influences its use and management, it is crucial to take the cultural value of the site into account in the assessment procedure.

Like ecological value, the influence of the cultural value in the GEOSSIT method is significantly reduced, while in the UNIL method, it is also assessed as an additional value. Considering works that demonstrate the importance of links between geomorphology and culture (e.g., Panizza and Piacente 2003, 2005; Coratza et al. 2016; Reynard and Giusti 2018), an inventory of geomorphological sites in which the cultural importance is disregarded may be considered incomplete. It is important to recall that in certain cases, the aim of the inventory may not be linked to certain values, thereby justifying their absence. However, if a method is intended to be applied widely, for example, to create a national inventory for geoconservation purposes, it should not ignore important values that are also directly related to use and management aspects.

## Conclusion

Studies on geomorphological heritage have made significant advances in recent decades. Such advances concern, among other aspects, methodological proposals for the creation of inventories and assessment of geomorphosites. Recognizing, protecting, and promoting forms of relief is not an easy task, especially due to the great range of uses and perceptions of different peoples and societies, which often result in land use conflicts.

The aim of the present study was to assess the influence of the specificities of geomorphosites on inventory and assessment procedures, which are considered essential stages in

geoconservation strategies. For this reason, it is crucial that the inventories are conducted using a consolidated methodological basis, so they can be effectively used in territorial management, with the focus on conservation and sustainable development.

The results obtained using two distinct methods in two completely different areas allowed us to analyze how specificities that had already been identified in the literature can have a direct influence on the results of the assessment of geomorphosites. The spatial and temporal scales are determinant factors in all steps of the procedure: selection, qualitative and quantitative assessment, as well as in proposals for use and management. The imbrication of scales may be responsible for a high degree of complexity and is responsible for major differences in the results obtained using the two methods we compared. The dynamic dimension also contributes to complexity, since active processes can, for instance, enhance the representativeness or impose modifications to the site, that in turn, can affect its integrity. The aesthetic value is usually one of the most important aspects of geomorphosites, especially when dealing with the potential for education or geotourism. The ecological value represents the link between geodiversity and biodiversity, which, in most cases, is demonstrated through geomorphology. Finally, the cultural value is present in many different aspects, representing the links between culture and geomorphology, and may be crucial for the evaluation of use and management.

We therefore conclude that the procedures for conducting an inventory and an assessment of geomorphosites should take the specificities of this category of geosites into account, and that there is a need for specific approaches. The application of two methods, one designed specifically for geomorphosites and one designed for any type of geosite, showed that not taking geomorphological peculiarities into consideration may lead to misjudgments and to inadequate assessment of the values and of the risk of degradation, which could lead to misuse and mismanagement. It does not necessarily mean that geomorphosites always need specific methods, but it endorses that a method designed to any type of geosites, including geomorphological ones, cannot ignore their specificities.

**Acknowledgments** This work was supported by the Coordination for the Improvement of Higher Personnel (CAPES – Brazilian government) and the Institute of Geography and Sustainability of the University of Lausanne. We express our gratitude to two anonymous reviewers for the helpful comments that improved the manuscript.

## References

- Asmus HE, Ferrari AL (1978) Hipótese sobre a causa do tectonismo cenozoico na região sudeste do Brasil. *Série Projeto REMAC* 4: 75–88 (in Portuguese)
- Becker P, Funk M, Schlüchter C, Hutter K (2017) A study of the Würm glaciation focused on the Valais region (Alps). *Geogr Helv* 72(4): 421–442
- Bétard F (2018) Géodiversité, biodiversité et patrimoines environnementaux. De la connaissance à la conservation et à la valorisation. Habilitation Thesis. University of Paris-Diderot (in French)
- Bollati I, Lenz BC, Golzio A, Masseroli A (2018) Tree rings as ecological indicator of geomorphic activity in geoheritage studies. *Ecol Indic* 93:899–916. <https://doi.org/10.1016/j.ecolind.2018.05.053>
- Bollati I, Lenz BC, Zanoletti E, Pelfini M (2017a) Geomorphological mapping for the valorization of the alpine environment. A methodological proposal tested in the Loana Valley (Sesia Val Grande Geopark, Western Italian Alps). *J Mt Sci* 14(6):1023–1038. <https://doi.org/10.1007/s11629-017-4427-7>
- Bollati I, Leonelli G, Vezzola L, Pelfini M (2015) The role of ecological value in geomorphosite assessment for the debris-covered Miage Glacier (Western Italian Alps) based on a review of 2.5 centuries of scientific study. *Geoheritage* 7(2):119–135. <https://doi.org/10.1007/s12371-014-0111-2>
- Bollati I, Pellegrini M, Reynard E, Pelfini M (2017b) Water driven processes and landforms evolution rates in mountain geomorphosites: examples from Swiss Alps. *Catena* 158:321–339. <https://doi.org/10.1016/j.catena.2017.07.013>
- Bollati I, Pelfini M, Pellegrini L (2012) A geomorphosites selection method for educational purposes: a case study in Trebbia Valley (Emilia Romagna, Italy). *Geogr Fis Din Quat* 35(1):23–35. <https://doi.org/10.4461/GFDQ.2012.35.3>
- Bollati I, Reynard E, Palmieri EL, Pelfini M (2016) Runoff impact on active geomorphosites in unconsolidated substrate. a comparison between landforms in glacial and marine clay sediments: two case studies from the Swiss Alps and the Italian Apennines. *Geoheritage* 8(1):61–75. <https://doi.org/10.1007/s12371-015-0161-0>
- Bollati I, Zucali M, Giovenco C, Pelfini M (2014) Geoheritage and sport climbing activities: using the Montestrutto cliff (Austroalpine domain, Western Alps) as an example of scientific and educational representativeness. *Ital J Geosci* 133(2):187–199. <https://doi.org/10.3301/IJG2013.24>
- Brihla J (2005) Património geológico e geoconservação: a conservação da natureza na sua vertente geológica. Palimage Editores, Viseu (in Portuguese)
- Brihla J (2016) Inventory and quantitative assessment of geosites and geodiversity sites: A review. *Geoheritage* 8(2):119–134. <https://doi.org/10.1007/s12371-014-0139-3>
- Brihla J (2017) Trends and challenges for geoconservation. *Geophys Res Abstr* 19:8626
- Brihla J (2018) Geoheritage: inventories and evaluation. In: Reynard E, Brihla J (eds) *Geoheritage: Assessment, protection and management*. Elsevier, Amsterdam, pp 69–86
- Bruschi VM, Cendrero A (2005) Geosite evaluation: can we measure intangible values? *II Quaternario* 18(1):293–306
- Castro JWA, Seoane JCS, Cunha AM, Malta JV, Oliveira CA, Vaz SR, Suguio K (2018) Comments to Angulo et al. 2016 on “Sea-level fluctuations and coastal evolution in the state of Rio de Janeiro, southeastern – Brazil” by Castro et al. 2014. *An Acad Bras Cienc* 90(2): 1369–1375. <https://doi.org/10.1590/0001-3765201820171010>
- Castro JWA, Suguio K, Seoane JCS, Cunha AM, Dias FF (2014) Sea-level fluctuations and coastal evolution in the state of Rio de Janeiro, southeastern Brazil. *An Acad Bras Cienc* 86(2):671–683
- Clivaz M, Reynard E (2018) How to integrate invisible geomorphosites in an inventory: a case study in the Rhone River valley (Switzerland). *Geoheritage* 10(4):527–541. <https://doi.org/10.1007/s12371-017-0222-7>
- Comanescu L, Nedelea A, Dobre R (2012) The evaluation of geomorphosites from the Ponoare Protected Area. *Forum*

- Geografic 11(1):54–61. <https://doi.org/10.5775/fg.2067-4635.2012.037.i>
- Coratza P, De Waele J (2012) Geomorphosites and natural hazards: teaching the Importance of Geomorphology in Society. *Geoheritage* 4(3): 195–203. <https://doi.org/10.1007/s12371-012-0058-0>
- Coratza P, Gauci R, Schembri J, Soldati M, Tonelli D (2016) Bridging natural and cultural values of sites with outstanding scenery: evidence from Gozo, Maltese Islands. *Geoheritage* 8(1):91–103. <https://doi.org/10.1007/s12371-015-0167-7>
- Coratza P, Giusti C (2005) Methodological proposal for the assessment of the scientific quality of geomorphosites. *Il Quaternario* 18(1):307–313
- Coratza P, Hobléa F (2018) The specificities of geomorphological heritage. In: Reynard E, Brilha J (eds) *Geoheritage: assessment, protection and management*. Elsevier, Amsterdam, pp 87–106
- Egli D, Mancktelow N (2013) The structural history of the Mont Blanc massif with regard to models for its recent exhumation. *Swiss J Geosci* 106(3):469–489. <https://doi.org/10.1007/s00015-013-0153-5>
- Escher A, Hunziker JC, Marthaler M, Masson H, Sartori M, Steck A (1997) Geologic framework and structural evolution of the Western Swiss Alps. In: Pfiffner OA, Lehner P, Heitzmann P, Mueller S, Steck A (eds) *Deep structure of Switzerland – results from the National Research Program 20 (NRP20)*. Birkhauser, Basel, pp 205–222
- Fassoulas C, Mouriki D, Dimitriou-Nikolakis P, Ilipoulos G (2012) Quantitative assessment of geotope as an effective tool for geoheritage management. *Geoheritage* 4(3):177–193. <https://doi.org/10.1007/s12371-011-0046-9>
- Fuertes-Gutiérrez I, Fernández-Martínez E (2012) Mapping geosites for geoheritage management: a methodological proposal for the regional park of Picos de Europa (León, Spain). *Environ Manag* 50(5): 789–806. <https://doi.org/10.1007/s00267-012-9915-5>
- García-Cortés A, Carcavilla L (2009) Documento metodológico para la elaboración del inventario español de lugares de interés geológico (IELIG), version 12. Instituto Geológico y Minero de España, Madrid
- García-Ortiz E, Fuertes-Gutiérrez I, Fernández-Martínez E (2014) Concepts and terminology for the risk of degradation of geological heritage sites: fragility and natural vulnerability, a case study. *Proc Geol Assoc* 125(4):463–479. <https://doi.org/10.1016/j.pgeola.2014.06.003>
- Garcia et al (2018) The inventory of geological heritage of the State of São Paulo, Brazil: methodological basis, results and perspectives. *Geoheritage* 10(2):239–258. <https://doi.org/10.1007/s12371-016-0215-y>
- Goudie AS (2002) Aesthetics and relevance in geomorphological outreach. *Geomorphology* 47(2):245–249. [https://doi.org/10.1016/S0169-555X\(02\)00090-9](https://doi.org/10.1016/S0169-555X(02)00090-9)
- Grandgirard V (1999) L'évaluation des géotopes. *Geologia Insubrica* 4(1):59–66
- Gray M (2013) *Geodiversity: valuing and conserving abiotic nature*, 2nd edn. Wiley-Blackwell, Chichester
- Henriques MH, Pena dos Reis R, Brilha J, Mota T (2011) Geoconservation as an emerging geoscience. *Geoheritage* 3:117–128. <https://doi.org/10.1007/s12371-011-0039-8>
- Hjort J, Gordon JE, Gray M, Hunter ML Jr (2015) Why geodiversity matters when valuing nature's stage. *Conserv Biol* 29(3):630–639. <https://doi.org/10.1111/cobi.12510>
- Hubbard M, Mancktelow NS (1992) Lateral displacement during Neogene convergence in the western and central Alps. *Geology* 20(10):943–946
- Jesus PB et al. (2017) Holocene paleo-sea level in southeastern Brazil: an approach based on vermetids shells. *Journal of Sedimentary Environments* 2(1):35–48. doi: 10.12957/jse.2017.28158
- Kubalíková L (2013) Geomorphosite assessment for geotourism purposes. *Czech J Tourism* 2(2):80–104. <https://doi.org/10.2478/cjot-2013-0005>
- Lambiel C, Maillard B, Kummert M, Reynard E (2015) Geomorphology of the Hérens valley (Swiss Alps). *J Maps* 12(1):160–172. <https://doi.org/10.1080/17445647.2014.999135>
- Lima FF, Brilha J, Salamuni E (2010) Inventory of geological heritage in large territories: a methodological proposal applied to Brazil. *Geoheritage* 2(3):91–99. <https://doi.org/10.1007/s12371-010-0014-9>
- Martin L, Suguio K, Flexor JM, Dominguez JML, Bittencourt ACSP (1996) Quaternary sea-level history and variation in dynamics along the Central Brazilian Coast: consequences on coastal plain construction. *An Acad Bras Cienc* 68(3):303–354
- Matthews TJ (2014) Integrating geoconservation and biodiversity conservation: theoretical foundations and conservation recommendations in a European Union context. *Geoheritage* 6(1):57–70. <https://doi.org/10.1007/s12371-013-0092-6>
- Migón P (2009) Geomorphosites and the World Heritage List of UNESCO. In: Reynard E, Coratza P, Regolini-Bissig G (eds) *Geomorphosites*. Pfeil, München, pp 119–130
- Migón P (2018) *Geoheritage and World Heritage Sites*. In: Reynard E, Brilha J (eds) *Geoheritage: assessment, protection and management*. Elsevier, Amsterdam, pp 237–249
- Migón P, Pijet-Migón E (2017) Viewpoint geosites – values, conservation and management issues. *Proc Geol Assoc* 128(4):511–522
- Obraczka M, Mansur KL, Silva Jr GC (2018) Sustainability and protection of threatened coastal ecosystems: Management strategies for a rare stone mangrove in Gorda Beach, Armação dos Búzios, Brazil. In: Makowski C, Finkl CW (eds.) *Threats to mangrove forests: hazards, vulnerability and management*. Springer International Publishing, pp 377–400
- Panizza M (2001) Geomorphosites: concepts, methods and example of geomorphological survey. *Chin Sci Bull* 46:4–5. <https://doi.org/10.1007/BF03187227>
- Panizza M, Piacente S (2003) *Geomorfologia culturale*. Pitagora Editrice, Bologna
- Panizza M, Piacente S (2005) Geomorphosites: a bridge between scientific research, cultural integration and artistic suggestion. *Il Quaternario* 18(1):3–10
- Pelfini M, Bollati I (2014) Landforms and geomorphosites ongoing changes: Concepts and implications for geoheritage promotion. *Quaest Geogr* 33(1):131–143. <https://doi.org/10.2478/quageo-2014-0009>
- Pena dos Reis R, Henriques MH (2009) Approaching an integrated qualification and evaluation system for geological heritage. *Geoheritage* 1(1):1–10. <https://doi.org/10.1007/s12371-009-0002-0>
- Pereira P, Pereira D (2010) Methodological guidelines for geomorphosite assessment. *Géomorphol Relief Process Environ* 2:215–222. <https://doi.org/10.4000/geomorphologie.7942>
- Pereira P, Pereira D, Caetano Alves MI (2007) Geomorphosite assessment in Montesinho Natural Park (Portugal). *Geogr Helv* 62(3): 159–168. <https://doi.org/10.5194/gh-62-159-2007>
- Perret A (2014) *Géopatrimoines des trois Chablais: identification et valorisation des témoins glaciaires*. Ph.D. thesis, University of Lausanne and University of Grenoble Alpes (in French)
- Piacente S, Coratza P (eds) (2005) Geomorphological sites and geodiversity. *Il Quaternario* 18(1):1–332
- Pralong JP (2005) A method for assessing tourist potential and use of geomorphological sites. *Géomorphol Relief Process Environ* 3:189–195. <https://doi.org/10.4000/geomorphologie.350>
- Reynard E (2005) Géomorphosites et paysages. *Géomorphol Relief Process Environ* 3:181–188. <https://doi.org/10.4000/geomorphologie.338>

- Reynard E (2009) Geomorphosites: definitions and characteristics. In: Reynard E, Coratza P, Regolini-Bissig G (eds) *Geomorphosites*. Pfeil, München, pp 9–20
- Reynard E, Brilha J (eds) (2018) *Geoheritage: assessment, protection and management*. Elsevier, Amsterdam
- Reynard E, Coratza P, Regolini-Bissig G (eds) (2009) *Geomorphosites*. Pfeil, München
- Reynard E, Coratza P (2013) Scientific research on geomorphosites. A review of the activities of the IAG working group on geomorphosites over the last twelve years. *Geogr Fis Din Quat* 36: 159–168. <https://doi.org/10.4461/GFDQ.2013.36.13>
- Reynard E, Fontana G, Kozlik L, Scapozza C (2007) A method for assessing scientific and additional values of geomorphosites. *Geogr Helv* 62(3):148–158. <https://doi.org/10.5194/gh-62-148-2007>
- Reynard E, Giusti C (2018) The landscape and the cultural value of geoheritage. In: Reynard E, Brilha J (eds) *Geoheritage: assessment, protection and management*. Elsevier, Amsterdam, pp 147–166
- Reynard E, Panizza M (2005) Geomorphosites: definition, assessment and mapping. An introduction. *Géomorphol Relief Process Environ* 3:177–180. <https://doi.org/10.4000/geomorphologie.336>
- Reynard E, Perret A, Bussard J, Grangier L, Martin S (2016) Integrated approach for the inventory and management of geomorphological heritage at the regional scale. *Geoheritage* 8(1):43–60. <https://doi.org/10.1007/s12371-015-0153-0>
- Rodrigues J (2013) Geosite management in Geopark Naturtejo da Meseta Meridional, Portugal: geomorphological viewpoints. In: Hobléa F, Cayla N, Reynard E (eds.) *Managing geosites in protected areas*. Collection Edytem, 15, pp 65–70
- Serrano E, González Trueba JJ (2005) Assessment of geomorphosites in natural protected areas: the Picos de Europa National Park (Spain). *Géomorphol Relief Process Environ* 3:197–208. <https://doi.org/10.4000/geomorphologie.364>
- Schlüchter C (compil) (2009) Die Schweiz während des letzteiszeitlichen Maximums (LGM), 1:500,000. GeoKarten 500. Bundesamt für Landestopografie swisstopo, Wabern (in German and French)
- Schmitt RS, Trouw RAJ, Van Schmus WR, Pimentel MM (2004) Late amalgamation in the central part of West Gondwana: new geochronological data and the characterization of a Cambrian collisional orogeny in the Ribeira belt (SE Brazil). *Precambrian Res* 133(1–2):29–61. <https://doi.org/10.1016/j.precamres.2004.03.010>
- Steck A, Epard JL, Escher A, Gouffon Y, Masson H (2001) Carte tectonique des Alpes de Suisse occidentale. Notice explicative. Office fédéral des eaux et de la géologie. Carte géologique spéciale n° 123
- Wimbledon WAP, Smith-Meyer S (eds) (2012) *Geoheritage in Europe and its conservation*. ProGEO, Oslo
- Zalán PV, Oliveira JAB (2005) Origem e evolução estrutural do Sistema de Riftes Cenozoicos do Sudeste do Brasil. *Boletim de Geociências da Petrobras* 13(2):269–300 (in Portuguese)
- Zouros N (2007) Geomorphosite assessment and management in protected areas of Greece. Case study of the Lesvos Island—coastal geomorphosites. *Geogr Helv* 62(3):169–180. <https://doi.org/10.5194/gh-62-169-2007>