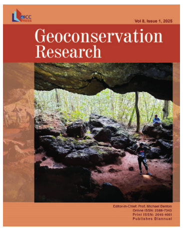

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New Geosites Inventory for Geoconservation and Geotourism Improvement in Alagna Valsesia, Sesia Val Grande UNESCO Global Geopark (Italy)

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Abstract

Geoheritage is an important resource for modern society, and the inventory of geosites is an increasingly crucial element to encourage geoconservation actions and foster the sustainable development of an area. The present paper offers an analysis aimed at assessing 25 potential geosites in Alagna Valsesia, an alpine area within the Sesia Val Grande UNESCO Global Geopark (NW Italy), both qualitatively and quantitatively. The qualitative assessment was performed using a descriptive form created for a project to catalog the geosites of the Piemonte Region, focusing on the scientific, aesthetic, conservation, and tourism relevance of the geoheritage elements. Statistical analysis of the new inventory, using both qualitative and quantitative assessments, has enabled a more detailed classification of the geosites and an understanding of benefits and limitations of both methodologies. We find that for a comprehensive territorial strategy, the qualitative and quantitative methods are complementary. The qualitative approach aids geoconservation with detailed geosite descriptions, benefiting spatial managers and geoparks, and the quantitativaAe method enables objective comparisons, supporting regional geotourism development.

Keywords: Geoheritage, Italian geoparks, Environmental management, Geotourism, Alps, Mountain geodiversity, Sustainable tourism

Introduction

Geoheritage and geodiversity are increasingly important both in research and in planning the sustainable development of territories (Brocx and Semeniuk 2007; Burek and Prosser 2008; Brilha *et al.* 2018; Migón and Migón 2022; Herrera-Franco *et al.* 2022; Bollati *et al.* 2023b). In this framework, UNESCO Global Geoparks are increasingly recognized as repositories of geological heritage and dedicated to its protection and enhancement (Henriques and Brilha 2017; Stoffelen 2020; Herrera-Franco *et al.* 2021; Pérez-Romero *et al.* 2023). The idea of geoparks emerged in the 1990s to identify regions with a distinct geological history and a plan for sustainable territorial development; a geopark must be large enough and have well-defined borders to support real territorial economic development, mostly from tourism (Frey *et al.* 2001). In fact, these areas use their geological heritage to support the economic well-being of the local population while simultaneously advancing protection in a sustainable manner (McKeever and Zouros 2005). The Global Geoparks Network (GGN) was established in 2004 as a global platform for collaboration among geoparks worldwide. In 2015, the UNESCO General Conference approved the UNESCO Global Geoparks operational guidelines and the statutes of the new International Geoscience and Geoparks Program (UNESCO 2024). This is considered as prestigious as the "Man and the Biosphere Program" and the "World Heritage List Program" (Henriques and Brilha 2017). This marked the introduction of the UNESCO Global Geopark brand as an award of excellence for regions that satisfy the requirements of the guidelines (Zouros 2016). At present, within GGN, there are 213 geoparks in 48 countries (UNESCO 2024).

The primary objectives of geoparks are threefold: sustainable development, geoconservation, and geotourism (Piranha *et al.* 2011; Hose 2012; Varriale *et al.* 2022; Ferreira and Valdati 2023). To achieve these goals, several strategies have been developed, such as field-based geoeducation events (Sütő *et al.* 2020) and education programs for indigenous people (Adryansyah Nazaruddin and Ab Manaf 2024). However, one of the most popular strategies is the recognition, inventory and quantitative assessment of geosites for both geoconservation (assessment of scientific value) and geotourism (assessment of educational value and potential use). In fact, the geosites inventory is generally acknowledged as an effective practice for nature conservation and geoheritage management (Brilha 2016; Berrezueta *et al.* 2021; Pasquaré Mariotto *et al.* 2023). Specifically, geosites can be defined as "site locations or territories in which it is conceivable to identify a geological or geomorphological significance for conservation" (Wimbledon 1995), despite the variety of interpretations that this concept has encountered (Mantovani 2024).

Academics and territorial managers use geosites inventories to highlight the scientific importance and potential for geotourism, thus promoting regional sustainable development (El Wartiti *et al.* 2008; Fuertes-Gutiérrez and Fernández-Martínez 2010; Fernández *et al.* 2014; Moura *et al.* 2017; Garcia *et al.* 2019). Moreover, systematic inventories represent the basis of geoconservation methods (Henriques *et al.* 2011; Brilha 2016). The absence of inventories or inadequate management of geoheritage can lead to the deterioration of geosites and the loss of geoheritage (de Lima *et al.* 2010). Conversely, the existence of such inventories enables the integration of geosites into administrative processes, thereby linking them to local economic strategies, a best practice for achieving integral real geoconservation (Fuertes-Gutiérrez and Fernández-Martínez 2010). During the creation of geosite inventories, several studies included a quantitative assessment, which involves the assignment of quantitative scores to assess geosite values (e.g., de Lima *et al.* 2010; Bollati *et al.* 2013; Reynard *et al.* 2016; Brilha 2016; Garcia *et al.* 2019; Santos *et al.* 2020; Ferrando *et al.* 2021; Sisto *et al.* 2022). Numerous research groups have analyzed or reviewed quantitative methods for evaluating geosites over the past decade, emphasizing the efficacy of these methods in reducing subjectivity in the evaluation and selection of geosites (Brilha 2016; Santos *et al.* 2019; Herrera-Franco *et al.* 2020; Mucivuna *et al.* 2022).

Furthermore, the assignment of quantitative scores may also allow a comparison between the geosites, enabling the identification of the most valuable ones. However, during these processes, a certain degree of subjectivity is inevitable (Bollati *et al.* 2013; Štrba *et al.* 2015) and using these assessment values to promote best practices in geotourism management may be challenging

(Štrba *et al.* 2018).

Our study aims to create an inventory and make a qualitative and quantitative assessment of 25 potential geosites recognized in Alagna Valsesia, within the Sesia Val Grande UNESCO Global Geopark (SVUGGp). Recent methodologies for assessing geosites, geoheritage, and their community services (Bollati *et al.* 2017; Perotti *et al.* 2019; Tognetto *et al.* 2021; Bollati *et al.* 2023a; Guerini *et al.* 2023) led to a geosites inventory for the geopark by Perotti *et al.* (2020), updated by Viani *et al.* (2020). However, the municipality of Alagna Valsesia lacks adequate geosite characterization. Recent research identified 25 potential geosites here but did not assess their heritage value or geotourism potential (Guerini *et al.* 2024). Hence, the central focus of this paper is the assessment phase of the potential geosites, both qualitative and quantitative. In this way, two main objectives will be achieved: 1) compare the results of the qualitative assessment with those of the quantitative assessment, discussing the potential benefits of both in providing geopark managers with a comprehensive inventory of geosites that is useful for both management and promotion of geosites; 2) create a systematic and comprehensive inventory of the geosites of Alagna Valsesia and contribute to the project for the creation of an accessible regional inventory of geosites in the Piemonte Region (Regione Piemonte 2023).

Study Area

The SVUGGp is located in the northwest of the Piemonte Region, Italy (Fig. 1). It extends from Lake Maggiore in the east, bordering Switzerland, to the Monte Rosa Massif in the west, bordering the Aosta Valley, covering about 2,200 km². In 2015, the territory was designated a "UNESCO Global Geopark".

From a geological point of view, the SVUGGp is included in the Alpine orogenic belt, which is subdivided into four main domains: Southalpine, Austroalpine, Penninic and Helvetic-Dauphinois. These domains indicate different paleogeographic contexts (e.g., whether the rocks come from the paleo-African or paleo-Europe plate) and orogenic phases (e.g., the Southalpine domain was not affected by any metamorphism during the Alpine orogeny, which, on the other hand, affected the Penninic and Austroalpine domains). The SVUGGp territory includes geologic units attributed to the Southalpine, Austroalpine and Penninic domains, giving the territory very high geodiversity from the different types of rocks that compose the bedrock (sedimentary, magmatic and metamorphic), their genetic processes, their metamorphic grade and their age.

The municipality of Alagna Valsesia, which is our study area, shows a part of the geodiversity of the geopark. In fact, it is in the upper Sesia Valley (Fig. 1), at the foot of the Monte Rosa Massif, and straddles the Penninic and Austroalpine domains. From north to south, we find (Piana *et al.* 2017b):

- The geologic units of the Monte Rosa Massif, which is one of the Internal Crystalline Massifs of the Alps (part of the Penninic Domain). These massifs (Monte Rosa, Gran Paradiso and Dora Maira) represent part of the paleo-European continental margin and consist of a composite pre-alpine basement and the related Permo-Mesozoic cover (Gasco *et al.* 2013). The Monte Rosa Massif is composed mainly of metamorphic rocks (such as orthogneiss, paragneiss and mica schists) that record several tectono-metamorphic phases, which occurred both before and during the Alpine orogeny (pre-alpine metamorphism and syn-orogenetic metamorphism).
- Serpentinites, prasinites, calc-schists of the Zermatt-Saas and Combin geo-

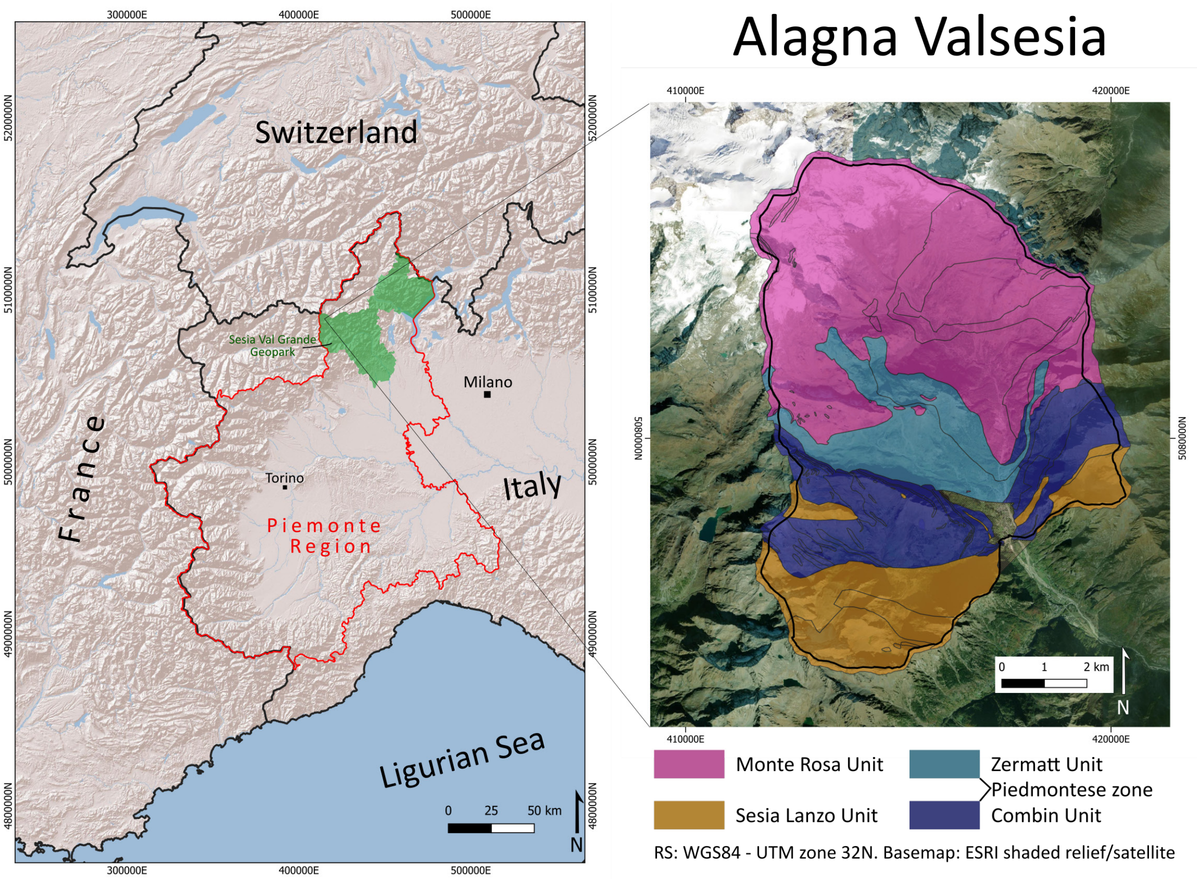

Figure 1. Overview of the Sesia Val Grande Unesco Global Geopark and simplified geological map of Alagna Valsesia. In red is the administrative border of the Piemonte Region, in green, the geopark area.

logic units ("Zona Piemontese"). These units, traditionally included in the Penninic Domain, are interpreted as ophiolites, i.e., remains of oceanic crust involved in the orogenic processes, and represent the remains of the Liguria-Piemonte Ocean (Alpine Tethys) (Piana *et al.* 2017a).

- In the southern part of the study area, we find the gneiss and schists of the Sesia Lanzo Zone. This unit is included in the Austroalpine domain, which represents the relic of the subducted part of the Adriatic continental margin along the SE border of the Tethys Ocean during the Cretaceous, about 80–66 million years ago (Babist *et al.* 2006).

The geodiversity of Alagna Valsesia is also driven by its geomorphological history. The Sesia Valley is one of the major valleys in the SVUGGp, which during the Messinian period (about 7 Ma), was deeply incised, with slopes currently > 3000 m above sea level (Bini *et al.* 1978). Subsequently, it experienced further geomorphic changes, as a result of regressive continental sedimentation and significant Quaternary glaciation (Carraro and Giardino 2004). In fact, during the Quaternary period, specifically in the Last Glacial Maximum (around 20,000 ya; Clark *et al.* 2009), a single large glacier covered and shaped present-day Valsesia (and therefore the area in which Alagna Valsesia stands today), initiating its movement downstream from the southern slope of Monte Rosa. This glacier had a profound impact on the shaping of the valley, with the formation of secondary glaciers that contributed to the development of the hanging

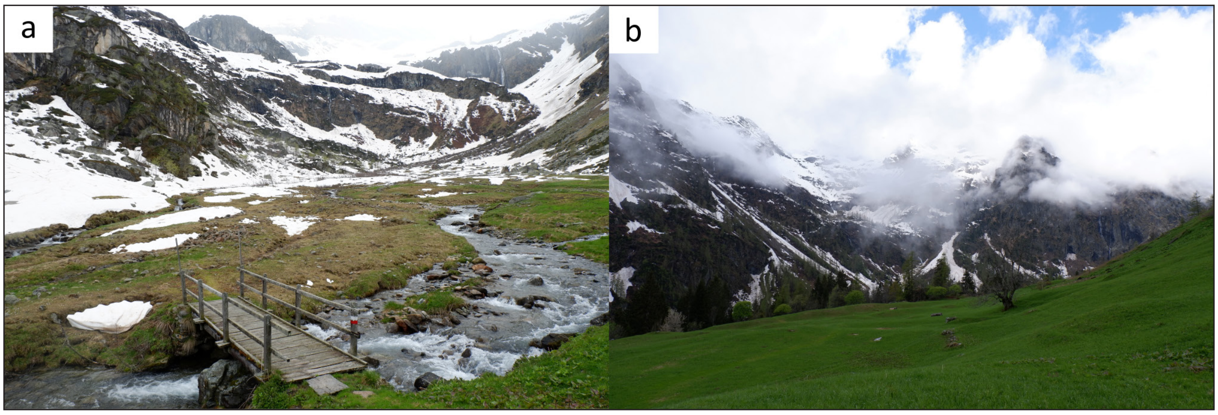

Figure 2. A) Bors valley; **B)** Otro valley. These are two of the western hanging valleys of Alagna Valsesia.

valleys within the study area, including the Otro valley, Olen valley and Bors Valley (Fig. 2).

The Alagna Valsesia area has also been shaped by earlier glacial periods, although the most visible traces today originated during the last glaciation. More recently, during the Little Ice Age (between 13th and 19th centuries), a glacial advance took place, impacting the study area (Grove 2019). Consequently, some features still retain traces of this recent expansion, including the seven glaciers that are still visible on the south side of Monte Rosa (Smiraglia and Diolaiuti 2015).

By location and mountainous landscape, Alagna Valsesia is a significant tourist destination within the geopark, attracting visitors throughout the year. It is a famous destination among alpinists from across Europe, who come to climb one of the easier 4000 m peaks of the Alps (Gniffetti Peak of Monte Rosa, 4554 m, Gorączko 2018). Moreover, during the winter season, the area offers skiing and other winter sports activities, while during the summer, it provides numerous natural and cultural tourism opportunities (Beltramo *et al.* 2024b). An important characteristic of Alagna Valsesia is the Walser community who migrated from the Canton of Valais (Switzerland) to Alagna Valsesia during the Middle Ages and who are still German-speaking and preserve their centuries-old traditions despite the severe climatic challenges they faced (Rizzi and Gianoglio 2023). For example, during the Little Ice Age, they were able to live at high altitudes by adapting the way they built their houses to make them more efficient in terms of insulation, developing a characteristic vernacular architecture (Fantoni 2008, Fig. 3), and they knew how to build structures to protect themselves from avalanches. Their culture has significantly influenced the landscape of the Alagna Valsesia through their vernacular knowledge (Ganzerli and Ganzerli 2012; Di Paola *et al.* 2022). This characteristic environment presents excellent opportunities for cultural and sustainable tourism development (Beltramo *et al.* 2024c; Beltramo *et al.* 2024a).

Method

A three-step approach was used to produce the inventory of geosites. First, we conducted field observations in each of the 25 potential geosites recognized in Alagna Valsesia (Guerini *et al.* 2024) to observe directly both the conservation status of the geosites (integrity) and their valorization for geotourism purposes. Second, we completed a descriptive form (Giardino *et al.* 2024) in each part to characterize and assess the geosites qualitatively, including a cartographic frame produced using Google Earth Pro, version 7.3. From the form data, we then produced a comprehensive map including all 25 geosites using Geographic Information System (GIS) software, QGIS, Version 3.28.13. Third, we analyzed the results of the inventoried geosites and used the information from the forms

Figure 3. Example of vernacular architecture in Alagna Valsesia: a typical Walser house.

to assess the geosites quantitatively.

We proceeded directly to the evaluation phase, bypassing the geosite recognition and pre-selection stages, as these initial stages had already been completed in a prior study that recognized geosites in the same area (Guerini *et al.* 2024). Nevertheless, field observations were conducted in the study area for this work to collect primary data directly from the field through field notes, thus validating and complementing existing data sources (Fuertes-Gutiérrez and Fernández-Martínez 2010; Pereira and Pereira 2010; Brilha 2016).

Qualitative Evaluation

We collected data for each geosite through the literature review, including geological and geomorphological maps of the area (Bartolini *et al.* 2023a; Bartolini *et al.* 2023b). Then, we integrated this information with that collected during the field observations to complete the qualitative evaluation phase. Such a form reflects a method common in the literature (Serrano and González-Trueba 2005; Pereira and Pereira 2010; Santos *et al.* 2020).

We used a new descriptive form created by the research team of the University of Torino, Piemonte Region and ARPA Piemonte (GeoSIT Piemonte Team). This form aims to create an accessible regional geosites inventory for the Piemonte Region, supported by the promulgation of the 23/2023 Regional Law on geoheritage conservation (Regione Piemonte 2023). The whole inventory methodology was presented during the 2024 Italian Geological Society Congress and considered useful for geosite promotion and preservation (Giardino *et al.* 2024). Particularly, this form is an operational representation of a workflow based on a structured ontology (Mantovani *et al.* 2020b; Mantovani *et al.* 2020a), which guides the user through a process divided into six main sections. Organized logically and sequentially, these sections allow the geosites to be characterized from both a scientific point of view and from the point of view of their potential use and management. A comprehensive description of the methodology for geosites inventory of the Piemonte Region is in preparation in a targeted paper by the GeoSIT Piemonte Team (*in prep.*).

The first part of the descriptive form is divided into three basic sections that aim at the qualitative characterization of the geosite through an approach based on the assignment of interest:

- **General Information**: The general description has the aim of contextualizing the geosite within a broader geographical framework. Key elements include the official name of the geosite, coordinates, and land cover classification according to the Piemonte Land Cover program. Additional information includes the spatial classification and complexity of the geosite (such as types of landforms), based on Grandgirard (1999).
- **Geodiversity elements of interest for the geosites**: Next, the specific interest of the geosite is identified, following the ontological approach mentioned above. This includes data from scientific literature and is of particular importance as it is a highly descriptive section. In-depth scientific systematization was carried out, based on the division of disciplinary sectors in the Earth Sciences proposed by the Italian Government (MIUR 2005).
- **Scientific interests and additional values:** Finally, the geosites are assigned an interest according to identified elements of geodiversity. A distinction is made between scientific interests and additional value (Reynard 2009). Primary and secondary scientific interests are subject to qualitative assessment, with interests categorized into seven categories (Table 1). The criteria used to select the primary and secondary scientific interests are based on the model by Perry (1914), according to which the evaluation process consists of two steps: the identification of interest and the subsequent attribution of value. This approach allows the scientific interest of a geosite to be assessed in its most fundamental terms, providing a rigorous basis for any further analysis. Moreover,

Table 1. Description of the seven different categories of primary and secondary scientific values.

Category Number	Description
1	Earth's surface and interaction with the atmosphere area (physical geography, geomorphology; karst; geopedology)
2	Mineralogy and petrography
3	Internal structure of the Earth (structural geology; geophysics; geochemistry; volcanology)
4	Value related to sedimentary processes (stratigraphic geology; sedimentology)
5	Paleontology
6	Values related to the hydrosphere (environmental geology; hydrogeology; glaciology)
7	Others not included in those above (geo-mining, geo-historical; geo-economic)

in this phase, additional values of the geosites were assessed (Reynard *et al.* 2007). Finally, the scientific importance of geosites is assessed qualitatively according to the criteria of "Key Locality" proposed by Brilha (2018).

The following three sections of the descriptive form address the potential utilization of the geosite and the current state of its conservation:

- **Environmental Dynamics:** Natural or anthropogenic processes that have an influence on the geosite, to assess its stability and any critical issues related to environmental dynamics. The sources for this section are from the literature and direct observation.

- **Potential use of geosite:** Possibilities of using the geosite, in terms of accessibility, tourist use, the presence of services and facilities and the visibility of the geosite from nearby viewpoints. Moreover, potential hazards for visitors are identified. The categories are based on criteria for evaluating the potential use of geosites that have been widely explored in the literature (Panizza 2001; Reynard 2009; Gray 2013; Brilha 2016; Mucivuna *et al.* 2022).

- **Protection, conservation and valorization:** The final section evaluates the state of conservation and the risk of degradation of geosite in a qualitative manner (Brilha 2016). This enables the formulation of recommendations for its management, particularly regarding 1) geosite protection, understood as any protective action that allows the geosite to be offered to collective knowledge, 2) geosite conservation, understood as any activity aimed at maintaining the integrity, identity and functional efficiency of a geosite, and 3) geosite valorization.

Quantitative evaluation

In the third phase, data from the descriptive forms were used to assess the geosites using the quantitative methodology developed by Bollati *et al.* (2017). The method was developed for a mountainous area in the SVUGGp, the same geopark as the present study, so it is already optimized for the study area and does not need to be modified. As for the descriptive forms, indicators of the methodology are grouped into three categories proposed by many authors (Coratza and Giusti 2005; Reynard 2009; Brilha 2016; Suzuki and Takagi 2018; Santos *et al.* 2020; Mucivuna *et al.* 2022): scientific value (SV), added value (AV), and potential for usage (PU). In addition, the methodology also considered calculated accessibility (CA), intended as the degree of accessibility of the site (Table 2).

Following the assignment of scores for each attribute, the main category values (SV, AV, PU, and CA) were calculated on the basis of pre-determined equations (Table 3). Finally, the total score for each geosite was obtained through an iteration of sums among these macro criteria.

Finally, we carried out some descriptive statistical analyses on the main results of the geosites inventory. We focused on comparing the quantitative and qualitative assessments to understand the relative merits of each. This phase was important for territorial management because it gave a general overview of the geosites of Alagna Valsesia, highlighting patterns such as the main scientific interest, or highlighting those geosites with conservation needs, thus representing an important tool for geoconservation.

Table 2. Categories and indicators on which the methodology of quantitative geosites assessment is based (Bollati et al. 2017).

Scientific value (SV)	RGmP	Representativeness of the (paleo) geomorphological process
	RGP	Representativeness of the geological process
	EE	Educational exemplarity
	Gd	Intrinsic site geodiversity
	GI	Geohistorical importance
	ESR	Ecologic support role
	In	Integrity
	ra	Rareness
Additional value (AV)	Cu	Cultural value
	Ae	Aesthetic value
	Sec	Socio-economic value
Potential for use (PU)	TA	Temporal accessibility
	SAc	Spatial accessibility
	Vi	Visibility
	Ses	Services
	NT	Number of tourists
	SAs	Sport activities
	LCs	Legal constraints
	UGI	Use as geoheritage-related interest
	UAI	Use of additional interests
	SGs	Geo(morpho)sites in the surroundings
Calculated accessibility (CA)	Ti	Typology
	SL	Sloping
	SI	Slope inclination
	TI	Tourist information
	Wi	Width
	GM	Ground material
	SM	Slope material
	St	Steepness
	WSP	Water/snow on the path
	DC	Degree of path conservation

Results

The qualitative and quantitative assessment phase of 25 potential geosites enabled the observation, documentation and mapping of the geosites of Alagna Valsesia (Table 4). The methodology employed to map the geosites was the one proposed by Coratza *et al.* (2021), which integrates numerous useful pieces of information into a single map which has some advantages: for instance, it provides an overview of the landforms and the processes of the area; gives details about the current state of geomorphological activity; and highlights the boundaries of the geosites, all helpful for managerial decision-making.

Table 3. Equations to calculate the macrocriteria of the quantitative geosites assessment (Bollati et al. 2017).

Abbr.	Macrocriteria	Equations	Range of Values
SV	Scientific value	SV = (RGP + RGmP + EE + Gd + GI + ESR + In + Ra)	0–8
AV	Additional value	AV = (Cu + Ae + SEc)	0–3
GV	Global value	GV = (SV + AV)	0–11
IU	Index of use	IU = EE+ Ae	0–2
PUss	Potential for use	PUss = (TA + Vi + Se + NT + SA + LC + UGI + UAI + SGs)	0.25–9
PPU	Partial potential for use	PPU = (PUss + IU)	0.25–11
CA	Calculated accessibility	CA = (Ti + St + Sl + Wi + GM + WSP + SI + SM + DC + HI + TI)	0–11
AFc	Accessibility factor (on foot)	if SAc ≤ 0.4; AFc = (CA/11) × 0.5	0–0.5
AFs	Accessibility factor (other)	if SAc ≥ 0.6; AFs = SAc	0.6–1
SIn	Scientific Index	SIn = (RGmP + GI + GM)/3	0–1
EIn	Educational Index	EIn = [EE + Ae + (Afc-s)]/3	0–1
PUc	Potential for use (on foot)	PUc = PPU + AFc	0.25–12
PUs	Potential for use (other)	PUs = PPU + AFs	0.25–12
TS	Total Score	TS = GV + Puc-s	0.25–23

Qualitative assessment

The qualitative assessment of the geosites, as well as the subsequent analysis of the descriptive forms, resulted in a comprehensive depiction of the geoheritage within the designated study area. This assessment offered descriptive indications of the scientific value and potential utilization of the geosites.

Part One: Scientific Value

Analysis of the information contained in the first part of the form yielded useful results for geoconservation. In addition to information such as coordinates and altitude, crucial for the precise location of the geosites, a key piece of information is the typology of the geosites (Fig. 4), evaluated according to Grandgirard (1997), who proposed a classification of geomorphological landforms based on their structure and complexity. In Alagna Valsesia, most geosites are singular, i.e., characterized by the presence of a unique well-defined morphology. This is important for prioritizing protection measures, based on the uniqueness, representativeness and complexity of the geomorphological forms. For instance, recognizing that a geosite such as *Sesia Kettle* (Fig. 5) is unique, indicates that it may necessitate a greater degree of attention than a multiple or complex geomorphological system, where the value of the geosite is distributed over a set of elements and the loss of a single element may have a less critical impact.

The second section is hard to summarize, but it reveals that most of the geosites are associated with the glacial geomorphological history of the region because they show glacial landforms (Fig. 6). This section of the form was useful in the compilation of the third section, which focuses on the scientific values of geosites.

We confirm that the scientific values most frequently associated with the Alagna Valsesia geosites were geomorphological and glaciological.

Table 4. List and description of the 25 potential geosites of Alagna Valsesia.

Code	Name	Description
G1	Parrot glacier	Glacier on the Sud slope of the Monte Rosa massif
G2	Piode glacier	The biggest glacier on the Sud slope of the Monte Rosa massif
G3	Vigne glacier	Glacier on the Sud slope of the Monte Rosa massif
G4	Stofful pasture	Walser pasture where “pietra ollare”, a typical rock, were extracted
G5	Cimalegna plateau	High-altitude plateau characterized by glacially shaped landscapes and rich alpine biodiversity.
G6	Pulferstain	Landslide stone fell until the Alagna Valsesia settlements in the XVIII century
G7	Stolemberg	Rocky peak rich in geological history, where Monte Rosa nappe and the Piedmontese zone nappe are in contact
G8	Sesia kettle	Natural rock basins carved by the Sesia River, showcasing unique erosional features and crystal-clear waters
G9	Pile pasture	Scenic alpine pasture, home to traditional Walser huts and offering both stunning views of Monte Rosa and landforms made by ancient glaciers
G10	Fondecco morain	Big morain of the Late Glacial Maximum
G11	Bors plain	Glacio-lacustrine plan representing a hanging mountain valley
G12	Acquabianca waterfall	Stunning cascade where glacial waters plunge over ancient rocks
G13	Sesia springs	Springs of the Sesia river, currently flowing along the Sesia valley
G14	Sesia glacier	Glacier on the Sud slope of the Monte Rosa massif
G15	Pisse waterfall	Waterfall in the Bors valley, highlighting a significant glacial step
G16	Pisse “bocchetta”	High mountain pass where there Monte Rosa nappe and the Piedmontese zone nappe contact
G17	Locce sud glacier	Glacier on the Sud slope of the Monte Rosa massif
G18	Bors glacier	Glacier on the Sud slope of the Monte Rosa massif, modeling factor of the Bors plain
G19	Manganese mines	Historic manganese mines showcasing old extraction techniques and unique mineral formations
G20	S Maurizio gold mines	Ancient gold mines of San Maurizio, revealing centuries-old mining techniques and rich mineral veins in Alagna Valsesia.
G21	Kreas gold mines	It features historic excavations and traces of ancient gold extraction in the heart of Alagna Valsesia.
G22	Flua glacier	Glacier on the Sud slope of the Monte Rosa massif
G23	Otro glacier	Small, hanging glacier that highlights past glacial activity and ongoing climate change effects
G24	Otro valley	Hanging valley of the Sesia valley, with important gravitational landforms and Walser hamlets
G25	Otro kettle	Natural rock basin shaped by water erosion, showcasing unique geomorphological features in the Otro Valley of Alagna Valsesia

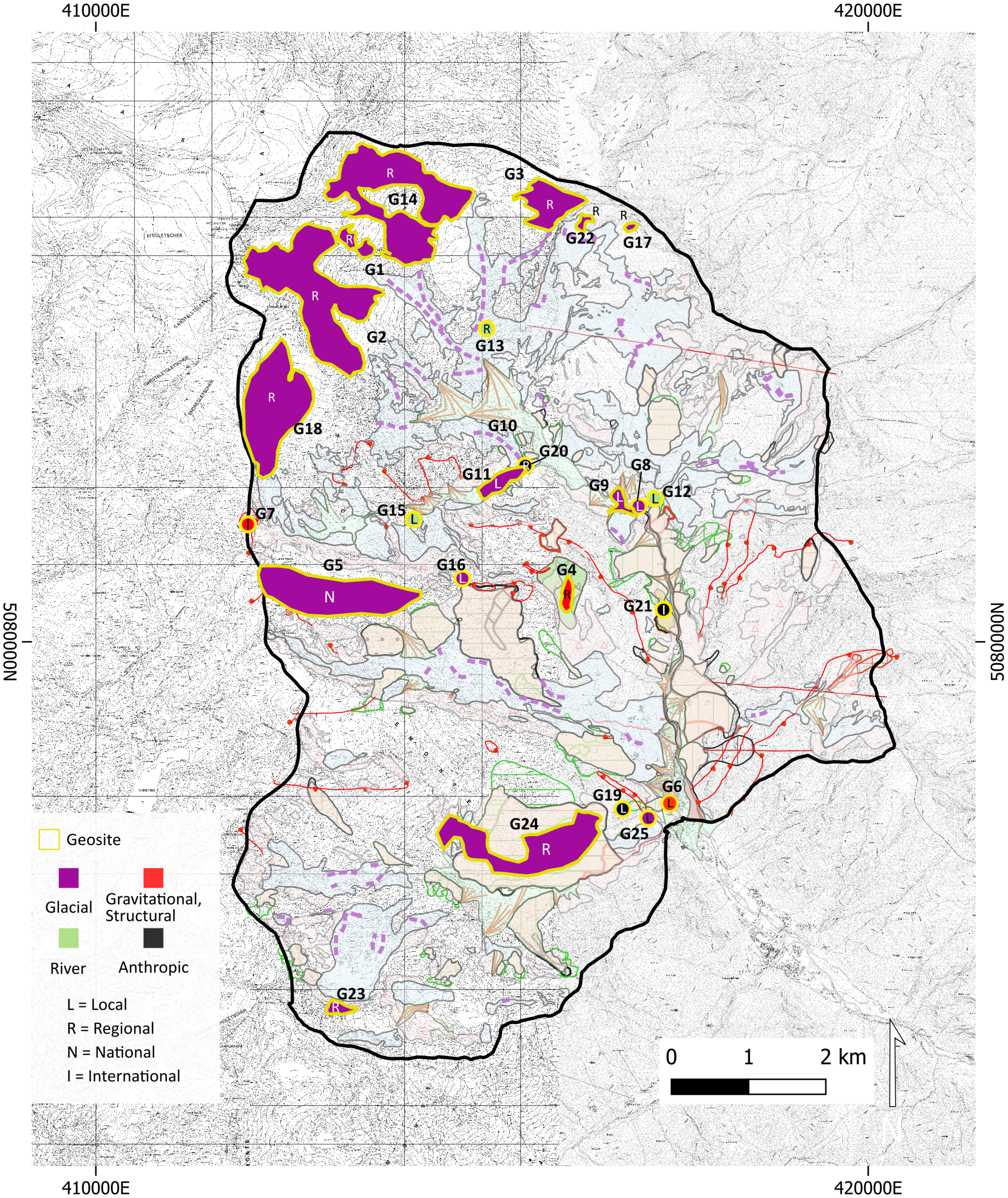

Figure 4. Geosite map of Alagna Valsesia. Geosites can be broad areas, points, or linear. Geosites are highlighted with a symbol with a gold border. The filling is the color of the genetic processes (following the geomorphological legend). Within each circle (or the geosite shape in the case of larger geosites), the letter shows the importance of each geosite.

Figure 5. Photo of the geosite Sesia Kettle, G8, a natural rock basin carved by the Sesia River, showcasing erosional features after glacier retreat.

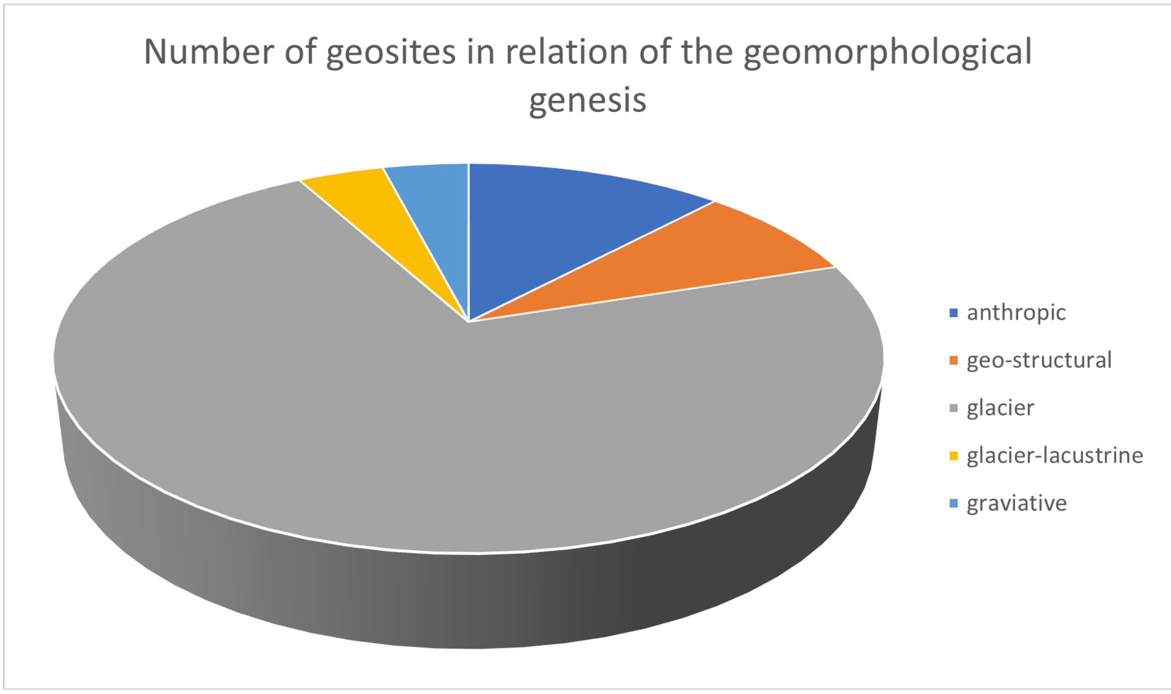

Figure 6. Pie chart showing the number of geosites in relation to the main geomorphological process that contributed to their genesis.

When considering only primary scientific interest, geomorphological interest accounts for 28% of geosites, while glaciological interest accounts for 36%. When considering secondary interest, geomorphology accounts for 48% of geosites, and glaciology 4% (Fig. 7). Thus, 19 geosites have primary or secondary geomorphological interest (i.e., 76% of the total). This is not surprising when considering the significant impact of glaciers on the region, particularly given the prevalence of glacial geosites in the area.

This is broadly true across the entire area; along the entire Alpine chain, there is widespread evidence of recent geomorphological processes, suggesting a high potential for additional geosites within this area. Therefore, we found that almost half of the geosites (12) were classified as having regional interest because they are directly related to the geological framework under consideration, and are thus of only national interest (Brilha 2016). Of these 12 geosites, 11 have a primary or secondary geomorphological scientific value. Of particular note are three geosites identified as having international scientific value: two gold mines with primary geo-mining value and the Stolemberg peak, where a clear tectonic contact emerges, giving it primary geo-structural value (Fig. 8). The descriptive forms indicate that most of the geosites in Alagna Valsesia have both aesthetic and cultural values. Of these, 16 have cultural values linked to the Walser community. Consequently, our inventory can support a comprehensive geoconservation project that aims to enhance the geological and geomorphological history of the region, as well as the historical relationship between nature and human communities living in this area.

Part Two: Potential Use and Management

The second part of the descriptive forms provided results on the potential use of geosites, their conservation status and numerous management recommendations for their preservation, especially from the environmental dynamic section. As might be anticipated, given the preponderance of glacial geosites in the area, the primary vulnerability is the impact of climate change, with 48% of the geosites affected (Fig. 9). Thus, it can be concluded that, although only 24% of the geosites are affected by human activities, most of the geosites are impacted by the effects of human-induced climate change. Moreover, looking at accessibility, 18 of the 25 inventoried geosites are only accessible on foot. Further, 12 geosites (48%) are only accessible during the summer months, while only four geosites (16%) are available all year round. In

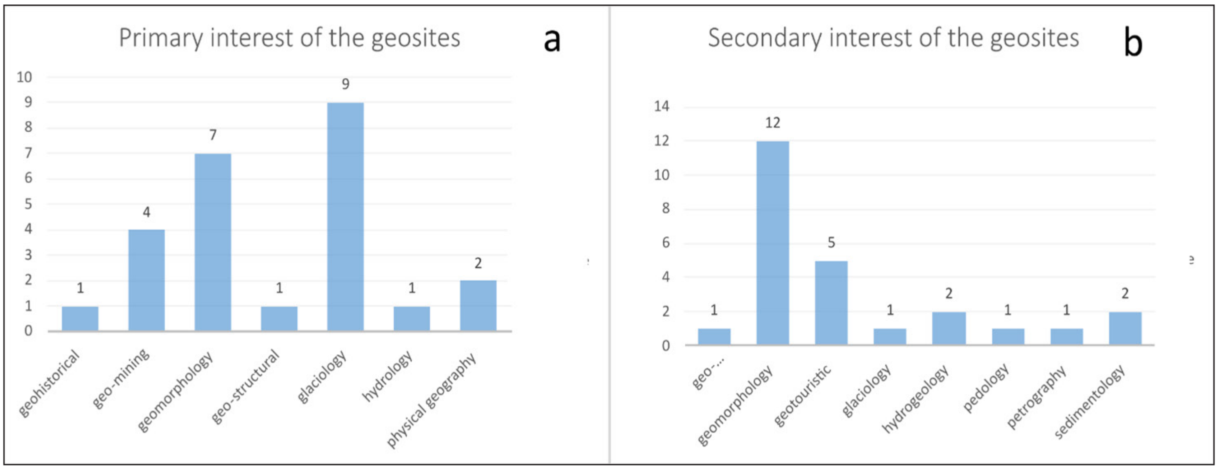

Figure 7. A) Pie chart of the number of geosites in relation to the primary ninterest; **B)** pie chart of the number of geosites in relation to the genetic processes.

Figure 8. Photo of the Stolemberg peak during winter. Photo: Idéfix, Wikimedia Commons

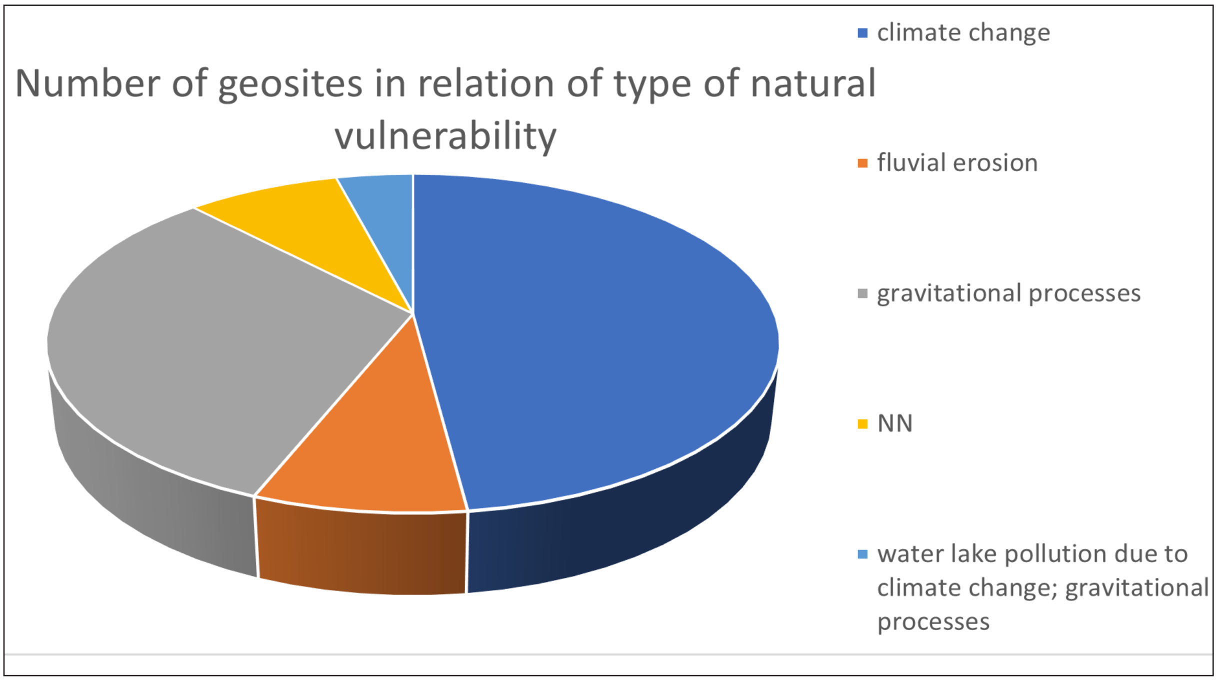

Figure 9. Pie chart showing the number of geosites in relation to their natural vulnerability.

fact, Alagna Valsesia is an alpine area in the foothills of Monte Rosa, and geosites can be found at different altitudes, with some reaching over 3,000 m above sea level, hardly accessible during the winter (only very few would be accessible by cable car).

The last section provided interesting results on the conservation status of geosites, indicating that many are in bad condition (36%). Further, when considering the degradation risk, 17 out of 25 geosites are reported to have a high or medium risk of degradation. Consequently, for 18 out of 25 geosites, a need for conservation (either necessary or suggested) was reported. Interestingly, there appears to be no correlation between the status of geosites and their occurrence in protected areas.

Quantitative Assessment

The quantitative analysis of all 25 geosites, employing the methodology of Bollati *et al.* (2017) illustrates the macrocriteria scores of each geosite (Table 5). By focusing on the primary values of the assessment (Fig. 10), five geosites show global values. Notably, these geosites do not correspond with those previously identified as being of international scientific value, with the exception of Stolemberg. This is confirmed by the analysis of the total score of geosites, which considers all calculated macro-criteria (Fig. 11). Finally, as proposed by Possenelli *et al.* (2024), the methodology suggests that only potential geosites with scientific value greater than 4 should be considered as representative of the area. In Alagna Valsesia, 18 of the 25 potential geosites can be identified as such.

Discussion and Conclusion

This study provides a qualitative and quantitative evaluation of 25 potential geosites in Alagna Valsesia, a significant mountainous and tourist area within the SVUGGp. A descriptive form was developed to support an inventory of geosites for qualitative assessment. Despite numerous studies that have resulted in inventories and assessments of local or regional geosites in Italy (Waele *et al.* 1998; Pica *et al.* 2016; Coratza *et al.* 2019; Ferrando *et al.* 2021; Fancello *et al.* 2022; Sisto *et al.* 2022; Chimento *et al.* 2023) and the national inventory of geosites (Giovagnoli 2023), the form used in this study enables a comprehensive characterization of each geosite. This is because it uses an ontology-based working scheme, which improves accuracy and consistency of the information (Mantovani *et al.* 2020a, 2020b). In particular, our methodology first identifies the elements of interest in geosites, which then allows for the evaluation of various attributes, including scientific interest, additional interests and potential use of geosites. This methodology involves recalling attributes deemed important and widely used in the literature (Reynard 2009; Rolfo *et al.* 2015; Brilha 2016; Poiraud *et al.* 2016; Zangmo *et al.* 2020; Mucivuna *et al.* 2022). Further, as in previous studies (Carrión-Mero *et al.* 2020; Saurabh *et al.* 2021), we show that a qualitative assessment can evaluate these elements, identify the state of integrity and risk of geosites and suggest solutions to be delivered to territorial managers.

On the other hand, quantitative assessment does not allow for the richness of information that is characteristic of qualitative research. Rather, it seeks to index these values in figures, risking a loss of complexity of the information (Štrba *et al.* 2018). However, quantitative assessment does have certain advantages over qualitative assessment, in that it reduces subjectivity and the limitations of qualitative assessment (Fassoulas *et al.* 2012; Brilha 2016; Mucivuna *et al.* 2022; Pasquaré Mariotto *et al.* 2023). Qualitative assessment produces a text that describes numerous characteristics of a geosite, including its value and potential use, which can be useful for each geosite but may be difficult for local tourism operators to use in developing broader geotourism plans (Mariani 2006; Štrba *et al.* 2018). Conversely, quantitative assessment facilitates the comparison of geosites according to diverse attributes, contingent upon the assessment methodology employed. This results in a more comprehensive understanding of how geosites can be utilized within a spatial strategy (Gönczy *et al.* 2020). In our study, we found that five geosites in Alagna Valsesia had a higher total score, designating them as the primary geosites in a unified geotouristic offer. Indeed, a comprehensive inventory of geosites as presented here enables the development of geotourism opportunities that facilitate the public's engagement, such as

Table 5. Final result of the quantitative assessment of the geosites, showing a quantitative value per geosite for each macrocriteria

		G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11
TS	Total Score	14.84	14.84	14.84	12.67	17.39	8.67	14.41	15.91	17.33	13.22	16.79
PUs	Potential for use (other)	8.15	8.15	8.15	6.82	10.22	7.63	6.59	9.62	10.92	8.22	8.67
PUc	Potential for use (on foot)	8.00	8.00	8.00	6.67	9.55	7.01	6.57	9.24	10.66	8.05	8.62
EIn	Educational Index	0.68	0.68	0.68	0.58	0.67	0.24	0.62	0.74	0.78	0.41	0.78
SIn	Scientific Index	0.56	0.56	0.56	0.45	0.67	0.00	0.89	0.44	0.33	0.56	0.67
AFs	Accessibility factor (other)	0.20	0.20	0.20	0.40	1.00	1.00	0.20	0.60	0.60	0.40	0.40
AFc	Accessibility factor (on foot)	0.05	0.05	0.05	0.25	0.33	0.38	0.18	0.22	0.34	0.23	0.35
CA	Calculated accessi-bility	1.20	1.20	1.20	5.45	7.35	8.27	3.86	4.93	7.57	4.95	7.71
PPU	Partial potential for use	7.95	7.95	7.95	6.42	9.22	6.63	6.39	9.02	10.32	7.82	8.27
PUss	Potential for use	5.95	5.95	5.95	4.92	7.55	6.30	4.72	7.02	8.32	6.82	6.27
IU	Index of use	2.00	2.00	2.00	1.50	1.67	0.33	1.67	2.00	2.00	1.00	2.00
GV	Global value	6.84	6.84	6.84	6.00	7.84	1.66	7.84	6.67	6.67	5.17	8.17
AV	Additional value	2.67	2.67	2.67	1.83	2.00	0.83	1.67	2.67	3.00	1.17	2.17
SV	Scientific value	4.17	4.17	4.17	4.17	5.84	0.83	6.17	4.00	3.67	4.00	6.00

Table 5. Final result of the quantitative assessment of the geosites, showing a quantitative value per geosite for each macrocriteria

G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24	G25
9.78	6.91	14.84	13.47	17.44	14.84	14.84	10.30	11.48	12.63	14.84	11.60	17.55	11.26
7.80	3.08	8.15	7.85	9.29	8.15	8.15	5.23	5.20	7.10	8.15	5.75	9.77	6.47
7.12	3.08	8.00	7.64	8.77	8.00	8.00	5.15	4.97	6.62	8.00	5.60	9.72	6.26
0.38	0.18	0.68	0.51	0.65	0.68	0.68	0.38	0.45	0.33	0.68	0.52	0.78	0.73
0.11	0.00	0.56	0.22	0.67	0.56	0.56	0.22	0.45	0.45	0.56	0.56	0.55	0.33
1.00	0.20	0.20	0.40	0.80	0.20	0.20	0.40	0.40	0.80	0.20	0.20	0.40	0.40
0.32	0.20	0.05	0.19	0.28	0.05	0.05	0.32	0.17	0.32	0.05	0.05	0.35	0.19
7.00	4.44	1.20	4.15	6.18	1.20	1.20	7.03	3.67	7.00	1.20	1.00	7.62	4.11
6.80	2.88	7.95	7.45	8.49	7.95	7.95	4.83	4.80	6.30	7.95	5.55	9.37	6.07
5.97	2.55	5.95	6.12	6.82	5.95	5.95	4.00	3.63	5.63	5.95	4.05	7.37	4.07
0.83	0.33	2.00	1.33	1.67	2.00	2.00	0.83	1.17	0.67	2.00	1.50	2.00	2.00
2.66	3.83	6.84	5.83	8.67	6.84	6.84	5.15	6.51	6.01	6.84	6.00	7.83	5.00
0.83	1.33	2.67	2.67	2.50	2.67	2.67	1.83	1.83	1.33	2.67	1.83	3.00	1.33
1.83	2.50	4.17	3.16	6.17	4.17	4.17	3.32	4.68	4.68	4.17	4.17	4.83	3.67

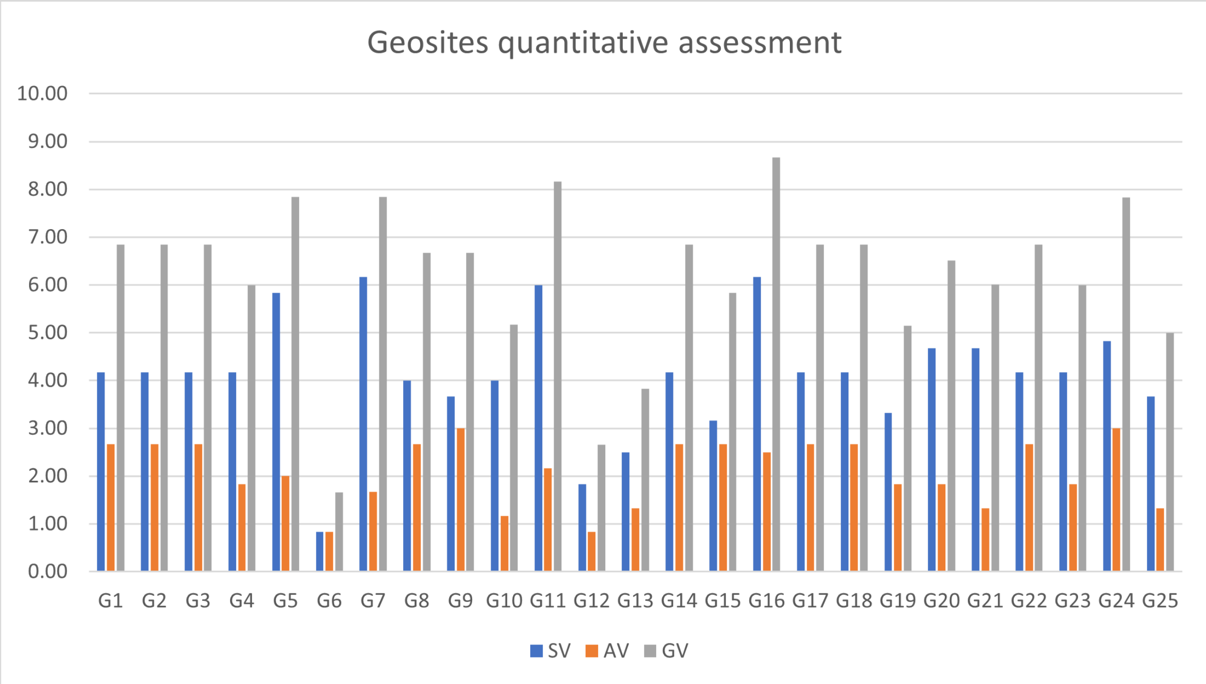

Figure 10. Results of the quantitative assessment of the scientific value, aesthetic value and global value of the 25 potential geosites in Alagna Valsesia.

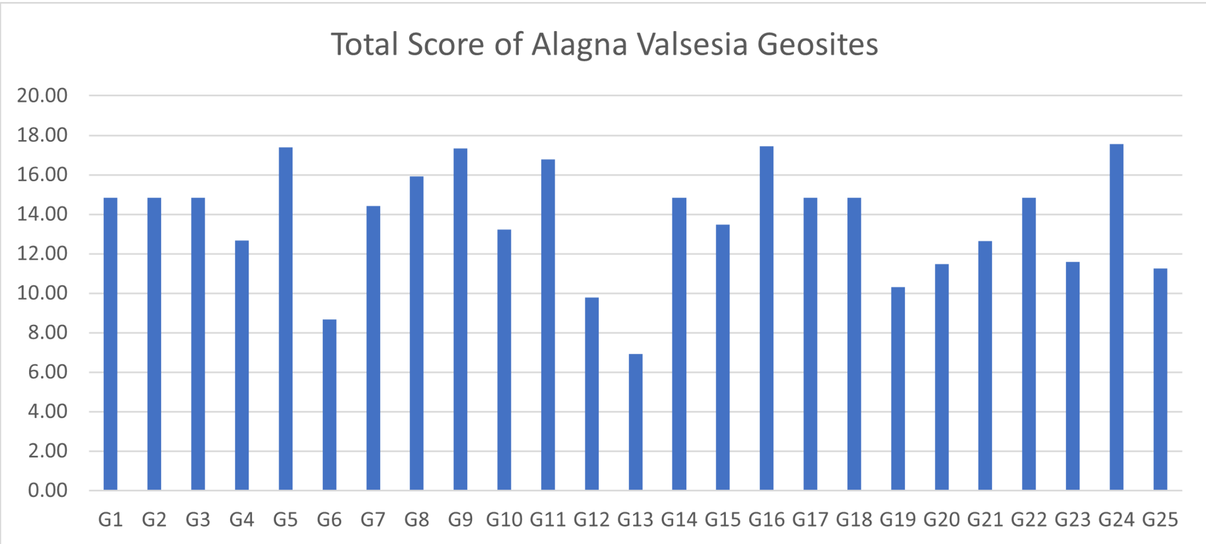

Figure 11. Results of the quantitative assessment of the total score of the 25 potential geosites in Alagna Valsesia.

geotrails (e.g., Pereira and Alves 2020).

In conclusion, both methods have benefits and limitations. Having compared both methods, we can say that they are complementary and must be integrated with each other. The qualitative method, by providing more detailed information, could be more useful for geoconservation. In this sense, an inventory of geosites characterized by a comprehensive and scientifically based descriptive form, such as the one presented in this study can be a crucial tool for spatial managers engaged in geoconservation of natural and cultural assets and on the promotion of education and geotourism. On the other hand, the quantitative method, allowing a less subjective analysis and thus enabling a comparison between geosites, may be more useful for the development of a regional geotourism strategy.

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Data Availability Statement

Original Data available via the Zenodo Digital Repository https: //doi.org/10.5281/zenodo.12191779

Conflict of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflict of interest statement

The authors declare that there are no conflicts of interest associated with this study.

Authors' contributions

Michele Guerini: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, text writing, visualization.

Arianna Negri: methodology, investigation, validation, text writing.

Alizia Mantovani: methodology, validation, text writing.

Marco Giardino: methodology, validation, supervision.

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