Geodiversity assessment for geomorphosites management: Derborence and Illgraben, Swiss Alps

Alicja Najwer[1]*, Emmanuel Reynard[2] and Zbigniew Zwoliński[1]

[1]Institute of Geoecology and Geoinformation, Adam Mickiewicz University in Poznań, 61-680 Poznań, Poland

[2]Institute of Geography and Sustainability and Interdisciplinary Centre for Mountain Research, University of Lausanne, CH-1015 Lausanne, Switzerland

AN, 0000-0002-9778-7895; ER, 0000-0001-5980-9902; ZZ, 0000-0002-3252-3143
*Correspondence: alijas@amu.edu.pl

Abstract: The paper reports on a geodiversity assessment method at the local scale based on spatial multi-criteria analysis (S-MCA). The study area consists of two geomorphosites: Derborence and Illgraben, located in the Swiss Alps and representative of different types of morphodynamics. Apart from glacial and fluvial landforms, the morphology of these two sites is largely due to extreme phenomena (rockslides, torrential processes). Both areas were incorporated in the list of Swiss geosites for their geomorphological interest. The geodiversity assessment criteria were selected and presented on five factor maps: the relief energy (relative height), the landform fragmentation, the landform preservation, the geological setting and the hydrological factor. The factor maps were aggregated using the weighted linear combination (WLC) technique. The accuracy of the final geodiversity maps of Derborence and Illgraben was verified during a field inspection. The final maps were qualitatively assessed in terms of the geodiversity value of specific areas within the selected geomorphosites. The proposed method allows assessing the intrinsic geodiversity differentiation of large geosites, in particular in protected and conserved areas (PCAs). The results can be used for purposes such as the designation of most valuable parts of the area for the preservation of certain abiotic features, spatial planning or tourism management, at least in the alpine fold mountains.

The growing interest in geoconservation and the wellbeing of our natural environment has moved over the last two decades far beyond the realms of governments, decision makers and media into the wider public arena (Newsome *et al.* 2013; Crofts 2018; Gordon *et al.* 2018). Caring about the natural environment is becoming more and more popular. Nowadays, in the social media era, many campaigns focus on the values and diversity of the nature, asking to keep its beauty for future generations. The #NatureForAll movement (http://natureforall.global/) is an example. The campaign was formally launched in 2016 by the International Union for Conservation of Nature (IUCN). It aims to build support and promote action for nature conservation by raising awareness and facilitating experiences and connection with the natural world. Another example is the concept of conserving nature's stage (CNS), where the assumption that conservation of geodiversity is of key importance for the preservation of biodiversity is particularly emphasized (Beier *et al.* 2015). Recently, an important achievement of the scientific community has been the establishment of the 'International Geodiversity Day' in order to increase global awareness of geodiversity and geoheritage (Brilha *et al.* 2021; Zwoliński *et al.* 2021). This event will enable coordinated activities around the world, and it is expected to include public educational, awareness raising and policy engaging activities.

The term 'geodiversity' was first used in 1993 (Sharples 1993; Wiedenbein 1993), and in the broader context, it was related to the issues of geoheritage and geoconservation. Rapidly, the concept of geodiversity was accepted by scientists worldwide (Kiernan 1996; Eberhard 1997; Australian Heritage Commission 2002; Gordon *et al.* 2002; Gray 2004; Kozłowski 2004; Zwoliński 2004). There are three main concepts related to the theory of geodiversity (Mizgajski 2001; Najwer and Zwoliński 2014). The classical connotation has evolved through research works of Australian geologists and geomorphologists (Sharples *et al.* 2018), and concerns mainly lithosphere conservation. In the second concept, geodiversity is considered as the basis for analyses conducted on biodiversity, and differentiation of the abiotic subsystem was pondered collaterally, usually as an auxiliary variable (Barthlott *et al.* 1999; Hjort *et al.* 2015; Ren *et al.* 2021). The third concept departs from the classical (geological) definition of geodiversity and is characterized more broadly, including topography, elements of the

From: Kubalíková, L., Coratza, P., Pál, M., Zwoliński, Z., Irapta, P. N. and van Wyk de Vries, B. (eds) 2023. *Visages of Geodiversity and Geoheritage*. Geological Society, London, Special Publications, **530**, 89–106.
First published online January 9, 2023, https://doi.org/10.1144/SP530-2022-122

hydrosphere and human activity, among others. For the purpose of this paper, the most holistic definition of geodiversity (Gray 2013) was accepted.

In the nature conservation community, the concepts of biodiversity and ecosystem services have become widely accepted, whilst the importance of geodiversity often goes unrecognized and undervalued (Gray 2011; Najwer and Zwoliński 2014; Najwer *et al.* 2016; Gordon *et al.* 2018; Zwoliński *et al.* 2018; Crofts *et al.* 2020). Despite recognized relationships between geodiversity and biodiversity (Parks and Mulligan 2010; Brazier *et al.* 2012; Hjort *et al.* 2012; Bétard 2013; Najwer *et al.* 2016; Tukiainen *et al.* 2017, 2019), the legal systems in many countries protect mostly biotic nature (Kostrzewski 2011; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019). That situation is reflected in the development of biodiversity assessment methods, while research on geodiversity is rather neglected (Najwer and Zwoliński 2014; Najwer *et al.* 2016, 2022; Gordon *et al.* 2018; Zwoliński *et al.* 2018; Boothroyd and McHenry 2019; Jankowski *et al.* 2020).

The lack of a commonly accepted methodology is clear. In 2013, the International Association of Geomorphologists' (IAG/AIG) Working Group on Landform Assessment for Geodiversity was established, with one of its aims being to standardize geodiversity assessment methods. Depending on the data source, Pellitero *et al.* (2014) specified direct and indirect methods of geodiversity assessment. In turn, Zwoliński *et al.* (2018) described quantitative, qualitative and qualitative–quantitative methods. At the current stage of development of geodiversity assessment methods, the latter are the most advanced ones. Their particular advantage is the capability of integrating diverse types of data sources and substantive content with the simultaneous use of expert knowledge and, above all, the possibility of use for research areas at various spatial scales (Zwoliński *et al.* 2018).

Geodiversity maps vary depending on the spatial scale, the available data and the purpose. Examples described in the literature mainly refer to areas at the local or regional scale, although implementation is also possible for large spatial units such as large protected areas, drainage basins, countries or states (Benito-Calvo *et al.* 2009; Zwoliński and Stachowiak 2012; Pereira *et al.* 2013; Najwer *et al.* 2016; Manosso *et al.* 2021). Most often, geodiversity maps are based on geological diversity and are designed to evaluate areas in terms of tourist attractiveness (Sapp *et al.* 2006; Zwoliński 2010; Serrano and González Trueba 2011; Asrat *et al.* 2012; Zwoliński and Stachowiak 2012). In some studies, geodiversity maps were created and applied to investigate the spatial or genetic relationships with the richness of particular environmental components (Burnett *et al.* 1998; Silva 2004; Jačková and Romportl 2008; Hjort *et al.* 2012). There are also examples of geodiversity assessment to efficiently manage protected and conserved areas (Pellitero *et al.* 2011, 2014; Serrano and González Trueba 2011; Melelli 2014; Perotti *et al.* 2019). In some studies, geodiversity maps were applied to investigate the relationships between geodiversity and geosites, geomorphosites, geoarchaeological and palaeontological sites (Panizza 2009; Serrano and Ruiz-Flaño 2009; Pellitero *et al.* 2011; Chrobak *et al.* 2021). However, so far, the spatial differentiation of geodiversity values in areas already accepted as large geomorphosites has not been undertaken. Despite the fact that the concept of geodiversity has a solid theoretical foundation, it does not benefit from a universal method and standards for its evaluation yet.

Climate changes, in addition to anthropogenic influences, are widely regarded as one of the most serious threats to the natural environment (Prosser *et al.* 2010). Frequency and intensity of extreme phenomena have significantly increased in recent years (Shukla *et al.* 2019; IPCC 2021). Furthermore, this trend is likely to continue in the upcoming decades. Climate variability primarily induces variations in the magnitude and frequency of Earth surface processes and, consequently, important changes in the landscape (Kostrzewski 2011; Gordon *et al.* 2022). As a result, abiotic heterogeneity may be threatened and the key elements of natural diversity even lost (Gordon *et al.* 2002; Kozłowski *et al.* 2004; Ruban 2010; Hjort and Luoto 2012; Gray 2013). Interestingly, ongoing climate changes not only contribute to the degradation of existing geodiversity but may also increase it (Gordon *et al.* 2022). Climate changes pose challenges for the management of geoheritage in protected and conserved areas (PCAs) at all spatial scales, from individual geosites to whole landscapes and even regions (Selmi *et al.* 2022).

Recognizing the parts of a territory that are the most diversified and vulnerable to changes is a crucial issue for management and planning of PCAs. It allows forecast changes in the environment and, above all, it enables the assessment of the suitability of environmental conditions to perform certain socio-economic functions (Richling and Solon 2011). The specific aims of this paper are: (1) to propose a method for geodiversity assessment for high mountainous areas characterized by passive and active morphodynamics, (2) to apply and verify the proposed method for the assessment of geomorphosites. The proposed method can be useful for the environmental management of natural protected areas at local and regional scales as well as for recognizing and assigning the most diversified parts of the territory to preserve for future generations.

Study areas

The study areas consist of two catchments in the Western Swiss Alps: Derborence in the Bernese Alps and Illgraben in the Penninic Alps, separated by the Rhone valley (Fig. 1). Apart from glacial and fluvial processes, which have shaped the morphology of the whole Rhone River catchment, the morphology of these two sites is largely due to extreme phenomena, i.e. rock avalanches in Derborence (Maret and Reynard 2015; Schoeneich and Reynard 2021) and torrential processes at Illgraben (McArdell and Sartori 2021). Illgraben catchment and Derborence were incorporated in the list of Swiss geosites (Reynard *et al.* 2012; Federal Office of Topography swisstopo and Swiss Academy of Sciences 2012) for their geomorphological interest, i.e. geomorphosites.

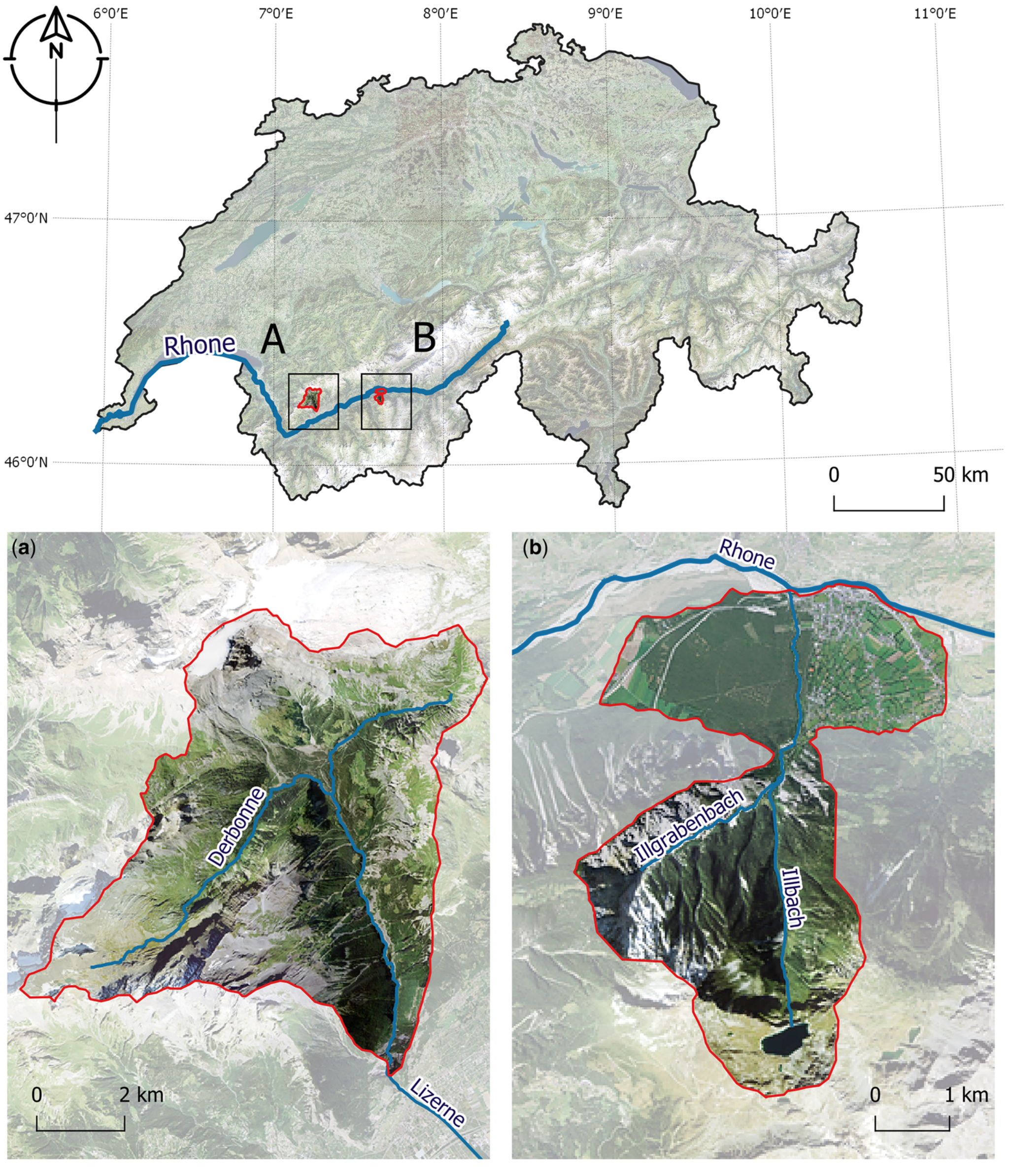

Fig. 1. Location of the studied catchments: (**a**) Derborence and (**b**) Illgraben on orthophotos of Switzerland with 25 m resolution. Source: Federal Office of Topography swisstopo 2016.

According to Panizza (2001), geomorphosites can be defined as landforms to which a value can be attributed. They can be single landforms, complexes of landforms (several landforms related to one process) or geomorphological systems (several landforms, several processes) (Grandgirard 1999; Reynard and Panizza 2005). They are testimonies of climate and environmental changes, as tectonic or denudational evolution and some related changes in the history of Earth surface. They make the reconstruction of palaeoprocesses and palaeoclimates possible, and allow the observation of current acting processes and geomorphological features (Reynard and Coratza 2013). Furthermore, geomorphosites play a significant role in landscape evaluation, particularly in sensitive geoecosystems, where climate changes induce variations in the magnitude and frequency of surface processes and, as a further consequence, important changes in the landscape (Pelfini and Bollati 2014). In order to express the dynamics of landscape systems, active, passive and evolving passive geomorphosites have been distinguished (Pelfini and Bollati 2014). Active geomorphosites allow the visualization of geomorphological processes in action (Reynard 2004). Passive geomorphosites testify to past environments and processes; they are an archival record of the history of Earth (Reynard 2005). Evolving passive geomorphosites are landforms created under processes no more in action, which are reshaped by currently active processes (Pelfini and Bollati 2014).

Derborence (Fig. 1a) covers the upper part (60.4 km^2) of the Lizerne catchment, a tributary of the Rhone River. For this study, the research area has been delimited by hydrographic analyses and is not exactly the same as the site incorporated in the list of Swiss geosites. Derborence is located in the Diablerets Massif, a limestone massif of the Bernese Alps (Schoeneich and Reynard 2021). The highest peak is Les Diablerets, 3210 m a.s.l. (Fig. 2a), which overlooks the Diablerets Glacier, which is almost entirely within the boundaries of the research area. The northwestern part of the catchment, where the spectacular Derborence Lake is located, is relatively isolated (Fig. 2b). It was created as the result of two large rock avalanches occurred in AD 1714 and 1749. Consequently, this part of the valley was isolated by a 2 km-long natural barrier and was subsequently covered by forest vegetation. Nowadays, the very shallow lake is threatened by sedimentation due to torrential processes (debris flows). It can be classified as an evolving passive geomorphosite even if large rock avalanches can still happen due to seismic or climatic (ground ice melting) processes. The whole area is a well-known tourist destination, and it attracts large numbers of visitors fascinated by the special character of this unspoilt nature spot (Reynard *et al.* 2021).

The Illgraben catchment is drained by the Illbach torrential stream, a left-bank tributary of the Rhone River (Fig. 1b). The quite small catchment (18.6 km^2) is characterized by a very deeply indented channel and a distinctive alluvial fan (Fig. 3a). The morphology of the Illgraben was largely shaped by debris flows, landslides as well as gully and gorge erosion in a context of highly deformed and fractured rocks, including quartzites, limestone deposits and dolomites, due to tectonic processes (McArdell and Sartori 2021) (Fig. 3b). The Illgraben torrential system is an example of active geomorphosite. The catchment has an extremely high debris-flow frequency (de Haas *et al.* 2020). Particularly, debris-flow activity is marked every year after heavy torrential rainfall events (Gwerder 2007) and during the snowmelt period. Due to the high risk for people settled nearby the channel, a special alarm system was designed (Badoux *et al.* 2009).

Data and methods

Considering the morphological and morphometric peculiarities of the high-mountain catchments of

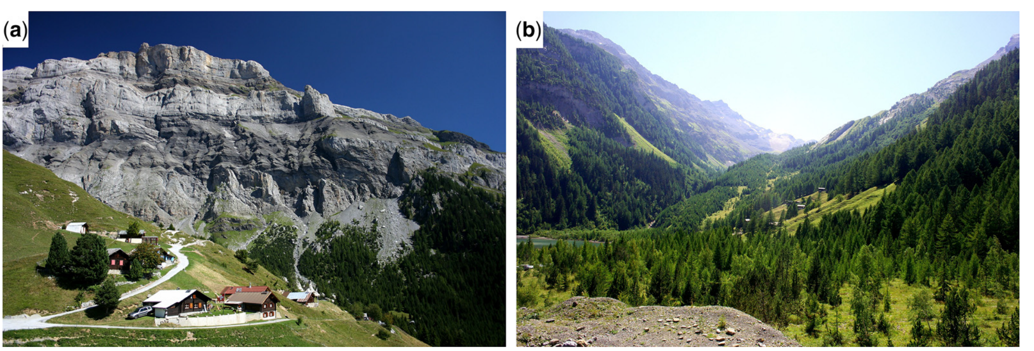

Fig. 2. (**a**) The southern ridge of the Diablerets Massif, which forms the boundary of the Derborence geomorphosite. (**b**) Derborence Lake and Derbonne valley.

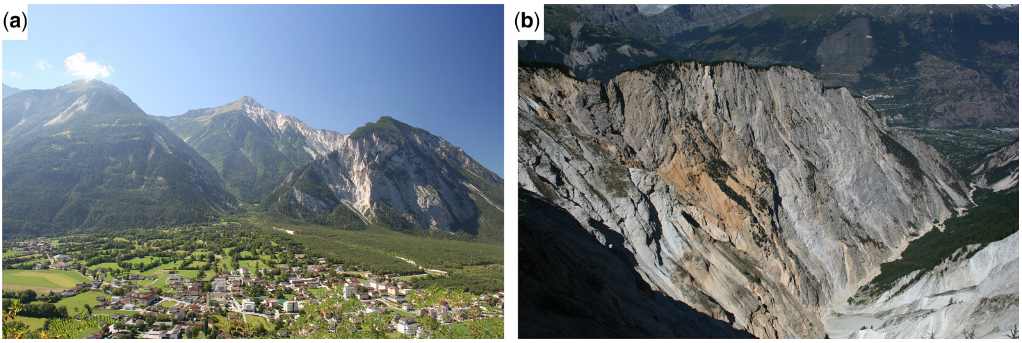

Fig. 3. (**a**) Illbach (left) and Illgraben (right) valley and alluvial fan. (**b**) Upper part of the Illgraben valley.

Derborence and Illgraben as well as their scale, the qualitative–quantitative geodiversity assessment approach (Zwoliński *et al.* 2018) – applying spatial multi-criteria analysis (S-MCA) and weighted linear combination (WLC) – was used. WLC is the most frequently used method of aggregation of Geographical Information Systems (GIS) based on geodiversity assessments. The attractiveness of WLC in S-MCA is related to the ease of calculation and result interpretation (Jankowski *et al.* 2020).

We followed the qualitative–quantitative method introduced by Najwer and Zwoliński (2014) (Fig. 4). The workflow includes five tasks: (1) geodatabase compilation, (2) input data and criteria selection, (3) factor maps geocomputation, (4) multi-criteria analysis, (5) geodiversity map creation. Geographic

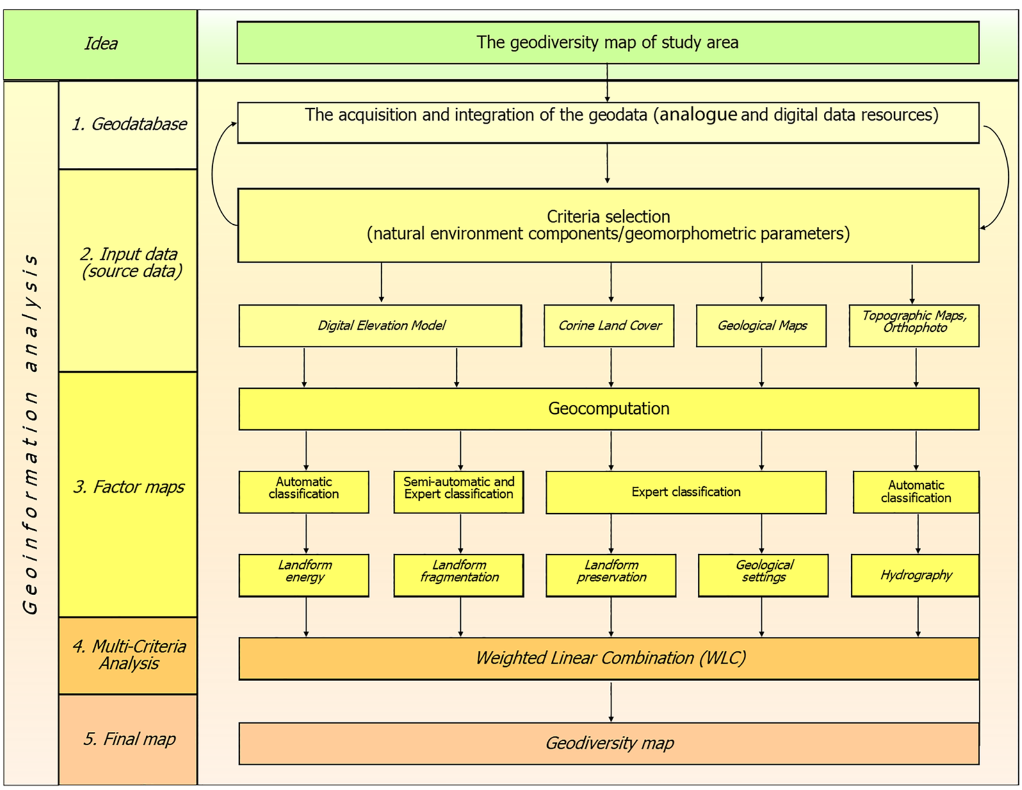

Fig. 4. Workflow of geodiversity assessment of the studied catchments based on Najwer and Zwoliński (2014).

Information Systems (ArcGIS 10.3 and GRASS GIS 7.6.1 software programs) were used for the stage of data collection and integration (task 2) through numerical geoprocessing of spatial data (tasks 3 and 4) to the final geodiversity map (task 5). All the analyses in the research procedure were performed at 25 m resolution.

The challenge in the assessment is to describe landforms and, at the same time, indicate geomorphometric and morphological differences. The most time-consuming stage is the acquisition and integration of analogue and digital resources into the geodatabase (task 1). The source dataset included a 25 m resolution Digital Elevation Model (DHM25, based on the 1:25 000 Swiss national map; Federal Office of Topography swisstopo 2005), CORINE Land Cover at 1:100 000 scale (European Environment Agency (EEA) 2018), geological maps at 1:25 000 scale, topographic maps at 1:25 000 scale and 50 cm resolution orthophotos. In order to avoid errors at the boundaries of the research area (some analyses use the cell neighbourhood), a 1000 m buffer zone (larger spatial extent) was added to all source data. The layers were integrated and transformed to the Swiss CH1903+ (EPSG 2056) coordinate system.

Geodiversity assessment usually involves an individual expert or a group of experts who evaluate the value of the contribution of discrete components of a given factor to the overall result of the geodiversity of the site (Jankowski *et al.* 2020). This input largely depends on the stated aim of the analysis performed and the expert's knowledge and experience. Selection of criteria (task 2) and definition of rules of classification of their individual components were performed with the collaboration of the authors. The geodiversity assessment criteria values for the particular factor maps of Derborence and Illgraben valleys are presented in Table 1. The share of each element of the natural environment in a given factor is expressed by a value on a Likert scale from 1 to 5 (Likert 1932). Continuous factors were classified automatically using the natural breaks method (Jenks 1967).

Five factor maps (task 3) were processed for each selected area (Figs 5 & 6) using ArcGIS 10.3 software:

(A) The **relief energy (relative height) map** was derived from a Digital Elevation Model (DHM25; Federal Office of Topography swisstopo 2005) using the Focal Statistics tool within three map cells neighbourhood (75 m in fact), and automatically reclassified into 5 classes using the Natural Breaks method (Jenks 1967).

(B) The **landform fragmentation map** was geocomputed using the Landform Classification tool (Jenness 2006). A smaller neighbourhood setting (four map cells; 100 m in fact) and a larger one (40 map cells; 1000 m in fact) were used. Ten landform types were derived and then expertly reclassified according to the value of geodiversity.

(C) The **landform preservation map** was obtained using CORINE Land Cover 2018 (EEA 2018) along with a small correction based on high-resolution orthophotos. The factor map was expertly reclassified in terms of relation between natural processes and anthropogenic activities that impact on the preservation of geodiversity. The highest values were assigned to areas not affected by human activity, e.g. bare rocks or bedrock under glaciers. On the other hand, the lowest values of geodiversity were assigned to areas significantly transformed by man, e.g. villages or agricultural areas.

(D) The **geological setting map** was prepared based on the Geological Atlas of Switzerland's analogue and vector maps. Sheets of maps and legends were integrated in ArcGIS. Legends and divergent boundaries in merging of the map sheets were expertly fixed. Finally, 73 geological settings in the Derborence research area and 26 in the Illgraben valley were expertly reclassified into six classes (an additional zero value class was assigned to areas of glaciers and lakes due to the lack of any information about the geological setting beneath them) in terms of possible impact of a particular geological setting on a landform's geodiversity.

(E) The **hydrological factor map** (surface waters: lakes, rivers and streams, glaciers) was derived based on topographic maps along with a small border correction (glaciers extent) with the use of high-resolution orthoimages. Lakes' evaluation was carried out on the basis of the chosen descriptive statistics. Values of area, shoreline development ratio and altitude above sea level were calculated and reclassified with Jenks's natural breaks method into five geodiversity values. The Illgraben area has three lakes, which have been assigned to the highest class of geodiversity. Four glaciers in the Derborence catchment received the highest value from the hydrological point of view. Linear elements (rivers and streams) were divided into 250 m-long segments (from the channel head to the next tributary or mouth of lake), for which, values of longitudinal slope were calculated. Subsequently, the obtained values were automatically reclassified into five classes using Jenks's natural breaks method.

Factor maps were standardized into five classes of geodiversity value (an additional class with a zero value was included for method accuracy, but does not affect the final result of the assessment). After

Table 1. *Geodiversity assessment criteria values for the factor maps of the Derborence and Illgraben sites*

Factor maps	Source data	Classification method	Derborence criteria	Illgraben criteria	Geodiversity value
(A) Relief energy	25 m Digital Elevation Model (DHM25; Federal Office of Topography swisstopo 2005)	Automatic classification with a natural breaks method (Jenks 1967)	Rh: 0–27.8 m	Rh: 0–21 m	1: very low
			Rh: 27.9–48.6 m	Rh: 21.1–45.8 m	2: low
			Rh: 48.7–75.3 m	Rh: 45.9–66.8 m	3: medium
			Rh: 75.4–121.6 m	Rh: 66.9–93.8 m	4: high
			Rh: 121.7–295.3 m	Rh: 93.9–191.3 m	5: very high
(B) Landform fragmentation		Semi-automatic classification and expert classification	Plains; open slopes		1: very low
			Midslope drainages, shallow valleys, midslope ridges, small hills in plains		2: low
			U-shaped valleys, upper slopes, mesas, local ridges, hills in valleys		3: medium
			Canyons, deeply incised streams, upland drainages, headwaters		4: high
			Mountain tops, high ridges		5: very high
(C) Landform preservation	CLC 2018 version v.20b2; orthoimages	Expert classification	Discontinuous urban fabric	Discontinuous urban fabric, sport and leisure facilities	1: very low
			Land principally occupied by agriculture, with significant areas of natural vegetation, broad-leaved forest, mixed forest	Non-irrigated arable land	2: low
			Coniferous forest		3: medium
			Pastures, natural grasslands, moors and heathland, transitional woodland–shrub, sparsely vegetated areas		4: high
			Bare rocks, glaciers and multiyear (perpetual) snow	Bare rocks	5: very high
(D) Geological setting	Geological Atlas of Switzerland 1:25 000 (GA25)	Expert classification	Glaciers and lakes		0
			Marls, flysch and schists	Marls and schists	1: very low
			Surface covers (Quaternary superficial deposits)		2: low
			Alternation of limestones and marls	Gneiss and amphipolites	3: medium
			Cornieules and gypsum	Gypsum and quartzites	4: high
			Dolomites and limestones	Dolomites, limestones and sandstones	5: very high

(*Continued*)

Table 1. *Continued.*

Factor maps	Source data	Classification method	Derborence criteria	Illgraben criteria	Geodiversity value
(E) Hydrological features	Topographic map of Switzerland (National Map 1:25 000)	Automatic classification with a natural breaks method (Jenks 1967)	A: 0.0–0.053 ha D_L :1.04–1.08 H: 559–1332 m a.s.l. S: 0–15.95‰ Br: 125 m	S: 0–6.1‰	1: very low
			A: 0.054–0.245 ha D_L: 1.09–1.26 H: 1333–1374 m a.s.l. S: 15.96–35.32‰ Br: 100 m	S: 6.11–15.07‰	2: low
			A: 0.246–0.995 ha D_L: 1.27–1.36 H: 1375–1452 m a.s.l. S: 35.33–65.34‰ Br: 75 m	S: 15.08–27.17‰	3: medium
			A: 0.996–4.323 ha D_L: 1.37–1.43 H: 1453–2269 m a.s.l. S: 65.35–117.38‰ Br: 50 m	S: 27.18–44.95‰	4: high
			A: 4.324–4.904 ha D_L: 1.44–1.97 H: 2270–2459 m a.s.l. S: 117.39–186.5‰ Br: 25 m Glacier des Diablerets, de Tchiffa; La Forcla; de Tita Naire	A: 0.54–20.88 ha D_L:1.2–1.24 H: 2360–2419 m a.s.l. S: 44.96–84.5‰	5: very high

Key: Rh, relative height; A, lake surface area; D_L, shoreline development ratio; H, lake altitude in metres above sea level (a.s.l.); S, stream segment longitudinal slope; Br, width.

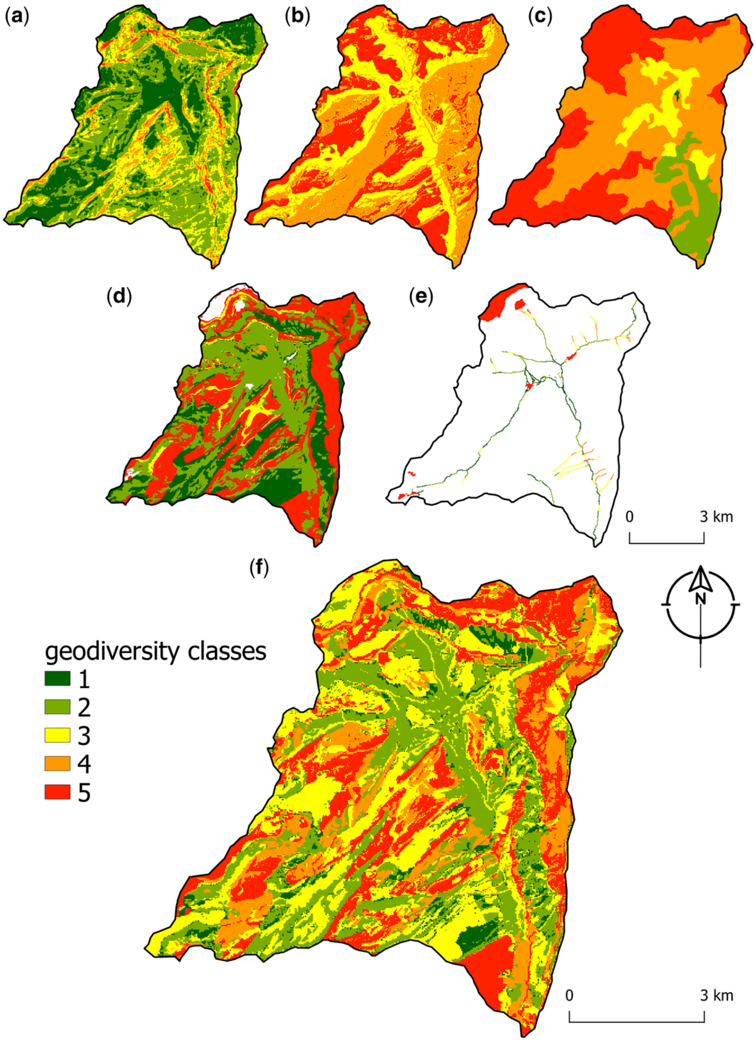

Fig. 5. Derborence factor maps of (**a**) relief energy; (**b**) landform fragmentation; (**c**) landform preservation; (**d**) geological setting; (**e**) hydrological; (**f**) geodiversity normalized to five classes: 1, very low; 2, low; 3, medium; 4, high; and 5, very high geodiversity.

integrating the data and carrying out the necessary geoinformation analyses (geocomputation), the most problematic activity, and one burdened with considerable subjectivity, was to assess the components of the natural environment from the point of view of their potential impact on the geodiversity of the research areas (task 4). Considering the above, weights for the factor maps for the two morphometrically and morphogenetically different catchments were treated individually. In order to objectively determine weights, it was decided to use Saaty's (Saaty 1977, 1980) pair comparison method, implemented in the AHP Priority calculator (Goepel 2018). The weights for the factor maps were calculated (Table 2) and assigned in the WLC analysis to Derborence with the 9.3% and to Illgraben with the 9.1% consistency ratio (CR). The aggregation result for each assessment map unit (in this case, a cell raster with a size of 25 m) is the geodiversity score, represented by the sum of the product of ratings and weights of the individual factor maps. Percentage shares of the areas by geodiversity class have been calculated and presented in Table 3. Using the r.covar tool implemented in GRASS GIS 7.6.1, the correlation matrix for all factor maps and the final geodiversity map were calculated (Tables 4 & 5).

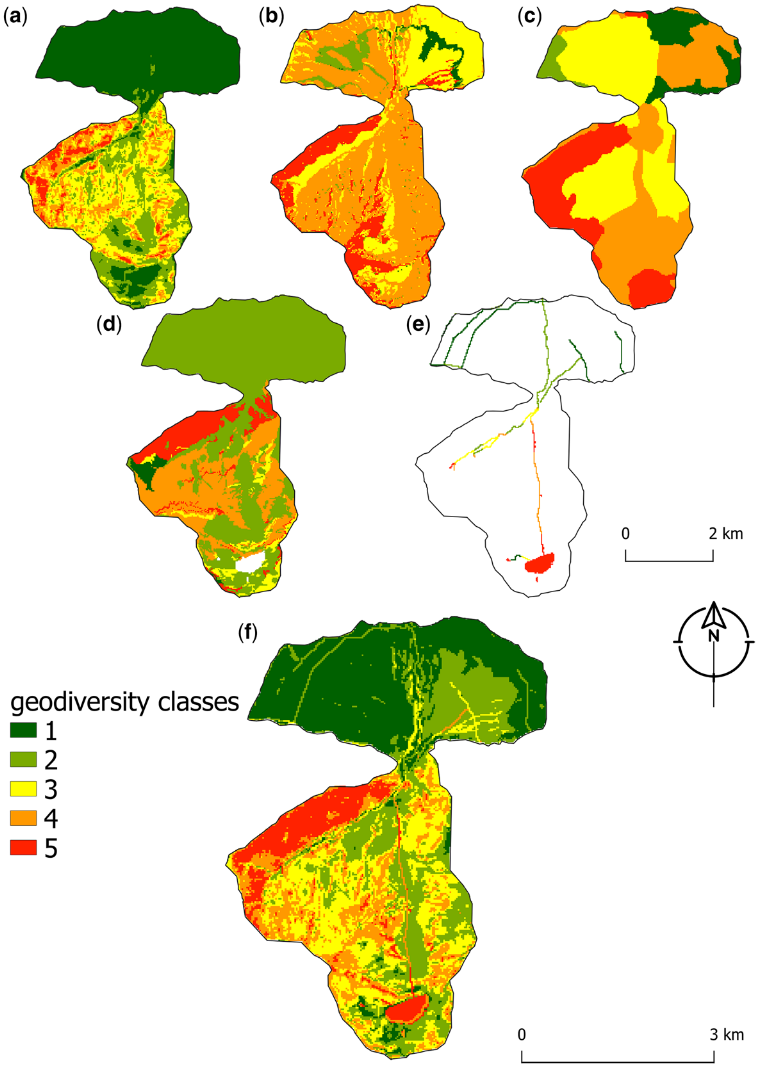

Fig. 6. Illgraben factor maps of (**a**) relief energy; (**b**) landform fragmentation; (**c**) landform preservation; (**d**) geological setting; (**e**) hydrological; (**f**) geodiversity normalized to five classes: 1, very low; 2, low; 3, medium; 4, high; and 5, very high geodiversity.

Results

As a result of the WLC analysis, the final geodiversity maps of Derborence (Fig. 5f) and Illgraben (Fig. 6f) were obtained (task 5). The research procedure for the selected catchments was based on the same workflow, although the classification rules – due to the large variability of the natural environment

Table 2. *Weights assigned for the factor maps in the WLC analysis for Derborence and Illgraben*

Catchment	(A) Relief energy	(B) Landform fragmentation	(C) Landform preservation	(D) Geological settings	(E) Hydrological
Derborence	0.07	0.31	0.04	0.41	0.17
Illgraben	0.33	0.09	0.04	0.19	0.35

WLC, weighted linear combination.

components between the morphogenetically and morphometrically different research areas – and the weights for the factor maps were dissimilar (Table 2).

Factor maps, aggregated to the final geodiversity map of the Derborence area using the WLC method, are presented on Figure 5. The maps of the relief energy (Fig. 5a) and geological setting (Fig. 5d) are characterized by the greatest diversity. Ridges and concentric converging valleys in the centre of the research area can be clearly delineated. The landform fragmentation map (Fig. 5b) stands out from the others because it consists almost entirely of the three highest geodiversity value classes, which represent well the mountain area. Very low and low geodiversity classes cover only single map cells. Completely different is the discontinuous hydrological factor map (Fig. 5e), where most of the study area has no hydrographic features. Glaciers and lakes are characterized by the highest value (Derborence, Le Godey, Lac de la Forcla); this is also the case for small streams although fragmentarily. The highest final geodiversity values of the Derborence study area (Fig. 5f) can be linked to the geological setting factor map (Fig. 5d). There is a strong positive correlation (0.87) between these maps (Table 4). To some extent, the Derborence geodiversity map also reflects well the landform fragmentation ($r = 0.49$). The final geodiversity map does not correlate with the landform preservation and hydrological ones. The correlation is close to zero and amounts to 0.02 and −0.02, respectively (Table 4).

The Derborence area is characterized by a large mosaic (dispersion) of geodiversity classes (Fig. 5f), with the highest percentages being those of medium (28.9%) and low (26.4%) values (Table 3). These are mainly the valleys of the Lizerne River and its tributaries, streams (Derbonne and La Chevillence) feeding Lake Derborence, the area around Lake Derborence and Le Godey reservoir, the Diablerets Glacier, the northeastern slopes of the peaks Haut de Cry and Mont à Perron and the southeastern slopes of Le Pacheu and Tête Pegnat. The highest values cover 22.3% of the research area and are characterized by a significant dispersion. These are mainly rocky mountain ridges: the summits of the Tête à Pierre Grept and Tête Tsernou in the SE, from Quille du Diable in the north to Tête Noire and La Fava in the NW and from the eastern slopes of Mont Gond in the west to Sex Riond in the SE. Moreover, in the central part of the Derborence research area, high geodiversity values are clearly marked by the northern slopes of Tête Pegnat and Mont à Cavouère, which are split by the Derbonne River valley. The high value of geodiversity clearly exposes the stratification of the landscape relief of the northern part of the study area, in the Diablerets Massif. This is controlled by differences in rock weathering resistance. The very low geodiversity class (4.8% of the research area) corresponds mainly to the area of Combe Neire in the southeastern part, the small Tchiffa glacier and Fenadze pasture in the north.

Table 3. *Percentage shares of the areas by geodiversity class in Derborence and Illgraben*

	1: Very low	2: Low	3: Medium (%)	4: High	5: Very high
Derborence	4.8	26.4	28.9	17.6	22.3
Illgraben	29.3	25.5	21.8	14.7	8.6

Figure 6 presents five factor maps corresponding to the geodiversity assessment criteria of the Illgraben area. The relief energy map (Fig. 6a) is characterized by a large mosaic of values, except the alluvial fan, which is distinguished by minimal relative height differences. The glacier-shaped area of the Illsee reservoir in the upper part of the catchment is also characterized by the lowest values. The landform fragmentation map is distinguished by a very high percentage of medium class geodiversity (Fig. 6b), which corresponds to the deeply incised streams and upland drainages (Table 1). In the landform preservation (Fig. 6c) and geological setting (Fig. 6d) maps, the highest geodiversity value is related to bare rocks. The hydrological factor map (Fig. 6e) is the least diversified one due to the discrete nature of the criterion, and is weakly correlated with the final map (Table 5). All the lakes were judged to have the highest value of geodiversity. Almost the entire river Illbach is classified as high and very high value, while the Illgraben is only in small parts. The final geodiversity map of the Illgraben catchment correlates mostly with the relief energy and geological setting factor maps (Table 5).

The final geodiversity map of Illgraben (Fig. 6f) clearly shows two parts of the catchment area: (i) the very dynamic upper part shaped by torrential activity, debris flows, surface runoff and gully and gorge erosion, and (ii) the lower one, in the form of an alluvial fan entering the Rhone valley. The percentage share of the area of geodiversity class at Illgraben differs significantly from Derborence (Table 3). The dominant value of geodiversity is very low, covering 29.3% of the area, and it relates mainly to the alluvial fan and the fragmentary Illsee lake's surroundings. The eastern part of the alluvial fan is associated with a slightly higher geodiversity value class. Low geodiversity value also characterizes the Illbach River valley and the southwestern bank of the Illgraben River. The outstanding northwestern part of the Illgraben riverbank is

Table 4. *Correlation matrix for all factor maps and the final geodiversity map of Derborence*

Derborence	(A)	(B)	(C)	(D)	(E)	(F)
(A) Relief energy	1.00					
(B) Landform fragmentation	0.16	1.00				
(C) Landform preservation	−0.02	0.02	1.00			
(D) Geological setting	0.13	0.10	0.03	1.00		
(E) Hydrological	−0.10	0.05	−0.26	−0.19	1.00	
(F) Geodiversity map	**0.22**	**0.49**	**0.02**	**0.87**	**−0.02**	**1.00**

distinguished by the highest value of geodiversity, which is associated with bare rocks and rock-waste cover. The bedrock is mainly made up of dolomites, limestones, sandstones, marls and schists in the upper part, where the most intense denudation processes take place. As a result, surface mesostructures are the most diversified. The Illsee reservoir and the Illbach River channel, which drains the lake, are also classified as highly diversified areas. The highest value of geodiversity covers only 8.6% of the studied area (Table 3).

Discussion

The percentage shares of the areas by geodiversity class in both geomorphosites are presented in Table 3. The results show that the Derborence catchment is characterized by a higher geodiversity than the Illgraben one. However, such a comparison should be approached with caution due to the different classification rules and weights applied. The comparative analysis of the studied geomorphosites is only methodical. The Derborence catchment has a higher proportion of area with the higher geodiversity values, i.e. 39.9%, while the lower value classes cover 31.2% of the area. In the Illgraben catchment area, the higher classes of geodiversity cover only 23.3%, while the lower classes cover as much as 54.8% of the area. The percentages of these classes reflect the high landscape complexity of the Derborence catchment area, shaped by many weathering and denudational processes. The Illgraben catchment, formed essentially by the occurrence of torrential rainfall and related runoff processes, manifests homogeneous morphogenesis and geomorphological evolution with successive rainfall events.

It is worth paying attention to the final geodiversity maps for both selected areas, and to their correlations with factor maps (Tables 4 & 5). It should be remembered that in the case of WLC multi-criteria analysis, where the weights for a particular criterion are not equal, the correlation result should reflect the compensation of a given factor. In the case of Derborence, the highest weight was assigned to the geological setting map (0.41), and indeed the final map shows a high positive correlation with this factor map (Table 4). In the case of Illgraben, the highest weight was assigned to the hydrological component (0.35), and the correlation is very low (Table 5). It is related to the discrete type of hydrological data that were used in the analysis. The hydrological data are 'direct' indicators and undoubtedly of the greatest value (Zwoliński *et al.* 2018). However, even after assigning the highest importance to the hydrological factor, assessing area which mainly owes its morphometry to the river system, this abiotic component was not clearly reflected in the final geodiversity value map. This means that hydrographic elements can only enhance the geodiversity value locally, and do not have a broad spatial significance. Therefore, there are suggestions to use the Topographic Wetness Index (TWI) in geodiversity assessments (Hjort *et al.* 2012; Najwer *et al.* 2016, 2022; Tukiainen *et al.* 2017; Jankowski *et al.* 2020). It is an 'indirect' indicator that expresses the spatial distribution of water occurrence and runoff. TWI is commonly used as a proxy for soil moisture and could be particularly useful in the absence of pedological 'direct' data.

Table 5. *Correlation matrix for all factor maps and the final geodiversity map of Illgraben*

Illgraben	(A)	(B)	(C)	(D)	(E)	(F)
(A) Relief energy	1.00					
(B) Landform fragmentation	0.39	1.00				
(C) Landform preservation	0.43	0.23	1.00			
(D) Geological setting	0.68	0.35	0.27	1.00		
(E) Hydrological	−0.12	−0.04	0.12	−0.22	1.00	
(F) Geodiversity map	**0.80**	**0.38**	**0.53**	**0.62**	**0.23**	**1.00**

Another high weight in MCE (multi-criteria evaluation) of Illgraben was given to relief energy, and the observed correlation with the final geodiversity map was very high (Table 5). It should be emphasized that in geodiversity assessment, each factor is important; however, depending on the specificity of the area, the individual weights of criteria should be appropriately differentiated. Usually, geology is treated as a key driver controlling geodiversity, and it has been suggested that the geological setting component exerts a strong influence on the overall geodiversity (Hjort and Luoto 2010; Pereira *et al.* 2013; Melelli *et al.* 2017; Forte *et al.* 2018). In the case of Illgraben, the relief energy diversity variable is the most important, which fits well with the findings in the literature (Zwoliński 2010; Hjort and Luoto 2012; Seijmonsbergen *et al.* 2018).

In research on the assessment and mapping of geodiversity, an extremely important and unfortunately usually overlooked aspect is the verification of results. The first attempt to validate the geodiversity model appeared recently (Najwer *et al.* 2022). Verification is extremely difficult and requires both an expert knowledge of the research area and experience with the assessment technique. In the case of geodiversity, there is no standard model to which the obtained results can be compared, and thus the efficiency of the used method can be assessed. One possible approach is model validation by comparing the assessment results with expert knowledge of the assessed area. The accuracy of the final geodiversity maps of Derborence and Illgraben was verified during a field inspection, with positive results.

Due to the lack of universal classification ranges for individual components of geodiversity, the proposed methodology should be treated with caution, even when applied to other areas of similar size and landscape characteristics. So far, the proposed method has been successfully used for lowland areas (Najwer *et al.* 2016), and with some modifications regarding basic units of analysis, i.e. elementary catchments instead of raster cells; for mountain areas (Jankowski *et al.* 2020; Najwer *et al.* 2022); uplands and coastal lowlands (Najwer *et al.* 2022); mountain areas (Kori *et al.* 2019; Chrobak *et al.* 2021); and administrative units (Stanley 2022). The creation of a universal framework for geodiversity assessment for the whole world, or at least for selected climatic zones, is certainly the biggest challenge. It is much easier to work out classification ranges for quantitative criteria (see Table 1) that can be assessed objectively using the available methods. However, it is much more difficult to create such classification ranges for expertly assessed components such as landform fragmentation, landform preservation, geological settings (see Table 1) and other geodiversity components that were not included in the present research procedure.

Depending on the purpose of the geodiversity assessment, the quality and resolution of the source data are extremely important. The required resolution for evaluating large geomorphosites and for the designation of areas characterized by high geodiversity for conservation and protection is 25 m. For the evaluation of smaller protected and conserved areas or their fragments, more accurate data with a resolution of at least 10 m should be used. The use of very high-resolution data affects the velocity and sometimes the ability to perform the analysis on a given hardware unit. The data require generalization at the input stage or spatial aggregation at the final map stage (Fig. 4). Moreover, a large mosaic of the final results is not adequate for managing protected and conserved areas. In the case of Derborence, it is worth considering the spatial aggregation of the final geodiversity map, which will facilitate the interpretation of the results and may be more useful for site spatial planning and environmental management. Contrarily, too low data resolution causes distortion of the final result and its generalization. At the stage of building the geodatabase and selecting the assessment criteria (Fig. 4), it is necessary to decide what is the basic evaluation unit size and whether the available data are in the same or in a similar and sufficient resolution. For this reason, it was decided to omit the soil component in the present analysis. The existing soil databases did not meet the resolution criterion – a scale of at least 1:100 000.

The upward trend in global mean temperatures, unfortunately, leads to many changes such as an increase in intense rainfall, changes in the cryosphere such as glaciers receding and permafrost thaw, as well as changes in river flow and sediment transfer regimes. More frequent and intense extreme events can be expected, including primarily geomorphological events significant to geodiversity (IPCC 2021). It should be considered that changes in geodiversity as a result of extreme processes – such as rockfalls, landslides and debris flows – also cause changes in biodiversity, which, in the form of fallen trees, can significantly threaten human life and affect the infrastructure along designated routes. In the case of PCAs that have high value for geotourism and geoheritage, potential changes in geodiversity, and consequently in biodiversity, should be taken into account in particular when assessing the condition of trails, existing safeguards and other tourist infrastructure. In light of this, the role of PCA managers is primarily to determine the current state of the area, to assess the risk and forecast changes as well as to develop and implement a possible adaptation plan. Geodiversity maps can be of great importance for this purpose.

Some changes in the natural environment are long-term and currently difficult to forecast. Understanding landscape morphogenesis and learning from past changes recorded in landforms and sediments can help to predict climate changes (Gordon *et al.* 2022). Geodiversity maps of entire PCAs or their fragments should be made periodically, according to the adopted research method. Series of geodiversity maps that represent dynamic geodiversity (Zwoliński 2009) are useful for comparing changes over time and to better conserve the most valuable parts of the area. Monitoring changes is an important part of the site management process, which allows us to deploy an appropriate evidence-based intervention (Wignall *et al.* 2018; Crofts *et al.* 2020).

Conclusions

The study reported herein had two objectives: (1) to propose a method for geodiversity assessment for high mountainous areas characterized by passive and active morphodynamics, and (2) to apply and verify the proposed method for the assessment of geomorphosites.

The first objective was realized by selecting two alpine protected and conserved areas (PCAs) representative of different types of morphodynamics. The proposed method of geodiversity assessment of the selected catchments, characterized by high-mountain landforms, required adaptation of the general research workflow proposed by Najwer and Zwoliński (2014). The main differences concern terminological aspects and some details regarding the type of input data (see Fig. 4, task 2) and factor maps (task 3), as well as specifications of analytical alternatives and the use of multi-criteria analysis (see Fig. 4, task 4).

To realize the second objective, geodiversity maps of the two selected geomorphosites were computed using spatial multi-criteria analysis (S-MCA). The geodiversity assessment criteria were selected and presented on five factor maps. The factor maps were aggregated using the weighted linear combination (WLC) technique. The accuracy of the final geodiversity maps of Derborence and Illgraben was verified during a field inspection. According to the state of the art of geodiversity research and methods for its assessment, there is no universal model for validating geodiversity map results. Therefore, verification of geodiversity maps is difficult and requires both experience with evaluation techniques and expert knowledge of the research area.

The percentage share of the area by geodiversity class in both geomorphosites shows that the Derborence catchment is characterized by higher geodiversity than the Illgraben one. Almost 40% of the Derborence area is distinguished by high and very high geodiversity. In the Illgraben site, these two classes of geodiversity cover 25%. On the other hand, very low and low classes of geodiversity cover as much as 55% of the Illgraben catchment area, while they cover only 31% in the Derborence one. When referring the obtained results to the types of geomorphosites, it should be noted that the Illgraben catchment, being an active geomorphosite, is characterized by lower geodiversity than the Derborence catchment, which is recognized as an evolving passive geomorphosite. It can be concluded that the active morphogenetic processes in the Illgraben catchment are not conducive to increasing the degree of geodiversity.

The adopted geosite inventories are a more or less qualitative–quantitative selection of sites considered by the scientific community to be of special importance due to their contribution to knowledge of Earth history and to society in general. Some geosites, in particular geomorphosites, can be quite large (dozens of square kilometres) and sometimes heterogeneous. The proposed methodology, tested on two Swiss geomorphosites, allows the intrinsic geodiversity differentiation of large geomorphosites as well as other PCAs (e.g. landscape protected areas, Biosphere reserves, World Heritage sites) to be assessed, and the results could be used for other purposes such as the preservation of specific features within the protected perimeter, spatial planning or tourist management, at least in the alpine fold mountains.

Acknowledgements The authors would like to thank the reviewers for their thoughtful comments and efforts towards improving our manuscript. The CLC2018 is one of the Corine Land Cover (CLC) datasets produced within the frame of the Copernicus Land Monitoring Service. The Corine Land Cover project was financed by the European Union. Project results were obtained from the website of the European Environment Agency (https://land.copernicus.eu/pan-european/corine-land-cover).

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **AN**: conceptualization (equal), data curation (lead), formal analysis (lead), funding acquisition (lead), investigation (lead), methodology (equal), project administration (lead), resources (lead), software (lead), validation (equal), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **ER**: conceptualization (equal), formal analysis (supporting), methodology (equal), resources (supporting), supervision (equal), validation (supporting), writing – original draft (supporting), writing – review & editing (supporting); **ZZ**: conceptualization (equal), formal analysis (supporting), methodology (equal), supervision (equal), validation (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Funding The internship in Switzerland of Alicja Najwer was funded by the European Union within the European Social Fund within the Interdisciplinary Environmental Life Sciences PhD programme in project UAM: Unikatowy Absolwent = Możliwości (AMU: A Unique Graduate = Possibilities). This publication was supported by the Polish Ministry of Science and Higher Education "Excellence Initiative - Research University" program no. 040/08/POB1/0043.

Data availability The datasets generated and analysed during the current study are not publicly available but are available from the corresponding author on reasonable request. Some of the source datasets analysed during the current study are available from the Federal Office of Topography swisstopo repository (https://www.swisstopo.admin.ch/) and the European Environment Agency's website (https://www.eea.europa.eu/).

References

Asrat, A., Demissie, M. and Mogessie, A. 2012. Geoheritage conservation in Ethiopia: the case of the Simien Mountains. *Quaestiones Geographicae*, **31**, 7–23, https://doi.org/10.2478/v10117-012-0001-0

Australian Heritage Commission 2002. *Australian Natural Heritage Charter for the Conservation of Places of Natural Heritage Significance*. Australian Heritage Commission in Association with Australian Committee for IUCN, Sydney.

Badoux, A., Graf, C. *et al*. 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. *Natural Hazards*, **49**, 517–539, https://doi.org/10.1007/s11069-008-9303-x

Barthlott, W., Biedinger, N., Braun, G., Feig, F., Kier, G. and Mutke, J. 1999. Terminological and methodological aspects of the mapping and analysis of the global biodiversity. *Acta Botanica Fennica*, **162**, 103–110.

Beier, P., Hunter, M.L. and Anderson, M. 2015. Special section: conserving nature's stage. *Conservation Biology*, **29**, 613–617, https://doi.org/10.1111/cobi.12511

Benito-Calvo, A., Perez-Gonzalez, A., Magri, O. and Meza, P. 2009. Assessing regional geodiversity: the Iberian Peninsula. *Earth Surface Process Landforms*, **34**, 1433–1445, https://doi.org/10.1002/esp.1840

Bétard, F. 2013. Patch-scale relationships between geodiversity and biodiversity in hard rock quarries: case study from a disused quartzite quarry in NW France. *Geoheritage*, **5**, 59–71, https://doi.org/10.1007/s12371-013-0078-4

Boothroyd, A. and McHenry, M. 2019. Old processes, new movements: the inclusion of geodiversity in biological and ecological discourse. *Diversity*, **11**, 1–17, https://doi.org/10.3390/d11110216

Brazier, V., Bruneau, P.M.C., Gordon, J.E. and Rennie, A.F. 2012. Making space for nature in a changing climate: the role of geodiversity in biodiversity conservation. *Scottish Geographical Journal*, **128**, 211–233, https://doi.org/10.1080/14702541.2012.737015

Brilha, J., Gray, M., Matthew, J. and Zwoliński, Z. 2021. International Geodiversity Day: developing a global outreach initiative. Building connections for global geoconservation. *10th International ProGEO Symposium*, 7–10 June, 127–128, https://digital.csic.es/bitstream/10261/273501/1/building_connections_global_2021.pdf

Burnett, M.R., August, P.V., Brown, J.H. and Killingbeck, K.T. 1998. The influence of geomorphological heterogeneity on biodiversity. I. A patch-scale perspective. *Conservation Biology*, **12**, 363–370, https://doi.org/10.1111/j.1523-1739.1998.96238.x

Chrobak, A., Novotny, J. and Struś, P. 2021. Geodiversity assessment as a first step in designating areas of geotourism potential. Case study: Western Carpathians. *Frontiers in Earth Science*, https://doi.org/10.3389/feart.2021.752669

Crofts, R. 2018. Putting geoheritage conservation on all agendas. *Geoheritage*, **10**, 231–238, https://doi.org/10.1007/s12371-017-0239-y

Crofts, R., Gordon, J.E. *et al*. 2020. Guidelines for geoconservation in protected and conserved areas. *Best Practice Protected Area Guidelines Series*, **31**, https://doi.org/10.2305/IUCN.CH.2020.PAG.31.en

de Haas, T., Nijland, W. *et al*. 2020. How memory effects, check dams, and channel geometry control erosion and deposition by debris flows. *Scientific Reports*, **10**, article 14024, https://doi.org/10.1038/s41598-020-71016-8

Eberhard, R. 1997. *Pattern & Process: towards a Regional Approach to National Estate Assessment of Geodiversity*. Australian Heritage Commission, Canberra.

European Environment Agency (EEA) 2018. *Corine Land Cover (CLC) 2018* version 20b2. Released December 21 2018. European Environment Agency, https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

Federal Office of Topography swisstopo 2005 DHM25. *Federal Office of Topography swisstopo*, https://www.swisstopo.admin.ch/en/geodata/height/dhm25.html

Federal Office of Topography swisstopo 2016. *SWISSIMAGE 25. Federal Office of Topography swisstopo*, https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage25.html [last accessed 30 June 2021].

Federal Office of Topography swisstopo and Swiss Academy of Sciences (SCNAT) 2012. *Geotopes in Switzerland*. Federal Office of Topography swisstopo, https://map.geo.admin.ch/?bgLayer=ch.swisstopo.pixelkarte-farbe&lang=en&zoom=1&Y=660549.00&X=183344.00&time_current=latest&topic=ech&layers=ch.swisstopo.geologie-geotope

Forte, J.P., Brilha, J. *et al*. 2018. Kernel density applied to the quantitative assessment of geodiversity. *Geoheritage*, **10**, 205–217, https://doi.org/10.1007/s12371-018-0282-3

Goepel, K.D. 2018. Implementation of an online software tool for the analytic hierarchy process (AHP-OS). *International Journal of the Analytic Hierarchy Process*, **10**, 469–487, https://doi.org/10.13033/ijahp.v10i3.590

Gordon, J.E., Dvorak, I., Jonasson, C., Josefsson, M., Kocianova, M. and Thompson, D.B.A. 2002. Geoecology and management of sensitive montane landscapes. *Geografiska Annaler*, **84A**, 193–203.

Gordon, J.E., Crofts, R., Diaz-Martinez, E. and Sik Woo, K. 2018. Enhancing the role of geoconservation in protected area management and nature conservation.

Geoheritage, **10**, 191–203, https://doi.org/10.1007/s12371-017-0240-5

Gordon, J.E., Tormey, D., Wignall, R., Brazier, V. and Crofts, R. 2022. Climate change will challenge the management of geoheritage in protected and conserved areas. *Parks Stewardship Forum*, **38**, 56–63, https://doi.org/10.5070/P538156119

Grandgirard, V. 1999. L'évaluation des géotopes. *Geol Insubrica*, **4**, 59–66.

Gray, M. 2004. *Geodiversity: Valuing and Conserving Abiotic Nature*. John Wiley and Sons, Chichester.

Gray, M. 2011. Other nature: geodiversity and geosystem services. *Environmental Conservation*, **38**, 271–274, https://doi.org/10.1017/S0376892911000117

Gray, M. 2013. *Geodiversity: Valuing and Conserving Abiotic Nature*. 2nd edn. John Wiley and Sons, Chichester.

Gwerder, C. 2007. *Temporal and Spatial Variation of Erosion Processes in the Illgraben, an Alpine Debris Flow Catchment*. Master's thesis, ETH Zürich, https://doi.org/10.3929/ethz-a-005327904

Hjort, J. and Luoto, M. 2010. Geodiversity of high-latitude landscapes in northern Finland. *Geomorphology*, **115**, 109–116, https://doi.org/10.1016/j.geomorph.2009.09.039

Hjort, J. and Luoto, M. 2012. Can geodiversity be predicted from space? *Geomorphology*, **153–154**, 74–80, https://doi.org/10.1016/j.geomorph.2012.02.010

Hjort, J., Heikkinen, K. and Luoto, M. 2012. Inclusion of explicit measures of geodiversity improve biodiversity models in a boreal landscape. *Biodiversity Conservation*, **21**, 3487–3506, https://doi.org/10.1007/s10531-012-0376-1

Hjort, J., Gordon, J.E., Gray, M. and Hunter, M.L. 2015. Why geodiversity matters in valuing nature's stage. *Conservation Biology*, **29**, 630–639, https://doi.org/10.1111/cobi.12510

Intergovernmental Panel on Climate Change (IPCC) 2021. Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/ [last accessed 7 January 2022].

IPBES 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. *In*: Brondizio, E.S., Settele, J., Díaz, S. and Ngo, H.T. (eds). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673 [last accessed 12 April 2020].

Jačková, K. and Romportl, D. 2008. The relationship between geodiversity and habitat richness in Šumava National Park and Křivoklátsko Pla (Czech Republic): a quantitative analysis approach. *Journal of Landscape Ecology*, **1**, 23–38, https://doi.org/10.2478/v10285-012-0003-6

Jankowski, P., Najwer, A., Zwoliński, Z. and Niesterowicz, J. 2020. Geodiversity assessment with crowdsourced data and spatial multicriteria analysis. *ISPRS International Journal of Geo-Information*, **9**, 716, https://doi.org/10.3390/ijgi9120716

Jenks, G.F. 1967. The data model concept in statistical mapping. *International Yearbook of Cartography*, **7**, 186–190.

Jenness, J. 2006. *Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x, v. 1.2. Jenness Enterprises*, http://www.jennessent.com/arcview/tpi.htm [last accessed 5 December 2017].

Kiernan, K. 1996. *Conserving Geodiversity and Geoheritage: the Conservation of Glacial Landforms*. Forest Practices Unit, Hobart.

Kori, E., Onyango Odhiambo, B.D. and Chikoore, H. 2019. A geomorphodiversity map of the Soutpansberg Range, South Africa. *Landform Analysis*, **38**, 13–24, https://doi.org/10.12657/landfana-038-002

Kostrzewski, A. 2011. The role of relief geodiversity in geomorphology. *Geographia Polonica*, **84**, 69–74, https://doi.org/10.7163/GPol.2011.S2.5

Kozłowski, S. 2004. Geodiversity. The concept and scope of geodiversity. *Przegląd Geologiczny*, **52**, 833–837.

Kozłowski, S., Migaszewski, Z.M. and Gałuszka, A. 2004. Geodiversity conservation – conserving our geological heritage. *Polish Geological Institute Special Papers*, **13**, 13–20.

Likert, R. 1932. A technique for the measurement of attitudes. *Archives of Psychology*, **140**, 1–55.

Manosso, F.C., Zwoliński, Z., Najwer, A., Basso, B.T., Santos, D.S. and Pagliarini, M.V. 2021. Spatial pattern of geodiversity assessment in the Marrecas River drainage basin, Paraná, Brazil. *Ecological Indicators*, **126**, article 107703, https://doi.org/10.1016/j.ecolind.2021.107703

Maret, H. and Reynard, E. 2015. Géomorphologie de la région de Derborence. *Bulletin de la Murithienne*, **132**, 45–55.

McArdell, B. and Sartori, M. 2021. The Illgraben torrent system. *In*: Reynard, E. (ed.) *Landscapes and Landforms of Switzerland*. Springer Nature, Switzerland, 367–378.

Melelli, L. 2014. Geodiversity: a new quantitative index for natural protected areas enhancement. *GeoJournal of Tourism and Geosites*, **1**, 27–37.

Melelli, L., Vergari, F., Liucci, L. and Del Monte, M. 2017. Geomorphodiversity index: quantifying the diversity of landforms and physical landscape. *Science of Total Environment*, **584–585**, 701–714, https://doi.org/10.1016/j.scitotenv.2017.01.101

Mizgajski, A. 2001. Odniesienie georóżnorodności do wybranych pojęć w naukach o środowisku. *In*: Karczewski, A. and Zwoliński, Z. (eds) *Funkcjonowanie geoekosystemów w zróżnicowanych warunkach morfoklimatycznych. Monitoring, ochrona, edukacja*. Bogucki Wydawnictwo Naukowe, Poznań, 369–375 [in Polish].

Najwer, A. and Zwoliński, Z. 2014. Semantyka i metodyka oceny georóżnorodności – przegląd i propozycja badawcza. *Landform Analysis*, **26**, 115–127, https://doi.org/10.12657/landfana.026.011

Najwer, A., Borysiak, J., Gudowicz, J., Mazurek, M. and Zwoliński, Z. 2016. Geodiversity and biodiversity of the postglacial landscape (Dębnica River catchment, Poland). *Quaestiones Geographicae*, **35**, 5–28, https://doi.org/10.1515/quageo-2016-0001

Najwer, A., Jankowski, P., Niesterowicz, J. and Zwoliński, Z. 2022. Geodiversity assessment with global and local spatial multicriteria analysis. *International Journal of Applied Earth Observation and Geoinformation*, **107**, article 102665, https://doi.org/10.1016/j.jag.2021.102665

Newsome, D., Moore, S.A. and Dowling, R.K. 2013. *Natural Area Tourism Ecology, Impacts and Management*. 2nd edn. Channel View Publications, Clevedon, UK.

Panizza, M. 2001. Geomorphosites: concepts, methods and examples of geomorphological survey. *Chinese Science Bulletin*, **46**, 4–6, https://doi.org/10.1007/BF03187227

Panizza, M. 2009. The geomorphodiversity of the Dolomites (Italy): a key of geoheritage assessment. *Geoheritage*, **1**, 33–42, https://doi.org/10.1007/s12371-009-0003-z

Parks, K.E. and Mulligan, M. 2010. On the relationship between a resource based measure of geodiversity and broad scale biodiversity patterns. *Biodiversity and Conservation*, **19**, 2751–2766, https://doi.org/10.1007/s10531-010-9876-z

Pelfini, M. and Bollati, I. 2014. Landforms and geomorphosites ongoing changes: concepts and implications for geoheritage promotion. *Quaestiones Geographicae*, **33**, 131–143, https://doi.org/10.2478/quageo-2014-0009

Pellitero, R., González-Amuchastegui, M.J., Ruiz-Flaño, P. and Serrano, E. 2011. Geodiversity and geomorphosite assessment applied to a natural protected area: the Ebro and Rudron Gorges Natural Park (Spain). *Geoheritage*, **3**, 163–174, https://doi.org/10.1007/s12371-010-0022-9

Pellitero, R., Manosso, F.C. and Serrano, E. 2014. Mid- and large-scale geodiversity calculation in Fuentes Carrionas (NW Spain) and Serra do Cadeado (Paraná, Brazil): methodology and application for land management. *Geografiska Annaler. Series A: Physical Geography*, **97**, 219–235, https://doi.org/10.1111/geoa.12057

Pereira, D.I., Pereira, P., Brilha, J. and Santos, L. 2013. Geodiversity assessment of Paraná State (Brazil): an innovative approach. *Environmental Management*, **52**, 541–552, https://doi.org/10.1007/s00267-013-0100-2

Perotti, L., Carraro, G., Giardino, M., de Luca, D.A. and Lasagna, M. 2019. Geodiversity evaluation and water resources in the Sesia ValGrande UNESCO Geopark (Italy). *Water*, **11**, 2102, https://doi.org/10.3390/w11102102

Prosser, C.D., Burek, C.V., Evans, D.H., Gordon, J.E., Kirkbride, V., Rennie, A.F. and Walmsley, C.A. 2010. Conserving geodiversity sites in a changing climate: management challenges and responses. *Geoheritage*, **2**, 123–136, https://doi.org/10.1007/s12371-010-0016-7

Ren, Y., Lü, Y., Hu, J. and Yin, L. 2021. Geodiversity underpins biodiversity but the relations can be complex: implications from two biodiversity proxies. *Global Ecology and Conservation*, **31**, article e01830, https://doi.org/10.1016/j.gecco.2021.e01830

Reynard, E. 2004. Geosites. *In*: Goudie, A. (ed.) *Encyclopedia of Geomorphology*. Routledge, London, p. 444.

Reynard, E. 2005. Geomorphosites et paysages. *Géomorphologie: Relief, Processus, Environnement*, **3**, 181–188. https://doi.org/10.4000/geomorphologie.338

Reynard, E. and Coratza, P. 2013. Scientific research on geomorphosites. A review of the activities of the IAG Working Group on geomorphosites over the last twelve years. *Supplementi di Geografia Fisica e Dinamica Quaternaria*, **36**, 159–168, http://doi.org/10.4461/GFDQ.2013.36.13

Reynard, E. and Panizza, M. 2005. Geomorphosites: definition, assessment and mapping. An introduction. *Géomorphologie: Relief, Processus, Environnement*, **3**, 177–180, https://doi.org/10.4000/geomorphologie.337

Reynard, E., Berger, J.-P. *et al*. 2012. *Révision de l'inventaire des Géotopes Suisses: Rapport Final*. Groupe de travail pour les géotopes en Suisse, Lausanne.

Reynard, E., Clivaz, M., Keller, R. and Backhaus, N. 2021. L'approche par les prestations paysagères, un cadre analytique et un outl de gestion des géopatrimoines à forte composante paysagère. *Géo-Regards*, **14**, 35–53, https://doi.org/10.33055/GEOREGARDS.2021.014.01.35

Richling, A. and Solon, J. 2011. *Ekologia Krajobrazu*. PWN Warszawa.

Ruban, D.A. 2010. Quantification of geodiversity and its loss. *Proceedings of the Geologists' Association*, **121**, 326–333, https://doi.org/10.1016/j.pgeola.2010.07.002

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, **15**, 234–281, https://doi.org/10.1016/0022-2496(77)90033-5

Saaty, T.L. 1980. *The Analytic Hierarchy Process*. McGraw-Hill, New York.

Sapp, M., Miró, M.F. and César, R. 2006. *Geological–Tourist Map of Calamuchita's Valley, Cordoba, Argentina, E:1/1.000.0000*. Servicio Geológico Minero Argentino, SEGEMAR, Córdoba.

Schoeneich, P. and Reynard, E. 2021. Structural landscapes and relative landforms of the Diablerets Massif. *In*: Reynard, E. (ed.) *Landscapes and Landforms of Switzerland*. Springer Nature, Switzerland, 123–141.

Seijmonsbergen, A.C., Guldenaar, J. and Rijsdijk, K.F. 2018. Exploring Hawaiian long-term insular geodiversity dynamics. *Landform Analysis*, **35**, 31–43, https://doi.org/10.12657/landfana.035.007

Selmi, L., Canesin, T.S., Gauci, R., Pereira, P. and Coratza, P. 2022. Degradation risk assessment: understanding the impacts of climate change on geoheritage. *Sustainability*, **14**, 4262, https://doi.org/10.3390/su14074262

Serrano, E. and González Trueba, J.J. 2011. Environmental education and landscape leisure. Geotourist map and geomorphosites in the Picos de Europa National Park. *GeoJournal of Tourism and Geosites*, **2**, 295–308.

Serrano, E. and Ruiz-Flaño, P. 2009. Geomorphosites and geodiversity. *In*: Reynard, E., Coratza, P. *et al.* (eds) *Geomorphosites*. Pfeil, Munich, 51–63.

Sharples, C. 1993. *A Methodology for the Identification of Significant Landforms and Geological Sites for Geoconservation Purposes*. Forestry Commission, Tasmania, Australia.

Sharples, C., McIntosh, P. and Comfort, M. 2018. Geodiversity and geoconservation in land management in Tasmania – a top-down approach. *In*: Reynard, E. and Brilha, J. (eds) *Geoheritage: Assessment, Protection, and Management*. Elsevier, 355–371.

Shukla, P.R., Skea, J. *et al*. (eds) 2019. *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. IPCC, https://

www.ipcc.ch/srccl/download/ [last accessed 13 March 2021].

Silva, J.X. 2004. Geodiversity: some simple geoprocessing indicators to support environmental biodiversity studies. *Directions Magazine*, February 17, http://www.directionsmag.com/articles/geodiversity-some-simple-geoprocessing-indicators-to-support-environmental-/123803 [last accessed 9 August 2014].

Stanley, K.B. 2022. *Toward Understanding Geodiversity Perception in Grayson County, Virginia through Geodiversity Mapping*. Master's thesis, Virginia Polytechnic Institute and State University, http://hdl.handle.net/10919/109276

Tukiainen, H., Bailey, J.J., Field, R., Kangas, K. and Hjort, J. 2017. Combining geodiversity with climate and topography to account for threatened species richness. *Conservation Biology*, **31**, 364–375, https://doi.org/10.1111/cobi.12799

Tukiainen, H., Kiuttu, M., Kalliola, R., Alahuhta, J. and Hjort, J. 2019. Landforms contribute to plant biodiversity at alpha, beta and gamma levels. *Journal of Biogeography*, **46**, 1699–1710, https://doi.org/10.1111/jbi.13569

Wiedenbein, F.W. 1993. Ein geotopschutz konzept für Deutschland. *In*: Quasten, H. (ed) *Geotopschutz Probleme: der Methodik und der Praktischen*. Praktischen Umsetzung. 1. Jahrestagung der AG Geotopschutz, Otzenhausen/Saarland, 17, University of Saarland, Saarbrucken, Germany.

Wignall, R.M.L., Gordon, J.E., Brazier, V., MacFadyen, C.C.J. and Everett, N.S. 2018. A climate change risk based assessment and management options for nationally and internationally important geoheritage sites in Scotland. *Proceedings of the Geologists' Association*, **129**, 120–134, https://doi.org/10.1016/j.pgeola.2017.11.003

Zwoliński, Z. 2004. Geodiversity. *In*: Goudie, A.S. (ed.) *Encyclopedia of Geomorphology*. Routledge, 417–418.

Zwoliński, Z. 2009. The routine of landform geodiversity map design for the Polish Carpathian Mts. *Landform Analysis*, **11**, 79–87.

Zwoliński, Z. 2010. Aspekty turystyczne georóżnorodności rzeźby Karpat. *Prace Komisji Krajobrazu Kulturowego PTG*, **14**, 316–327.

Zwoliński, Z. and Stachowiak, J. 2012. Geodiversity map of the Tatra National Park for geotourism. *Quaestiones Geographicae*, **31**, 99–107, https://doi.org/10.2478/v10117-012-0012-x

Zwoliński, Z., Najwer, A. and Giardino, M. 2018. Methods for assessing geodiversity. *In*: Reynard, E. and Brilha, J. (eds) *Geoheritage: Assessment, Protection, and Management*. Elsevier, 27–52.

Zwoliński, Z., Brilha, J., Gray, M. and Matthews, J. 2021. Initiative to establish the International Geodiversity Day. *EGU General Assembly Conference EGU21-13977*, April 19–30, European Geosciences Union, http://doi.org/10.5194/egusphere-egu21-13977