Geodiversity mapping in alpine areas

Seijmonsbergen, A.C.; De Jong, M.G.G.; Hagendoorn, B.; Oostermeijer, J.G.B.; Rijsdijk, K.F.

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EDITED BY
CARINA HOORN
ALLISON PERRIGO
ALEXANDRE ANTONELLI

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Mountains, Climate and Biodiversity

Edited by

Carina Hoorn
University of Amsterdam
Amsterdam, The Netherlands

Allison Perrigo
Gothenburg Global Biodiversity Centre
Sweden
Department of Biological and Environmental Sciences,
University of Gothenburg, Sweden
Forest Cat Editing
Uppsala, Sweden

Alexandre Antonelli
Gothenburg Global Biodiversity Centre
Sweden
Department of Biological and Environmental Sciences,
University of Gothenburg, Sweden
Gothenburg Botanical Garden
Sweden

WILEY Blackwell

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The superpáramo of the Sierra Nevada del Cocuy National Park, in Colombia, with rocky slopes of Cretaceous (Albian-Aptian) sedimentary quartzitic sandstone bedrock and shales with occasional limestone inclusions. Espeletia lopezii Cuatrec. grows here in a pit at the base of the vertical slopes of the Ritacuba Blanco peak.

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Geodiversity Mapping in Alpine Areas

Arie C. Seijmonsbergen[1]*, Matheus G.G. De Jong*[2]*, Babs Hagendoorn*[1]*, Johannes G.B. Oostermeijer*[1] *and Kenneth F. Rijsdijk*[1]

[1] *Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, Netherlands*
[2] *Research Foundation for Alpine and Subalpine Environments, Amsterdam, Netherlands*

Abstract

Geodiversity mapping has become an established tool for assessing the value of the abiotic part of the landscape. We present two methods, which have been developed in the mountains of the State of Vorarlberg (Austria), but have a wider application in alpine areas. The first is a region-wide index-based mapping of Vorarlberg that is designed with the purpose of generating, in a preliminary evaluation, an inventory of clusters of high geodiversity. The second method comprises detailed geomorphological mapping at a local scale and supports landscape planning and management by identifying potential geoconservation sites. The latter approach also enables the evaluation of the relationship between geodiversity and biotopes.

We generated a geodiversity (index) map of Vorarlberg in a GIS showing the spatial distribution of a combination of six abiotic factors (subindices) expressed as numeric values in five classes. Both conventional and unconventional data sets were used, ranging from field-based geological maps to digital data sets acquired in airborne LiDAR surveys. In this approach, high geodiversity is found more often in areas of combined complex topography and varied geological substrata. The geodiversity map can be used to rapidly assess the occurrence of clusters of high geodiversity, which subsequently can be evaluated in detail using a landform-based approach. As an example of the latter, we present the case study of a small area near the village of Au in central Vorarlberg, Austria. Using a detailed area-covering polygon-based morphogenetic map as the basis for the assessment of the Au West area, the various classes of the legend were weighted and ranked in an automated GIS procedure with four factors: scientific relevance and frequency of occurrence (primary factors) and vulnerability and disturbance (secondary factors). Three levels of importance for geoconservation potential are differentiated (low, medium and high significance) and displayed in a map on which the highly ranked units are identified as potential sites for geoconservation. Comparison of the morphogenetic types and existing biotope data in the case-study area suggests that most biotopes occur together with specific morphogenetic types. It appears that the distinction between "wet" and "dry" mass-movement processes is an important factor, together with slope steepness and material properties, for effectively characterizing the natural biotopes.

Keywords: *geomorphology, biotope, Vorarlberg, geoconservation, geodiversity index, land-surface parameters, GIS*

11.1 Geodiversity Mapping

Alpine areas are among the world's most geologically diverse and complex, as a result of the combined action of endogenic and exogenic mountain-building processes. They have endured multiple glacial and interglacial periods in the Quaternary, and consequently exhibit a wealth of landform types. The present diversity of active and inactive landforms, as well as the intensity of geomorphological processes, reflects these continually changing environmental conditions. Spatial variations in topography, soil and parent material, climatic conditions and hydrology over time also contribute to the high geodiversity of mountains.

Geodiversity, or the diversity of the geosphere, was defined by Gray (2013) as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes."

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Intimately linked to geodiversity is the concept of geoconservation, which can be defined as the active management of landscapes to conserve and enhance geological and geomorphological features, processes, sites and specimens. The landscape in this definition is seen as a part of our natural heritage that is locally threatened and worthy of conservation for future generations (Burek & Prosser 2008). Geodiversity and geoconservation revolve around the notion of the value of abiotic nature. As Gray (2013) puts it, "..things of value ought to be conserved if they are threatened."

"Value," or "quality," is a broad term, and various types of value can be used to assess geodiversity: intrinsic, cultural, esthetic, economic, functional (for both physical and ecological processes) and research/educational. At a practical level (e.g., in geoconservation projects or applied studies), the values selected depend on the aims of the study and determine to a large degree the approach to assessing geodiversity. Therefore, the first question to be answered in a geoconservation project is: Which value or values are to be "captured," and for what purpose? The subsequent question is: How should we map and evaluate geodiversity? And, at the next level, we ask questions such as: Which data are available? What is the scale of the area? Are there any legislative directives? How can geodiversity maps be used to support biodiversity studies?

Questions like these have been addressed in earlier studies, for example in a pan-tropical study by Parks & Mulligan (2010), in which the functional value of geodiversity takes a central position. These authors were interested in the geosphere as an environmental resource base for biodiversity, and thus aimed to build a bridge between geodiversity and biodiversity. According to their definition, resources are properties of relevance to the development and evolution of ecosystems: specifically, energy (temperature and solar radiation), water, space and nutrients. The environmental components include climate, topography, soils and geology, which are analyzed in terms of total resource availability and their spatial and temporal heterogeneity. For this purpose, in order to compare the abiotic components of a landscape with the patterns of species distribution, quantification of geodiversity is necessary. A compound geodiversity index (GI) is generated, which is then linked to biodiversity. It is noteworthy that Parks & Mulligan (2010) use a combination of expert-derived thematic maps (such as geological maps) and proxy data (such as parameters derived from digital elevation models, DEMs) in their assessment.

Expert-derived thematic maps are increasingly available in digital format, and allow for the calculation of geological, geomorphological and soil diversity for a predefined unit or a grid of cells. An example of this is found in a study by Serrano & Ruiz-Flaño (2007), who calculated GI as the number of different physical elements in a grid cell times a coefficient of roughness, divided by the natural logarithm of the surface area or unit in square kilometers. The index values calculated for the grid cells were then ranked into classes to produce a geodiversity map. This method was tested for an area in semi-arid central Spain by Serrano & Ruiz-Flaño (2007), and Hjort & Luoto (2010) applied the same method to a boreal landscape in Finland. The need for a flexible use of GIs – as opposed to the use of a standard index for all areas – is shown by a range of studies in different environments and across different spatial scales. For example, they have been used to identify geodiversity hot spots in the Iberian Peninsula (Benito-Calvo et al. 2009) and in a Romanian highland region (Năstase et al. 2012), for geotourism in a mountainous area of Poland (Zwoliński & Stachowiak 2012), for geo- and bioconservation in the Scottish Highlands (Brazier et al. 2012) and in a rural Spanish highland (Pellitero et al. 2011; Serrano & Ruiz-Flaño 2007) and on national and regional scales in Brazil (Pereira et al. 2013).

These examples demonstrate that the different aims and the particular spatial analysis scales of applied studies, together with data availability, determine which environmental variables or sub-indices of geodiversity are appropriate, in spite of a general desire for a universal GI (Kozłowski 2004).

Geodiversity assessment studies use sets of selected fit-for-purpose indicators, or correlations among the same. For example, geosite-based approaches exist that emphasize the scientific, educational, cultural, esthetic and ecological values of geodiversity, often using weighting and ranking procedures (Brilha 2016; Reynard et al. 2016). Knowledge of the geodiversity of a landscape may help conservationists to identify regions suitable for maintaining species diversity and to design efficient corridors (Anderson & Ferree 2010). Currently, there is a trend towards using geodiversity as a surrogate for biodiversity (Hjort et al. 2012; Anderson et al. 2015). One main reason for this is that in areas without sufficient species-occurrence data, a combination of specific environmental factors can be used to estimate biodiversity, for example by using biodiversity models (Hjort et al. 2012). Recently, Anderson et al. (2014) used DEM-derived measures of landscape diversity (i.e., the diversity of topography and range of elevation at a site and in its surrounding neighborhood) to map site resilience.

DEMs ensure a transparent and repeatable calculation of topographical variables such as slope angle, aspect, solar radiation, landscape diversity and openness, which are often referred to as "land surface parameters" (LSPs). Many of these – and other, more complex quantitative indicators – are commonly used in geomorphometry, a relatively young discipline of geomorphology, to model the variation of landforms over Earth's surface (Hengl & Reuter 2009). Another new development is the inclusion of high-resolution laser altimetry (LiDAR)-based LSPs in geodiversity research (Seijmonsbergen et al. 2014). Such advances in technological developments allow for the quantification of geodiversity patterns with input data at sub-meter resolution.

In light of these developments, this chapter describes two different workflows for geodiversity mapping: an index-based geodiversity method applied on a regional scale for the state of Vorarlberg in Austria (2601 km^2) and a combined local-scale expert-driven and GIS-supported method with a focus on geomorphological mapping, implemented west of the village of Au (2.15 km^2) in central Vorarlberg. The regional approach aims to identify region-wide clusters of high geodiversity, while the local-scale approach aims to assess geoconservation potential by applying a weighting and ranking scheme for geomorphosites. The International Association of Geomorphologists Working Group defines a geomorphosite as a portion of the geosphere that presents a site of particular importance in the comprehension of Earth's history (IAG Working Group 2005). We use the term in a broader sense to include all sites, including those of no particular importance. In Section 11.4.3, the results of a local-scale assessment of geomorphosites are used to compare potential geoconservation areas to an existing inventory of biotope areas that are already protected.

11.2 Geological and Geomorphological Overview of Vorarlberg

The landscape of Vorarlberg (Figure 11.1) varies widely over relatively short distances. The elevation ranges from 396 m at Lake Constance in the north-west to 3312 m at the Piz Buin summit in the south-east. It is beyond the scope of this chapter to present an in-depth review of the highly diverse geology and geomorphology of Vorarlberg. Hence, we will give only a brief overview, largely based on Friebe (2007), Oberhauser & Rataj (1998) and Seijmonsbergen et al. (2014).

Vorarlberg is situated on the northern side of the Alps, where the Western and Eastern Alps meet. The major tectonic units of the Eastern Alps are the Silvretta Nappe (crystalline) and the Lechtal Nappe (Northern Calcareous Alps), while the Western Alps are dominated by the Helveticum and Flysch nappes, all of which have a general strike from south-west to north-east due to the collision of the African and European plates. The sedimentary rock formations of these nappes comprise a large variety of clastics, carbonates and sulfates. To the north, the rock formations of Molasse consist essentially of erosional products, deposited from the emerging Alps. The Molasse zone was partially tectonically deformed in the final stage of the mountain-building process.

Epeirogenic uplift of the Alps started about 4 million years ago (Jäckli 1985). The resulting west–east elongated and ridge-like plateau was gradually dissected by rivers, the drainage pattern of which was controlled by the structural grain of the bedrock. Broadly speaking, fluvial activity alternated with glacier activity as a function of global climate changes, especially during the last 2 million years. The action of rivers and glaciers was, and is, primarily erosive, the products being largely transported to the foreland and beyond. A subordinate amount of material is, temporarily, stored in the Alps as fluvial, deltaic and lacustrine sediments in a variety of landforms (e.g., valley fills, terraces and alluvial fans). An even smaller amount is stored in glacial deposits, such as ablation and subglacial till. Mass movement is continually active in shaping and reshaping the landscape, driven by high-precipitation events and promoted by extremes in temperature. Periglacial processes and carbonate and sulfate karst also continue to play a role in the modeling of the mountain landscape.

The natural vegetation of the lowest regions of Vorarlberg (mainly the Rhine Valley) is a mosaic of deciduous forests, reed beds and peat bogs. Moving upslope, montane coniferous–deciduous forest (500–1200 m) is succeeded by pure sub-alpine coniferous forest (comprising spruce and mountain pine) up to a tree line that varies between 1800 and 2100 m. Above the tree line, various alpine dwarf shrubland, grassland and bog communities occur. The natural vegetation has been strongly affected by different types of land use: mainly intensive agriculture in the lower regions and low- to mid-intensity agriculture (dairy farming combined with mowing and haymaking), forestry and alpine ski slopes at higher elevations. In addition to the biodiverse natural biotopes, the long land-use history (logging followed by grazing and/or mowing) has resulted in a variety of semi-natural biotopes with high biodiversity. Even though there are still many threats, biodiversity conservation has been very successful in Vorarlberg. Traditional mowing and hay-making schemes have been maintained or reinstated to conserve and restore large stretches of species-rich meadows on nutrient-poor soils, for example.

Although not densely populated (378 000 inhabitants, mainly in the valleys of the Rhine and Ill rivers and on the

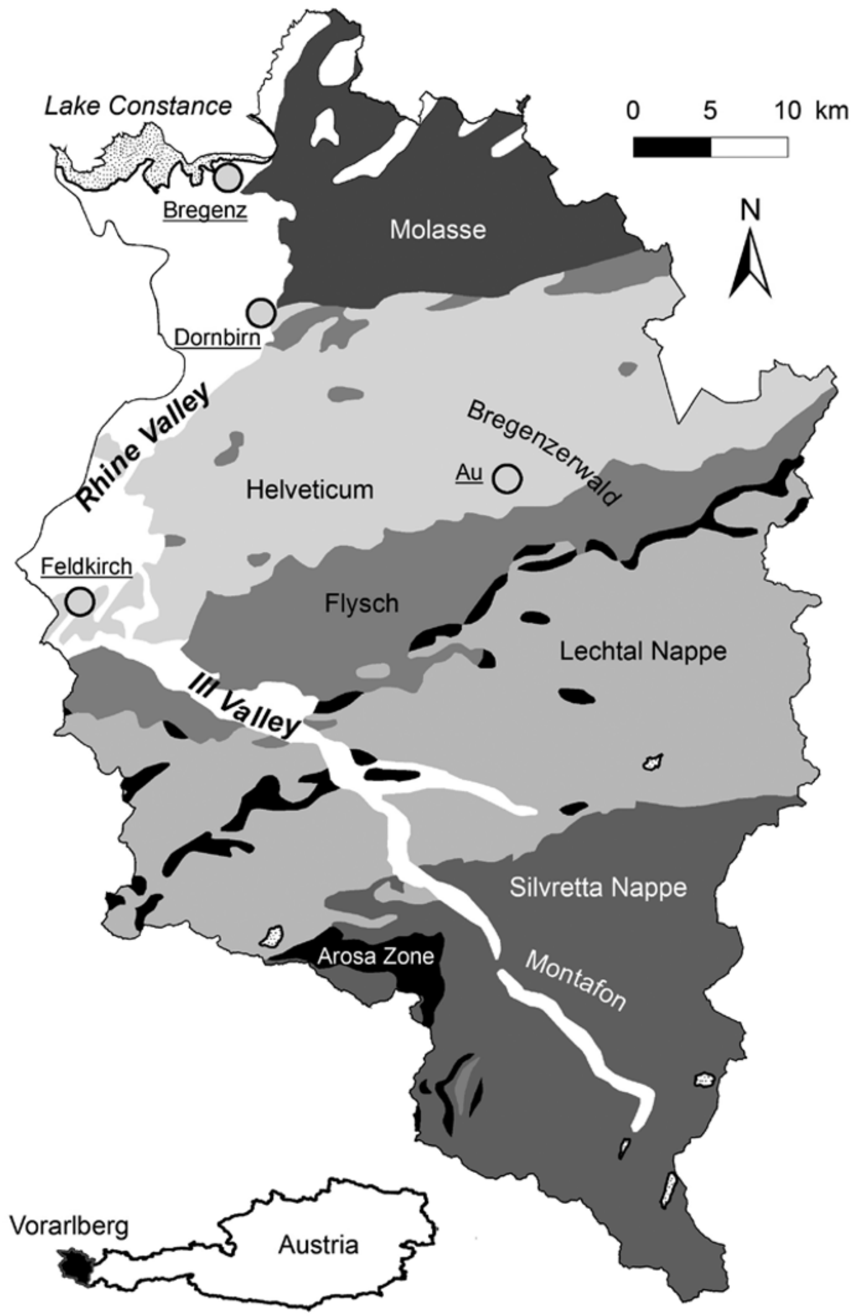

Figure 11.1 Outline of Vorarlberg, showing its main tectonic zones (in different shades of gray). The names of cities and villages are underlined. The lowest area is at Lake Constance, the highest mountains are in and around the Montafon region. The case study area is located west of the village of Au in the Bregenzerwald region. *Source:* Adapted from Friebe (2007).

border of Lake Constance), human influence on the landscape is evidenced by the dense buildings in large parts of the main valleys, the well-established infrastructure, the many reservoirs, the well-maintained natural and artificial drainage network and a highly managed forest, which functions as protection against natural hazards, especially in the steeper areas where ski resorts are also abundant.

11.3 Index-Based Geodiversity Mapping of Vorarlberg

11.3.1 General Overview

An index-based geodiversity map may be used to rapidly assess the occurrence of potential clusters of high geodiversity (hot spots) in a large area. Such a region-wide

Table 11.1 Metadata for the original input data sets used to calculate the geodiversity index (GI) for the Vorarlberg case study.

Data set name	Contains	Data type	Scale/cell size	No. of different features	No. of different variables or range	Data source
Tectonic map	Nappe units	Polygon	1 : 500 000	222	18 tectonic units	Oberhauser & Rataj (1998)
Geological map	Geological formations	Polygon	1 : 100 000	5417	109 geological formations	Geologische Bundesanstalt Wien (2007)
Fluesse50t (drainage)	Streams and large rivers	Line	1 : 50 000	11 460	1	Land Vorarlberg (2015)
Seen (lakes)	Lakes	Polygon	–	1048	1	Land Vorarlberg (2015)
LiDAR DEM	Elevation	Raster	5 m		391–3308 m	Land Vorarlberg (2015)
Slope map	Slope angle per cell	Raster	5 m		0–89.8°	Calculated from DEM
Solar radiation	Solar radiation per cell	Raster	25 m		$1186–1.8 \times 10^6$ WH/m^2	Calculated from DEM

assessment can then be followed by a fine-scale evaluation of geodiversity of selected areas, using a landform-based approach. The geodiversity (index) map of Vorarlberg shows the spatial distribution of a combination of abiotic factors, expressed as numeric values for a predefined grid. We have selected tectonic diversity, geological diversity, drainage diversity, elevation diversity, slope diversity and solar radiation diversity as sub-indices. The mapping requires a number of steps, including: (i) data collection; (ii) grid definition; (iii) data pre-processing; (iv) calculation of the GI; (v) visualization of the index; and (vi) interpretation of the patterns. The main considerations behind – and the procedures for – each of these steps are addressed in the following sections.

11.3.2 Data Collection

Collecting digital map data sets for a given area usually produces a digital database of thematic maps, with differences in factors such as scale, quality, legend units, coverage and age. Tectonic and geological maps are available for Vorarlberg (Friebe 2007; Oberhauser & Rataj 1998; Geologische Bundesanstalt Wien 2007), but a state-wide inventory of soils and geomorphology does not exist. Detailed topographical information is available, however: we used a 1 m-resolution LiDAR DEM (Land Vorarlberg 2015), which was resampled in the pre-processing phase to 5 and 25 m (Table 11.1). Elevation diversity, slope-angle diversity and solar radiation diversity were derived from the DEM and were input when calculating the GI. The elevation and slope-angle maps are considered proxy data of the geomorphology at a regional scale, as they contain information on topographical variation and geometry. However, information on the genesis of landforms – glacigenic, fluvial or by mass movements, for instance – is not included. Solar radiation (i.e., the amount of solar energy received over the period of a year) as a function of shielding and exposure induced by topography is included. Solar radiation indirectly controls soil-moisture conditions, and as such affects vegetation. Separate GIS vector layers for streams, large rivers and lakes are available in the Vorarlberg digital database and were used. Calculating the drainage network from the DEM was an alternative, but this was not employed here. The metadata of the input data sets are listed in Table 11.1, and include information on content, data type, original map scale or cell size, total number of features or range and data source.

11.3.3 Grid Definition

The optimal grid size for the generation of a GI map depends on the scale/cell size and on the quality and comprehensiveness of the input data. Hengl (2006) suggests using the scale of the input maps to calculate the coarsest (in our case, 1250 m), finest (50 m) and recommended (250 m) grid size; we decided to use a 1000 m grid in our approach, to reduce computation time. The Create-fishnet tool was used in ArcGIS 10.2 to prepare the analysis raster for the areal extent of Vorarlberg.

11.3.4 Data Pre-processing

For the region-wide analysis, we used six geodiversity sub-indices, which were subsequently classified into five classes of increasing geodiversity. The tectonic and geological maps were both rasterized at 1 m resolution using the polygon-to-raster tool in ArcGIS. The number of different tectonic and geological units per 1×1 km cell was counted in both maps with the variety option in the zonal-statistics

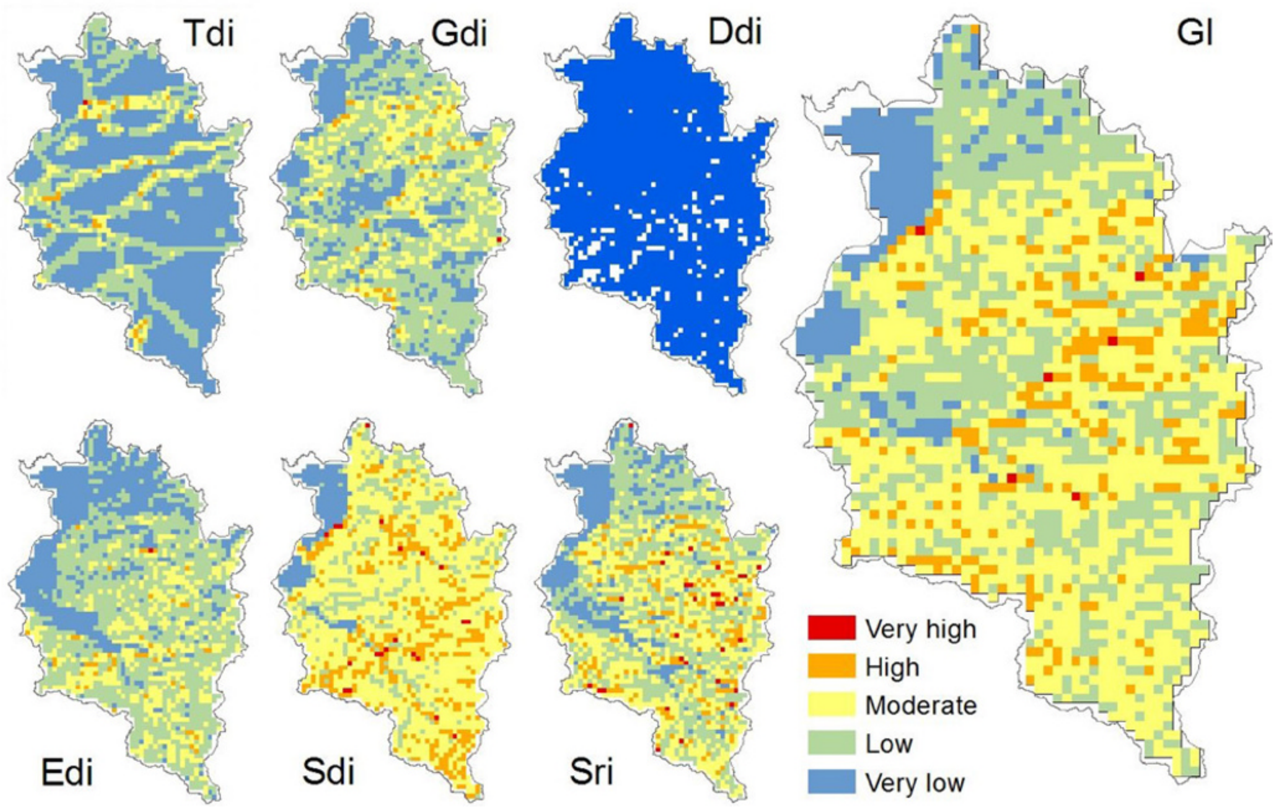

Figure 11.2 Geodiversity index (GI) map of Vorarlberg. Grid size in all maps is 1 × 1 km. Geodiversity for each cell follows the five-class scheme presented in the figure, ranging from very low to very high for each index, with the exception of the map for Ddi, where each cell is marked solely on presence (dark gray) or absence (white) of drainage. Tdi, tectonic diversity index; Gdi, geological diversity index; Ddi, drainage diversity index; Edi, elevation diversity index; Sdi, slope diversity index; Sri, solar radiation diversity index; GI, geodiversity index. See also Plate 22 in color plate section.

tool, generating a tectonic diversity index (Tdi) and a geological diversity index (Gdi). Given the 18 tectonic units in Vorarlberg (Table 11.1) and their generally large areal extent vis-à-vis the size of the grid cells, the Tdi range is relatively low – between 1 and 5 – and, therefore, reclassification was not deemed necessary. The maximum number of geological formations occurring in a single cell is 14; these were regrouped into five classes for the calculation of the index. The highest Gdi class (5) only covers 0.04% of the total area of Vorarlberg, while the most frequent class (2) covers 51.5% (Figure 11.2). The two hydrology data sets (see Table 11.1) were merged, and a buffer zone of 100 m was created around the drainage to reflect the potential influence of surface hydrology on the surrounding abiotic landscape. A spatial join of buffered streams to the grid in ArcGIS resulted in a drainage diversity index (Ddi) with either drainage present (1) or drainage absent (0). As there are rivers or lakes present in 93% of the cells, the Ddi subindex is not very discriminatory. The 5 m DEM was used to construct an elevation diversity index (Edi) by calculating the standard deviation of the elevation per 1 × 1 km cell with the zonal-statistics-as-table tool. The standard deviation ranges from 0.287 to 349 m; the results were reclassified into five equal size classes. In a similar way, the standard deviation of the slope angle was used to calculate a slope diversity index (Sdi). The standard deviation of the slope ranges from 0.55 to 21.8°. To reduce computational time, the 2004 solar radiation diversity index (Sri) was calculated at a lower resolution (25 m) with the ArcGIS area-solar-radiation tool. The values vary between 1186 and 1.78×10^6 WH/m^2. The standard deviation (range: 2234–440425 WH/m^2) of the solar radiation was divided into five equal size classes.

11.3.5 Calculating the Geodiversity Index

The final GI is the summation of the six diversity subindices, with a theoretical range of values between 5 and 26. The raster-calculator of ArcGIS was used to compute a GI raster with the following equation:

$$GI = Tdi + Gdi + Ddi + Edi + Sdi + Sri \qquad (11.1)$$

Table 11.2 Classification and areal coverage of the geodiversity classes in Vorarlberg.

Geodiversity class	Geodiversity variety per cell	Distribution (%): area/total area
1) Very low	5–8	9.27
2) Low	9–11	34.5
3) Moderate	12–14	45.7
4) High	15–17	10.2
5) Very high	18–20	0.25

In practice, the values range between 5 and 20. They were reclassified according to the class-versus-variety values set in Table 11.2.

Instead of using classified values per sub-index, the original values of the sub-indices can be used to calculate the GI, and, for example, weighting of the individual sub-indices may be considered. One should keep in mind, however, that thematic maps already contain expert-based information collected on a specific scale, and therefore they usually differ in content detail. Assigning weights to individual sub-indices should therefore be done with prudence, if at all, keeping the effect on the total GI in mind.

11.3.6 Visualization and Interpretation

The maps of the sub-indices and the resulting GI map of Vorarlberg are displayed in Figure 11.2. We emphasize that the spatial pattern can only be meaningfully interpreted with the nature and distribution pattern of the original input data in mind. The pattern of geodiversity (GI in Figure 11.2) appears to primarily reflect the diversity trends in geology (Gdi) and topography (Edi and Sdi). The very low and low geodiversity values (classes 1 and 2 in Table 11.2) of north and west Vorarlberg correspond to the valley floors of the Rhine and Ill valleys and to the relatively low topography of the Molasse zone, which are also characterized by low geological variety. High and very high GI values (classes 4 and 5 in Table 11.2) are found more frequently in areas of combined complex topography and varied geological substrata. Such areas occur in the Northern Calcareous Alps at relatively high altitudes. However, among the highest areas of Vorarlberg, the Montafon region (Figure 11.1) is characterized by low to moderate GI values, high GI values being rare as a function of the generally low to very low Gdi values. High GI scores also occur in the Hintere Bregenzerwald of central-eastern Vorarlberg, in which the Au West study area of geodiversity mapping (see Section 11.4) is situated.

It is important to realize that the function of the GI is to identify areas with potential clusters of high geodiversity; that is, those areas with a concentration of cells with high and very high GI scores.

11.4 Fine-Scale Geodiversity: The Au West Case Study

11.4.1 Area Description

The case-study area is located in the municipalities of Au and Mellau in the Bregenzerwald region of central-northern Vorarlberg (Figure 11.1), in the catchment of the Bregenzerache River and its tributary, the Argenbach. Locally, the Leuebach, Vorriedbach and Augenfallbach rivers flow to the east, into the Argenbach (Figure 11.3). The geological substratum is formed by rocks of the Helvetic Säntis Nappe. The area is the eastern part of a structurally controlled east–west-running topographic low, to the south of the Kanisfluh summit (2044 m) – with its impressive southern dip slope of Late Jurassic limestone – and to the north of the Gungern-Klippern (2066 m) mountain range – with steep face slopes of (in part) siliceous limestone, marls and shaley marls of early Cretaceous age. In contrast to the corresponding cell values of the index-based $1 \times 1\,\text{km}^2$ geodiversity map (Figure 11.2), which range between 9 and 13 (low to moderate geodiversity), we show that clusters of high geoconservation potential are identified by applying the fine-scale, expert-based geomorphological approach. The discrepancy is largely due to classical geological maps focusing on bedrock geology and showing only poorly the intricacies of the glacial overburden.

11.4.2 Mapping and Assessment of Geoconservation Potential

Driven by the need for detailed information in support of landscape planning and management at the community and state levels in Vorarlberg, a method was developed by Seijmonsbergen et al. (2014) to evaluate the potential for conservation of small landforms and deposits and their surrounding areas. The method uses detailed area-covering geomorphological maps as the basis for assessment. The resulting polygon-based maps, including their attributes, depict morphogenetic classes, which are weighted and ranked in an automated GIS procedure with four factors: scientific relevance and frequency of occurrence (primary factors) and vulnerability and disturbance (secondary factors); see Table 11.3a. Three levels of importance for geoconservation potential are differentiated as rankings of low, medium and high significance (Table 11.3b). Landforms created by glacial

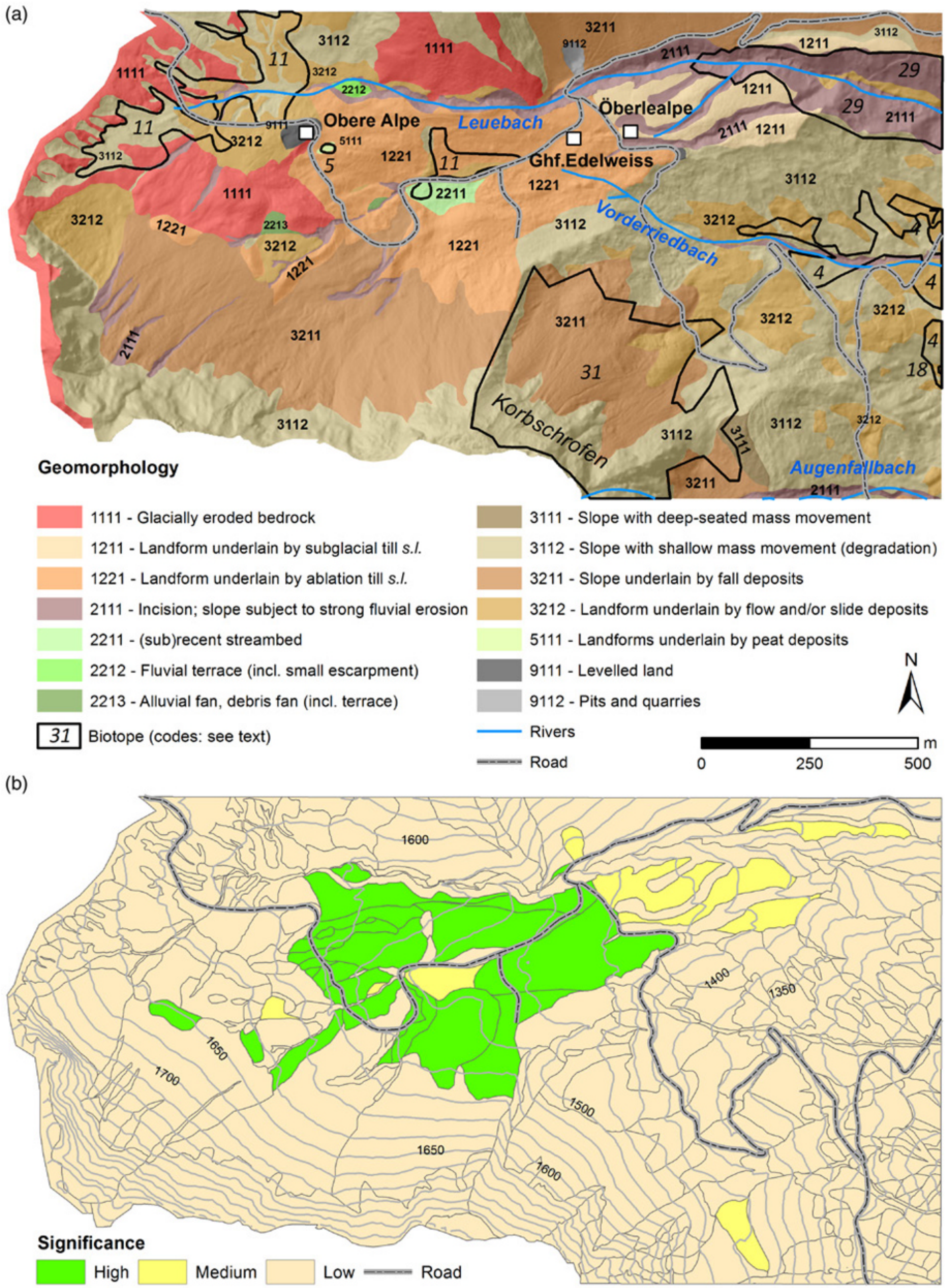

Figure 11.3 (a) Digital geomorphological map of the Au West area, displayed as a semi-transparent overlay on a DEM-derived hillshade map. The location of the biotope units is indicated. (b) Potential geoconservation map of the Au West area, shown on a background of 25 m-contour lines. Refer to Section 11.4.3 for further explanation. See also Plate 23 in color plate section.

Table 11.3 (a) The morphogenetic classification scheme used to generate the digital geomorphological map of Au West in Figure 11.3 (subset of the Seijmonsbergen et al. 2014 scheme). The standard weighting and ranking criteria (including the numerical values) used in the assessment of geoconservation potential are also shown for the morphogenetic types (see Box 11.1 for a detailed explanation). Columns include the following data for each process group: GIS code of types of geomorphosites, explanation of the GIS codes (landform and deposit types) and standard numerical values of weighting and ranking criteria used in GIS. (b) Classes of geoconservation potential. The numerical values are the summed scores of the weighting and ranking criteria for the morphogenetic types described in (a).

(a)

Process group	GIS code	Landforms and deposits	Scientific relevance (1–4–7)	Frequency of occurrence (1–3–5)	Vulnerability (1–2–3)	Disturbance (1–2–3)
Glacial	1111	Glacially eroded bedrock	1	1	1	3
	1211	Landform underlain by subglacial till *s.l.*	4	3	3	3
	1221	Landform underlain by ablation till *s.l.*	7	5	2	3
Fluvial	2111	Incision; slope subject to strong fluvial erosion	1	1	3	3
	2211	(Sub)recent streambed	1	5	3	3
	2212	Fluvial terrace (incl. small escarpment)	4	5	2	3
	2213	Alluvial fan, debris fan (incl. terrace)	4	3	1	3
Mass movement	3111	Slope with deep-seated mass movement	4	5	2	3
	3112	Slope with shallow mass movement (degradation)	1	1	3	3
	3211	Slope underlain by fall deposits	1	1	2	3
	3212	Landform underlain by flow and/or slide deposits	1	3	1	3
Organic	5111	Landforms underlain by peat deposits	7	5	3	3
Anthropogenic	9111	Levelled land	1	5	1	1
	9112	Pits and quarries	4	5	1	1

(b)

Geoconservation potential	Ranking summation
Low significance	4–8
Medium significance	9–13
High significance	14–18

Box 11.1 Brief description of the main morphogenetic mapping units in Table 11.3

Landforms and deposits of the glacial environment are formed or affected by the action of glaciers. Glacially eroded bedrock (GIS code 1111) typically has a fairly smooth surface and is relatively unaffected by postglacial processes such as weathering, erosion and mass movement. The most common deposits formed by a glacier are subglacial till *s.l.* (1211) and ablation till *s.l.* (1221). The former is an unsorted mixture of clays, silts, sands and larger rock fragments formed at the base of a glacier and compacted by the weight of it. Ablation till *s.l.* consists predominantly of sands, gravels and rock fragments, with a subordinate amount of clays and silts. It forms at the glacier margin, below the snowline, and is typically not very compacted. The main ecological difference between the types of tills is that soils developed in subglacial till are often swampy/wet and unstable due to the generally fine-grained and impermeable nature of the material, while soils in ablation till tend to be dry, permeable and stable. Fluvial activity is an important process in mountainous areas: incisions abound and many slopes are subject to strong fluvial erosion (2111). Locally, (sub)recent streambeds, fluvial terraces and small alluvial fans occur, composed of gravels and sands (2211–2213). Driven by gravity, mass movement is widespread in mountainous areas. With the disappearance of the glaciers at the end of the last ice age, many slopes, which were often oversteepened due to glacial erosion, became instable to depths tens to hundreds of meters below the land surface and collapsed (3111). Fluvial erosion also triggered – and continues to trigger – mass movements on the flanks of incisions. Surficial mass movements occur widely in mountains, resulting from the downslope movement of loose rock fragments and soil. Degradational slopes are widespread. In these, several meters of unstable wet soil have been removed to form shallow niches and gullies in an irregular topography (3112). Landforms underlain by flow and/or slide deposits (3212) form by the accumulation of relatively wet material flowing, sliding or creeping down the slopes, often coming to rest at their feet. Slopes underlain by fall deposits (3211) are the product of the accumulation of relatively dry debris which has fallen, rolled or glided from a steep cliff, usually in limestone or sandstone. Locally, peat or peaty deposits (5111) form, often in small depressions produced by mass movement and affected by high groundwater levels in a clay-rich environment. A comparison of these morphogenetic units and biotopes in the Au West area is presented in Section 11.4.3.

accumulation, glaciofluvial landforms, deep-seated mass movements, periglacial features and landforms of sulphate karst, among others, are ranked as highly significant in the standard application of the protocol (Table 11.3). Upgrading or downgrading the ranking of individual morphogenetic classes may be done by the application of additional assessment criteria (pedological, geological, etc.). Similarly, the standard ranking of units or associations of units may be changed on the basis of expert knowledge.

The digital geomorphological map of Au West (Figure 11.3) has been prepared in GIS using scanned and georeferenced published and unpublished classical geomorphological maps (Rupke et al. 1988) in combination with the GIS-based mapping techniques of Seijmonsbergen et al. (2014). The potential geoconservation map (Figure 11.3) was constructed by the application of the assessment protocol in Table 11.3.

11.4.3 Geomorphological Description

For a good understanding of the expert-derived geomorphological map and the subsequent assessment of geoconservation potential of the fine-scale landforms and deposits, the following explanatory notes are provided. The western part of the study area (i.e., the upper catchment of the Leuebach) can generally be described as a glacial niche with a headwall formed by the north- and east-exposed faces of Klippern. The floor of the glacial niche, which is covered in places by subglacial and ablation tills, extends from Obere Alpe (1593 m) to Öberlealpe (1473 m) along the structurally controlled low. Rockfall and debris-flow processes modify the original glacial shape of the niche (Figure 11.4).

The eastern part of the study area is dominated by erosion and mass movement, completely altering the original glacial landscape. Scree is actively produced and debris flows take place on and at the foot of the steep Korbschrofen cliff (Figure 11.3). Downslope accumulations of blocky debris are evidence of massive rockfall events. Further downslope, the irregular topography of niches and lobate features are indicative of sub-recent slope degradation, in which degradation and temporary accumulation have interacted – and are continuing to interact on a small scale – in a spasmodic way. Large slump-like features, now modified by surficial mass movement, are indicative of past deep-seated instability.

A more detailed survey of the glacial *s.l.* part of the study area reveals the presence of several types of moraines: morainic ridge, block-moraine cover and

Figure 11.4 (a) View to the south of part of the Obere Alpe glacial niche. Rockfall and debris-flow deposits cover the lower slopes of the headwall, which is part of the Gungern-Klippern mountain range. The hummocky topography around and to the left of Obere Alpe (center-right) is formed by an intricate pattern of glacially eroded bedrock and ablation tills. (b) View to the south-west of the glacial landscape in the central part of the study area. The east-sloping surface to the left of Ghf. Edelweiss is underlain by subglacial till (exposed in the flank of the Leuebach incision in the lower-central part of the photo). The steep Korbschrofen cliff (left) produces abundant scree. The central-right cliff, with an apron of talus, is the headwall of the Obere Alpe glacial niche. See also Plate 24 in color plate section.

subglacial till. A terrace with a relatively flat and gently east-sloping top, underlain by subglacial till, occurs east of Öberlealpe and Alpengasthof Edelweiss; it forms the easternmost remnant of the glacial landscape. Erosion and mass movement by the Leuebach and its small tributaries have created the terrace out of a landform that is thought to have extended much farther east. Going west to the low between the Kanisfluh and Klippern mountain ranges, the terrace grades to a surface covered by limestone erratics; remarkably, a tributary of the Leuebach flows in an unconfined manner through/below the blocky surface. Going farther west, the blocky cover becomes a hilly topography of morainic blocks, which merges with the actively building scree slope at the foot of the rock cliff of the south-eastern part of the Obere Alpe glacial niche. More morainic hills and ridges occur in the central part of the glacial niche. Their identification is not always straightforward: scree accumulation and debris-flow deposition have masked the original morphology. The subglacial till accumulation was deposited when the local Obere Alpe glacier extended in an easterly direction during the last glaciation. The cover and hills of blocks, as well as the other moraines, are interpreted to have been deposited by this local glacier while it was spasmodically receding to and in the Obere Alpe glacial niche during the final stages of deglaciation.

Table 11.4 Cross-tabulation (%) showing the occurrence of morphogenetic units in the seven main biotope units in the Au West area. For the locations of the biotope units, refer to Figure 11.3. The numerical coding of the biotope units refers to the classification presented in the municipality reports of Mellau and Au.

Biotope/ morphogenetic type	Area (%)	Glacially eroded bedrock – 1111	Landform underlain by subglacial till *s.l.* – 1211	Landform underlain by ablation till *s.l.* – 1221	Incision: slope subject to strong fluvial erosion – 2111	(Sub)recent streambed – 2211	Slope with deep-seated mass movement – 2212	Slope with shallow mass movement (degradation) – 3111	Slope underlain byfall deposits– 3112	Landform underlain by flow and/or slide deposits– 3211	Landforms underlain by peat deposits – 5111
Grassland and wet seepage forests – 04	9.5	–	–	–	8.2	–	–	54.6	–	37.1	–
Nutrient-poor meadows (complex) –18	<0.1	–	–	–	–	–	–	–	–	100	–
Ravine, slope and valley forests – 29	19.1	–	1.4	–	86.6	–	–	4.1	0.1	7.7	–
Montane and subalpine coniferous forests – 31	51.3	–	–	–	–	–	0.8	42.3	49.8	7.1	–
Mires and bogs –11	19.0	6.9	–	9.7	2.2	1.8	–	46.4	–	33.1	–
Lakes/ponds – 05	0.1	–	–	16.5	–	–	–	–	–	–	83.5
Reedland – 07	1.0	–	–	–	–	–	–	–	–	100	–

Source: Adapted from Gemeinde Au (2009) and Gemeinde Mellau (2014).

The ablation-till landforms (GIS code 1221), small fluvial terraces (2212) and a small pond bordered by wet and peaty deposits (5111) in the Obere Alpe glacial niche are highly significant in the standard application of the protocol. A deep-seated slump (3111) is also classified as highly significant. Although relatively well preserved and, unlike other deep-seated mass movement landforms in the eastern part of the study area, not modified by shallow mass movement, the latter is down-ranked to the level of medium significance in the protocol: it is not considered important enough within the context of the study area or that of the State of Vorarlberg to be high-ranking. No changes in the ranking of the other highly significant landforms are proposed. The final geoconservation potential is shown in Figure 11.3.

11.4.4 Comparing Geomorphological Diversity and Biotope Data

The geodiversity assessment of the Au West area paves the way for a comparison of geodiversity and biodiversity (or, more specifically, vegetation diversity): map inventories are available for both. A biotope inventory has been prepared for the State of Vorarlberg in two surveys, on two scales. The initial inventory was made between 1984 and 1989, and was revisited, updated and digitized between 2005 and 2009 (see also Broggi et al. 1991). Explanatory reports are available for all individual municipalities. Biotopes are areas with a combination of environmental conditions that host specific biological communities. In the inventory, only biotopes of conservation interest have been mapped, based on criteria such as naturalness, rarity, diversity, protected and/or endangered species and scientific relevance (Broggi et al. 1991). Using the output of the Au West analysis, a comparison of the existing biotopes on the one hand and (morphogenetic) geodiversity or geoconservation potential on the other is possible. For this study, we have done a cross-tabulation analysis of the relationship between the areal coverage of biotope units and the morphogenetic types occurring within these biotopes (Table 11.4).

In general, Table 11.4 shows that the cross-tabulation approach is promising for the quantification of geodiversity in terms of morphogenetic types within biotope units (Box 11.2). Biotope-management strategies may benefit from taking into account such relationships between biodiversity and geodiversity.

Visual inspection of the map of the geoconservation potentials and locations of biotopes (Figure 11.3) shows that there is little agreement between the grouping of morphogenetic types and biotope units. A possible explanation is that the landforms in which the biotopes predominantly occur are not unique but widespread in Vorarlberg, and, consequently, are ranked low for geoconservation purposes. In addition, such landforms are often intensely used and therefore not included in the official biotope inventory.

11.5 Conclusion

Various approaches to geodiversity mapping are possible. Common to all is that they take into account: (i) the specific goals and objectives of the study or project;

Box 11.2 Morphogenetic types and biotopes in the Au West area

Seven biotopes have been mapped within the 2.15 km^2 area covered by the morphogenetic map of Au West (see Figure 11.3 and Tables 11.3 and 11.4). The vegetation composition of these biotopes is described in detail in the municipality reports of Mellau (Gemeinde Mellau 2014) and Au (Gemeinde Au 2009) and in the associated ArcGIS database. The percentages of the surface area of the morphogenetic types falling within the boundaries of the seven biotopes are listed in Table 11.4. A few strong similarities are observed: for example, 92.1% of the biotope unit "montane and subalpine coniferous forests – 31" occurs in the morphogenetic types "slope underlain by fall deposits" (GIS code 3211) and "slope with shallow mass movement (degradation)" (3112). Such areas are characterized by steep slopes/cliffs, generally developed in resistant bedrock, with abundant talus production and large accumulations of coarse permeable debris at their feet (see Figure 11.4). Also, 86.6% of the biotope unit "ravine, slope and valley forests – 29" occurs in the morphogenetic type "incision; slope subject to strong fluvial erosion" (2111). Streamlets, such as the Leuebach, are creating well-defined incisions characterized by steep slopes, dynamic geomorphological processes and ample water supply. These incisions are potential biotopes for the rich mixture of forests of river valleys and canyons.

The biotope units "grassland and wet seepage forests – 04," "nutrient-poor meadows (complex) – 18," "mires and bogs – 11," and "reedland – 07" seem to be present more frequently in units of the morphogenetic types "slope with shallow mass movement (degradation)" (3112) and "landform underlain by flow and/or slide deposits" (3212), although with only limited extent in the study area. These are generally low-angle slopes underlain by fine-grained weathering materials derived from marl and/or subglacial-till deposits that promote wet surface conditions due to poor drainage and the occurrence of spring zones.

(ii) the physiography of the area under consideration; (iii) the quality and scale of available data; and (iv) the required detail of mapping. We have presented the workflow of two methods, the first on a region-wide scale for inventory-mapping purposes, the second on a local scale in support of geoconservation management. The latter approach also enables the evaluation of the relationship between geodiversity and biotopes. The index-based approach is applied to the entire area of the State of Vorarlberg with the objective of identifying, in a first pass of evaluation, clusters of high geodiversity. The objective of the second approach is the identification of potential geoconservation sites (i.e., areas with high value in terms of morphogenetic type) on a local scale. Whereas the signal function is the strength of the region-wide method, the local method generates information for land-management purposes. The link between the two is clear: the quick index-based method of geodiversity assessment, although it depends on the quality, comprehensiveness, and scale of the input data, may reveal clusters of high geodiversity that subsequently can be evaluated more efficiently on a finer scale.

The index-based approach focuses on finding cells or groups of cells of geodiversity classes derived from a computer-based analysis of geological and DEM-derived data sets. On a local scale, the emphasis is on detailed geomorphological information. Expert-derived knowledge of landscape genesis is used to delineate and interpret landforms and processes, which are subsequently assessed for their degree of significance by the application of quantitative and qualitative evaluation criteria.

The fine-scale mapping approach has the potential to be supplemented by a semi-automated geomorphological mapping or classification technique, as was attempted by Anders et al. (2013) and Seijmonsbergen et al. (2014), giving the potential to transfer the method to other mountain areas (Anders et al. 2015). While the geodiversity results presented here are relevant and valid within the legislative boundaries of Vorarlberg, this does not rule out any validity within a larger frame of reference (e.g., the northern Alps). Wider application of the results, however, should be carried out with caution, taking into account possible supraregional differentiation. Alternative geosite-based approaches exist that emphasize not only the scientific, but also the educational, cultural, esthetic and ecological values of geodiversity (Brilha 2016; Reynard et al. 2016).

In all cases, geodiversity assessments provide a sound basis for geoconservation. Moreover, they are a relatively new way of analyzing the abiotic part of the environmental heterogeneity of mountains, to which biodiversity is generally thought to be closely linked (Stein et al. 2014). Comparison of morphogenetic types on a local scale with existing biotope data suggests that most biotopes occur in specific morphogenetic types. It appears that the distinction between "wet" and "dry" mass-movement processes is an important factor, together with slope steepness and material properties (e.g., coarse- vs. fine-grained), for effectively characterizing natural biotopes. Clearly, other factors, such as local land management (drainage, cattle grazing, mowing, etc.), are to be included in the analysis of biodiversity in mountain areas.

The potential of the concept of geodiversity and of DEM-derived approaches for biodiversity conservation has been demonstrated in recent studies, such as that of Anderson et al. (2015), in which eight case studies are described. These studies illustrate the mapping of ecological land units and land facets for the design of species corridors and the prioritization (from both a geodiversity and a biodiversity perspective) of conservation portfolios, all of which include particular aspects of geodiversity. Strategies for implementing geodiversity in conservation decision plans are addressed in the work of Comer et al. (2015), who emphasize the importance of support in law and policy. These recent developments acknowledge the importance of continuing research in geodiversity to our understanding of biodiversity.

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