Geodiversity and Geomorphometry: Methods and Applications in Landscape Assessment

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Abstract: **Geodiversity – the natural range of Earth's abiotic features – plays a fundamental role in shaping geoecosystems, supporting biodiversity, and guiding conservation planning. This paper examines current methodologies for assessing geodiversity, with a focus on integrating geomorphometric analysis with thematic mapping and Spatial Multi-Criteria Analysis (S-MCA). Through case studies, we illustrate how varying methodologies influence geodiversity mapping outcomes. We highlight the strengths and limitations of qualitative, quantitative, and hybrid approaches, with particular attention to uncertainty and scale of analysis. The study underscores the value of participatory tools, such as geo-questionnaires, and proposes best practices for transparent, repeatable, and policy-relevant geodiversity assessment.**

I. Introduction

Geodiversity – the diversity of Earth's abiotic components – has gained attention in recent decades as a complement to biodiversity (Gray, 2004, Zwoliński, 2004). It encompasses the range of geological, geomorphological, and soil features, along with their assemblages, relationships, and processes. While geodiversity is recognized for underpinning biodiversity and ecosystem functioning, it also possesses intrinsic value independent of its ecological roles. For example, Gray (2004) identifies multiple geodiversity values – intrinsic / existence, cultural, aesthetic, economic, functional, and research / educational – emphasizing how abiotic diversity contributes to landscapes, natural resources, and human understanding. Geodiversity underlies geoheritage, geosites, and geoparks, playing an increasingly important role in geotourism and conservation planning (Najwer & Zwoliński, 2014). Mapping and assessing geodiversity are therefore important for protected and conserved areas (PCAs) management and land-use planning (Jankowski *et al.*, 2020, Najwer *et al.*, 2016, 2023). The current study aims to synthesize recent developments by exploring the integration of geomorphometry – the quantitative analysis of land surface characteristics – with geodiversity assessment. Geomorphometry provides a powerful toolkit for characterizing topography and modelling spatial patterns of terrain-related factors such as slope, curvature, solar radiation, and moisture indices (Evans, 2012, Minár *et al.*, 2020). When combined with thematic datasets on geology, hydrology, and soils, geomorphometric parameters can support the creation of reproducible, high-resolution geodiversity maps. This fusion holds promise for developing scalable, transferable methods applicable across various landscapes and spatial planning contexts.

II. Definitions and Conceptual Background

Many authors have offered formal definitions of geodiversity. Gray (2004) defined it as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, processes) and soil features" including their assemblages, interactions, and systems. Zwoliński (2004) similarly emphasizes the natural range of bedrock, landform, and soil deposits, plus associated systems and processes, as constituting geodiversity. More recent definitions expand geodiversity to include hydrological (Gray 2013) and climatic elements (Najwer *et al.*, 2016, Tukiainen *et al.*, 2023). In practice, these dimensions are often treated as factors in geodiversity assessments (e.g., geology, relief, hydrography, soils, climate).

Outstanding geodiversity landscapes are those that are rare, unique, well-expressed, and of regional significance, whereas representative landscapes serve as exemplars of common abiotic types. Thus, geodiversity mapping often seeks to identify areas with exceptional or representative abiotic diversity. Indeed, geodiversity forms the foundation of many aspects of geoheritage: geo(morpho)sites, fossil sites, and geoparks all derive significance from their underlying abiotic diversity. Effective geodiversity mapping requires integration of datasets on geology, geomorphology, soils, hydrology, and climate at appropriate spatial scales.

III. Methodology

Assessment approaches. Geodiversity assessment methods vary widely in terms of data sources and procedures. One way to categorize them is into **direct and indirect** approaches (Pellitero *et al.*, 2014). Direct methods quantify specific abiotic components through field surveys or thematic maps (e.g., inventories of rock types or landforms). Indirect methods infer geodiversity from surrogate indicators of environmental conditions that are associated with abiotic diversity: for example, using elevation variability or climate zones as proxies for underlying abiotic variety.

A second classification distinguishes methods by procedure: **qualitative, quantitative, and hybrid** approaches (Zwoliński *et al.*, 2018, 2025). *Qualitative* methods rely on expert-based classification or ranking of abiotic features, often based on experience or interpretation. While such methods are relatively fast and adaptable, they are also subjective and difficult to replicate (results "often not comparable" across studies). *Quantitative* approaches, on the other hand, use numerical data and measurements (digital elevation models, geological maps, field data) to compute indices or spatial metrics. These methods offer high-precision outputs and reproducibility, but they often require extensive data processing and can be costly to acquire. *Hybrid* (qualitative–quantitative) methods aim to combine the strengths of both approaches by integrating expert judgment with numerical data, for example, by applying expert-defined weights to GIS-derived factor maps. This approach leverages both specialist knowledge and the objectivity of measured data, though it still depends on the selection of factors and weighting schemes. The authors argue that hybrid methods "support the collection of quantitative data (i.e., digital) and cause–and–effect data (i.e., relational)", making them particularly useful for geodiversity mapping.

Due to the lack of a single standardized methodology, most studies adopt customized indices or multicriteria analysis frameworks. Among quantitative approaches, the **Geodiversity Index (Gd)** is commonly used. For example, Serrano & RuizFlaño (2007) proposed the following formula:

$$\mathbf{Gd = Eg\ R\ /\ \mathit{ln}\ S}$$

where *Eg* is the number of different abiotic elements in a spatial unit, *R* is a roughness coefficient (terrain variability), *S* is the unit area, and *ln* is the natural logarithm. This formula follows the concept that first linked element richness (*Eg*) with topographic roughness in a geodiversity index (on an area basis). Since then, numerous variants have emerged, modifying or expanding the index by incorporating additional factors, such as lithology counts, curvature measures, moisture indices, etc., depending on the study's objectives and data availability (Pereira *et al.*, 2013, Melelli, 2014, Pellitero *et al.*, 2014, Martinez-Grana *et al.*, 2015, Bétard *et al.*, 2017). Ultimately, the goal of all such approaches is to capture abiotic variety in a single metric.

Another quantitative approach is **GIS-based multi-criteria analysis (MCA)**. Here, a set of thematic layers (geological map, landform fragmentation map, hydrographical map, etc.) is overlaid with assigned importance weights, typically using a Weighted Linear Combination (WLC) method. Each factor layer is first scored; then, for each map cell, the Geodiversity Score = Σ(weight_i • score_i) is computed. Weights are often derived using the Analytical Hierarchy Process (AHP), based on pairwise comparisons following Saaty's (1980) method, which ensures consistency. For example, Najwer *et al.* (2023) assigned weights to streams, lakes, geology, landform fragmentation, and relief energy (0.288, 0.288, 0.174, 0.096, 0.096, and 0.058, respectively) in a study of an Alpine region, achieving a consistency ratio of 0.07. In practice, the final geodiversity map is produced by classifying the combined score, using methods such as natural breaks or expert-defined thresholds.

A recent innovation in this field is the *local WLC* (L-WLC). Unlike standard WLC, i.e., global WLC (G-WLC), where weights are global constants, L-WLC allows weights to vary spatially, capturing local variability (like applying a high-pass filter). Jankowski *et al.* (2020), Zwoliński *et al.* (2021), and Najwer *et al.* (2022) applied L-WLC alongside G-WLC in a crowdsourced study of Karkonosze National Park, Roztocze National Park, and Wolin National Park in Poland. Their findings showed that combining local and global aggregation methods produces a more nuanced geodiversity assessment.

Data sources and factors. Geodiversity mapping draws on a wide range of data sources, including geological maps, soil surveys, DEMs, satellite imagery, etc. Geomorphometric analysis is particularly widespread: researchers compute **DEM-derived indices** such as relief energy (terrain ruggedness), slope, curvature (profile/plan), surface roughness (rugosity), topographic position index (TPI), convergence index, potential/total solar insolation and wetness indices (Topographic Wetness Index - TWI, Topographic Relative Moisture Index - TRMI), among others. For example, Jačková & Romportl (2008) used relative elevation and landform fragmentation metrics, finding strong links between geodiversity and habitat richness in Czech protected areas. These digital layers are often combined through map algebra to compute geodiversity scores. In some studies, additional static attributes such as lithology, hydrographic density, and climate variables are also incorporated.

Due to methodological diversity, **comparing and integrating** geodiversity maps can be challenging. Outputs can vary significantly depending on spatial resolution and the algorithm used. Scale plays a crucial role: Seijmonsbergen *et al.* (2018) showed that mapping the Hawaiian Islands at a10 km resolution (using global datasets) vs. 500 m (using local datasets) produced markedly different spatial patterns. Similarly, Vregelaar (2015) reported scale sensitivity in the Netherlands. Thus, both the scale classification method (equal-interval vs. natural breaks) and the selection of input factors have a substantial influence on the final results. Moreover, all methods rely on expert decisions (rating scales, weights, and criteria), introducing a degree of subjectivity. Regardless of whether a quantitative or semi-quantitative approach is applied, the final geodiversity classification remains relative to the specific area under investigation. To enable meaningful comparison across regions, a standardized classification system should be developed for each abiotic component, ideally at a global or continental scale. Additionally, the development of classification scales adapted to specific morphoclimatic zones is also worth considering.

IV. Case Studies

Dębnica catchment (Poland). Najwer *et al.* (2016) and Zwoliński *et al.* (2018) illustrate how methodology affects outcomes. They assessed geodiversity in the Postglacial Dębnica River catchment (Western Pomerania) using two approaches applied to the same dataset: (1) a GIS-AHP approach (featuring fine 30×30 m grids and expert weights) and (2) a classical index-based method following Serrano & Ruiz-Flaño (2007) (using coarse 1×1 km grids). The two resulting geodiversity maps were assessed as “diametrically opposed”. In the index map, roughness coefficient (R) was the dominant factor, highlighting broad areas of high relief energy. In contrast, the AHP map’s highest geodiversity arose in areas with complex geomorphology - characterised by high relative altitudes and varied landform types. In other words, the index method emphasized vertical ruggedness, while the multicriteria method emphasized spatial landform diversity (horizontal ruggedness). The authors conclude that both methods are *equipotential* – each yielding meaningful but not directly comparable results. Interestingly, both approaches identified similar clusters of high- and low-diversity areas despite methodological differences. This case highlights how grid size (spatial assessment unit) and factor prioritization can invert perceived geodiversity.

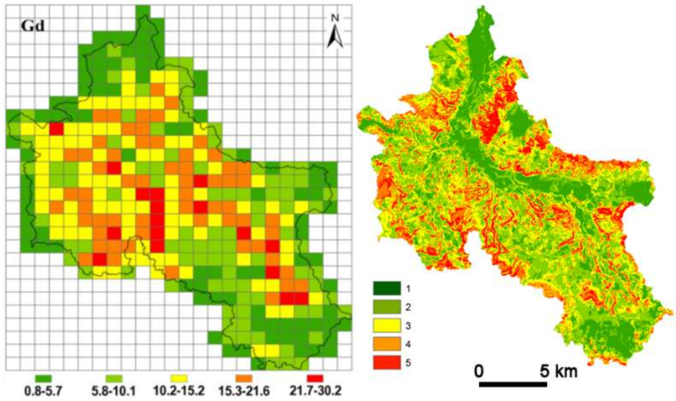

Figure 1. Total geodiversity maps for Dębnica River catchment. On the left, geodiversity is calculated according to geodiversity index (Serrano & Ruiz-Flaño, 2007), and on the right, according to GIS-AHP approach (Najwer *et al.*, 2016). Classes of geodiversity: 1 – very low, 2 – low, 3 – medium, 4 – high, and 5 – very high.

Karkonosze National Park (Poland). In another study, Jankowski *et al.* (2020) conducted a geodiversity assessment of the Karkonosze NP using a novel *crowdsourcing* approach. They gathered ratings from 57 Earth science researchers via a geo-questionnaire (Jankowski *et al.*, 2016) to determine factor scores and weights for variables such as lithology, relief energy, landforms, land cover and land use, soils, solar irradiance, hydrography. The study computed two types of aggregate geodiversity maps: standard WLC (G-WLC) and local WLC (L-WLC, Malczewski, 2011). Key findings were that L-WLC produced more extensive areas of high geodiversity – reflecting localized hotspots – than the G-WLC map. In total, more high geodiversity area was identified by L-WLC (31 km²) than by G-WLC (27.3 km²). Moreover, integrating the two maps with an uncertainty analysis revealed seven areas of high geodiversity with low uncertainty (e.g., Mumlawski Slope, Szrenickie Wetlands, White Gorge, etc.). The authors emphasize that using both local and global weighting in combination provides a more comprehensive picture than using either method individually. This case demonstrates the feasibility of combining crowdsourced expert knowledge with spatial multi-criteria methods to generate detailed geodiversity maps for PCAs.

Mountain catchments (the Alps, Tatra Mts., and Sudetes). Najwer *et al.* (2023) performed a full GIS-WLC analysis with factors like streams, lakes, geology, landform fragmentation, relief energy, and landform preservation in two catchments, i.e., Derborence and Illgraben in the Swiss Alps. Weights were determined using AHP (pairwise comparisons), and the final maps reflected the weighted sum of these layers. In smaller mountain catchments (Wrzosówka Stream in Sudetes, Sucha Woda Stream in Tatra Mts.), and comprehensive DEM-based workflow was used: the researchers derived several factor maps from a DEM, including relief energy, convergence index, general curvature, topographic openness, topographic position index, topographic wetness index, and total incoming solar radiation. These were then combined using expert-defined weights, into a final geodiversity map (Fig. 2). Across these cases, multi-criteria GIS-based analysis enabled the integration of diverse abiotic data into interpretable geodiversity assessments.

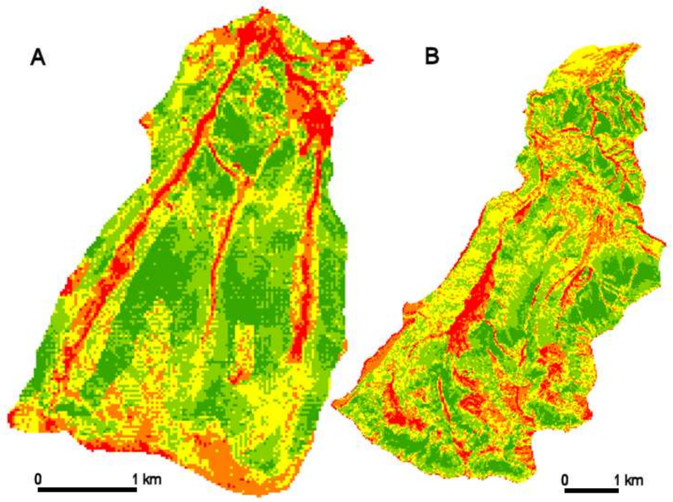

Figure 2. Total geodiversity maps for Wrzosówka Stream (A) and Sucha Woda Stream (B). The colours are explained in Fig. 1.

Scale of geodiversity. A methodological issue of particular importance is the application of the five-point Likert scale (Likert, 1932) for classifying geodiversity across 23 national parks in Poland, based on geomorphometric parameters. A flowchart illustrating the process is shown in Figure 3. A key challenge—relevant to virtually all geodiversity assessments, regardless of the primary evaluation method chosen—is the classification of individual component values and cumulative geodiversity values relative to the value range of the area under investigation. This often leads to a lack of comparability between areas characterized by differing morphometry and morphogenesis. The most commonly applied approach involves calculating geodiversity values separately for each national park (see A in Fig. 4), resulting in an individual range of values for each park. While this method allows for a more detailed characterization of individual areas, it significantly limits the potential for cross-site comparison, making it difficult to identify the park with the highest or lowest level of geodiversity. An alternative approach calculates geodiversity scores using a unified value range for all assessed indices across a broader region (see B in Fig. 4) – in this case, the entirety of Poland. This approach preserves methodological consistency and ensures that the analysed spatial units can be directly compared, facilitating the identification of relative differences in geodiversity levels across the 23 national parks (Fig. 4).

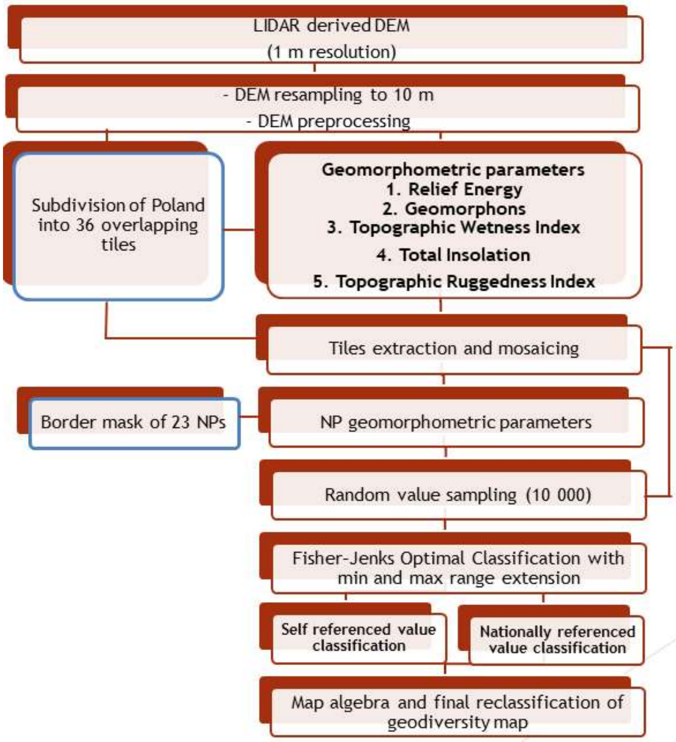

Figure 3. Flowchart for calculating self referenced and nationally referenced values of geodiversity for 23 national parks in Poland.

V. Results and Discussion

These case studies illustrate the **sensitivity** of geodiversity maps to methodological choices. Different approaches can produce markedly different maps even when based on the same raw data. In Dębnica, the coarse-index method compared to the fine-scale AHP method highlighted different features of the landscape, yet both consistently identified key geodiversity clusters. In Karkonosze, allowing weights to vary locally (L-WLC) revealed additional high-diversity zones that a global model might overlook. These findings underscore that geodiversity is not a unique observable quantity but depends on how it is measured (factor selection, weights, resolution) – a point frequently emphasized in the literature (Najwer *et al*., 2016, Zwoliński *et al*., 2018). Thus, geodiversity mapping is inherently *relative* and method-dependent; results must be interpreted with care.

At the same time, common patterns emerge: areas with complex geology or rugged relief tend to score high, while uniform plains consistently receive low scores. Geomorphometric factors (roughness, curvature, TPI, etc.) often dominate index-based maps (as seen in Wrzosówka and Sucha Woda streams).

Qualitative judgments (through AHP in Dębnica River) tend to emphasize varied landform types and processes. Both approaches are complementary. Zwoliński *et al.* (2018) suggest using combined outputs (e.g., overlaying multiple methods) to identify robust geodiversity hotspots. In our cases, despite methodological differences, clusters of high geodiversity were found in analogous zones, such as old glacial cirques, tectonic ridges, and similar landforms.

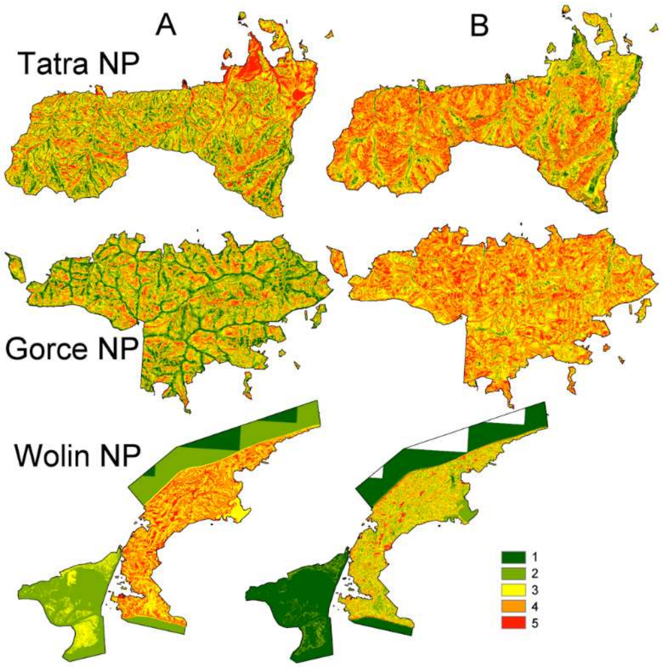

Figure 4. Self referenced (A) and nationally referenced (B) values of geodiversity for Tatra National Park, Gorce National Park, and Wolin National Park. Classes of geodiversity: 1 – very low, 2 – low, 3 – medium, 4 – high, and 5 – very high.

Key challenges remain in geodiversity assessment. The availability of data and the issue of scale are critical: coarse global datasets may miss local detail, while high-resolution local data can be expensive to obtain. Scale effects (global vs. local DEMs) have been clearly demonstrated in places like Hawaii and the Netherlands. Subjectivity is another issue: expert-derived ratings or weights can introduce bias, and different experts may disagree (leading to uncertainty). Even quantitative indices involve choices (e.g., which "elements" to include in *Eg*). As Jankowski *et al.* (2020) note, these ambiguities limit comparability across studies.

Despite these challenges, geodiversity maps provide valuable insights. They can inform management of protected areas by highlighting abiotic diversity patterns that are often invisible in land-cover maps. For example, the Karkonosze NP maps (Jankowski *et al.*, 2020) identified small-scale features of high geodiversity (e.g., rock glaciers, glacial ponds) that warrant conservation attention. The Dębnica map delineated wetland complexes and moraine hills of high geodiversity. Such spatial knowledge can guide zoning, tourism planning, and geo-conservation strategies, enriching the traditional focus on biological diversity with an abiotic perspective.

VI. Conclusion

Geodiversity mapping synthesizes geology, geomorphology, soils, hydrology, and climate into integrated maps that characterize landscape heterogeneity. No single standard method exists; instead, a toolbox of qualitative, quantitative, and hybrid techniques is used to capture the multifaceted nature of the abiotic environment. Quantitative indices (e.g., Serrano & Ruiz-Flaño's formula) and GIS-based multi-criteria models are widely applied to integrate data layers. Case studies (Dębnica, Karkonosze NP) show that methodological choices – grid resolution, factor weighting, index vs AHP – strongly affect the final map outcome. In practice, combining approaches (e.g., global and local weighting) and involving experts helps identify consistent geodiversity hotspots. Geomorphometric analysis (using DEM-derived metrics) underpins most quantitative assessments, offering **objective, reproducible measures** of Earth surface diversity.

Overall, geodiversity mapping is a valuable complement to biodiversity studies, providing a framework to assess, conserve, and utilize Earth's abiotic diversity. The reviewed examples demonstrate how diverse methods can be coherently applied to real landscapes, yielding actionable maps for geoconservation and land management. Moving forward, efforts to standardize methods and to incorporate multi-scale, participatory, and uncertainty-aware approaches will strengthen the rigor of geodiversity research.

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