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Quantitative Assessment of Geodiversity for Conservation Purposes in Slovenské rudohorie Mountains (Slovakia)

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Abstract: A geodiversity assessment is one of the basic steps in the development of geoprotection activities. It is important to establish parameters that quantify the elements and locations of abiotic nature. Here, the focus is on those who are richer than the average population. In doing so, it is possible to manage areas for the protection of important geoheritage and develop sustainable activities, e.g., geotourism. The monitored territory (Slovenské rudohorie Mts.) lies in southeast Slovakia and occupies an area of 4986 km^2. The geodiversity assessment is based on overlaying a grid onto different maps at a scale of 1:500,000, where the final geodiversity index is the sum of six indices calculated in 5 × 5 km grid squares. These indices consist of a geological index, a geomorphological index (composed of two sub-indices: geomorphological subdivision and morphological–morphometric types), a hydrological index (composed of three sub-indices: the type of aquifer, the density of the river network, and the occurrence of springs and mineral waters), a soil index, a tectonic index, and a mineral resources index (composed of four sub-indices: the occurrence of ore, non-ore, construction, and energy resources). The resulting geodiversity index map is presented in the form of five isoline classes: very high (10% of the monitored area), high (28%), medium (32%), low (23%), and very low (7%). The geodiversity map of the territory of the Slovenské rudohorie Mts., together with the indices, creates a useful tool for conservation, management, sustainability programs, and education at the national level. However, Slovak legislation does not mention the concept of geodiversity, its protection, valuation, restoration, or responsible usage. Only its specific forms and processes are preserved as a natural resource supporting biodiversity. Considering the mineralogical richness of the area, some locations with a very high geodiversity may be the focus of mineral exploration. It is very important to set up appropriate landscape management for these sites. Valuable geotopes located in biodiversity cold spots that are not subject to protection within the state's nature protection program should be considered as small protected areas (up to 1000 ha) at the fourth or fifth level of protection under Act No. 543/2002 Coll. or could form the core areas of a possible Geopark.

Keywords: geoheritage; geodiversity index; grid analysis; GIS; landscape management

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1. Introduction

It is widely accepted that geodiversity is a resource that enhances natural heritage. It also influences microclimates and provides ecosystem services [1]. A commonly used definition of geodiversity proposes to consider it as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil, and hydrological features", including "their assemblages, structures, systems, and contributions to landscapes" [2]. As it includes all natural processes (such as tectonics, sediment transport, and pedogenesis) that continue to influence, preserve, or alter the composition or shape of the Earth's surface, the study of the interactions between these elements and those required for life is made possible by the practical application of geodiversity [3,4].

The concept of geodiversity was first introduced in 1993 after the agreement of the Convention on Biological Diversity at the Earth Summit in Rio de Janeiro. It is now widely used across Europe and by the International Union for Conservation of Nature (IUCN), which has a strong bioconservation focus, creating a Geoheritage Specialist Group in 2013 to "provide expert advice on all aspects of geodiversity in relation to protected areas and their management".

Gray [2,5–8] examines in more detail the theory of geodiversity, including its value, and its application to geoconservation. Numerous authors [9–11] draw attention to geodiversity and conservation initiatives and ask for a better comprehension of the distribution of geodiversity and its connection to biodiversity [1,12–14]. The main objective of geoconservation is to protect geodiversity for its intrinsic, ecological, and geoheritage value [15]. Every geoconservation strategy should start with an inventory of locations with the highest concentrations of geodiversity and a quantitative assessment of those sites in order to determine management objectives regarding these sites [16]. Effective indicators of conservation value, the reduction in biodiversity partialities, and a wider inclusion of geodiversity in conservation literature are just a few of the tangible conservation benefits that can be realized by combining geodiversity and biodiversity assessment methods [17]. The roughness and surface of the previously identified geomorphological units are related to a variety of physical factors (geomorphological, hydrological, and soil) via the geodiversity index. The geodiversity index of a specific area is calculated using methods based on a set of characteristics and indicators. To evaluate geodiversity, qualitative, quantitative, and qualitative–quantitative methodologies can all be used. The descriptive nature of qualitative approaches makes them appropriate for ordinal and nominal data. Quantitative (i.e., digital) and causal (i.e., relational and explanatory) data are combined as a result of qualitative–quantitative approaches [4,18–20]. Continuous data should be preferred as the primary data for any area. However, there are no standards for measuring geodiversity, and continuous geographic objects are of greater significance than discrete ones [21]. Because satellite data are continuously monitored and can be aggregated across many extents and grains, remote sensing helps to clarify links between the scaling of biodiversity and geodiversity [22]. Geodiversity should not only refer to richness but also to the spatial distribution of environmental components in the study region according to frequency levels [21]. Regions with particularly high geodiversity that are simultaneously threatened by human activities are known as geodiversity hotspots [23], but they are often not appreciated by the public. Using numerical measurements of geodiversity, Somma evaluated initiatives to improve the general public's understanding of the various kinds of geoheritage [24]. For increased abiotic value protection and landscape management, a quantitative approach to geodiversity assessment is combined with cultural, anthropological, and biological studies [3,21].

Among first, Serrano emphasized the need for a geodiversity index [25] and evaluated the geodiversity in the Tiermes–Caracena area (Soria, Spain) [26]. Many other authors have addressed this topic and have characterized geodiversity in various geomorphological and geological units, for example, in the Basilicata region in southern Italy [27], the city of Belgrade, capital of Serbia [28], Estonia [29], the entire Iberian landscape [30], Brazil [21,31–33], subarctic Finland [10], Basque Country (Spain) [34], Soria province in Spain [35], Messina province in Italy [24] and the Coromandel Peninsula in New Zealand [36]. From the perspectives of geoheritage and geoconservation, Australia has played a significant contribution in the development of the concept of geodiversity. The idea is included in a lot of the Australian Heritage Commission's documents from 2002 [37].

Concerning Slovakia, several Slovak authors dealt with former mining landscape [38,39], its use in geotourism [39–45], and the conditions of protection [46–48]. In the declining mining district of Rožňava, Clarke [49] was attempting to advertise a competitive tourism service. The Novohrad–Nograd Geopark's promotion of stronger ties between Slovakia and Hungary has attracted increased attention from other authors [50]. They also characterized [51] and discussed the economic and social comparisons within the karst area of Aggtelek National Park and Slovak Karst NP [52–54].

According to Gray [7], geodiversity is a strategy for incorporating natural diversity into planning, education, and conservation (e.g., geotopes, geosites, geomorphosities, geoparks, and protected landscapes). Opportunities to connect landscape-centered strands and tourism are made possible by geotourism [55]. Although geotourism has historical precedents that stretch back to the seventeenth century, the term only entered common usage in the early 1990s. Pralong [56] defined geotourism with its potential for regional development as a "multi-interest kind of tourism exploiting natural sites and landscapes containing interesting Earth-science features in a didactic and entertaining way". Geosites, museums, libraries, and archive collections, as well as creative outputs, make up its resource base. It has substantial foundations in industrial archaeology and social history and offers an innovative perspective on sustainable travel that is more complete than earlier specialized travel [57–59].

Tourist interest in geodiversity is growing, but many geosites are declining due to anthropogenic impacts. The majority of areas with high geodiversity indices are exposed to multiple dangers from both natural and human causes, which highlights the vulnerability of these resources and the inadequate management of the region. If the geomorphological balance is disturbed, the entire area may become unstable, endangering the geodiversity and associated biodiversity of the area and causing further damage that worsens over time [60,61]. The application of geoethical principles to geotourism and speleotourism can also help safeguard caves, provide advantages for the local community in the short term, and benefit future generations in the long term [62–66].

However, non-living (abiotic) natural resources and processes are also frequently overlooked in national and international policies that support sustainable development [3]. According to Erikstad, the Habitats Directive should incorporate geoheritage and geoconservation, and EU landscape strategies should be enhanced to include geodiversity [67]. Only if the components and processes of geodiversity are categorically taken into account in the global agenda of the United Nations Sustainable Development Goals (SDG) can the addressing of non-living (abiotic) natural resources and processes be achieved [3]. A good example of local government involvement in the implementation of effective geoconservation strategies is the designation of geosites as local natural monuments [68]. Geotouristic routes may be another solution [69]. The geomorphological sites, geological sites, historic and cultural heritage components, and information on tourist accommodations and facilities could all be integrated into the multidisciplinary and multiscale database [70]. Above all, geoparks, which could represent a real "open air museum" [71] have the potential to improve the local community's economy [72,73]. Ruban [74] draws attention to hydrodiversity in geoparks. More research should also be conducted in order to incorporate marine, glacier, cave, valley, and underground habitats into the larger group of environmental categories used in geodiversity assessments [1,37].

The purpose of this work was not only to perform a quantitative assessment of geodiversity in the Slovenské rudohorie Mts., contributing to the development of this methodology and its implementation in land management studies, but also to avoid the overestimation of any particular component, such as lithology or relief, which is a frequent shortcoming of many other methods. A second aim is the production of a geodiversity index map based on the calculation of the geodiversity index and to compare it with the occurrence of geosites (significant geological sites). In addition, to define the links between geodiversity and initiatives to utilize and protect the existing geological heritage, an assessment was carried out through thematic cartography based on six partial indices, the geological index, tectonic index, geomorphological index, soil index, hydrological index, and mineral resources index. The geodiversity map produced is intended to serve as a cartographic application reference and is a convenient planning tool that allows for easy interpretation by persons with little to or no geological training. The proposed methodology was tested in a region with available cartographic data.

2. Study Area

The monitored area (Slovenské rudohorie Mts.) lies in the center and southeast of Slovakia and covers an area of 4986 km^2 (coordinates 48°45′ N 20°15′ E) (Figure 1). Geologically, it belongs to the Inner Western Carpathians subprovince and has a varied geological structure. Geomorphologically, it consists of eight geomorphological units, including the Veporské vrchy hills, Stolické vrchy hills, Revúcka vrchovina upland, Volovské vrchy hills and Čierna hora hill. They are characterized by a predominantly massive, often plateau relief. In the northwest lies the Spišsko-gemerský kras karst, and in the southeast lies the Slovenský kras karst. In the center of the region lies only one intermountain basin, the Rožňavská kotlina basin. Slovenské rudohorie Mts. received their name, Slovak Ore Mountains, from the past mining of a variety of ores there, particularly iron ore. At present, the mining of non-ore resources, such as magnesite and talc, continues here.

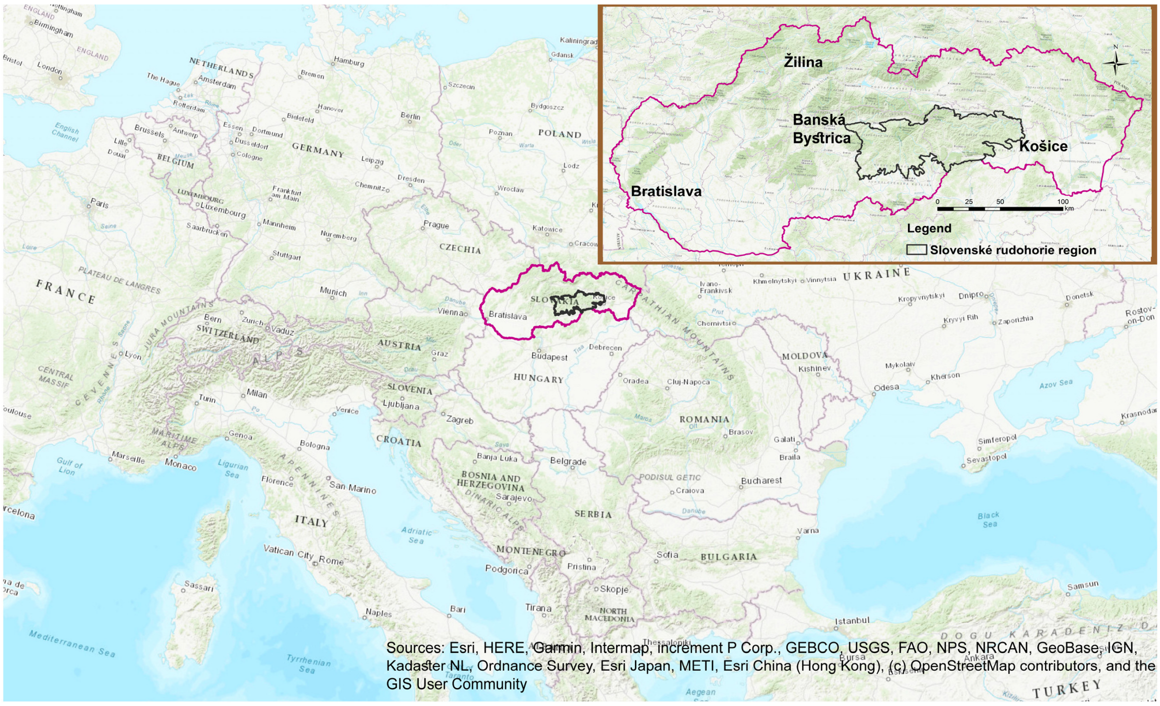

Figure 1. Study area.

As part of the state protection of nature, four national parks (NPs) have been established so far: the NP Nízke Tatry (Low Tatras NP, 1978); the NP Slovenský raj (Slovak Paradise NP, 1988); the NP Muránska planina (Muran plateau NP, 1997); and the latest declared national park, NP Slovenský kras (Slovak karst NP, 2002). This area includes a portion of Protected Landscape Area Pol'ana (PLA Pol'ana). Within the small protected areas (SPAs), there are 19 national natural monuments (NNM), 21 national nature reserves (NNR), 15 protected areas (PA), 29 nature reserves, and 21 nature monuments.

Within the NATURA 2000 network, there are seven Special Protection Areas (SPAs) within or encroaching on the territory and 61 Special Areas of Conservation (SACs). Domica Cave, located in the Slovak Karst National Park, is one of 14 wetlands in Slovakia that are included on the Ramsar Convention's list of Wetlands of International Importance. In the framework of the UNESCO programs, two of the four biosphere reserves (BR) are located in Slovakia (BR Pol'ana, BR Slovak Karst), and one of the two natural sites of Slovakia is also inscribed on the World Heritage List (Caves of Aggtelek Karst and Slovak Karst).

3. Materials and Methods

The methodology described below is based on the definition of partial numerical indices derived from different maps of geodiversity elements that show the greatest diversity.

The geodiversity index is calculated by adding these partial indices, with the latter being the number of units or occurrences of geodiversity elements in grid-defined areas.

Scale selection is critical since it reflects the level of detail in the given data. Due to the large size of the study area, small scale maps with a scale of 1:500,000 were used. These maps provide a sufficient source of information to use in the assessment of geodiversity. The choice of scale is crucial since it reflects the level of detail in the given data. The overlay of a grid onto a map is regarded as a fundamental tool for analyzing any region's geodiversity.

We have drawn on the methodologies according to Pereira et al. [31], Silva et al. [32], Goncalves et al. [20], Forte et al. [18], and Santos et al. [75]. In order to improve the aforementioned approaches, this study adds and evaluates new sub-indices and quantifies each on a scale from 1 to 5.

In order to cover the entire research region, 261 grid squares, each with an area of roughly 5 × 5 km, were created using the geodiversity assessment methodology, which is based on the quantification and integration of abiotic variables displayed on thematic maps. These maps serve as a good informational resource to help with this geodiversity evaluation process. Six partial indices reflect the major elements of geodiversity using the GIS geoprocessing tool:

- Geological diversity (lithological units, stratigraphic representation, and 1:500,000 scale, according to Lexa et al. [76]);
- Tectonic diversity (tectonic units and 1:500,000 scale, according to Bezák et al. [77]);
- Geomorphological diversity (geomorphological subdivision, morphological-morphometric types, and 1:500,000 scale, according to Kočický et al. [78]);
- Soil diversity (soil types and 1:500,000 scale, according to ESPRIT [79] and SSCRI [80]);
- Hydrological diversity (type of aquifer, river network, springs and mineral waters, and 1:500,000 scale, according to Hydrological maps [81] and ESPRIT [82]);
- Mineral resource diversity (ore, non-ore, energy and construction resources, and 1:500,000 scale, according to Zuberec et al. [83]).

The counting of the occurrences in each grid square for each sub-index was carried out using the "multiparts" technique; geometries with the same attribute were counted only once, regardless of whether they appeared in more than one polygon [20]. This is the most common method used in studies.

Abiotic diversity was evaluated on a broad scale to encompass all of these components. The diversity of components in each square is represented by partial indexes that reflect the number of units of the components in each square. The first step in evaluating the overall geodiversity was to calculate each partial index. The next step was to divide the values of each partial index into five levels. We did this to put the individual partial indices on the same level of evaluation. The last step was to calculate the geodiversity index score for each grid square by summing these indices.

Squares were divided into five classes, very low, low, medium, high, and very high, based on their geodiversity index score. A raster map was then converted to one with isolines. The reason for this was to avoid overrating any specific factor, a typical problem with many previous evaluation methods, and to give comparable weight to the various components of geodiversity. The total geodiversity was compared with the occurrence of geosites listed in the database of the State Geological Institute of Dionýz Štúr.

The objective of the method used in this study is to outline a geodiversity evaluation strategy that can be used as a tool for environmental planning, but particularly for defining and designating priority regions for conservation.

3.1. Geological Diversity

The geological diversity index was calculated on the basis of a geological map (Figure 2). There are 84 lithological units (LU), which represent the richness and complexity of the region's geological subsurface. Due to the difficulty of visualizing this many units, we employed a stratigraphic representation. Each distinct geological unit is given a number on the map (Figure 2). The units present in each grid square were added to determine the geological index (Figure 3).

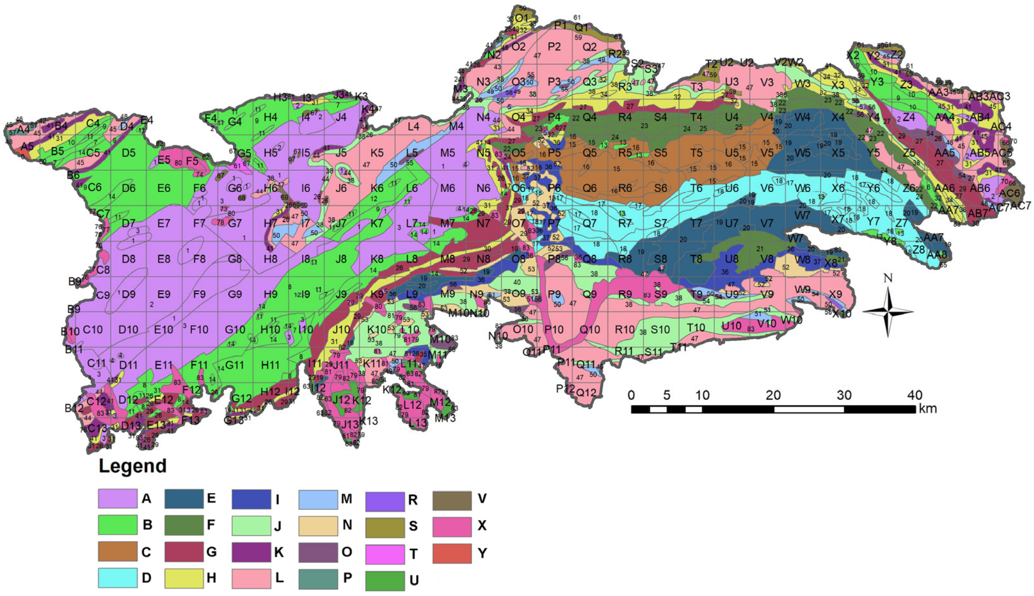

Figure 2. Geological map of the Slovenské rudohorie Mts. Legend: A—Paleozoic (LU from 1 to 5), B—older Paleozoic (LU from 6 to 14), C—Late Cambrian (LU from 15 to 16)–Early Silurian (LU from 17 to 18), D—Ordovician–Silurian (LU from 19 to 20), E—Silurian–Early Devonian (LU from 19 to 20), F—Middle to Late Devonian (LU from 21 to 25), G—Early to Late Carboniferous (LU from 26 to 30), H—Permian (LU from 31 to 34), I—Early Permian (LU from 35 to 37), J—Late Permian–Early Triassic (LU from 38 to 40), K—Early Triassic (LU from 41 to 42), L—Middle to Late Triassic (LU from 43 to 47), M—Late Triassic (LU 48 to 51), N—Jurassic (LU from 52 to 53), O—Middle to Late Jurassic (LU from 54 to 56), P—Late Jurassic–Early Cretaceous (LU 57), R—Late Cretaceous (LU 58), S—Eocene (LU 59) T—Eocene–Oligocene (LU from 60 to 61), U—Early Miocene (LU from 62 to 64), V—Middle Miocene (LU from 65 to 69), X—Late Miocene (LU from 70 to 83), Y—Pliocene (LU 84). Legend for LU: 1—porphyritic granodiorites to granites; 2—biotite tonalites to granodiorites, locally porphyritic; 3—hybrid granodiorites to tonalites passing locally into migmatites; 4—diorites to gabbros; 5—ultramafic rocks, mostly serpentinites; 6—phyllites, schists, metasandstones, metavolcanics, locally metacarbonates; 7—phyllites, schists, metasandstones, metavolcanics, locally metacarbonates; 8—mica schists, subordinate phyllites and schists; 9—mica schists, gneisses and products of their diaphtoresis; 10—banded gneisses and augengneisses (mostly orthogneisses), migmatites; 11—metamorphosed basic rocks (amphibolites, amphibole gneisses, chlorite—epidote schists, metagabbros); 12—orthogneisses; 13—biotite to two-mica granites; 14—leucocrate granites to granodiorites, locally porphyritic; 15—sericite-chlorite phyllites, metasandstones and conglomerates, metavolcanics, carbonate rocks, cherts; 16—mostly acid metavolcanics, porphyroids; 17—metasandstones, phyllites, carbonates, cherts, conglomerates, basic metavolcanics; 18—acid volcanics; 19—metasandstones, phyllites, carbonates, cherts, rare conglomerates, basic volcanics; 20—acid volcanics; 21—metasandstones, phyllites, rare metabasalts; 22—metamorphosed spilite-keratophyre volcanics, phyllites, rare carbonates; 23—metabasalts; 24—metasandstones, phyllites; 25—spilite-keratophyre volcanics; 26—conglomerates, sandstones, shales, acid volcanics, rare coal; 27—conglomerates, sandstones, siltstones, shales, basic volcanics, rare organodetritic carbonate rocks; 28—phyllites, metasiltstones, sandstones, rare conglomerates, acid volcanics and carbonate olistoliths; 29—metamorphosed sandstones and conglomerates, phyllites, mafic volcanics, in the upper part dolomites and magnesites; 30—metabasalts, metagabbrodiorites; 31—conglomerates, sandstones, shales, rhyolite/dacite volcanics; 32—conglomerates, sandstones, variegated shales, volcanics; 33—andesite-basalt volcanics; 34—rhyolite volcanics; 35—conglomerates, sandstones, shales

of the red beds type; 36—conglomerates, sandstones, rare rhyolite volcanics; 37—strongly deformed; 38—sandstones, shales, calcareous shales, limestones, dolomites, locally rauwackes, gypsum, anhydrites; 39—rhyolites; 40—shales, sandstones, rhyolite volcanics, subordinate dolomitic limestones and phosphatic sandstones; 41—quartzites, sandstones and shales; 42—quartzites, sandstones, calcareous shales, limestones; 43—dark-grey limestones and dolomites; 44—dolomites, recrystallized and cherty limestones, shales; 45—dark to light limestones and dolomites; 46—dark and light limestones, dolomites, cherty limestones; 47—limestones, dolomites ("carbonate platform"); 48—variegated shales, sandstones, evaporites, dolomites; 49—variegated limestones, locally shales; 50—pale, mainly organodetritic limestones, dolomites; 51—metamorphosed cherty limestones of the Turna sequence, Bükk; 52—dolomites, recrystallized limestones with glaukophanites, phyllites, metasiltstones; 53—dolomites, metamorphosed light massive and dark cherty limestones, shales, tuffite; 54—limestones, sandstones, sandy and spotted limestones, nodular and radiolarian limestones, radiolarites; 55—sandy and crinoidal limestones, cherty and nodular limestones at the upper part; 56—bedded clayey limestones, marlstones; 57—bedded clayey limestones, marlstones; 58—marls, carbonate sandstones, limestones, conglomerates; 59—conglomerates, sandstones, limestones, breccias, rare claystones; 60—sandstones, subordinate shales: flysch; 61—sandstones, calcareous claystones, locally conglomerates: flysch, mostly claystones towards the base; 62—conglomerates (Drienovec, Vajsková, and Szuhogy Congl.), gravels, sands, sandstones, siltstones, clays, claystones, subordinate thin coal seams and limestones—continental facies; 63—grey calcareous siltstones, sands/sandstones, conglomerates, variegated clays, carbonaceous clays, thin coal seams; 64—organodetritic limestones, conglomerates, marlstones; 65—grey calcareous clays/claystones, siltstones, sands/sandstones, conglomerates, acid tuffs, bentonite, limestones, diatomites, evaporites; 66—grey claystones/siltstones, sandstones, conglomerates, coal seams, acid tuffs, andesite epiclastic rocks (in Carpathian nappes without volcanics); 67—basaltic, px and amf-px andesites with small, often irregular intrusions; 68—basaltic, px and amf-px andesites with coarse to fine epiclastic volcanic breccias; 69—subvolcanic intrusions, e.g., diorites and diorite porphyry; 70—grey and variegated, often calcareous claystones, siltstones, sandstones, conglomerates, gravels, breccias, evaporites, subordinate diatomites and thin coal seams in the foredeep, also lumachella limestones; 71—alkali basalts and basanites from lava flows, effusive complex outside of the volkanic cone; 72—rhyolites and rhyodacites with fine, primary and reworked tuffs (distal facies); 73—amf-px, px-amf, and bi-amf andesites to dacites with extrusive domes and dome flows; 74—amf-px, px-amf, and bi-amf andesites to dacites with coarse to fine epiclastic volcanic breccias; 75—basaltic, px, and amf-px andesites with effusive cones; 76—basaltic, px, and amf-px andesites with coarse to fine epiclastic volcanic breccias; 77—basaltic, px, and amf-px andesites with epiclastic volcanic conglomerates and sandstones; 78—basaltic, px, and amf-px andesites with effusive cones; 79—basaltic, px, and amf-px andesites with pyroclastic breccias, agglomerates, and tuffs (proximal facies); 80—basaltic, px, and amf-px andesites with coarse to fine epiclastic volcanic breccias; 81—basaltic, px, and amf-px andesites with epiclastic volcanic conglomerates and sandstones; 82—basaltic, px, and amf-px andesites with epiclastic volcanic sandstones and siltstones; 83—variegated kaolinite clays, sands, gravels, rare lignite seams; 84—grey and variegated clays, silts, sands, gravels, thin lignite seams, freshwater limestones, tuffite horizons.

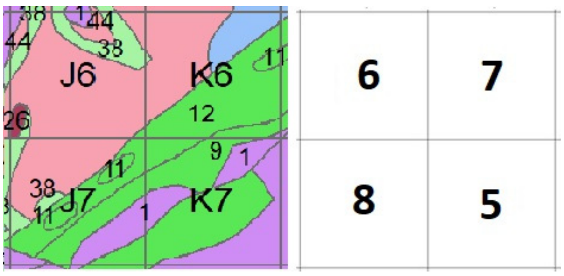

Figure 3. Example of geological diversity index assessment in a 5 × 5 km grid. Each color represents a different lithological unit. Square J6 contains 6 geological units; square J7 contains 8 geological units, square K6 contains 7 geological units, and K7 contains 5 geological units.

3.2. Tectonic Diversity

The majority of the Western Carpathian Mountain range is located in Slovakia. This mountain range's tectonic evolution has been lengthy and intricate. The tectonic diversity index was derived using a 1:500,000 scale tectonic map (Figure 4), which contains 10 units [77]. The Tatricum is the lowest tectonic unit of the Central Western Carpathians. Its structure consists of a crystalline core and the so-called enveloping Young Paleozoic and mainly Mesozoic sequences. The Fatricum (Križňa nappes) is a tectonic unit of the Western Carpathians that occurs in the immediate tectonic overburden of the Tatricum. Its stratigraphic extent is variable. The stratigraphic sequence usually terminates in the lowermost Upper Cretaceous with sediments of a flyschoidal nature. The Hronicum, like the Fatricum, represents a system of sub-nappes that were structured during the Middle Cretaceous from a single facies-divided sedimentary compartment. It occurs in the tectonic overburden of the Fatricum and Tatricum (or possibly the Veporicum). The stratigraphic range of the Hronicum spans from the Carboniferous to the Lower Cretaceous. Gemericum rises in a large arc and geomorphologically builds the Volovské vrchy hills (Spišsko-Gemerské rudohorie). It differs substantially from the other basic tectonic units of the Western Carpathians in terms of rock fill, age, and metamorphosis. In contrast to the Tatricum and Veporicum, it is mainly built by low metamorphosed rocks mainly of the Old Paleozoic age. The Meliaticum is a tectonic unit with nappe characteristics, mainly composed of Triassic carbonates, radiolarites, and volcanics deposited on dark-to-black shales with layers of radiolarites of Jurassic age. Silicicum is structurally the highest tectonic unit of the Alpine nappe structure of the inner Western Carpathians. It stands out as a relatively flat-lying nappe body in the area of the Slovenský kras karst, Slovenský raj paradise, Galmus, and Muránská planina plateau. Similarly, to the Hronicum, the Silicicum has been divided into several sub-nappes in the past. The layered sequence of the Silicicum (silicic nappe) is from the Late Permian–Early Triassic to the Early Jurassic. The Turnaicum is a tectonic unit with nappe characteristics protruding from beneath the Silicicum. It occurs in the southern part of the Gemera zone, mainly in the Slovenský kras karst. The layering sequence of the Turnaicum is from the Late Carboniferous to the Early Triassic. It is mostly composed of Late Triassic grey hornblende limestones and dark shales with interbedded volcanics and sandstones. The Veporicum is the middle tectonic unit of the central Western Carpathians and, like the Tatricum, is composed of crystalline basement and enveloping sequences of Paleozoic to Mesozoic age. It consists mainly of Paleozoic crystalline schists and granitoids, and less sedimentary and altered rocks of the younger Paleozoic and Mesozoic age. By counting the number of units that appeared in each grid square, the tectonic index was determined (Figure 5).

3.3. Geomorphological Diversity

Geomorphological subdivision (Figure 6) and morphological-morphometric types (Figure 7) are two sub-indices that make up the geomorphological diversity index. The sub-indices are based on mapping data [78]. The territory is divided into one region (Slovenské rudohorie Mts.), eight units (Čierna hora hill, Revúcka vrchovina upland, Rožňava kotlina basin, Slovenský kras karst, Spišsko-gemerský kras karst, Stolické vrchy hills, and Veporské and Volovské vrchy hills), 36 sub-units, and 17 parts, according to the geomorphological subdivision. This sub-index is calculated by adding one point for each unit represented by individual parts, sub-units, and the Rožňavská kotlina basin unit (54 units). The forms of georelief (morphotopes), which were developed from the fundamental forms (contrasting georelief), are included in the second sub-index. It has 28 units, and the sub-index was calculated by counting the number of units in each grid square. The aggregate of the two sub-indices produced the overall geomorphological diversity index (Figure 8).

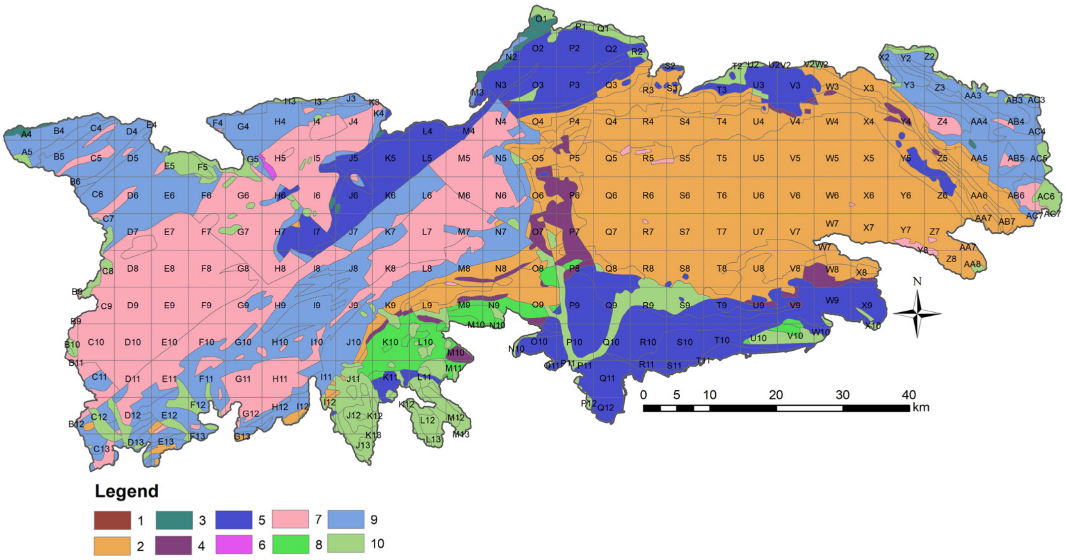

Figure 4. Tectonic map of the Slovenské rudohorie Mts. Legend: 1—Fatricum, 2—Gemericum, 3—Hronicum, 4—Meliaticum, 5—Silicicum, 6—Tatricum, 7—Tatricum and Veporicum, 8—Turnaicum, 9—Veporicum, 10—formations of the inner Western Carpathians.

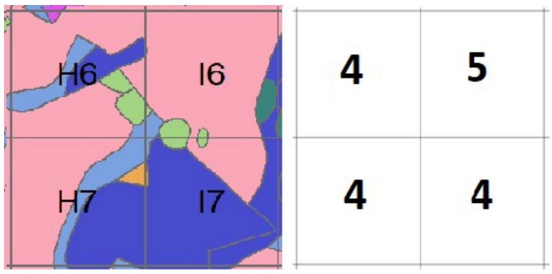

Figure 5. Example of tectonic diversity index assessment in a 5 × 5 km grid. Each color represents a different tectonic unit. Square H6 contains four tectonic units; square H7 contains four tectonic units, square I6 contains five tectonic units and I7 contains four tectonic units.

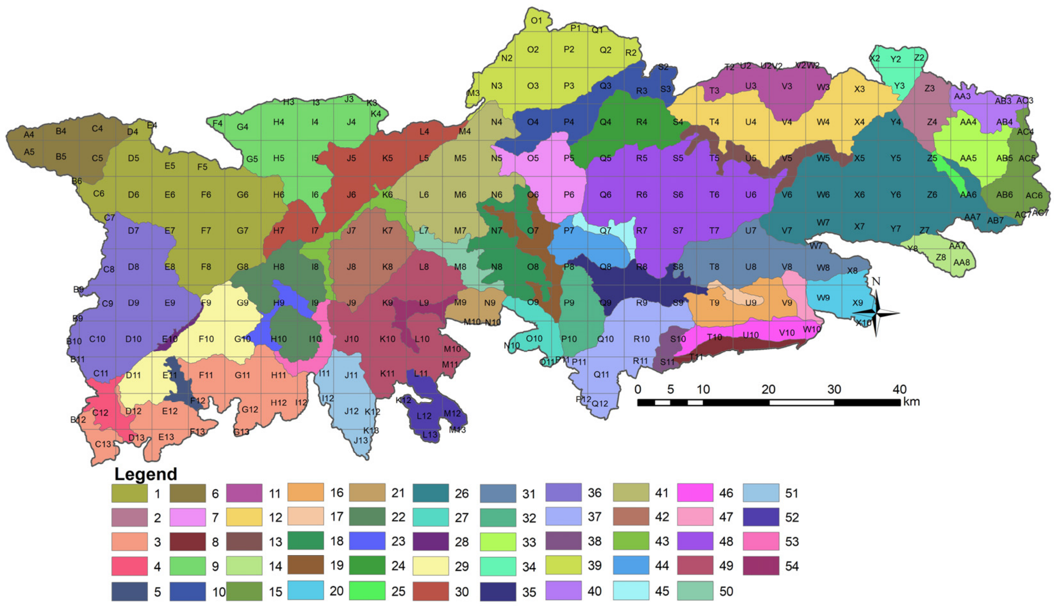

Figure 6. Geomorphological subdivision of the Slovenské rudohorie Mts. Legend: 1—Balocké vrchy, 2—Bujanovské vrchy, 3—Cinobanské predhorie, 4—Lovinobanská brázda, 5—Málinská brázda,

6—Čierťaž, 7—Dobšinské predhorie, 8—Dolný vrch, 9—Fabová hoľa, 10—Havranie vrchy, 11—Galmus, 12—Hnilecké vrchy, 13—Hnilecké podolie, 14—Holička, 15—Hornádske predhorie, 16—Horný vrch, 17—Borčianska brázda, 18—Hrádok, 19—Štítnicke podolie, 20—Jasovská planina, 21—Jelšavský kras, 22—Klenovské vrchy, 23—Kokavská brázda, 24—Knola, 25—Hámorská brázda, 26—Kojšová hoľa, 27—Koniarska planina, 28—Ipeľská brázda, 29—Málinské vrchy, 30—Muránska planina, 31—Pipitka, 32—Plešivská planina, 33—Pokryvy, 34—Roháčka, 35—Rožňavská kotlina, 36—Sihlianska planina, 37—Silická planina, 38—Silické úbočie, 39—Slovenský raj, 40—Sopotnické vrchy, 41—Stolica, 42—Tŕstie, 43—Muránska brázda, 44—Turecká, 45—Slanské podolie, 46—Turnianska kotlina, 47—Zádielska planina, 48—Zlatý stôl, 49—Železnícke predhorie, 50—Jelšavské podolie, 51—Pokoradzská tabuľa, 52—Blžská tabuľa, 53—Rimavské podolie, 54—Železnícka brázda.

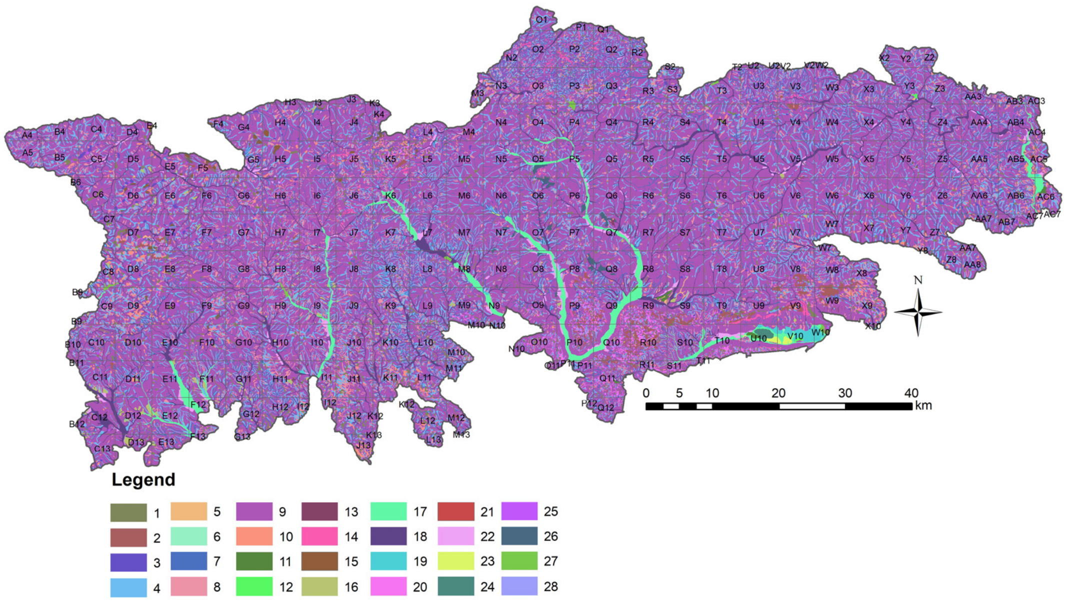

Figure 7. Morphological–morphometric types of the Slovenské rudohorie Mts. Legend: 1—flat summit, 2—summit plateau, 3—dome-shaped summit, 4—back, 5—valley in whole, 6—valley floor, 7—slope valley floor, 8—slope valley in whole, 9—transport slope, 10—slope plateau, 11—extensive accumulation plain, 12—terrace (river), 13—pothole to gully, 14—rocky precipice, 15—markedly undulating slope, 16—slope dissected by potholes and small valleys, 17—wide river alluvium, 18—narrow alluvium of mountain streams, 19—fan (alluvial cone), 20—sinkhole, 21—river bed in a notch (both natural and anthropogenic), 22—hillslope in a downstream position, 23—more pronounced elevations within the floodplain, 24—bottom of a waterlogged depression, 25—saddle, 26—terraced slope, 27—bottom of a reservoir, 28—anthropogenic forms.

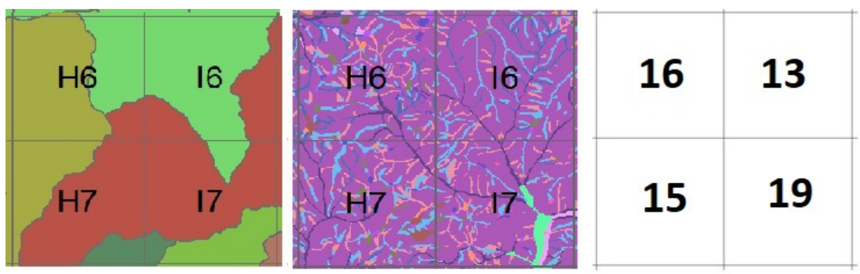

Figure 8. The result of the overall geomorphological diversity index was the summation of the individual sub-indices. Square H6 contains 16 units, square H7 contains 15 units, square I6 contains 13 units, and square I7 contains 19 units.

3.4. Soil Diversity

The soil diversity index is determined by adding the soil types shown on the soil map [79] (Figure 9). The soil map includes information on 41 soil subtypes, which are categorized in accordance with the Soil Morphogenetic Classification System, in addition to the 14 main soil types [80]. Because soils, geomorphology, and lithology are closely related, the soil diversity index is evaluated depending on how many different soil types are represented in each square (Figure 10). The soil diversity index would be overstated in comparison to the geological and geomorphological diversity index if soil subtypes were taken into account.

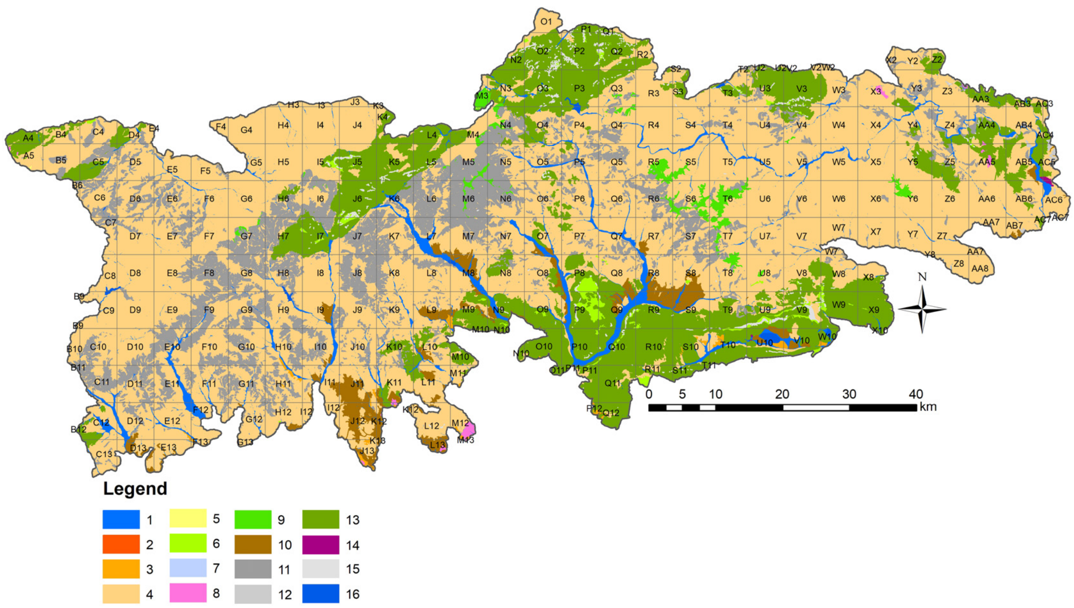

Figure 9. Soil types of the Slovenské rudohorie Mts. Legend: 1—Eutric Leptosols, 2—Haplic Gleysols, 3—Haplic Luvisols, 4—Eutric Cambisols, 5—Hortic Anthrosols, 6—Lithic Leptosols, 7—Albic Luvisols, 8—Calcaric Cambisols, 9—Haplic Podzols, 10—Dystric Planosols, 11—Skeletic Leptosols, 12—Eutric Regosols, 13—Rendzic Leptosols, 14—Haplic Chernozems, 15—rocks, 16—water.

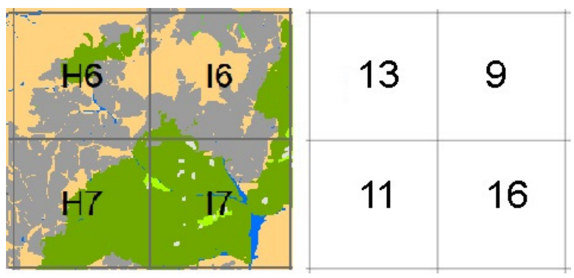

Figure 10. Example of soil type assessment in a 5 × 5 km grid. Each color represents a different soil unit. Square H6 contains six units, square H7 contains six units, square I6 contains seven units, and square I7 contains six units.

3.5. Hydrological Diversity

The type of aquifer (Figure 11), the density of the river network (Figure 12), and the presence of springs and mineral waters (Figure 13) are the three sub-indices that make up the hydrological diversity index [81]. The permeability of the rocks and the density of the river network directly influence the aquifer sub-index. When the permeability of the rocks is low, the amount of surface run-off can be significant (high value of the density river network sub-index), which results in the absence of aquifers (low value of the aquifer sub-index). Conversely, when the permeability of the rocks is high, surface run-off will be little, and there will be many aquifers. Finally, the sub-index on the presence of springs and mineral waters provides information on the plentiful aquifer supply. The aquifer type sub-index is represented as the number of units in each grid square. The length of watercourses separated into levels serves as the foundation for the river network density sub-index. The research area's river network is separated into seven tiers on the base map [82]. The headwater streams represent the first tier, and confluence with other streams increases the tier for each confluence by one, until reaching tier seven. We classified the tiers into two categories based on length variability, with the first and second tier streams falling under category one, and the other (tiers three through seven) into category two. Streams within each category are divided into five degrees based on their length (Table 1). We gave each tier a coefficient of significance (CS) for the values in each square, with streams in tiers one and two receiving a CS of 0.25, tier three receiving a CS of 0.5, tier four receiving a CS of 1, tier five receiving a CS of 2, and tiers six and seven receiving a CS of 5. The river network density sub-index is then calculated as the sum of products of the degrees of flow lengths and CS.

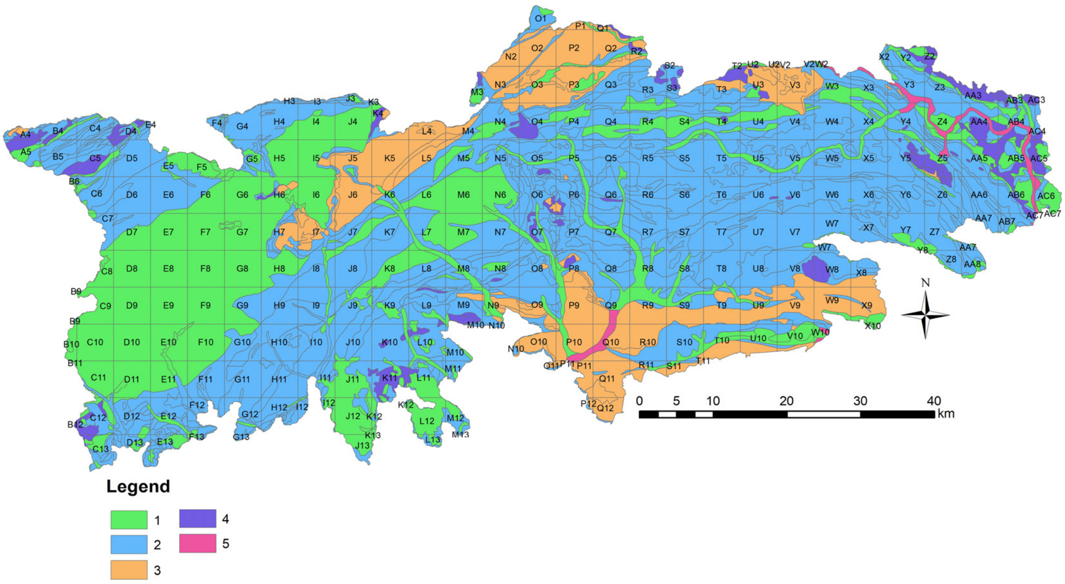

Figure 11. Aquifer types of the Slovenské rudohorie Mts. Legend: 1—aquifers in which flow is mainly intergranular (minor aquifers with local and limited groundwater resources); 2—aquifers in which flow is mainly intergranular (areas with essentially no groundwater resources); 3—Fissured aquifers, included karst aquifers (extensive and highly productive aquifers); 4—Fissured aquifers, included karst aquifers (local or discontinuous productive aquifers, or extensive but only moderately productive aquifers); 5—aquifers in which flow is mainly intergranular (local or discontinuous productive aquifers, or extensive but only moderately productive aquifers).

Table 1. Distribution of flows by length.

Degree	Category 1 Flow Length of Flows (in m), 1st and 2nd Tier Flows	Category 2 Flow Length of Flows (in m), 3rd, 4th, 5th, 6th, and 7th Tier Flows
0	0	0
1	1–11,000	1–2400
2	11,001–22,000	2401–4800
3	22,001–33,000	4801–7200
4	33,001–44,000	7201–9600
5	above 44,001	above 9601

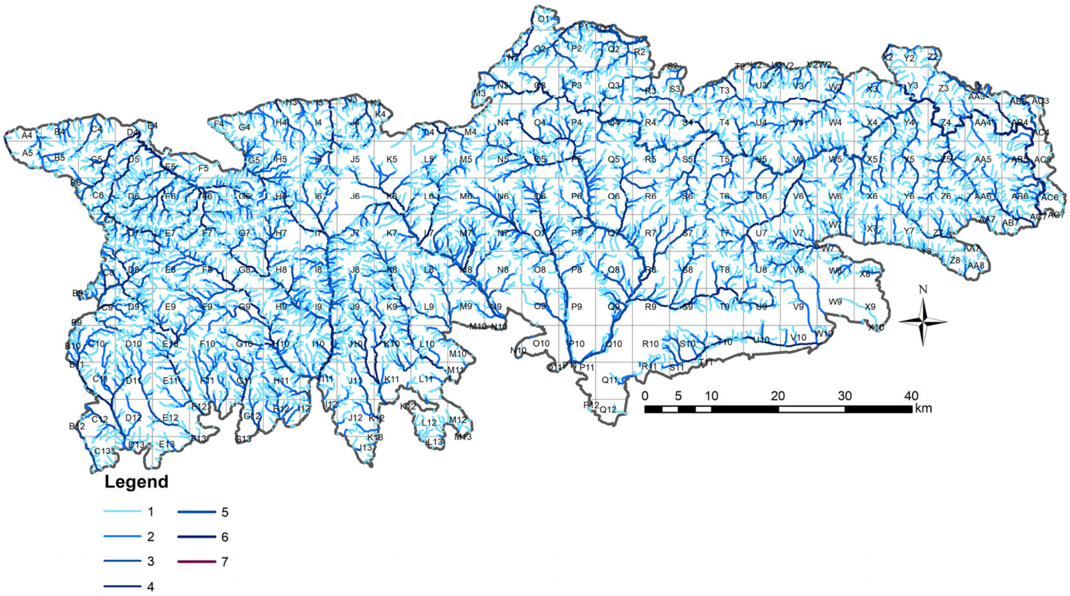

Figure 12. The river network of the Slovenské rudohorie Mts. Legend: 1—first tier flow, 2—second tier flow, 3—third tier flow, 4—fourth tier flow, 5—fifth tier flow, 6—sixth tier flow, 7—seventh tier flow.

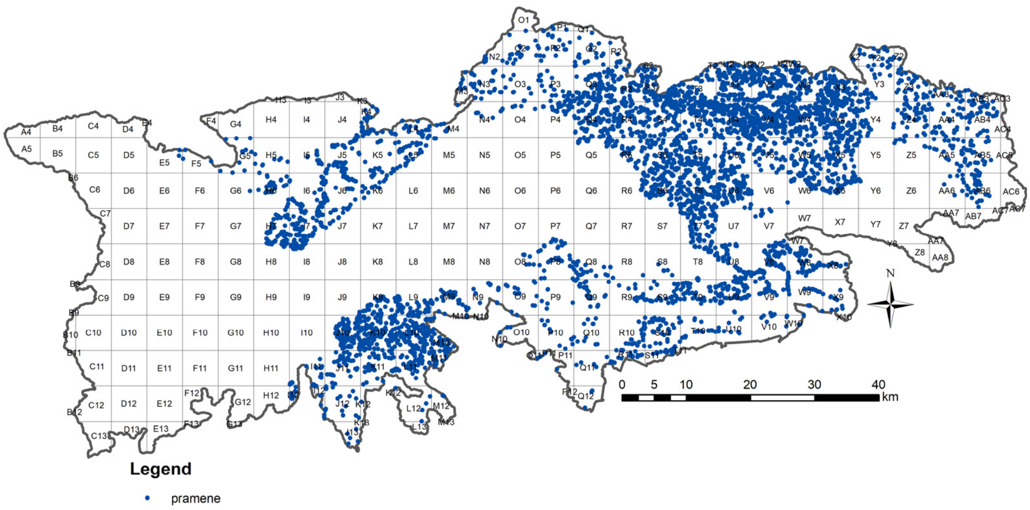

Figure 13. Springs and mineral waters of the Slovenské rudohorie Mts.

The following is an example of river network density sub-index calculation for square H6:

$$\text{H6} = \text{degree of flow length (1st + 2nd tiers)} \times \text{CS } (0.25) + \text{degree of flow length (3rd tier)} \times \text{CS } (0.5) + \text{degree of flow length (4th tier)} \times \text{CS } (1) + \text{degree of flow length (5th tier)} \times \text{CS } (2) + \text{degree of flow length (6th + 7th tiers)} \times \text{CS } (5)$$

$$\text{H6} = 4 \times 0.25 + 5 \times 0.5 + 2 \times 1 + 0 \times 2 + 0 \times 5$$

$$\text{H6} = 5.5$$

The presence of springs and mineral waters in each square was evaluated for the third sub-index related to the occurrence of these features. The following are the ratings: 1 point—occurrence of 1–10 springs in a square, 2 points—11–30 springs, 3 points—31–60 springs, 4 points—61–100 springs, and 5 points—over 101 springs. The combination of the sub-indices produced the overall hydrological diversity index (Figure 14). The final results are rounded to ensure overall consistency.

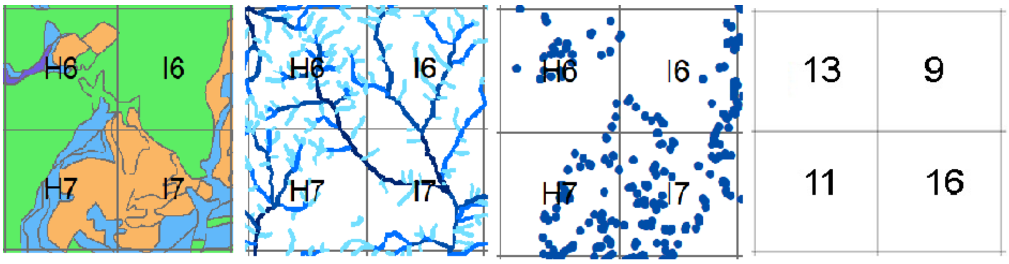

Figure 14. Example of the overall hydrological index score in squares H6, H7, I6, and I7. Square H6 contains 13 units, square H7 contains 11 units, square I6 contains 9 units, and square I7 contains 16 units.

3.6. Mineral Resources Diversity

Based on the 1:500,000 map base [83], which gives details on the distribution and reserves of mineral deposits and important occurrences of natural resources in the territory of Slovakia, the mineral resources index was calculated. The index is further broken down into two sub-indices: one for ore and non-ore resources (Figure 15) and the other for energy and construction resources (Figure 16). The territory's ore resources (antimony, tin, aluminum, complex iron, manganese, copper, molybdenum, nickel-cobalt, mercury, polymetallic, tungsten, rare earths, gold, and silver ores) are represented by the first sub-index, along with the following non-ore resources: asbestos, barite, black shale, ornamental stone, dolomite, limestone, quartz, feldspar, magnesite, talc, gypsum, anhydrite, etc. Each occurrence received one point. Energy (peat and uranium ore) and construction raw materials (building stone, brick raw materials, gravels, and sands) are represented by the second sub-index. Each occurrence received 1 point, similar to the first sub-index. The two sub-indices were added together to create the overall mineral diversity index (Figure 17).

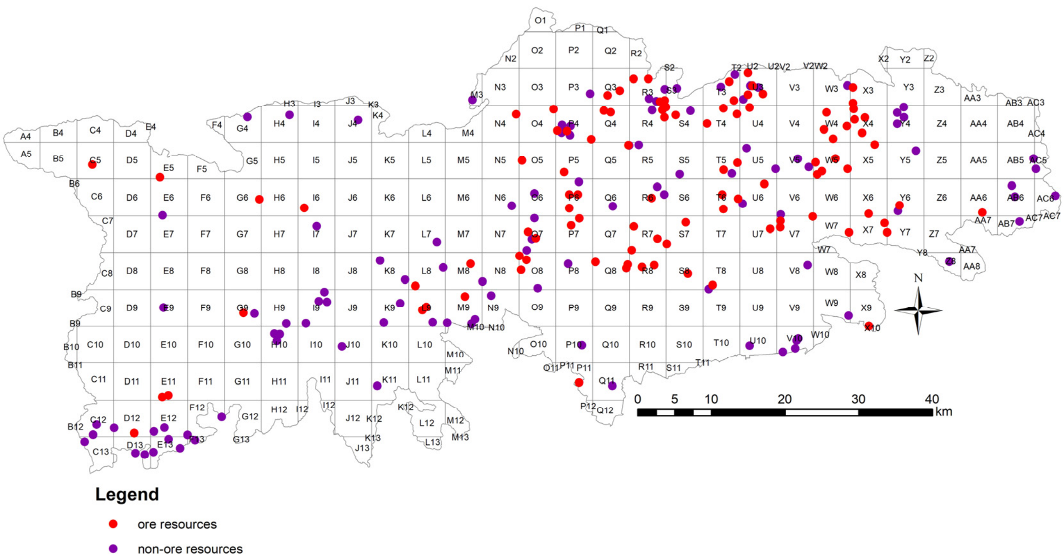

Figure 15. Ore and non-ore resources of the Slovenské rudohorie Mts.

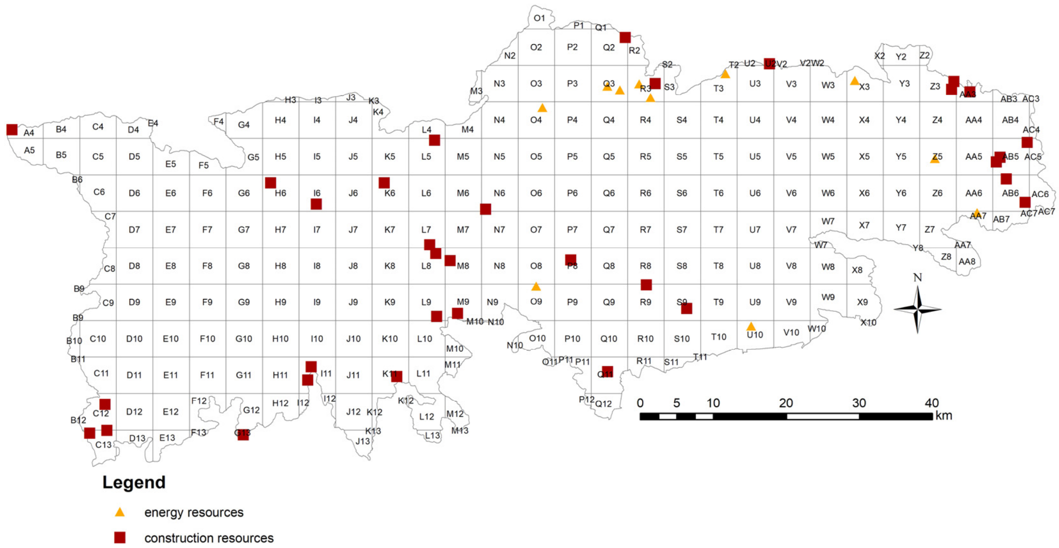

Figure 16. Energy and construction resources of the Slovenské rudohorie Mts.

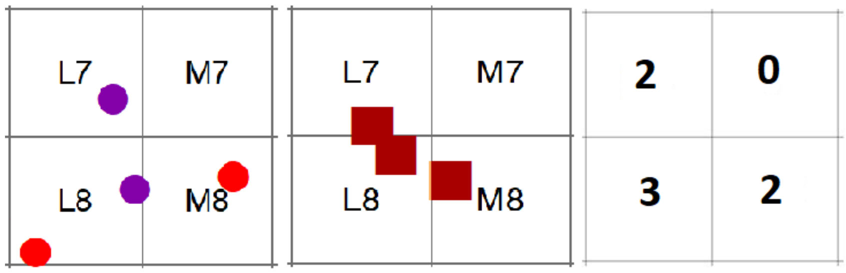

Figure 17. Example of the total mineral resource's diversity squares L7, L8, M7, and M8. The squares contain their occurrence and score. Square L7 contains two occurrences, square L8 contains three occurrences, square M7 contains no occurrences, and square M8 contains two occurrences.

4. Results

A geodiversity index map for the multipart technique was produced after the merging of the partial diversity maps. The sum of the six indices determines the final geodiversity value for each square of the systematic network. According to the number of units in each square, the partial diversity index was calculated. The legend displays the normalization using natural breaks of five values: 1 (very low), 2 (low), 3 (medium), 4 (high), and 5 (very high). The total of the normalized data is the geodiversity index.

4.1. Geological Diversity Index

Two fundamental units can be discerned in the extremely complex geological structure of this mountain range. The paracrystalline and granitoid massifs that make up the western Slovenské rudohorie (Slovak Ore Mountains, also known as the Veporské pohorie) are moderately to significantly changed. Poorly changed Paleozoic rocks make up the Spišsko-gemerské rudohorie, the eastern portion of the mountain range, which is connected at the edges by sections formed of Mesozoic rocks. The Slovenský kras karst lies in the south; Galmus, Stratenská hornatina, and Muránska planina plateau (relocated to the Veporids) are in the north. The Gemerides are a tectonic unit represented by the eastern portion of the mountain range.

The diversity of the geological subsoil in the area is also reflected in the number of units in the individual squares. The five levels of the geological diversity index were determined as follows: 1 (1–2 units), 2 (3–5 units), 3 (6–8 units), 4 (9–11 units), and 5 (12–13 units) (Figure 18A). The highest values of the geological diversity index in the analysis occur in the Revúcka vrchovina upland (Dobšinské and Železnícke predhorie foothills, and

Štítnické podolie foothills), the Volovské vrchy hills (Hnilecké vrchy hills), the Veporské vrchy hills (Balocké vrchy hills), and the Čierna hora hills (Roháč hills). Squares with lower values are more abundant in the study area. Low diversity (up to 45%) and medium diversity (31%) had the highest number of squares. In 12% of the squares, high or very high diversity was attained (Figure 19A).

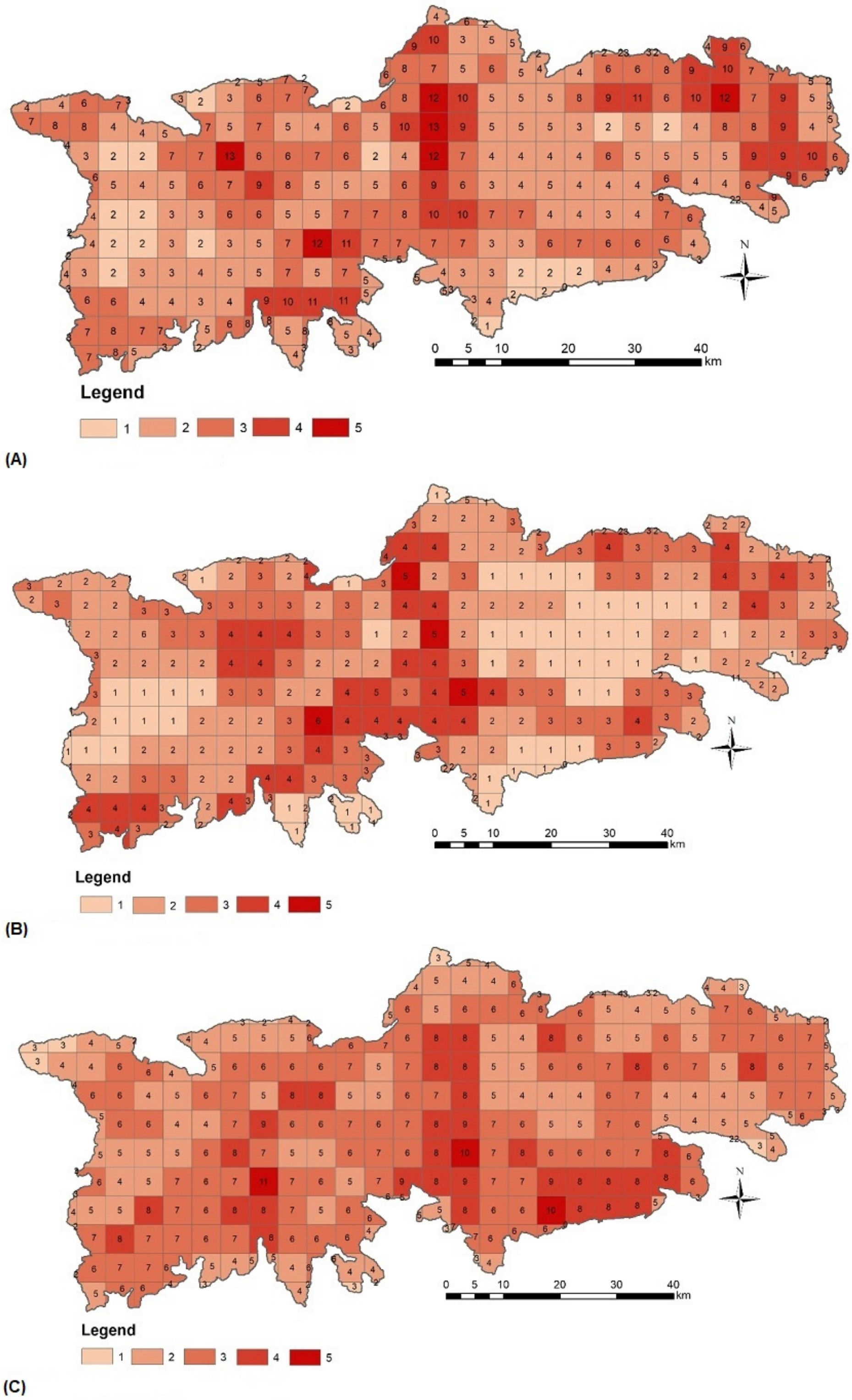

Figure 18. *Cont.*

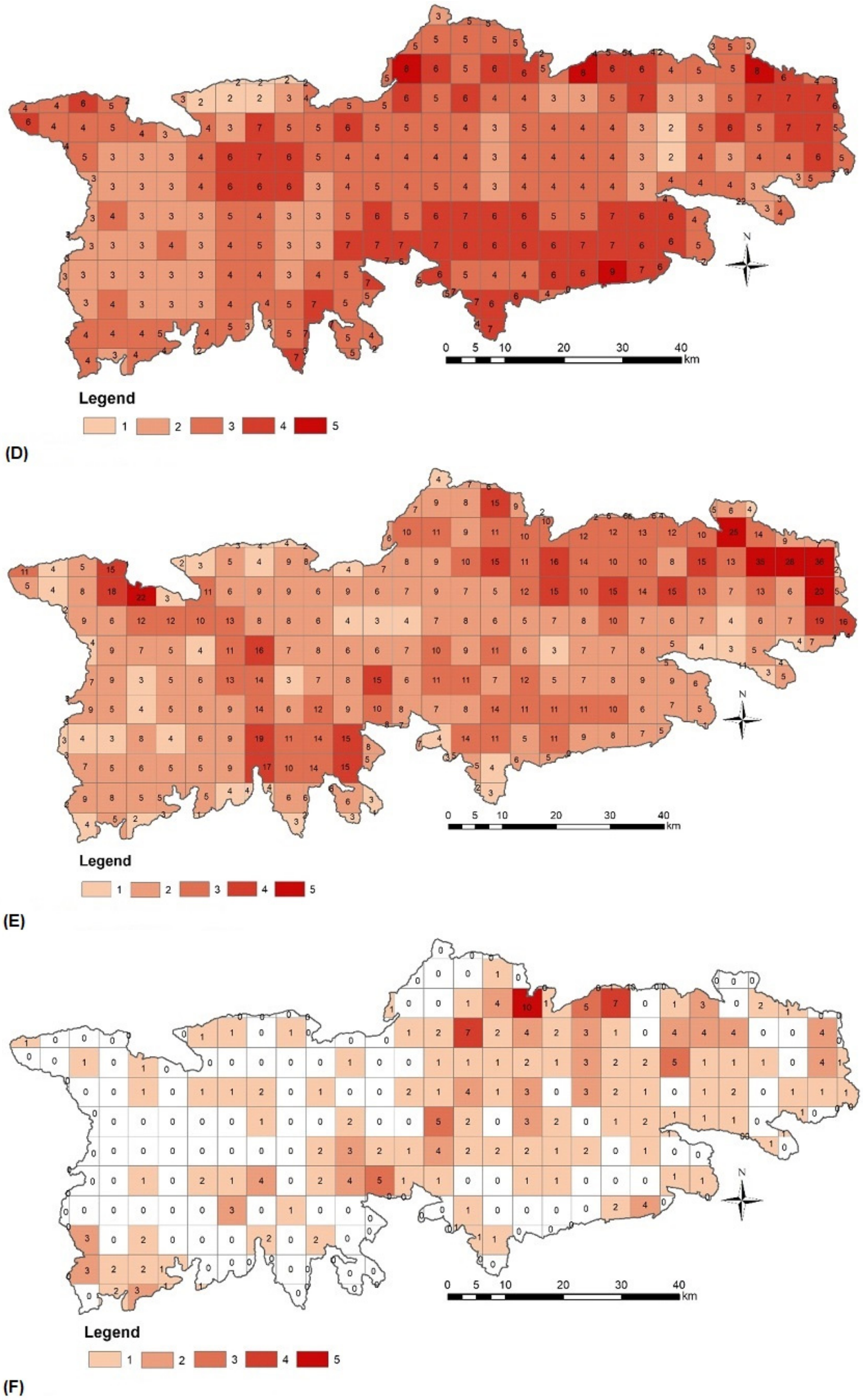

Figure 18. Diversity indices: (**A**) Geological diversity index; (**B**) Tectonic diversity index; (**C**) Geomorphological diversity index; (**D**) Soil diversity index; (**E**) Hydrological diversity index; (**F**) Mineral resources diversity index.

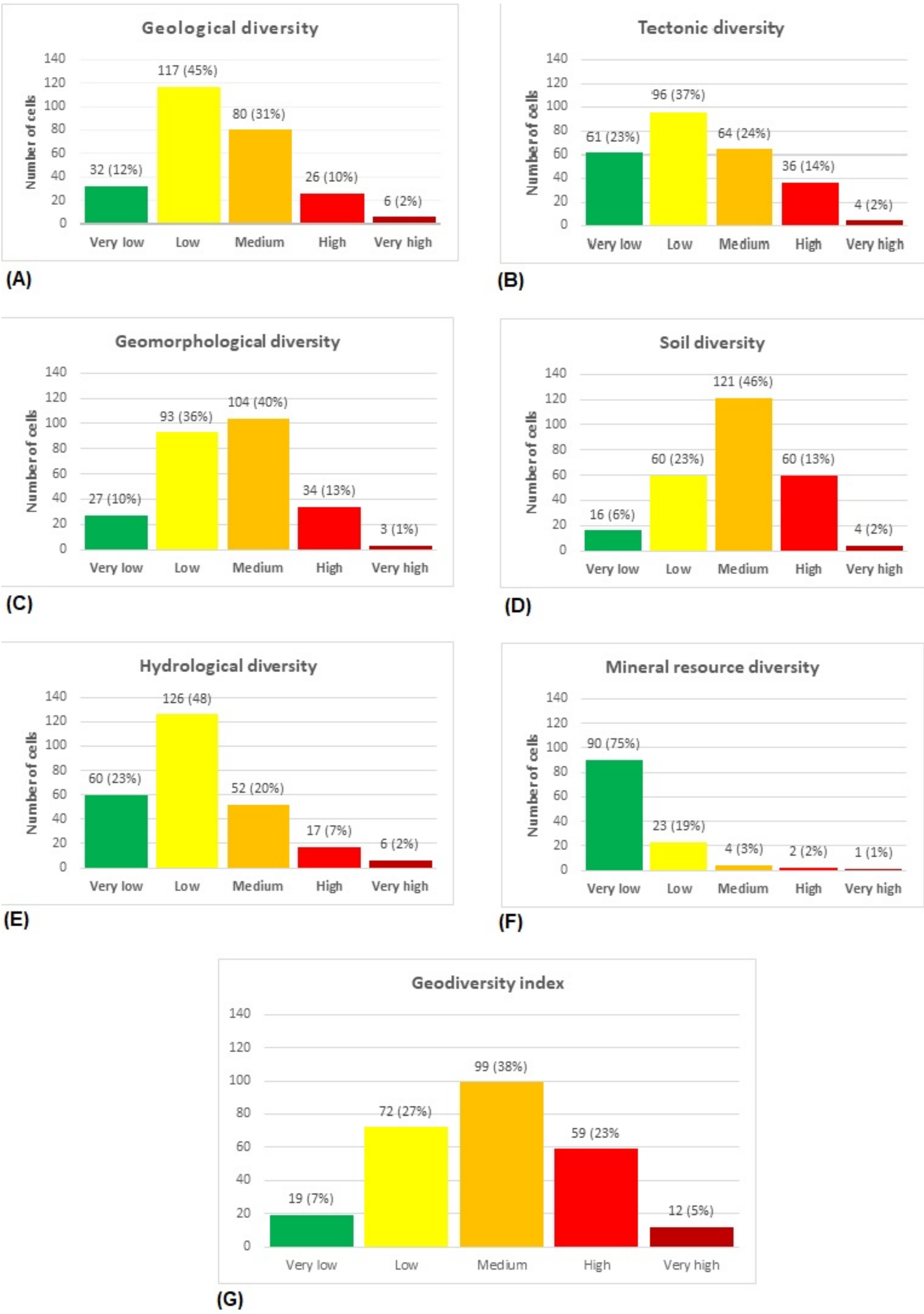

Figure 19. Histograms representing the percentage of area occupied for each category of diversity indices and geodiversity index: (**A**) histogram of the geological diversity; (**B**) histogram of the tectonic diversity; (**C**) histogram of the geomorphological diversity; (**D**) histogram of the soil diversity; (**E**) histogram of the hydrological diversity; (**F**) histogram of the mineral resources diversity; (**G**) histogram of the geodiversity index.

From a geological point of view, the areas with very high diversity are mainly covered by Permian and Late Carboniferous units (conglomerates, sandstones, siltstones, shales, rhyolite/dacite volcanics, and basaltic volcanics), Middle to Late Devonian (metamorphosed spilite-keratophyre volcanics and phyllites), and Late Cambrian–Early Silurian (mostly acid metavolcanics and porphyroids). The areas with high diversity are mainly covered by Late Permian–Early Triassic units (sandstones, shales, calcareous shales, limestones, dolomites, locally rauwackes, gypsum, anhydrites, and quartzites), Late Carboniferous (conglomerates, sandstones, siltstones, shales, basic volcanics, and rare organodetritic carbonate rocks), Permian (conglomerates, sandstones, variegated shales, and volcanics), and Middle to Late Triassic (limestones and dolomites, carbonate platform" Reichenhall, Gutenstein, Steinalm, and Wetterstein).

4.2. Tectonic Diversity Index

Tectonic diversity ranged from 1 to 6 units in each square. We adjusted the tectonic diversity index as follows: 1 (1 unit), 2 (2 units), 3 (3 units), 4 (4 units), and 5 (5–6 units) (Figure 18B). The highest values of tectonic diversity occur in the Revúcka vrchovina uplands (Železnícke and Dobšinské predhorie foothills, Jelšavské podolie foothills, Plešivská planina plateau, and Železnícka brázda furrow) and the Stolické vrchy hills (Stolica hills). Low diversity (37%) and medium diversity (24%) had the highest number of squares. In 16% of the squares, high or very high diversity was attained (Figure 19B). The highest number of units was recorded in the Železnícke predhorie foothills and the Železnícka brázda furrow. Tatricum, Veporicum, Gemericum, Turnaikum, Meliaticum, and the formation of the inner Western Carpathians meet here.

4.3. Geomorphological Diversity Index

The Triassic limestones and, to a lesser degree, the dolomites, which make up a portion of the monitored area, are what distinguish the geomorphological diversity. It is in the limestone areas that the remnants of the surface relief from many millions of years ago are well preserved. They are completed by karst phenomena, such as sinkholes, valleys, ponors, and scrapes and, to a large extent, also by underground karst phenomena, such as caves and chasms. Two geomorphological formations, karst plains and river valleys, which divide this region, dominate the relief. The other part of the territory is made up of mountain ranges, characterized by fragmented mountainous relief.

Geomorphological diversity ranged from 1 to 11 units in each square and is the result of two sub-indices (geomorphological subdivision and morphological-morphometric types). We adjusted the morphological diversity index as follows: 1 (2–3 units), 2 (4–5 units), 3 (6–7 units), 4 (8–9 units), and 5 (10–11 units) (Figure 18C). The highest values of morphology occur in the Revúcka vrchovina uplands (Cínobanské and Železnícke predhorie foothills, Lovinobanská brázda furrow, and Jelšavské podolie foothills), Slovenský kras karst (Plešivská and Koniarska planina plateaus, and Jelšavský kras karst), Stolické vrchy hills (Stolica hills), Spišsko-gemerský kras karst (Muránska planina plateau), and Veporské vrchy hills (Balocké vrchy hills). Low diversity (36%) and medium diversity (40%) had the highest number of squares. In 14% of the squares, high or very high diversity was attained (Figure 19C).

4.4. Soil Diversity Index

Soil diversity ranged from 1 to 9 units in each square. We adjusted the soil diversity index as follows: 1 (2 units), 2 (3 units), 3 (4–5 units), 4 (6–7 units), and 5 (8–9 units) (Figure 18D). The highest values of soil diversity occur in the Veporské vrchy hills (southern part of Fabová hol'a hill, eastern part of Balocké vrchy hills), Spišsko-gemerský kras karst (south-western part of Muránska planina plateau, central part of Slovenský raj paradise, Slovenský kras karst (northern parts of Plešivská and Silická planina plains), and Čierna hora hill. Medium diversity (46%) had the highest number of squares. 25% of the squares reached high or very high diversity (Figure 19D).

4.5. Hydrological Diversity Index

Hydrological diversity ranged from 1 to 36 units in each square and is the result of three sub-indices (type of aquifer, density of the river network, and occurrence of springs and mineral waters). We adjusted the hydrological index as follows: 1 (1–4 units), 2 (5–9 units), 3 (10–14 units), 4 (15–19 units), and 5 (more than 20 units) (Figure 18E). The highest values of morphology occur in the Veporské vrchy hills (Balocké vrchy hills) and Čierna hora hill (Bujanovské and Sopotnícke vrchy hills, Roháčka hill). Low diversity (48%) had the highest number of squares. 25% of the squares had high or very high diversity (Figure 19E).

4.6. Mineral Resource Diversity Index

Mineral resource diversity ranged from 1 to 10 points of occurrence in each square and is the result of two sub-indices (ore and non-ore resources and energy and construction resources). We adjusted the mineral resource diversity index as follows: 1 (1–2 points); 2 (3–4 units); 3 (5–6 units); 4 (7–8 units); and 5 (9–10 units) (Figure 18F). The highest values of the mineral resources index occur in the Volovské vrchy hills (Figure 19F).

4.7. Geodiversity Index

The geodiversity index takes the form of an isoline map that can be used as a tool for spatial planning, in particular for identifying priority areas for the conservation, management, and use of natural resources at the national level. Resulting values of the geodiversity index in the Slovenské rudohorie Mts. range between 5 and 22 (Figure 20). Very low geodiversity scores (<9) occur mainly in the Sihlianska planina plateau area, which is composed of andesites, granodiorites, and granites in the Tatricum and Veporicum. Very low values are also found along the edges of the southern part of the study area and in the northern part of Fabová hol'a hill. These low values are also related to the absence of mineral resources and low soil diversity. Overall, they cover 7% of the area (Figure 19).

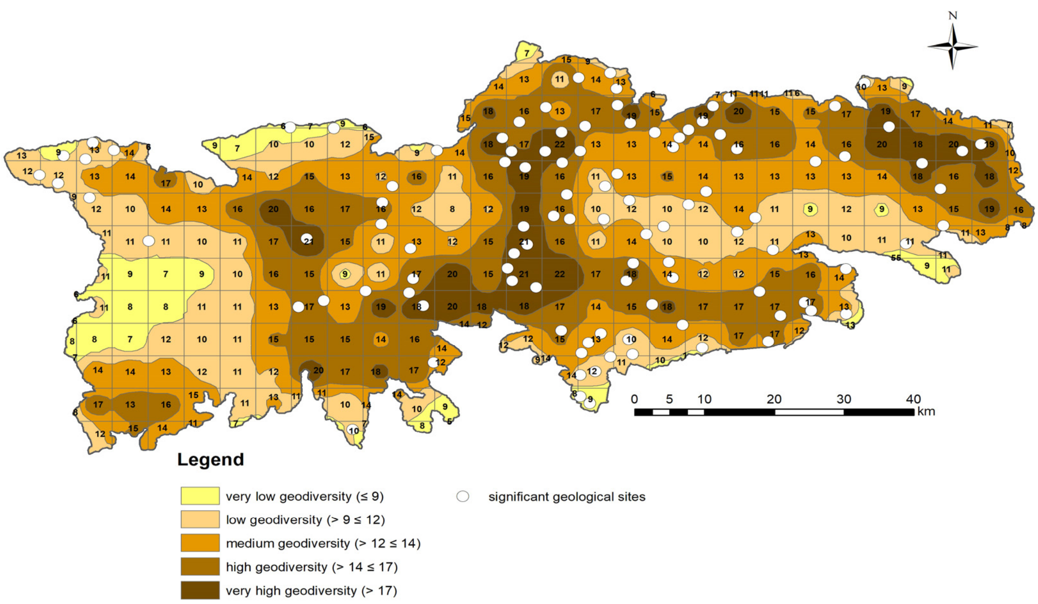

Figure 20. Geodiversity index map with geosites.

The increase in the geodiversity index values to low scores (9–12) in the western part of the territory (Balocké and Málinské vrchy hills) is due to the increased geological diversity (andesites, granodiorites, and granites have been joined by phyllites, quartzites, shales, sandstones, mica schists, gneisses, rhyolites, limestones, dolomites, etc.), geomorphological diversity (sub-index of morphometric types) and soil diversity. The increase in the index in the eastern part of the territory (central part of Kojšová hol'a hill and Zlatý stôl hill) is due to the presence of higher values of the hydrological index (sub-index of the river network) and increased diversity of mineral resources (sub-index of ore and non-ore resources). This level of geodiversity covers 23% of the territory.

Medium geodiversity scores (12–14) cover slightly less than a third of the area (32%). These increased geodiversity index scores are the result of geomorphological diversity (higher number of morphological-morphometric types sub-index), pedological diversity, partly hydrological diversity (springs and mineral waters sub-index), and mineral resource diversity.

High geodiversity scores (14–17) cover up to 28% of the area. These high geodiversity index values are due to the high geological diversity (alternating units from the older Paleozoic to the middle Miocene), tectonic diversity (mostly 3–4 units per square), geomorphological diversity (the sum of the two sub-indices adds up to a maximum of 8 points), pedological diversity (there are 4–8 soil types in a square), hydrological diversity (the sum of the three sub-indices adds up to a maximum of 19 points), and also a high diversity of mineral resources.

The areas with very high geodiversity scores (>17) cover 10% of the territory. This geodiversity is mainly supported not only by high geological diversity (alternation of units from Cambrian to Pliocene), geomorphological diversity (sum of two sub-indices in squares ranging from 8 to 10 points), pedological diversity (there are 5–8 soil types per square), hydrological diversity (the sum of the three sub-indices is a maximum of 36 points per square), but also by high mineral diversity (the number of deposits per square is a maximum of 10).

Areas of high and very high geodiversity (38% of the territory) are also confirmed by the distribution of geosites (Figure 20). Of the 104 geosites, 49 are located here, of which 16 are protected under Act No. 543/2002 Coll. on Nature and Landscape Protection. These are mainly geomorphological, hydrogeological, mineralogical, paleontological, and geological sites.

Based on the above-mentioned methodology, we have identified 29 hotspots of very high geodiversity value (10% of the monitored area) in the territory, 20 of which are not part of large protected areas (NPs or SPAs). By using isolines to connect squares with very high geodiversity values in the form of isoline classes, three larger areas can be delineated. The smallest area, the only one under NP protection, lies in the southern part of the NP Muránska planina plateau (A). The most extensive area stretches across the north–south direction of the mountain range and crosses the center of the Slovenské rudohorie Mts. (B). Several units (Revúcka vrchovina upland, Stolické vrchy hills, and Volovské vrchy hills) are included in the area. Another large area is located in the eastern part of the Slovenské rudohorie Mts. and includes the eastern part of the Volovské vrchy hills and Čierna hora hill (C). Smaller islands of very high geodiversity (D, E, F, G, H, I, J, K, L, M, and N) are also found in the northern and southern parts of the mountains (Figure 21).

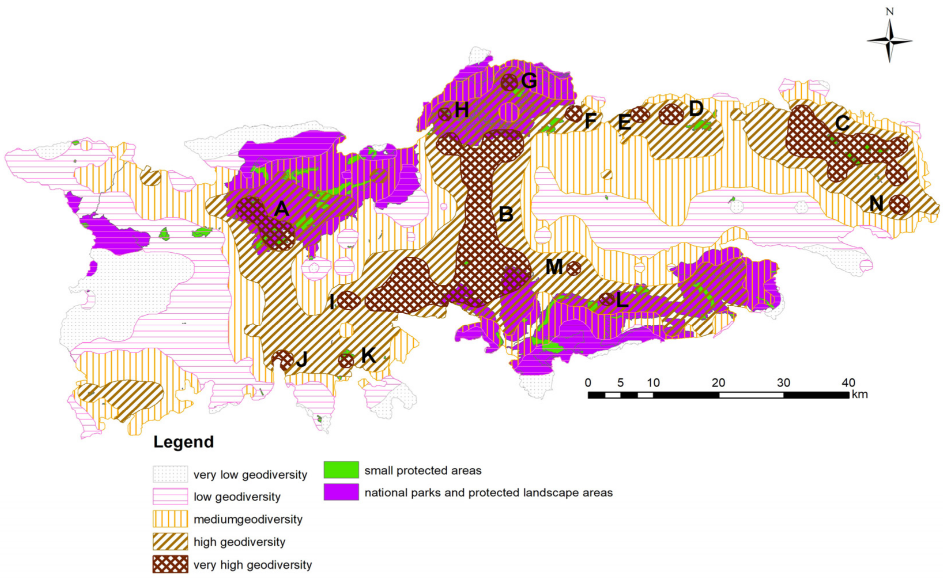

Figure 21. Overlay of geodiversity index map with state protected areas.

5. Discussion

In this work, the geodiversity assessment was mainly based on the methodology described in Pereira et al. [31], later refined by de Paula Silva [84], Araujo and Pereira [85], and da Silva et al. [33], and based on methodologies that use grids and geoprocessing software to quantify geodiversity elements (e.g., [20,23,32,86]). Our goal was to improve the aforementioned methodologies by adding and evaluating additional sub-indices. With some modifications, a quantification tool—multiparts [20]—was used.

5.1. Map Scales

Several studies debate the map scales used for geodiversity assessment. Despite the difficulties in gathering maps at the same scale, it is undeniable that the results of a geodiversity quantitative assessment can be more accurate in such conditions. In addition, depending on the scale of the maps, the grid square size may also have an impact on the outcomes. In this work, maps of the same scale (1:500,000) with a square size of 5 × 5 km were used. The same scale was used in their work by Bétard and Peulvast [23] and Pereira et al. [31], but their grid sizes were 10 × 10 km and 25 × 25 km. The difference in grid size was due to the different size of the study area. More detailed scales have been worked with, e.g., Paula Silva et al. [32,84] (1:25,000), Fernández et al. [86] (1:50,000), and Gonçalves et al. [20] (1:100,000). In this case, the grid sizes were 13.8 × 13.8 km, 5 × 5 km, and 1 × 1 km, respectively.

5.2. Geodiversity Indices and Sub-indices

We employed six diversity indices, which, in our case, represent the key elements of geodiversity, to generate the final geodiversity index. Because the tectonics in the research area indicate the intricate evolution of the Western Carpathians, we included tectonic variety as one of the primary elements of geodiversity. It consists of the inner and outer Western Carpathians' Neo-Alpine tectonic structures as well as the inner Western Carpathians' Paleo-Alpine tectonic units. In their analysis, Gonçalves et al. [20] used structural geological units (faults and folds). The authors used a variety of methods to evaluate geomorphological diversity, including the relief model [20], landforms and river networks [32], the maximum hierarchical level of rivers [86], and the index of fluvial hierarchy [85]. In our work, geomorphological diversity is based on the sum of geomorphological subdivisions and morphographic–morphometric types. The authors made various assessments of the hydrological index.

Runoff density was used by [20], three sub-indices (hierarchy of rivers, aquifers, and annual average rainfalls) were used by Gonçalves et al. [20], and surface (rivers, lakes, and sea) and underground waters (aquifer productivity) were assessed by Bétard and Peulvast [23]. We employed aquifer type as one of the sub-indices of hydrological diversity, much like [86]. The quantity of the river network and the presence of springs and mineral waters made up our other sub-indices. The majority of authors assessed paleontological sources. We did not analyze this factor because there are not many notable paleontological sites in our region. Instead, we focused on comparing the occurrence of geosites [87] with the evaluation of the geodiversity index. Geosites are abundantly represented in the study area, and most of them are of extraordinary scientific importance. One third of them are spatially protected.

The aim of the geodiversity index is therefore to express, in the most balanced way possible, all of these aspects without emphasizing any particular geodiversity element, as was noted to occur in previous studies [10,25,30,88].

5.3. Geodiversity vs. Biodiversity

Discussion of the research's methodology and findings is also possible in the context of the conservation biology field's lessons learned and critiques of the hotspot idea. According to Gray [7], geodiversity hot spots are areas with a high geodiversity index. However, there is no correlation between the geodiversity index and biological indices. These findings disagree with how national park areas are defined for nature conservation [87]. Finding hotspots for geodiversity may be very important and beneficial for creating more comprehensive environmental management strategies (geoheritage values, and provision of ecosystem services). However, focusing on "hotspots" could have the unintended consequence of neglecting "geodiversity coldspots", which may submerge a number of key geosites that hold immeasurable historical values (cultural, aesthetic, and/or archaeological qualities) [23]. Geodiversity is not always correlated with the value of geoheritage. Despite having extremely little diversity, a given geosite may contain significant geoheritage significance. Overall, the index reveals a fairly uneven distribution, with multiple hot spots [2,7] dispersed across several study areas [87]. Geodiversity hotspots frequently possess significant geoheritage value; however, it is necessary to evaluate these in light of the preceding values [23].

5.4. Geoecosystem Services and Their Protection in Slovakia

Since species variety and ecosystem services are severely endangered by climate change, the geodiversity index does not adequately explain species diversity or ecosystem function at the regional scale; instead, combinations of the environmental variable's climate, habitat, and soil provide a better explanation. Also, this makes it difficult to facilitate conservation management [14]. However, small-scale geodiversity and geosites are crucial to biodiversity because they can support rare or distinctive biota that are suited to particular environmental conditions or create niches that increase biological diversity [89,90] and geoheritage [23]. We identified precisely such geotopes within the territory of the Slovak Ore Mountains. Some of them are protected by Act No. 543/2002 Coll. on Nature and Landscape Protection as small protected areas in the fourth and fifth level of protection. Act No. 543/2002 on the Protection of Nature and Landscape is a fundamental legal document that provides framework for the identification and protection of geological heritage in Slovakia. It outlines how the government, businesses, and private individuals are to care for minerals, fossils, and geological and geomorphological formations. These include, for example, cascading waterfalls, rock seas, natural rock outcrops, cliffs, canyons, an eroded rock formation, a rock wall, an example of a Paleogene basal layer, but also various geomorphologically distinctive landforms, varied geology and karst relief with both surface and subterranean landforms, and a geomorphologically distinctive rock formation, which we have also observed in the area of interest. Act No. 569/2007 on Geological Works is another act that governs the provision, maintenance, and disposal of geological works and geological objects as well as the transfer of their management or ownership. It also offers protection of geological works and geological objects. The protection, collection, social valuation, and social value of protected minerals and protected fossils are outlined in Decree No 213/2000 of the Ministry of the Environment of the Slovak Republic on protected minerals and protected fossils and on their social valuation of the Act of the National Council of the Slovak Republic No 287/1994 Coll. on the Protection of Nature and Landscape. Identified protected minerals and protected fossils, their locations of occurrence, the places of deposit and possession of the removed finds, the recorded places of their natural occurrence, and other documentation are all registered in the National Database of Protected Minerals and Protected Fossils.

Another important tool for the protection of diversity in general are the NATURA 2000 Special Areas of Conservation (SACs). They are also located within the territory of the Slovenské rudohorie Mts.; however, they are intended only for the protection of specific invertebrates, amphibians, plants, mammals, animals, fish and their biotopes. Even in karst areas, geomorphological or geological features are not subject to protection. Geological and geomorphological features are dealt with only in the description of the area.

In Slovakia, preserving the natural world has essentially meant preserving its biodiversity. Overall, awareness of geodiversity in Slovakia is very low and very little has been done to preserve the geological diversity and landforms. Although the majority of geosites are located within protected landscape areas, their protection is random and not a result of their worth being recognized [48]. Several authors point to the importance of geotopes in Slovakia for nature conservation, geotourism, and local development [45,48,49,52–54]. Nevertheless, the concept of geodiversity is not included in Slovak legislation, as no legislative document contains a definition of geodiversity, its protection, valuation, restoration, or wise use. As a natural resource supporting biodiversity, only its defined forms and processes are protected.

6. Conclusions

The geodiversity index's graphical depiction has the potential to be a very effective tool for management. The geodiversity index map shown in this study combines data that is typically dispersed across several sources and is simple enough for non-Earth science specialists to understand. Areas with high geodiversity should receive special attention due to their significance in land-use planning. The definition of priority conservation areas may benefit from the examination of this data. Areas with a high level of geodiversity have a greater chance of being utilized for tourism and educational reasons.

The geodiversity index map, which is a graphical representation of several physical components that describe the area, may be particularly relevant for land-use planning. This methodology, along with others devoted to natural aspects, may be helpful in defining ecological structures, protected areas, geoparks, etc. Therefore, the geodiversity index ought to be taken into account as a tool for natural resource management, environmental protection, and nature tourism policies.

The Slovenské rudohorie Mts. geodiversity index map is important at the national level for the recognition and identification of areas of geodiversity significance. Many valuable geotopes with a very high geodiversity index are located in biodiversity coldspots. It is advisable to protect such localities as small protected areas (up to 1000 ha) at the fourth or fifth level of protection under Act No. 543/2002 Coll.

Some areas of very high geodiversity may be the subject of not only nature protection and geotourism but also mineralogical research or mineral extraction in the future. These regions should be examined in light of potential future uses, and the conservation and management of the landscape should be adjusted accordingly.

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