

A New Quantitative Model for Comprehensive Geodiversity Evaluation: the Škocjan Caves Regional Park, Slovenia

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Received: 7 June 2016 / Accepted: 26 January 2017 / Published online: 8 February 2017
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Abstract The article presents a simple quantitative model for geodiversity evaluation, which merges spatial relationship of geodiversity elements with terrain data. The model is partially automated in geographic information system tools to eliminate the majority of subjectivity in evaluation. As a result, it can be used for different environment types and is applicable for comparative studies. The method was applied to the Škocjan Caves Regional Park, which is one of the most diverse karst areas in the world. The geodiversity element types were identified through remote sensing data and basic field mapping. Their diversity was subsequently defined through block statistic tools in a geographic information system programme. The geodiversity index was calculated from a number of different geodiversity element types within defined spatial units and from the terrain ruggedness index. Areas of high geodiversity index or geodiversity hotspots are in strong correlation with the most diverse areas of the regional park, which are also currently promoted for geotouristic and educational purposes.

Keywords Geodiversity · Mapping · Block statistics · Geodiversity hotspot · Karst

Introduction

The diversity of nature is supposed to be determined by both biotic and abiotic components. Nevertheless, a great deal of natural variability attention is devoted solely to biodiversity enhancement and protection (Pettersson and Keskitalo 2013). The current focus of the scientific community on biodiversity became widespread after the signing of the Convention on Biological Diversity at the Earth Summit held in Rio de Janeiro in 1992 (Serrano and Ruiz-Flaño 2007). Geological and geomorphological conservation in many countries generally commenced in the late twentieth century although in places began as early as the early nineteenth century. The general term ‘nature conservation’, which has been practised for almost 200 years, has focused most or all of its attention to ‘wildlife conservation’, almost entirely neglecting the role of abiotic elements in the natural diversity (Gray 2013; Melelli 2014).

The concept of geodiversity succeeds the one of biodiversity. It was introduced widely around two decades ago due to renewed interest in the conservation and evaluation of abiotic elements of the natural environment (Gray 2013; de Paula Silva et al. 2014). The contemporary term geodiversity comprises the natural diversity of geological (rocks, minerals, fossils), geomorphological (landforms, physical processes) and soil features (Gray 2013). According to various authors, the term also incorporates features resulting from anthropogenic processes as well as topographic and hydrographic components of the nature (Serrano and Ruiz-Flaño 2007; de Paula Silva et al. 2014).

Nowadays, the geodiversity definition, evaluation and recognition are acquiring significance within Earth Sciences (Gray 2013; Melelli 2014) due to geoconservation management, geotourism enhancement and educational aspects. Established methods of geodiversity evaluation merged

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various criteria which are usually divided into scientific values of geodiversity elements and their additional values (Pereira et al. 2007; Reynard and Coratza 2007; Zouros 2007; e.g. Gray 2013). The scientific values aim to assess the basic value of the elements in terms of rareness, representativeness, paleogeographical values, etc. (Reynard 2009a). The additional values differ according to the scope of geodiversity evaluation emphasising either conservation, touristic or educational aspects. Therefore, it can include ecological, aesthetic, cultural, educational, cultural, functional, research or any other value (Reynard 2009b; Gray 2013). Even though majority of the aforementioned evaluations are described as quantitative formulations, their value is generally defined on the basis of subjective estimation criteria.

Despite the excellent results achieved by geodiversity evaluation so far, an automated quantitative assessment, which would largely exclude subjectivity in assessment of various indices, is required. Only a few studies utilising automated method of cartographic data in order to evaluate geodiversity have been published so far (e.g. Kozłowski 2004; Benito-Calvo et al. 2009; Pellitero et al. 2011; Pereira et al. 2013; de Paula Silva et al. 2014; Melelli 2014).

The aim of this article is to present a simple quantitative model of geodiversity evaluation. The model merges spatial correlation of geodiversity elements with terrain data. Geodiversity elements were identified systematically by means of remote sensing data and field mapping. Furthermore, terrain data analyses were performed using digital elevation model (DEM) with employment of geographical information systems (GIS). Numerical indices for natural diversity were calculated from both data values. The method is simple to use and partially automated in order to be applicable at different landscape types, to avoid subjectivity of evaluation and to be suitable for comparative studies. The method was tested within one of the most diverse karst environments, the Škocjan Caves Regional Park, Slovenia (Fig. 1).

Significance of Quantitative Assessment of Geodiversity

The diversity of abiotic nature is unquestionable; thus, identification, interpretation and evaluation of geodiversity elements is required. As a result, a geodiversity concept was developed in order to organise particular regions and the entire Earth and to coordinate its efficient conservation or management (Gray 2013). Diversity of nature is a dimensionless attribute, which can be assessed both qualitatively and quantitatively (Sharpley 1995; Necheş 2016).

Qualitative geodiversity evaluation that is conclusively classified in numerical values has been extensively used. Those straightforward methods which evaluate specific

attributes of particular geodiversity elements are appropriate for defining geotouristic, geoeeducation and geoconservation values (e.g. Serrano and González-Trueba 2005; Reynard et al. 2007; Pellitero et al. 2011; Gray 2013; Necheş 2016). They are usually applied in the evaluation of the most valuable sites, which were already considered as geoheritage or within areas of higher geodiversity concentrations. Their purpose was to manage popularising and protecting of the geosites (Ruban 2010). Those qualitative parameters are preferable and more suitable for the evaluation of actual geosites (Ruban 2010; Necheş 2016).

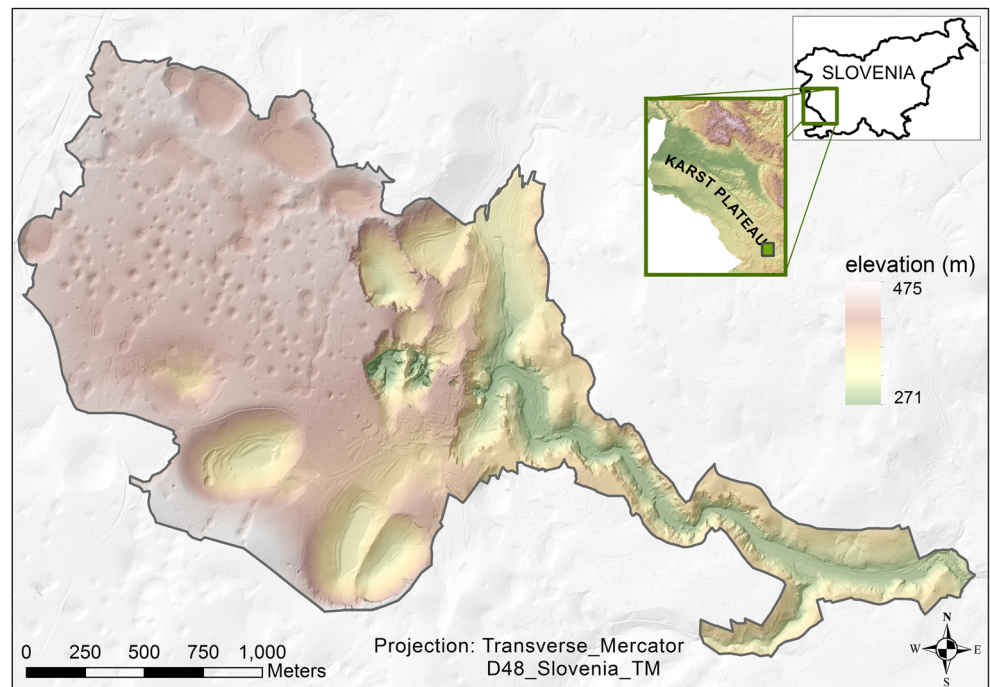
The quantitative assessment of geodiversity measures the number and diversity of abiotic elements of nature within a specified area. Application of this method maintains a clear record of the spatial distribution of geodiversity elements and their types across the whole specified area regardless of spatial distribution of actual geoheritage sites. It illustrates how heterogeneous or homogeneous a particular area is, diversity of geodiversity element types and identification of areas with high concentration of resources. This information has more relevance in comparative studies where spatial distribution of the elements is of uttermost importance as well as in single-area studies (Ruban 2010). By means of quantitative assessment of the geodiversity elements, geodiversity *loci* or hotspots (Ruban 2010) characterised by a high concentration of different element types can be identified.

Regional Settings of the Škocjan Caves Regional Park

The Karst Plateau is situated in the western Slovenia in the north-westernmost part of the Dinaric Alps. The plateau stretches in a northwest–southeast direction and covers an area of 440 km². It has a longer length of about 40 km and width of about 14 km. In general, the bedrock comprises bedded Cretaceous and Palaeocene limestones, which are surrounded by areas of flysch and alluvium. Karst landscape and subsurface drainage prevail due to the carbonate bedrock.

The main inflow area of the Karst Plateau is on the south-easternmost edge where the Reka River flows into the Škocjan Caves. The surroundings of the caves referred to as the Škocjan Karst is one of the most diverse areas from a geomorphological perspective. Along with the Škocjan Caves, there are a great number of other caves within the area. The blind valley and the canyon of the Reka River, numerous collapse dolines, dissolution dolines, denuded caves and other karst features, which are typical for the ponor type of contact karst, encompass them. Due to the concentration of speleological and geomorphological features, the area was scientifically examined several times (Mihevc 1991a; e.g. Mihevc 1991b;

Fig. 1 Location of the Škocjan Caves Regional Park



Mihevc 1998; Mihevc 2001; Stepišnik 2008). The Škocjan Caves were inscribed on the UNESCO World Heritage List in 1986, while the surrounding diverse karst surface was legally proclaimed as a regional park. Due to an exceptional biodiversity value, the area is also included in the Ramsar List of Wetlands as well as a Karst Biosphere Reserve and within Natura 2000 sites.

The Škocjan Caves Regional Park covers an area of about 4 km² and includes the wider ponor zone of the Reka River, which is the largest underground river within the whole Dinaric Karst. Even though the whole area is built of Cretaceous and Palaeocene limestone and dolostone (Buser 1968; Šikić et al. 1972), the Reka River flows on the karst surface for about 2.5 km before submerging into the Škocjan Caves. The 5800-m-long cave is organised as a paragenetic system of the contact karst (Mihevc 2001). The surface river flow is positioned within a canyon that is almost 100 m entrenched into the surrounding karst surface. The surrounding surface which is positioned within the regional park is dissected by numerous dissolution dolines and other middle-sized karst depressions which are denuded cave systems (Mihevc 2001; Mihevc and Stepišnik 2012). Furthermore, the surface comprises 12 huge collapse dolines which were formed as a result of the undermining of the subsurface streams (Radinja 1967; Gams 1983; Mihevc 1984; Stepišnik 2008).

Materials and Methods

The quantitative geodiversity index of the study area was determined by means of an interdisciplinary approach

combining morphographic mapping (Pavlopoulos et al. 2009) and a variety of spatial analysis. GIS tools utilised for spatial analysis were performed by using the Esri ArcGIS 10.3.1 software (Fig. 2).

The elements of geodiversity were determined on the basis of the classifications of Gray (2013) and of Serrano and Ruiz-Flaño (2007). Only geomorphological and hydrological features, not geology and pedology, were included within the research. The reason for omitting both feature groups are the almost uniform geological and pedological settings of the whole study area. It consists of Cretaceous bedded limestone that is covered mostly by leptosols. Geomorphological and hydrological features were identified using aerial photographs (The Surveying and Mapping Authority of the Republic of Slovenia 2014), shaded relief map derived from Light Detection and Ranging (LIDAR) data (Slovenian Environment Agency 2015), Nature conservation atlas (Institute of the Republic of Slovenia for Nature Conservation 2013) and various national digital maps in different scales (1:5000, 1:25,000). It was followed by a classification and spatial documentation of the geodiversity elements using a comprehensive field survey that included morphographic mapping and defining the exact extent using GPS devices. The whole study area was examined in detail to provide consistent data for further spatial GIS analysis.

Geodiversity elements obtained with fieldwork were digitalised in vector layers represented by polygons, lines and points. The vector layers were converted into a raster format. For each raster layer of separate element type, a block statistics analysis was performed in order to determine the

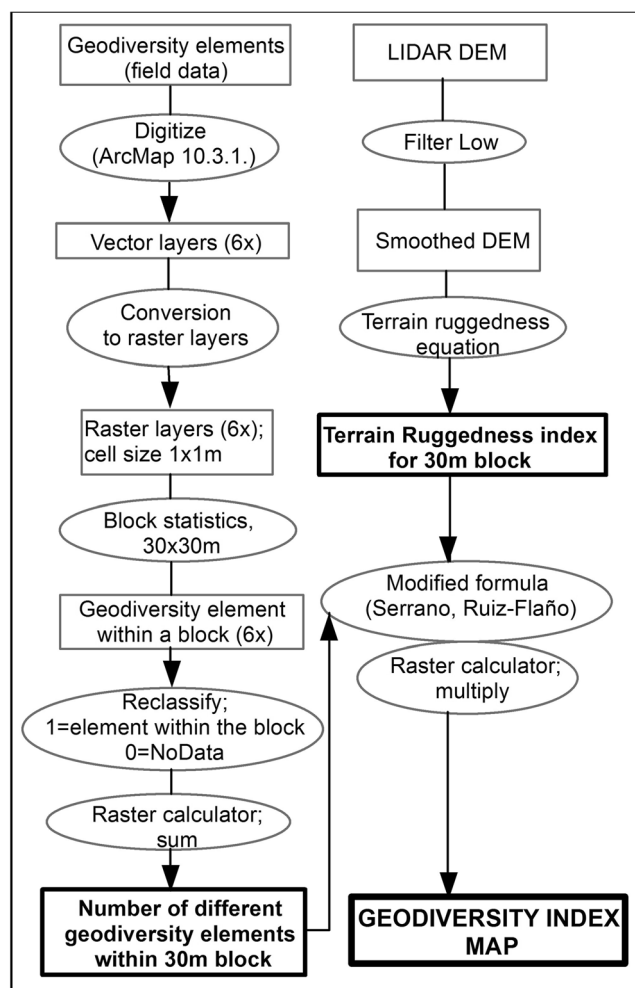


Fig. 2 Methodological procedure used to assess the geodiversity

number of different elements within a basic spatial unit. A 30-m block was used as a basic spatial unit as we consider it as appropriate for detailed geodiversity index assessment. The whole research area was divided into equal blocks; thus, an objective comparison is possible. The Block Statistics tool performs a neighbourhood operation that calculates a statistic for input cells within a fixed set of non-overlapping windows or neighbourhoods. Since the neighbourhoods do not overlap, any particular cell will be included in the calculations for one block only (ArcGIS for Desktop 2016).

Additionally, all the layers were reclassified and summed up with raster calculator tool. The final output raster layer displayed a number of different geodiversity elements in a defined block. It was followed by the calculation of the terrain ruggedness index according to Riley et al. (1999). The calculation was based on 1 m resolution DEM derived from LIDAR data (Slovenian Environment Agency 2015). The digital elevation model was smoothed (*filter, low*) to avoid the noise prior to the procedure. The index was calculated for 30-m blocks with the aim to correspond with the layer of different geodiversity elements. The quantitative geodiversity index

(Gd) was calculated by employing modified equation proposed by Serrano and Ruiz-Flaño (2009):

$$Gd = Eg \times IR$$

where Eg is a number of different elements in a block and IR is the terrain ruggedness index of the block.

The different geodiversity element layers and the terrain ruggedness index layer were multiplied with raster calculator tool in order to get the geodiversity index map of the area. The multiplied layers were not divided by the surface area as suggested in the original equation (Serrano and Ruiz-Flaño 2007) since the calculated block area is uniform. The geodiversity index map of the Škocjan Cave Regional Park was classified into three classes on the basis of the Jenks classification (Jenks 1967) with low, medium and high geodiversity value.

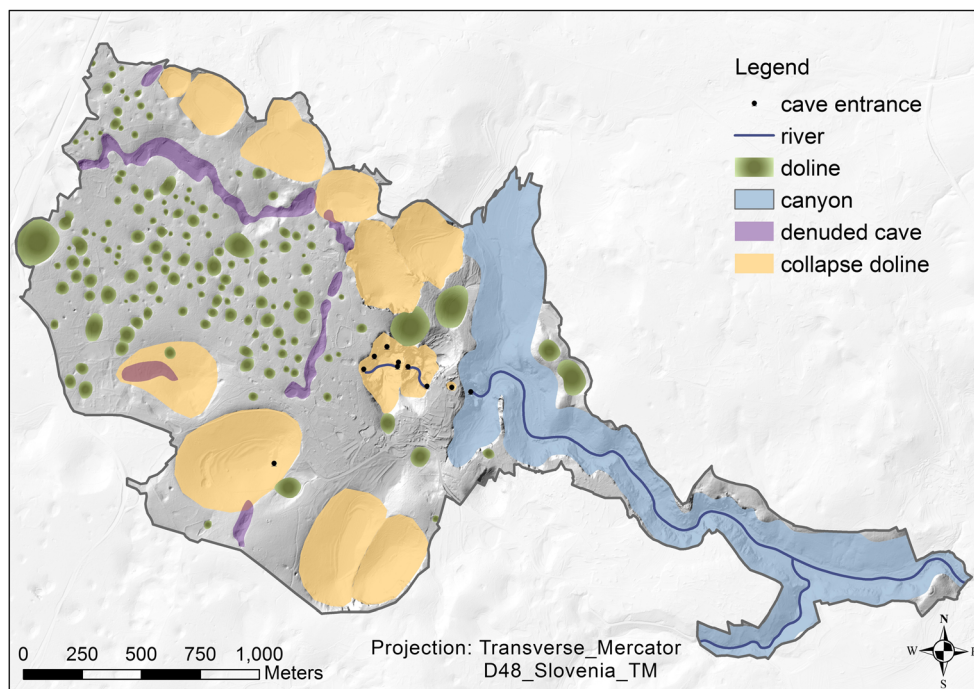
Geodiversity of the Škocjan Caves Regional Park

The geodiversity index for the Škocjan Caves Regional Park was calculated by applying the modified equation proposed by Serrano and Ruiz-Flaño (2007, 2009). Distribution of the geodiversity index depends on two parameters: the occurrence of various abiotic elements and the terrain ruggedness index in the researched area.

A variety of remote sensing data that was supported by detail geomorphological mapping were utilised for the identification of the geodiversity elements. The total number of identified geodiversity elements within the study area is 185. They were distributed into six different geodiversity element types. The most typical and numerous geomorphological element in this karst area are dolines (150) followed by collapse dolines (12) and large cave entrances (6). The surface of the study area is dissected also by longer denuded cave sections (6). The contact karst geomorphological elements are canyons (2). The only hydrological element within the area is a river (1), which passes into the Škocjan Caves. These geodiversity elements are scattered consistently within the whole area of the park (Fig. 3). We did not extend our survey into the extensive subsurface systems of the area since assessment of the geodiversity index within the caves needs completely different approach and cannot be included in our numerical surface analysis.

The whole study area of about 4 km² was divided into 4843 separate 30-m blocks. The block statistical analysis, which was performed for each type, revealed a total number of different geodiversity elements within the blocks. A number of different geodiversity elements in a separate block varied from zero to three (Fig. 4). The majority of the blocks had only one geodiversity element type, and four blocks had the highest value of three.

Fig. 3 Map of the identified geodiversity element types



The terrain ruggedness index was calculated from LIDAR data for the corresponding 30-m blocks of the latter analysis. According to Riley et al. (1999), the terrain ruggedness index provides an objective quantitative measure of topographic heterogeneity. The calculated values are on scale from zero to 333 (Fig. 5). Blocks having the highest ruggedness values are in the steepest sections of the study area, such as within canyon or collapse doline slopes. Then again, the lowest

ruggedness values are for a planed surface that is not intensively dissected by a variety of surface karst features.

The final geodiversity index was calculated by multiplying the total number of different geodiversity element types and terrain ruggedness index within each block. Those calculated values were classified into three classes on the basis of the Jenks natural breaks classification (Jenks 1967) with low, medium and high geodiversity index (Fig. 6a; Table 1).

Fig. 4 Spatial distribution of different geodiversity element types within 30-m blocks

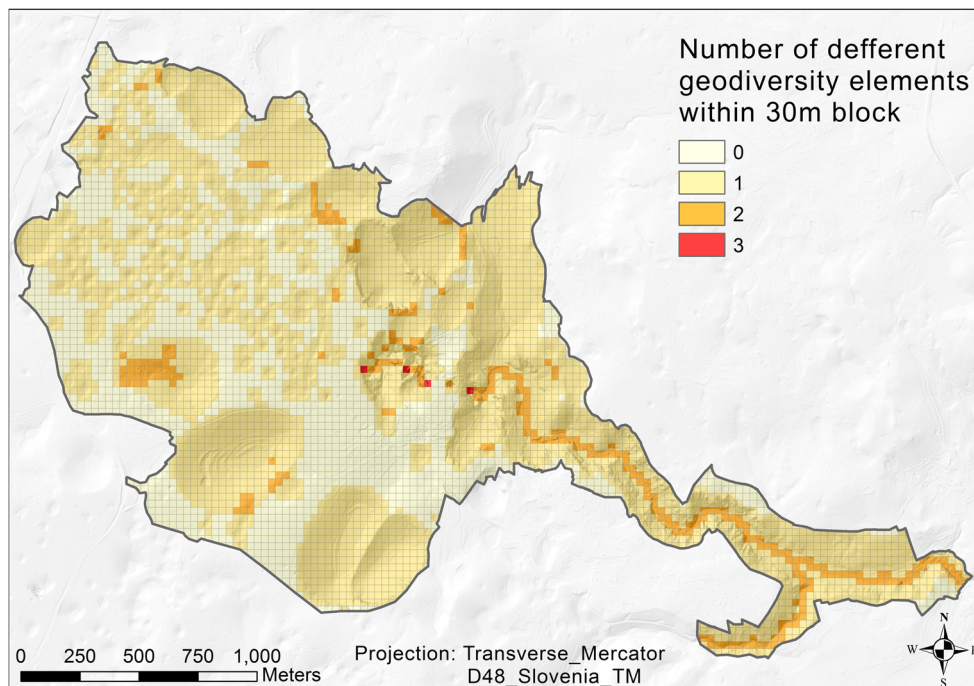
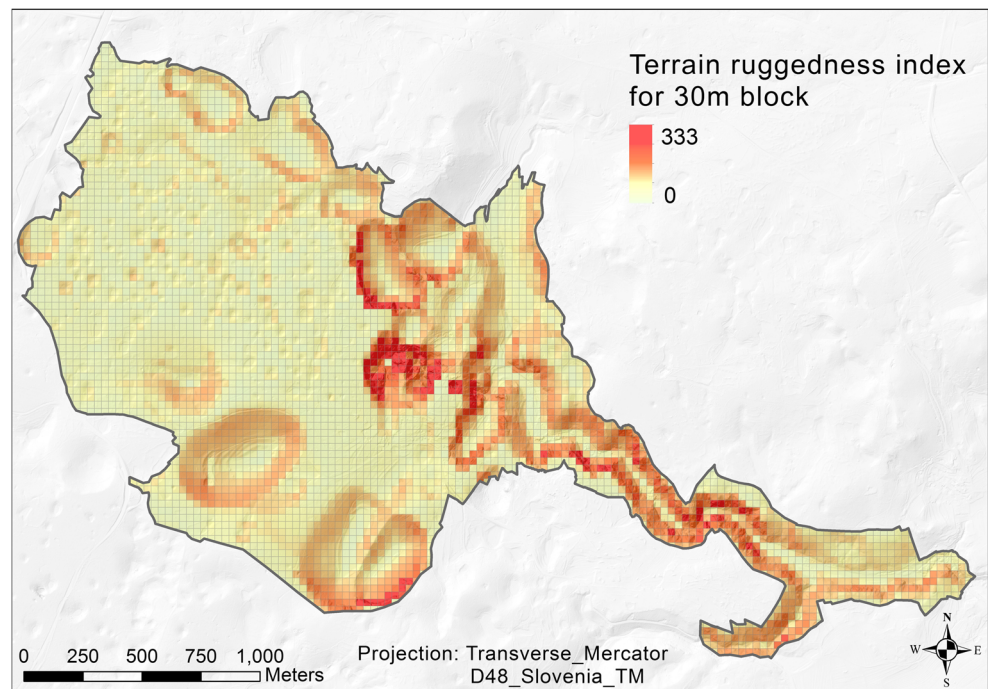


Fig. 5 Spatial distribution of the terrain ruggedness index for a 30-m block



The results of the applied method show that about more than one third (36%) of the Škocjan Caves Regional Park has low values for the geodiversity index. These areas are positioned mostly on a karst surface with low terrain ruggedness index and low variety of geodiversity elements. They correspond to a planed karst surface covered by a few scattered dolines.

The areas of medium geodiversity index cover almost a half (49%) of the study area. They are situated in the areas of higher variety of geodiversity elements or where the surface has higher ruggedness index. Within the park, they are located on the planed karst surface where dolines, collapse dolines or denuded caves are combined. They are also on steeper slopes of the collapse dolines and the canyon, which have high ruggedness index.

The areas of high geodiversity index cover about 15% of the study area (Fig. 6b). They are positioned in the areas where a high variety of geodiversity elements merges with a high surface ruggedness index. They appear in the central part of the canyon (Fig. 7c), within the area of the collapse dolines close to the ponors of the Reka River (Fig. 7b) and on steep slopes of other collapse dolines (Fig. 7a). Those areas of high geodiversity index can be also referred to as the *geodiversity hotspots* or *geodiversity loci* (Ruban 2010).

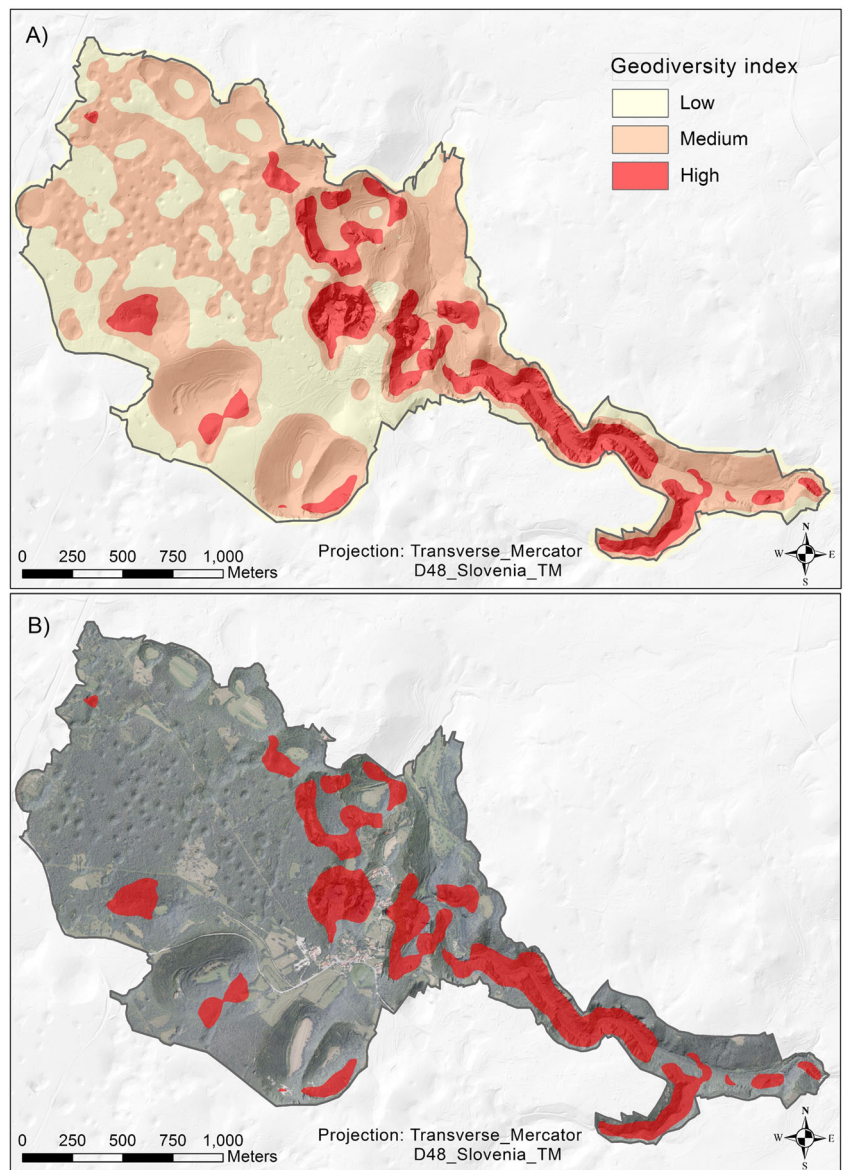
Discussion

The concept of geodiversity has been introduced over the last two decades due to a renewed interest in the abiotic elements of the nature (Gray 2013; de Paula Silva et al. 2014). It was

established in part to help manage the geoconservation, geotouristic and/or educational use of particular regions or sites. Natural diversity is a dimensionless attribute, which can be evaluated by both qualitative and quantitative methods. Many different evaluation methods have been proposed, and the most common methods used in geodiversity evaluation are qualitative ones. They merge a range of criteria according to which geodiversity elements are assessed. Each of them is stated in a descriptive manner that is regularly classified and expressed in a numerical value afterwards. The criteria are divided into scientific values and additional values. Scientific values define a general significance for the sites while additional values aim to assess applicable value for further management. The problem of qualitative methods is the subjectivity of evaluators as they are encouraged to reflect their values in the geosite process. Therefore, the results of the surveys vary significantly among them. As a result, comparative studies among various study areas as well as studies involving more evaluators are not reasonable. Additionally, the majority of qualitative methods are suitable for evaluation of actual geoheritage sites (Ruban 2010) rather than the systematic identification of geodiversity elements within designated area and their ensuing evaluation.

A quantitative approach towards geodiversity assessment is required for an objectivity of the results (Ruban 2010; Hjort and Luoto 2010; Meelli 2014). These could be compared later, even if multiple evaluators perform the analysis. Additionally, separate studies can be merged into a geodiversity assessment on a regional or even global scale. An additional advantage of the quantitative approaches, which are usually GIS supported, is the capability for the efficient processing of large data

Fig. 6 The final geodiversity index of the Škocjan Caves Regional Park. **a** The geodiversity index classified into three classes. **b** The highest index (*red colour*) visualised on orthophoto of the Škocjan Caves Regional Park



quantities. This is practical when dealing with large areas or areas with high natural diversity. The evaluation of relief properties that illustrates the heterogeneity of a surface is one of the most valuable resources of a quantitative geodiversity evaluation. It allows the evaluation of a whole study area regardless of spatial distribution of previously identified geodiversity elements. Quantitative methods not only assign values only to

Table 1 The areas and percentages of homogenous geodiversity areas in the Škocjan Caves Regional Park

Geodiversity index	Area (km ²)	Ratio (%)
Low	1.44	36%
Medium	1.96	49%
High	0.60	15%

specific elements but they also evaluate the landscape on the basis of the spatial relationship between geosites and relief morphology. Evaluation of relief morphology is attainable through DEM-derived data by the application of GIS tools. Systematic GIS-supported quantitative evaluation of the study area allows the calculation of geodiversity indices for separate spatial units within the study area. Accordingly, areas of high geodiversity index or geodiversity hotspots can be located. Furthermore, the objectivity of the method allows the comparison of data within different timeframes, hence allowing the assessment of geodiversity loss or gain due to various processes through time.

A series of quantitative GIS-supported methods of geodiversity evaluation has been developed (e.g. Hjort and Luoto 2010; de Paula Silva et al. 2014; Melelli 2014), all evaluating surface morphology, combined with elements of

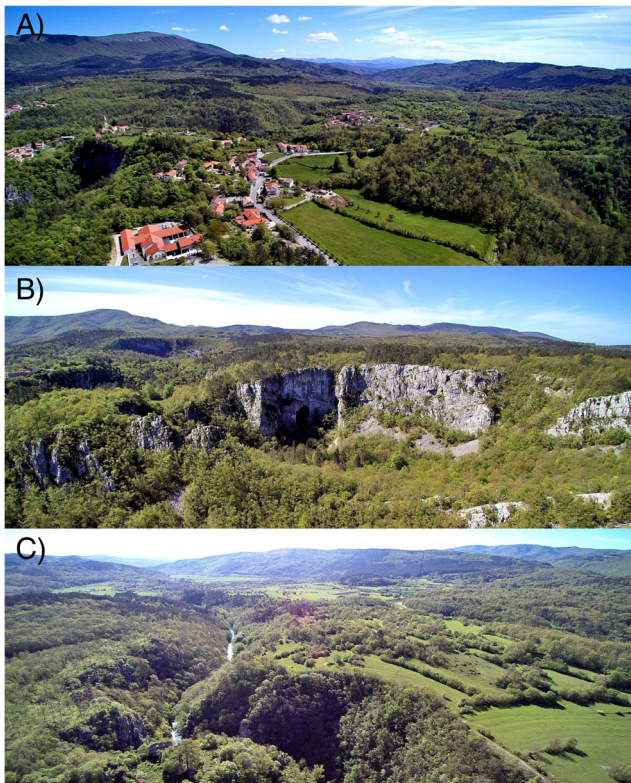


Fig. 7 Areas within the Škocjan Caves Regional Park with high geodiversity index. **a** Surroundings of collapse dolines. **b** Rocky slopes of collapse doline. **c** Central part of the canyon of the Reka River

geodiversity, their number and distribution over specified area. Their approach differs significantly within three different key aspects, which greatly affect the implementation of evaluation and results. The first is the input data that is taken into account, the second are the different GIS tools applied and the third are the spatial units to which the geodiversity is calculated.

All of the three aspects have to be consistent and precisely defined to acquire a suitable quantitative approach that could be used indiscriminately. Acquiring input data must be simple and very clearly defined, because this segment of evaluation involves a large possibility for subjectivity. The geodiversity elements included in the survey need to be basic elements that can be clearly identified. Obtaining these data must be simple enough that the assessor with a basic geoscience training or degree can identify them. In that respect, the subjectivity factor is greatly reduced but not completely excluded. Secondly, the critical aspect in the data analysis process is the GIS tools. The working tools and precise procedure of the data analysis must be specified. This step of the method must be simple enough to be applicable not only to the study area but can be applied to any environment. The most difficult aspect of a universal method is the scale, and this must be adapted to the size of the study area and to the size of the elements in the same manner as in any other mapping or other spatial survey.

Therefore, a number of different scale approaches can be applied for local, regional and global geodiversity assessment.

Our proposed model aims to deal with all three critical aspects of geodiversity evaluation. Data acquisition was limited to hydrological and geomorphological elements where geological and pedological data was excluded. Additional reason for the exclusion of pedological and geological elements is that they are located within the subsurface. They do indirectly influence the morphology of the overlying terrain, but this aspect had been previously documented by the geomorphological part of the survey. The identification of geodiversity elements was limited to a basic morphographic survey in the form of the identification and special documentation without any further interpretation or evaluation of the elements. A range of geomorphological and hydrological elements was linked to the most basic, so that an average evaluator with basic training in geosciences could identify them. The majority of those features can be identified by means of remote sensing data that has to be supported by fieldwork for final confirmation or possible correlation. Morphographic analysis by means of fieldwork is time-consuming, but it ensures an additional test to avoid input data errors.

A heterogeneity of the surface was established through the calculation of the terrain ruggedness index provided by Riley et al. (1999). Its use in a variety of scales (Riley 1999) is very significant for the aim of the geodiversity evaluation. The index calculation was derived from LIDAR data, and it was afterwards generalised to the basic spatial units used within the model. Generalisation also reduces noise from the data which is a result of high-detail LIDAR-derived DEM.

Various authors have used various GIS tools and techniques in defining various different geodiversity elements within spatial units. A focal statistic tool applied by Meelli (2014) provides an overlapping analysis; thus, the exact number of different elements within single spatial unit cannot be specified. Other techniques subtract repetitive elements (de Paula Silva et al. 2014) or sum the elements (Hjort and Luoto 2010) within a given spatial unit. Both are suitable from the objective point of view, but the authors (Hjort and Luoto 2010; de Paula Silva et al. 2014) did not provide exact information about the GIS method applied.

Our model used the Block Statistics tool in ArcGIS to define the number of different geodiversity elements within the spatial units. The tool is applicable for analysing the content of the input data for different sized blocks and statistic types. The analysis can be performed for input data with or without spatial continuity and for overlapping elements. In this way, we solved the important issue of analysing two different data types with one tool. An additional advantage is that the value of each cell in the analysis is taken into account only once, so the repetition of the same data in multiple blocks is avoided.

Our model was adopted for local-scale geodiversity assessment. Therefore, we used a 30-m cell size for the basic spatial unit. In addition, we tested other different spatial units and confirmed that 30 m offers a good compromise between data generalisation and excessive detail study. Regional and global spatial units will have to be defined in the future. The proposed model provides an effective foundation for further automated GIS-supported method for geodiversity index assessment.

Conclusions

A simple quantitative model for geodiversity evaluation is needed in order to obtain objective geodiversity data that can be used for comparative studies. The proposed method merges the spatial relationship of geodiversity elements with terrain data within a partially automated GIS-supported method. The method is simplified, and field-work is supported in order to achieve an objectivity of data used for further analysis and applied to the Škocjan Caves Regional Park. The geodiversity element types were recognised through remote sensing data and basic morphographic mapping. Their diversity was defined through block statistic tools in GIS tools. The geodiversity index was determined from the number of different geodiversity element types within defined spatial units and from the terrain ruggedness index. Areas of high geodiversity index strongly correlate with areas of the regional park which are currently promoted for geotouristic and educational purposes. The method has been proved to be suitable for local-scale geodiversity assessment. With future adjustment, the model can present a foundation for a universal geodiversity assessment method that could be applied in any environment.

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