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The routine of landform geodiversity map design for the Polish Carpathian Mts.

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Abstract: The main objective of this paper is to present a method for deriving a map of landform geodiversity in GIS environment. Three maps: a map of landform energy derived from SRTM-3 digital elevation model, a map of landform fragmentation created from geomorphological map and a map of contemporary landform preservation derived from CORINE Land Cover database are processed for the construction of a map of landform geodiversity. The paper presents a workflow for the map compilation procedure. The final map of landform geodiversity is created in the course of spatial analysis in GIS in two steps: first three input maps are combined in an overlay and next the overlay results are reclassified into the map of landform geodiversity with the following descriptions: very high, high, medium, low, and very low landform geodiversity. The study uses GIS to trace the patterns and changes of the natural landscapes and man-made transformations of natural landforms in the Polish Carpathians.

Key words: landform, geomorphology, geodiversity, GIS, Carpathians

Introduction

The relief of Poland is greatly diversified from high mountains in the southern part of the country to coastal plains in the north. Especially the southern part of Poland comprises very interesting and diversified area. This area is the Polish Inner and Outer Carpathians with high-mountain landscapes of the Tatra Mts. inside. The whole range has Alpine provenance with Pleistocene glacial modifications as well as Holocene retouch (Starkel 1972, Margielewski et al. 2008). Relatively simply geological settings and considerably complicated tectonic pattern of the Carpathians (Zuchiewicz 2009) produce a large number of landforms with mountain, highlands and denudative origin. Many parallel ranges with different heights up to 1,725 m a.s.l. in the Beskidy Mts and up to 2,499 m a.s.l. in the Tatra Mts. form an arc within the Polish section of the Carpathians. They are dissected by deep and long valleys like Skawa River, Wisłoka River or San River. The relief of the Polish Carpathians is enriched by basins, hollows, and elongated massifs very often. Therefore such mosaic of numerous landforms composes Carpathian landform geodiversity depicting exceptional and unique character of landforms in morphometric, morphographic, morphogenetic and morphochronological terms.

These extraordinary natural circumstances of the Polish Carpathians create favourable conditions for designing a map of landform geodiversity. It is the main objective of this paper to give an overview of the method to derive a map of landform geodiversity implemented in a Geographic Information System (GIS) tool. The method is evaluated according to its:

- applicability for geodiversity studies of Carpathian landforms, i.e. testing the new approach to description and assessment of such spectacular landforms for which the method gives meaningful and significant information;
- data requirements and limitations of the GIS setting.

The evaluation is based on the information gained by applying the method to a country-scale data set representing different types of landforms as well as different morphogenetic, climatic and geoecological zoning. The data requirements and limitations can depend on the particular methodol-

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ogy as well as they can be introduced by digital and analogue data properties of landforms.

The paper is arranged as follows: firstly, I discuss some aspects of the definition of geodiversity in general terms, secondly, I present a new approach to designing the landform geodiversity map, thirdly, I introduce some digital and analogue geodata for the procedure of map algebra and GIS numerical processing, fourthly, I present examples of how GIS concepts and tools can be utilized in making the map of landform geodiversity for the Polish Carpathians, and finally, I offer the summary of the presented approach. It is worth mentioning that this approach was also applied to mapping the geomorphology of entire Poland a few years ago (Zwoliński 2002).

Definition of landform geodiversity

The concept of geodiversity in general terms was presented among others Gray (2004), Zwoliński (2004) and Serrano & Ruiz-Flaño (2007). The most popular definition of geodiversity was put forward by the Australian Natural Heritage Charter (AHC 2002). According to this definition geodiversity means the natural range (diversity) of geological (bedrock), geomorphic (landform) and deposit (soil) entities (features), assemblages (sets), systems (geoecosystems) and natural and man-made activities (processes). Geodiversity includes the evidence of the past and present environments and geoecosystems in the history of the earth. In assessing geodiversity it is necessary to take into account a range of atmospheric, hydrological and biological processes currently functioning on bedrock, landforms and deposits. Geodiversity is now being used in a very holistic way to emphasise the links between geosciences, ecosciences and anthroposciences in one system or environment.

The term geodiversity is commonly used in two meanings, simpler and broader. In the approach presented in this paper, geodiversity is used in simpler, narrower sense which conveys the idea that geodiversity refers specifically to particular geoecosystems, i.e. mountain geoecosystems that are in themselves diverse or complex (Joyce 1997, Semeniuk 1997, Stock 1997). Obviously, this situation calls for some clear-cut criteria of geodiversity. One of the possible solutions is a hierarchical classification of landforms. In the case of the Polish Carpathians it can be the following hierarchical classification as an exemplary pattern –

morphoclimatic zone: temperate mountain,
morphogenetic zone: mountain,
morphosystem: denudational system,
type of relief: depositional relief,
set of landforms: slopes, and
single form: talus.

This classification is a function of complexity lowering. One might argue that an upgrade in complexity entails an increase in geodiversity, and variations in this relationship are a matter of two functions: asymptotic and exponential.

Geodiversity is valuable from a variety of perspectives like intrinsic, geological, geoecological, ecological, geoheritage, as well as scientific, educational, social, cultural, tourist, and so on. Therefore landforms with outstanding geodiversity should undergo geoconservation as a result of which it is possible to create geosites or geoparks for present and future generations.

Thus landform geodiversity describes landscape complexity from the geomorphological point of view and evaluates all morphogenetic patterns of different types of relief. The identification of landform geodiversity in the Polish Carpathians includes the indication of entities like morphogenetic zones, morphosystems, relief types, sets of landforms and single landform which are worth preserving and protecting (Kozłowski 1997, Kostrzewski 1998, Zwoliński 2004, Cañadas & Ruiz-Flaño 2007). These features should be exceptional and unique in geological and morphological terms.

Map design approach

The procedure of designing a map of landform geodiversity in the Polish Carpathians is based on the assumption that a modern landform is reflected by:

- hypsometric contrasting,
- the degree of tectonic and denudational fragmentation of the relief, and
- the state of relief preservation as an effect of the natural land cover or its transformation as a result of a changing land use, i.e. man-made activity, anthropopressure on natural environment.

This assumption exactly refers to the concept of geodiversity in general terms which was presented in previous section. These above three conditions allow composing three maps that are the framework for the construction of a map of landform geodiversity. These three thematic layers are:

- a map of landform energy – created by a numerical transformation of a SRTM–3 digital elevation model (Michalak 2004),
- a map of landform fragmentation – created manually as the Starkel's creative study (1998),
- a map of contemporary landform preservation – created by digital postprocessing of the CORINE Land Cover database (EEA 2004).

Therefore landform geodiversity GDL can be modelled in two alternative ways:

$$GDL_d = \frac{LE_{0\to N} + LF_{0\to N} + SP_{0\to N}}{T_{0\to N}}$$

or

$$GDL_s = \frac{LE_0 + LF_0 + SP_0}{T_0}$$

where:
GDL_d – dynamic geodiversity of landform,
GDL_s – static geodiversity of landform,
LE – local elevation or relative elevation,
LF – landform fragmentation (segmentation),
SP – state of contemporary relief preservation (natural vs man-made processes),
T – evolution of the relief over time,
$_{0 \rightarrow N}$ – number of observations/stages in landform development, and
$_0$ – observation of landform development at–a–time.

It is very important to consider landform geodiversity within some period of time (T). If it is possible to acquire a big time span for landform development with many stage points and/or phases of this development then this kind of landform geodiversity is dynamic. The landform geodiversity is static in the case of geodiversity statement made once, at a specific moment of observation. Advisable kind of geodiversity is dynamic but it is difficult to realise because of many factors influencing relief evolution. Static geodiversity is more common and easy to implement. This kind of geodiversity is a subject of presented map design procedure. The procedure is illustrated on Fig. 1. The input layers for the presented procedure are depicted at level 1 – the collection of existing analogue and digital maps:

- digital elevation model based on ellipsoid WGS84 and resulting form the SRTM mission in February 2000 (Michalak 2004) with horizontal resolution ~ 90 m and ~ 30 m as well as vertical resolution 1 m, which corresponds to accuracy of topographic map at 1:50,000 scale,
- geomorphological map of Poland in scale 1:500,000 edited by Starkel (1980) and general hypsometric maps; these maps were the bases for creation of the map of landform fragmentation as a manual interpretation of general topographic surface and variability of landforms; it was created by Starkel (1998) as the author's creative study,
- map of land cover and land use for Europe from the CORINE Land Cover database for the year 2000 (EEA 2004); this raster cartographic data model has resolution 250 m; the map of contemporary landform preservation was created by digital postprocessing of CORINE Land Cover database considering natural types of land cover and man-made types of land use.

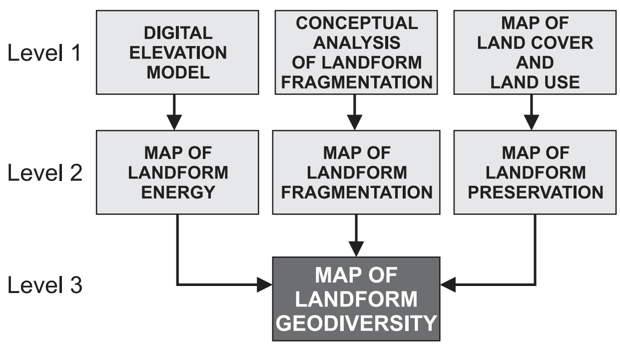

Fig. 1. Flowchart for creation of landform geodiversity map: level 1 – input analogue and digital maps and databases, level 2 – transformed maps as an input to logical map algebra, level 3 – output map

Imperfection of this input map collection is different time of their production, different accuracy and different resolution. All input maps were transformed to coordinate system PUWG 1992.

GIS workflow for transformation of input geodata

The set of input maps underwent multiple spatial data processing steps in preparation for further GIS analyses. The aim of these steps was to produce a five-degree scale of geodiversity classes for each analytical map. There are five universal classes of geodiversity independent of the theme of these maps:

- the category of very high geodiversity – 5 points,
- the category of high geodiversity – 4 points,
- the category of medium geodiversity – 3 points,

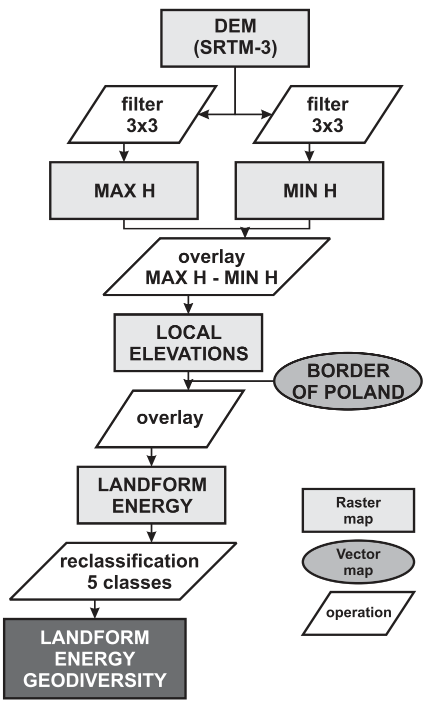

Fig. 2. Flowchart of GIS operation on raster and vector layers for creation a map of landform energy geodiversity on the basis of DEM

Table 1. Categorisation of geodiversity in context of relative heights

Category of geodiversity	Amount of points	Local elevation	Examples in the Carpathians
very high geodiversity	5	more than 50 m	mainly in main stem of Tatra Mts. and in some places of the Western Beskidy Mts. and Bieszczady Mts.
high geodiversity	4	between 25 and 50 m	mainly in all main ranges of the Beskidy Mts. as well as Lower Regel in Tatra Mts.
medium geodiversity	3	between 10 and 25 m	mainly slopes of the Beskidy Mts. and highlands, foothils
low geodiversity	2	between 2 and 10 m	mainly slopes of intramontane basins and hollows
very low geodiversity	1	between 0 and 2 m	vast bottoms of intramontane basins and hollows as well as bottoms of river valleys

– the category of low geodiversity – 2 points, and
– the category of very low geodiversity – 1 point.

Each class has assigned the amount of points for final map algebra operation.

SRTM–3 digital elevation model was processed by two analysis steps at level 2. The first step involved the transformation of elevation data from absolute values to relative ones (Fig. 2). The second step involved assigning geodiversity classes to relative heights (Table 1). Digital elevation model was filtered with moving window 3×3 resulting in grids for maximum and minimum elevation. Next, the overlay operation was performed with logical operator difference between maximum and minimum elevation for a given grid. The resulting final product is the map of landform energy (or local elevations or relative heights, Fig. 3A). The last operation was reclassification of local elevations into 5 classes (Table 1).

The second input includes a map of tectonic segmentation and denudational fragmentation of the Carpathian relief (Fig. 3B) complied on the basis of the geomorphological map of Poland at scale 1:500,000 edited by Starkel (1980) and general hypsometric maps. The interpretation of that map is based on assumptions listed in Table 2, which were proposed by Starkel (1980).

This map was produced by Starkel (1980) manually in the analogue format as his original creative study. Therefore this original map was digitised and adapted to digital form according to the procedure of digital adaptation of analogue maps proposed by Dmowska et al. (2010). Unfortunately, the original map was compiled at the scale 1:3 500 000. This caused numerous generalisations of the boundaries for many distinguished units in the final map of landform geodiversity.

The last but not least in the input map collection is the map of contemporary landform preservation (Fig. 3C). This map was derived from CORINE Land Cover database (EEA 2004) by digital postprocessing. The processing of this map involved assigning one of five geodiversity classes to 37 types of land cover and land use (Table 3). It is worth mentioning that from 44 types of LC/LU in CLC database only 37 could be adopted to Polish environmental conditions. The classification process revealed the contribution of natural versus man-made factors in landform creation, development, and changes in-

Table 2. Categorisation of geodiversity in context of relief fragmentation/segmentation

Category of geodiversity	Amount of points	Types of relief fragmentation/segmentation	Examples in the Carpathians
very high geodiversity	5	high-mountain relief transformed by glacial and periglacial processes, with arętes and gullies	Tatra Mts.
high geodiversity	4	medium and low mountains and high foothills, a dense network of both valleys and ridges, linear tectonic and denudation thresholds with steep slopes as well as high and precipitous (often also densely incised) scarps of gorges	ranges of the Beskidy Mts.
medium geodiversity	3	low foothills, low tectonic and denudation thresholds as well as deeper river gorges	Wieliczka Foothils
low geodiversity	2	intramontane basins, stretches of low uplands, scarps of varying genesis	Doły Jasielsko-Krośnieńskie (Depression)
very low geodiversity	1	valley floors (margins of river terraces were omitted)	Podhale Basin, Dunajec River, Wisłoka River, San River

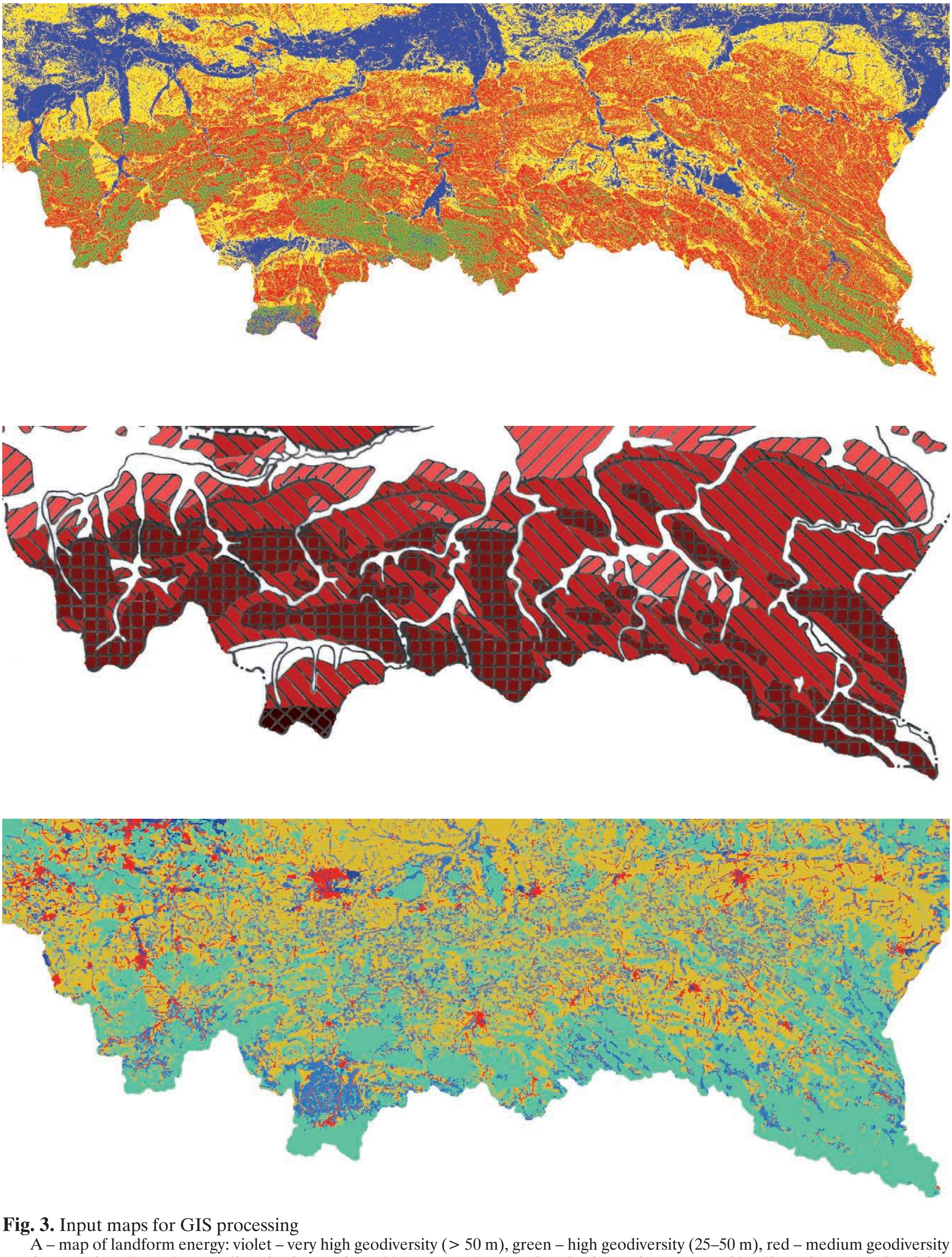

Fig. 3. Input maps for GIS processing
A – map of landform energy: violet – very high geodiversity (> 50 m), green – high geodiversity (25–50 m), red – medium geodiversity (10–25 m), yellow – low geodiversity (2–10 m), and blue – very low geodiversity (< 2 m), B – map of landform fragmentation (after Starkel 1998): very dark brown with diagonal grid – very high geodiversity, dark brown with plain grid – high geodiversity, brown with left-diagonal lines – medium geodiversity, light brown with right-diagonal lines – low geodiversity, and white – very low geodiversity, C – map of contemporary landform preservation: green – very high geodiversity (very distinct level of relief preservation), blue – high geodiversity (distinct level of relief preservation), yellow – medium geodiversity (medium level of relief preservation), red – low geodiversity (poor level of relief preservation), and light blue – very low geodiversity (very poor level of relief preservation)

Table 3. Categorisation of geodiversity in context of relief preservation

Category of geodiversity	Amount of points	Types of relief fragmentation/segmentation [extracted from Starkel (1998) for mountain areas only]	Examples in the Carpathians
very high geodiversity	5	very high level of relief preservation: the morphological surface is the least transformed by morphogenetic processes and almost untouched by man-made processes, i.e. primeval mountain forests, peat bogs, swamps	High Tatras, Babia Góra Mt., Orawa-Nowy Targ Basin – peatbogs
high geodiversity	4	high level of relief preservation; areas sporadically affected by morphogenetic processes with a slight contribution of man-made processes, i.e. slopes with landslides	landslide slopes in Beskid Sądecki Mts.
medium geodiversity	3	medium level of relief preservation as a result of both morphogenetic and man-made processes, i.e. arable grounds	intramontane basins, Carpathian Foothill zone (partially)
low geodiversity	2	poor level of relief preservation indicating substantial changes in the relief as a result of human activity, i.e. urban areas	Bielsko-Biała, Nowy Sącz
very low geodiversity	1	very poor level of relief preservation, i.e. a complete transformation of the relief by man, the transformation being usually irreversible, i.e. mine-industrial areas, quarries, dam reservoirs	post-peat areas in Orawa-Nowy Targ Basin, Goleszów quarry, Rożnów dam reservoir

cluding the complete metamorphosis from natural landforms to anthropogenic relief. This procedure has the advantage of technical simplicity and makes an important assumption that modern landform is reflected by the state of relief preservation as an effect of remaining natural land cover over centuries or its land use transformation by man-made changes. The resolution of this map is 250 m.

Computation of landform geodiversity map

The final map of landform geodiversity was created via a geoinformation analysis in two steps within level 3. The map of landform geodiversity was obtained by the overlay of three input maps: landform energy, landform fragmentation and contemporary landform preservation during first step of analysis. Each input map is featuring five classes of geodiversity. These qualitative classes ranging from very high to very low geodiversity were assigned quantitative values from 5 to 1, respectively. Consequently the overlay analysis gave 13 classes as the sum of values from three maps in range from 3 to 15 points (Fig. 4A). It is worth to note very large differentiation of distinguished landform units on stage map. This differentiation is similar to distinguished geomorphological units on geomorphological map edited by Starkel (1980). It means that this procedure is unsatisfactory for arranging landforms in bigger divisions than on detailed geomorphological map. Therefore, to adjust this wide class scale for final synthetic map of landform geodiversity to the five classes of geodiversity (Fig. 4B) I used simple clustering analysis in the second step. For the sake of map simplification the 13 classes were reclassified into 5 classes with the following descriptions:

- class 1: very high landform geodiversity – point totals from 13 to 15,
- class 2: high landform geodiversity – point totals from 10 to 12,
- class 3: medium landform geodiversity – point totals from 7 to 9,
- class 4: low landform geodiversity – point totals from 4 to 6, and
- class 5: very low landform geodiversity – a point total equal to 3.

Conclusions and prospect

The landforms of the Polish Carpathian Mts. are dominated by two classes of geodiversity, namely those of high and medium geodiversity in similar proportion. Jointly they take up nearly 90% of the whole Carpathians area, embracing mainly ridges and slopes of ranges and highlands. Landforms of very high geodiversity spread mostly in Tatra Mts. (Fig. 5) as well as in the Beskidy Mts. as very small places but very often, especially in Pieniny and Gorce. The class of low landform geodiversity extends in the area of bottoms of basins and hollows as well as of floors of the river valleys. Man-made areas and some urban centres are classed as displaying very low landform geodiversity. These places occur in small areas of the lower Skawa River and mainly very far from northern limit of Carpathians.

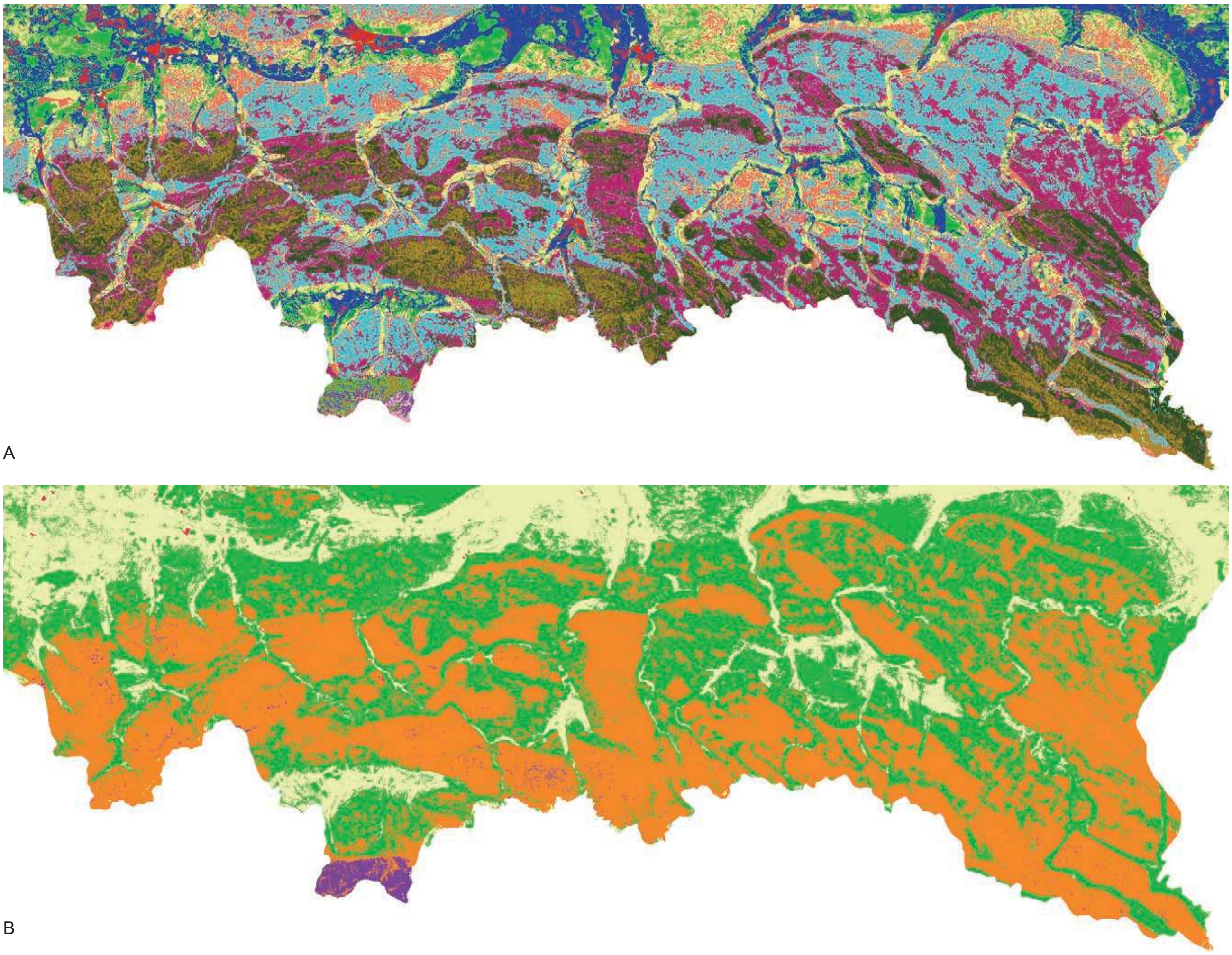

Fig. 4. The maps of landform geodiversity for the Polish Carpathian Mts.
A – stage map as a result of overlay in the first step of geoinformation analysis with 13 classes of geodiversity (no key because of very large differentiation of distinguished landform units - see text for explanation), B – final map as a result of clustering in the second step of geoinformation analysis with 5 classes of geodiversity: purple – very high landform geodiversity, orange – high landform geodiversity, green – medium landform geodiversity, yellow – low landform geodiversity, and red – very low landform geodiversity

The map of landform geodiversity is mostly similar to the map of relief energy, but it is worth emphasizing that its informative content was markedly enriched with details from the map of landform fragmentation, best visible in the course of most river valleys. In turn, the map of landform preservation contributed the most to the identification of landscapes with man-made types of landform. The proposed procedure for determining landform geodiversity is scalable. For example, there is currently an on-going research on the enhanced procedure applied to Tatra Mts. (Fig. 6).

In this paper I presented a procedure for integrating geographic information system analysis with hypsometric, morphological and land use investigations. The study uses GIS to trace the patterns and changes of the landscape and man-made transformations of natural landscapes. Using GIS in conjunction with spatio-temporal techniques one can better synthesize and visualize the extent and rate of geodiversity as the combined effect of phenomena depicted on constituent maps. However, the potential of geoinformation analysis for studying geodiversity and its dynamics reaches far beyond what the analysis presented in this paper presented. GIS analyses can offer multiple alternatives to aid the regionalisation, clustering and so on. Lastly, GIS

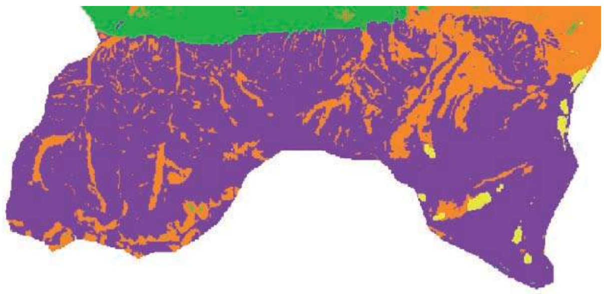

Fig. 5. The map of landform geodiversity for Tatra Mts. classes of geodiversity
Purple – very high landform geodiversity, orange – high landform geodiversity, green – medium landform geodiversity, and yellow – low landform geodiversity. Note a lack of very low landform geodiversity (red)

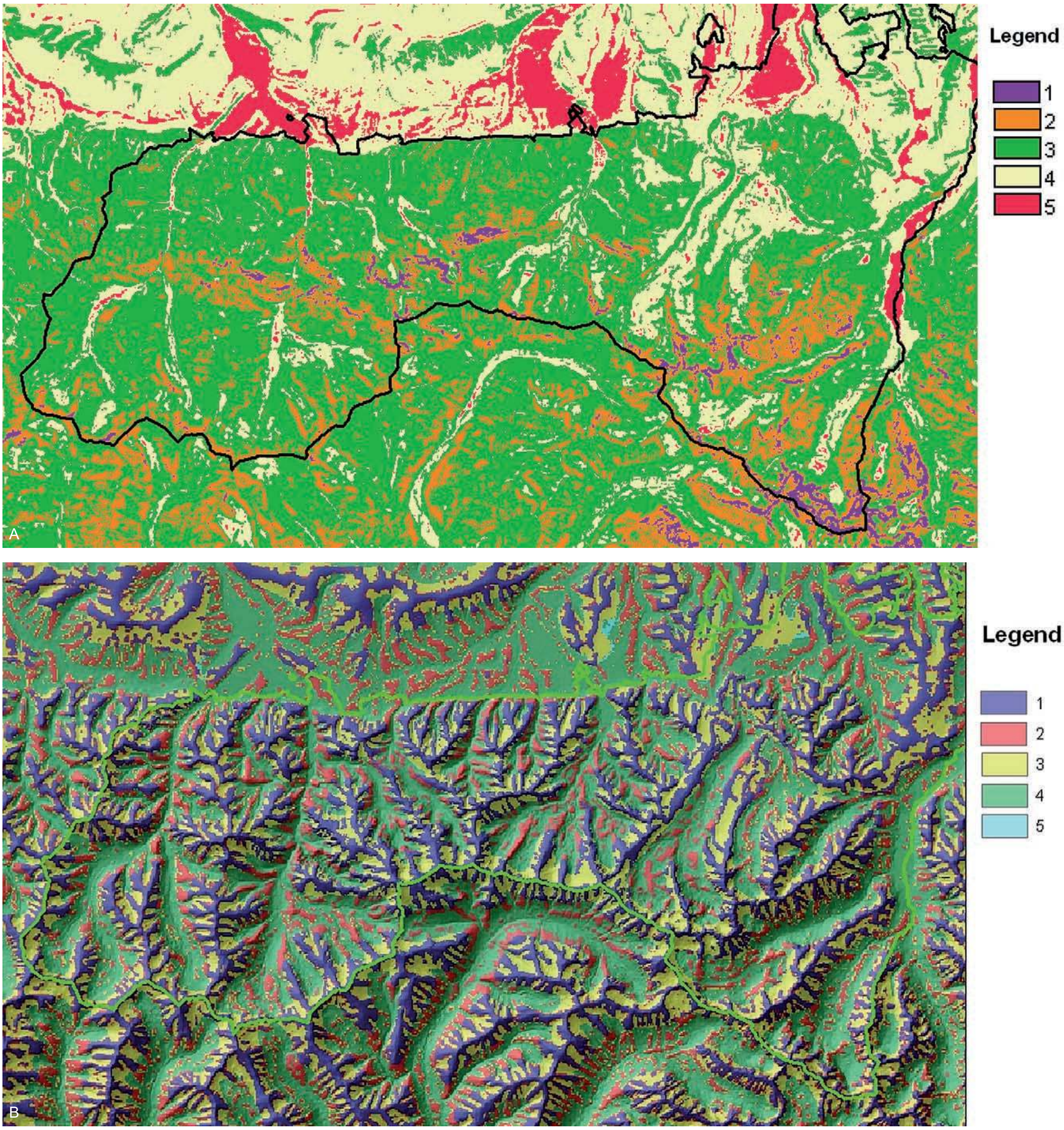

Fig. 6. Trial versions of a new approach to landform geodiversity tested on the Tatra Mts.
A – map of landform energy, B – map of landform fragmentation, 1 – very high geodiversity, 2 – high geodiversity, 3 – medium geodiversity, 4 – low geodiversity, and 5 – very low geodiversit

can produce numerous alternatives, enabling scientists or decision makers to review initial theories and hypotheses for feasibility before environmental proposals are made.

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