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MAPPING LANDFORMS AND GEOMORPHOLOGICAL LANDSCAPES OF HUNGARY USING GIS TECHNIQUES

Abstract. Modern geomorphological analyses largely benefit from GIS tools developed for landform and landscape mapping. Semi-automated methods with the use of public domain elevation datasets ensure the mapping of large areas with relatively low time and cost requirements, leaving less space for subjectivity. For our analysis we chose the geomorphons approach, a robust cell-based method to identify landform elements at a broad range of scales. Based on the delineated landforms and auxiliary morphometric parameters it was possible to map the geomorphological landscapes occurring in Hungary with the supervised classification algorithm implemented in the GeoPAT toolset. The scientific output of the presented work is twofold: one aspect is the creation of an objective and quantifiable map of landforms and geomorphic landscapes of Hungary, while the successful application of the available methodology and the evaluation of SRTM1 model's applicability for geomorphological purposes are also significant results.

Keywords: digital geomorphological mapping, geomorphometry, semi-automated GIS algorithm, SRTM1, Hungary

INTRODUCTION AND AIMS

Since digital elevation models provide snapshots of the landscape with constantly improving horizontal and vertical resolutions and GIScience became widely used Digital Geomorphological Mapping (DGM) is no longer an unorthodox geographical research subject (Hegedűs 2004; Minár, Evans 2008; Telbisz 2009; Bishop et al. 2012; Drăguţ, Eisank 2012; Evans 2012; Jasiewicz, Stepinski 2013). Based on the scientific results of the recent years it can be stated that the improvement in applicability of GIS software, terrain modelling methods and satellite-based elevation data led to irreversible changes in the nature of geomorphological research and mapping, considering data collection, analysis and presentation mode as well (Smith et al. eds. 2011). Terrain analysis toolsets ensure the mapping of large areas with relatively low time and cost requirements, leaving less space for subjectivity and due to the application of rulesets the resulting maps can be easily upgraded (Drăguţ, Blaschke 2006; van Asselen, Seijmonsbergen 2006). According to several authors the development of readily adaptable, semi-automated methods for landform delineation and landscape mapping became the most prosperous subdivision of geomorphometry (Pike et al. 2009; Drăguţ, Eisank 2011).

Based on the absolute altitudes and relative elevation differences Hungary can be divided into three height levels, or so called relief steps: lowlands, hills and low mountains (Bulla 1962). Approx. 20-20% of the country is characterized by mountainous and hilly environments, accordingly its major area belongs to plains (Pécsi 1984). On the other hand, F. Schweitzer (2009) claims that 73% of the area is considered as plains, 20% belongs to hills and pediment surfaces and only 7% can be categorized as mountainous. Different authors discriminate different subtypes, and while these broadly coincide, their spatial delineation or exact categorization typically varies. Exclusively on the basis of orographic and morphologic conditions the authors describe the mountainous regions as medium and low mountains with narrower and wider ridges; they discriminate between hills in mountain forelands and isolated hilly districts characterised by erosion-derasion valleys; while separating lowlands into the categories of flat floodplains and gently undulating alluvial plains, which are in some cases heightened by loess or sand cover (Prinz 1936; Bulla 1962; Pécsi, Somogyi 1967; Pécsi 1977, 1984, 1996; Schweitzer 2009; Lóczy 2015). In the present study, we divided each major relief type into two subtypes of geomorphic landscapes.

The largest units of the hierarchic landscape system of Hungary are the macroregions i.e. Great Hungarian Plain (GHP), Little Hungarian Plain (LHP), West Hungarian Borderland (WHB), Transdanubian Hills (TDH), Transdanubian Range (TDR), North Hungarian Range (NHR), which are territories with natural conditions significantly differing from their neighbouring regions and reflect the conditions of the geomorphic regions as well (Mészáros, Schweitzer eds. 2002). Based on the spatial arrangement and connection of the natural factors there are 33 mezoregions and 230 microregions with a more homogenous landscape potential on the lower levels of the system (Marosi, Somogyi eds. 1990; Dövényi ed. 2010). As the microregions are most commonly chosen to be the base unit of analysis in researches related to earth sciences and the geomorphological and relief type maps were in some cases incomplete or incompatible, we decided to classify the microregions based on their characteristic geomorphic landscape (Fig. 1). We could do so because in the delineation process of these microregions the morpho-lithological elements, geostructural features and orographical conditions provided the frame of the landscapes' regionalization (Pécsi 1984).

The main objective of the research was a geomorphological characterisation of the terrain in Hungary based on a public domain height dataset using GIS algorithms. The landform map and the derived geomorphological landscape map reveal objective information about the spatial arrangement and characteristics of the topography in order to revise the traditional geomorphological maps.

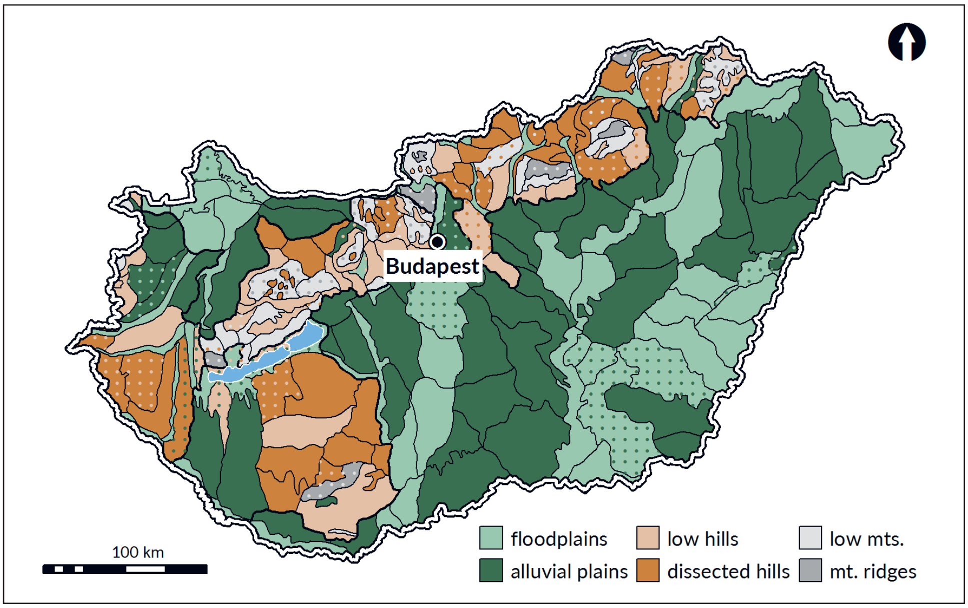

Fig. 1. The microregions of Hungary classified into the characteristic geomorphic landscape and a potential secondary type. (Edited by: E. Józsa based on Pécsi, Somogyi 1967; Pécsi 1977; Schweitzer 2009; Dövényi ed. 2010)

The presented research goes beyond the practical application of these digital maps; it connects to a series of studies that aim to establish the new principles of DGM by testing the suitability of methods and datasets as well.

MATERIALS AND METHODS

The research objectives required a digital elevation dataset with reasonable information content about the topography and acceptable spatial resolution in an affordable price range, considering the analysis was carried out on the total 93.030 km^2 area of Hungary. Several nearly global elevation models are at the disposal of geoscientists, but our previous studies proved the advantages of the 30 m resolution SRTM1 over other datasets with similar horizontal spacing (NASA JPL data; Józsa et al. 2014; Józsa 2015). A pre-processing algorithm was compiled to correct the major issues affecting the model to reduce error propagation to the derived geomorphometric maps. The elevations of larger water bodies were replaced by single values approximated from height values of shorelines. Forested and built-in areas were mapped using public domain auxiliary data (Global Forest Change 2000–2014 data; Hansen et al. 2013; OpenStreetMap data). M.C. Hansen and his research team created the Global Forest Change dataset. SRTM1 data was corrected based on the elevation difference of cells located on the inner and outer border of these land cover units. Lastly, an adaptive smoothing algorithm (Stevenson et al. 2010) was implemented to reduce the effect of noise and remove the outliers.

The methods of DEM-based geomorphometric mapping are constantly developing into the direction of multi-scale landform delineation and the classification of landscapes. For our analysis, we chose the geomorphons approach, a robust cell-based method to identify landform elements at a broad range of scales

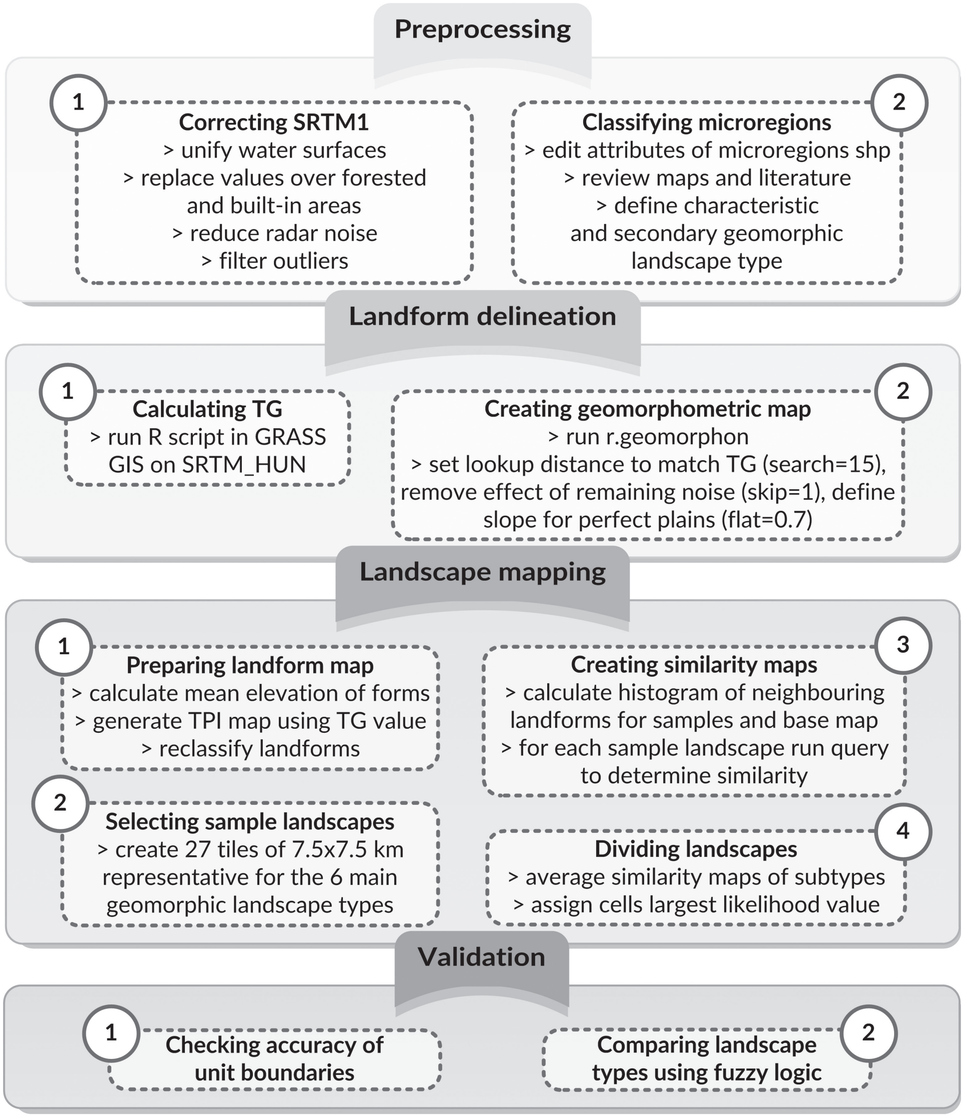

Fig. 2. Flowchart of the landform and geomorphological landscape mapping procedure. (Edited by: E. Józsa)

by using line-of-sight based neighbourhoods (Stepinski, Jasiewicz 2011; Jasiewicz, Stepinski 2013). The characteristic of geomorphons map depends largely on the value of lookup distance defining the maximum scale of mapping, the skip radius to eliminate forms that are too small to be of interest and the flatness threshold to prevent the analysis of flat areas. A possible way to determine the suitable value for the lookup distance parameter is to consider the topographic grain principle by detecting the characteristic local ridgeline-to-channel spacing (Pike et al. 1989). The calculation of the parameter is implemented as a bash shell script for GRASS GIS and R. By calculating the relative relief values with nested neighbourhood matrices it is possible to define a break-point where the increase rate of local relief encountered by the sample is significantly reducing. The results suggested 450 m as the topographic grain (TG) value, which fits the basic rules of geomorphological mapping concepts adopted in Hungary.

Based on the delineated landforms and other morphometric variables (mean elevation of form, Topographic Position Index [TPI]) it was possible to map the physiographic units occurring in Hungary. For this analysis, a supervised classification algorithm was chosen – implemented in the GeoPAT toolset – to derive similarity maps based on 27 study sites representing the distribution and spatial arrangement of landforms in the analysed geomorphic types (Jasiewicz et al. 2014). These datasets were interpreted to create map of geomorphologic landscapes. This resulting map was compared with the classified map of microregions (Fig. 1) to reveal the deviations from the available expert-based, hierarchical landscape maps for quality and applicability control. As a result of our study we generated a landform map with ~30 m resolution and a landscape map with ~1 km cell size covering the entire territory of the country. The steps of the analysis are organized into a flow chart (Fig. 2) for a better perspicuity. A more detailed description of the methods is given with the resulting maps' presentation.

It is important to emphasize that all steps were carried out using GNU GPL (General Public License), open-source software including GRASS GIS 7.0.3 (http://grass.osgeo.org) to create and process the maps and R (http://r-project.org) to perform the statistical analyses.

RESULTS AND DISCUSSION

GEOMORPHOMETRIC MAP OF HUNGARY

A common drawback of geomorphological analyses based on digital elevation datasets is the definition of search window size for the derivation of morphometric variables. The size of neighbourhood matrix determines the scale of the mapping, which can lead to the generalization of smaller surface details or the elimination of larger landform elements; changing the extent of window size can completely change the character of the output (Jasiewicz, Stepinski 2013). In our presented methodology, we achieved to create a map of comparable

Table 1

Distribution and topographic characteristics of 10 main landform types. (1 – flat, 2 – summit, 3 – ridge, 4 – shoulder, 5 – spur, 6 – slope, 7 – hollow, 8 – footslope, 9 – valley, 10 – depression)

	1	2	3	4	5	6	7	8	9	10
rate	52.3%	0.6%	5.0%	3.9%	6.1%	17.6%	4.5%	4.7%	4.9%	0.4%
min elev. (m)	69.6	73.6	72.3	71.0	32.3	29.9	28.9	69.7	23.5	22.6
max elev. (m)	462.4	1044.0	1031.8	831.0	1021.8	1007.8	997.6	819.4	919.0	885.5
standard deviation	25.3	127.2	110.6	37.4	111.4	93.1	103.5	35.1	88.9	86.6

landform units by using the Topographic Grain value as search parameter in the geomorphons mapping approach.

The geomorphometric map allows the statistical (Table 1) and spatial (Fig. 3) analysis of the 10 dominant landforms in the country. Even though we selected the flatness threshold to represent only perfect plains as flat forms the vast majority of the cells belongs to this category. On the other hand, the value is slightly lower than expected considering the literature, which can be explained by the effect of erroneous cells on the SRTM1, where the method misinterpreted the more rugged surface of forested regions.

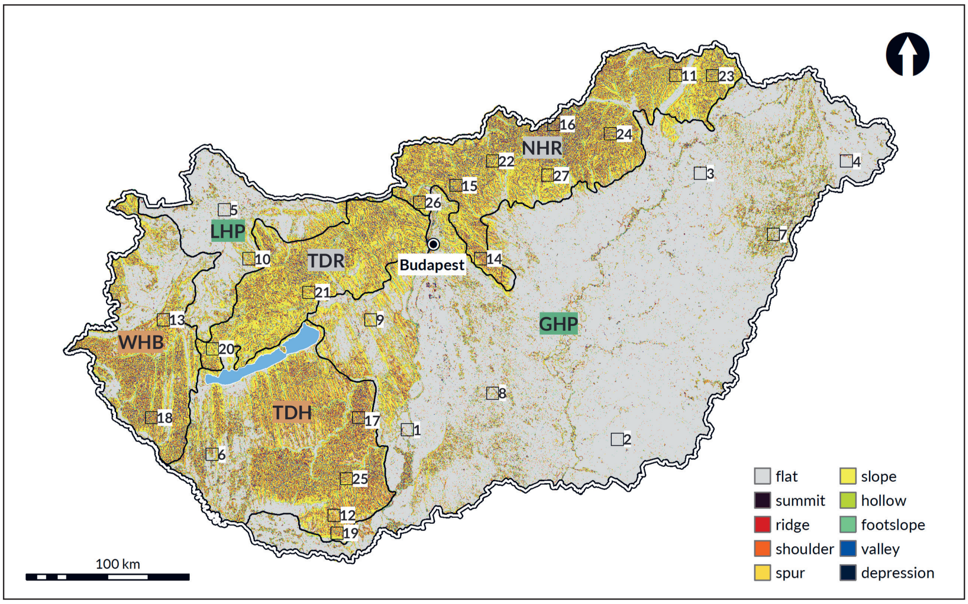

Fig. 3. Landform element map of Hungary with the locations of sample landscapes and boundaries of macroregions. (Edited by: E. Józsa)

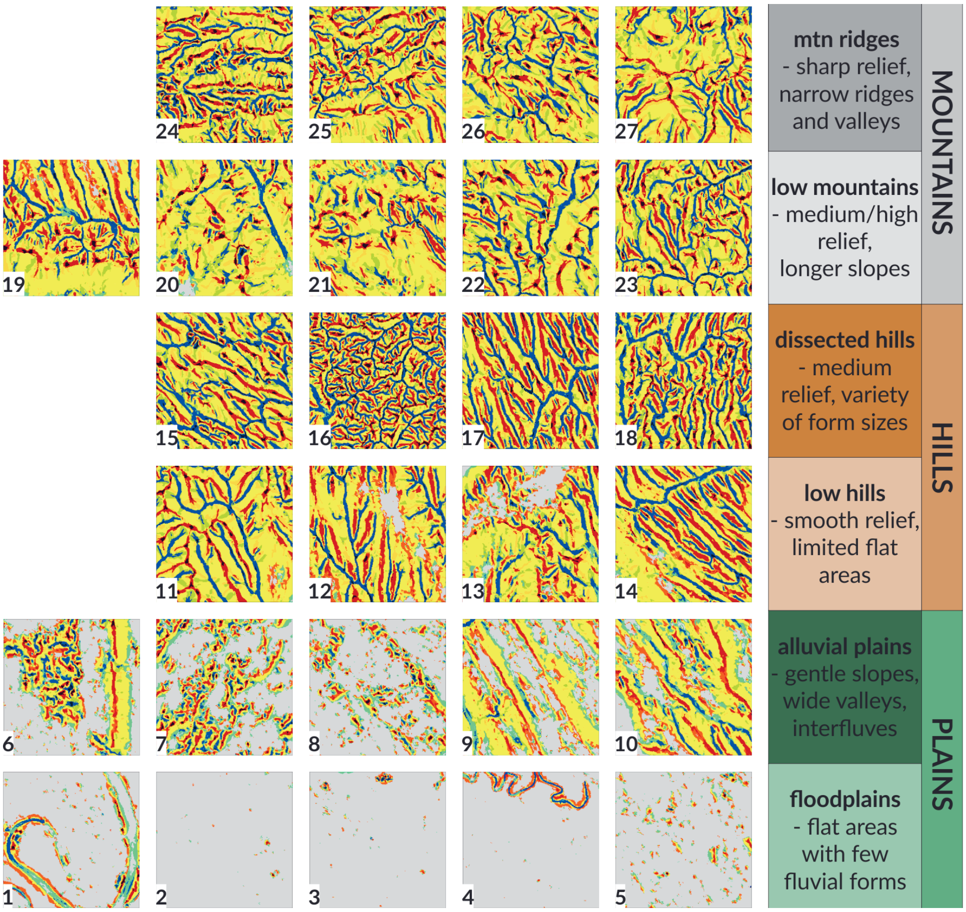

Fig. 4. Landform elements of sample sites and description of analysed geomorphic landscape types. [Colours correspond to the legend of Fig. 3] (Edited by: E. Józsa)

The raster map holding the landform elements provides the opportunity to visually analyse the characteristics of a given topography, but more importantly the dataset allows the automatic separation of landscapes by following a predefined set of rules. To get a good representation about the varying topographic characteristics of the analysed geomorphic landscape types we selected 4–5 sample sites per type scattered throughout the country (Figs. 3 and 4). The landform elements of plains show a well distinguishable pattern, even though the effect of surface objects and remaining errors of the SRTM1 are visible. Due to the small range of altitudes occurring in the country, the long-lasting denudation and the relatively minor effects of neotectonics on the landscape the landform pattern of the hilly and mountainous environments show a high degree of similarity. The hills are made up of Tertiary molasse sediments and the lower regions of the mountains are also covered by loess or sand layers, thus the valleys and ridges are frequently smooth with gentle slopes (Csillag, Sebe 2015). Characteristic N-S, NW-SE oriented valleys appear in the Transdanubian Hills, the western parts of the Great Hungarian Plain and the eastern region of the West Hungarian Borderland. Even though the general wind directions in Transdanubia coincide with these wide, meridional valleys dissecting the alluvial plains, it was proven that they have complex erosion-deflation origin (Sebe 2011; Pécsi 1996).

To successfully discriminate geomorphic landscapes of hills and mountains it was unavoidable to calculate auxiliary morphometric parameters and reclassify the original map of landform elements. The TPI (Weiss 2001) was used to separate flat regions of top surfaces or bottom of wide valleys. By calculating the mean elevation of summits, it was possible to distinguish between peaks of mountain ridges (above 400 m), outlier values on plains (below 100 m) and top surfaces in hilly regions (between 100–400 m).

As an intermediate step, we averaged the similarity maps of the 3 main landscape types to visualise the spatial distribution of likelihood values (Fig. 5). The hilly and mountainous regions are clearly distinguishing from the plains. In the TDR and NHR it can be observed, that the group of cells possibly belonging to mountains are surrounded by regions more similar to the hilly category. On the southern part of Transdanubia, in case of the Mecsek Mountains and Tolna-Baranya Hills it is more difficult to separate these types. The likelihood map of plains hold unexpected cell values, but according to the authors it can be explained by the principles of the mapping technique (Jasiewicz et al. 2014). Flat landscapes show relatively smaller values of similarity, which is particularly evident on the south-eastern parts of Hungary, which can be considered as a perfect plain between the Tisza, Körös and Maros rivers.

The resulting map (Fig. 6) was created by assigning every cell the category of the highest likelihood value. Visually comparing the map to the maps available in literature we can conclude that the information content hold by ~1 km cells corresponds well to the traditional maps. Within the limits of DSM resolution, the generated map gives a semi-automatic interpretation of the main landscape types on a lower level of generalization than other published maps. The biggest advantage of the result is that it is already available in GIS system, hence we

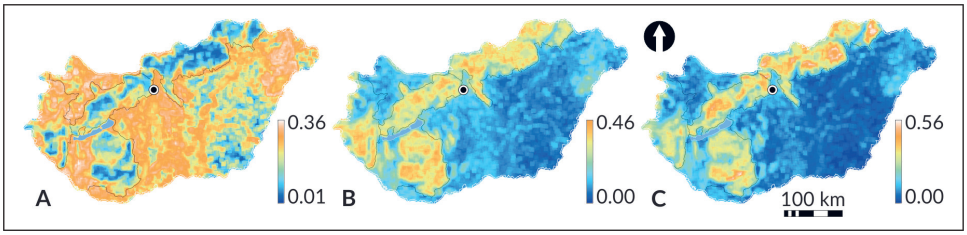

Fig. 5. Spatial distribution of likelihood values of main geomorphic landscape types. [A = similarity map of plains; B = similarity map of hills; C = similarity maps of mountains] (Edited by: E. Józsa)

have information about every km^2 area of Hungary and we can conduct further studies. Using overlay operations, the presence of certain boundaries can be explored by calculating auxiliary morphometric parameters (e.g. slope, relative relief) or visually assessing the topography on shaded relief maps.

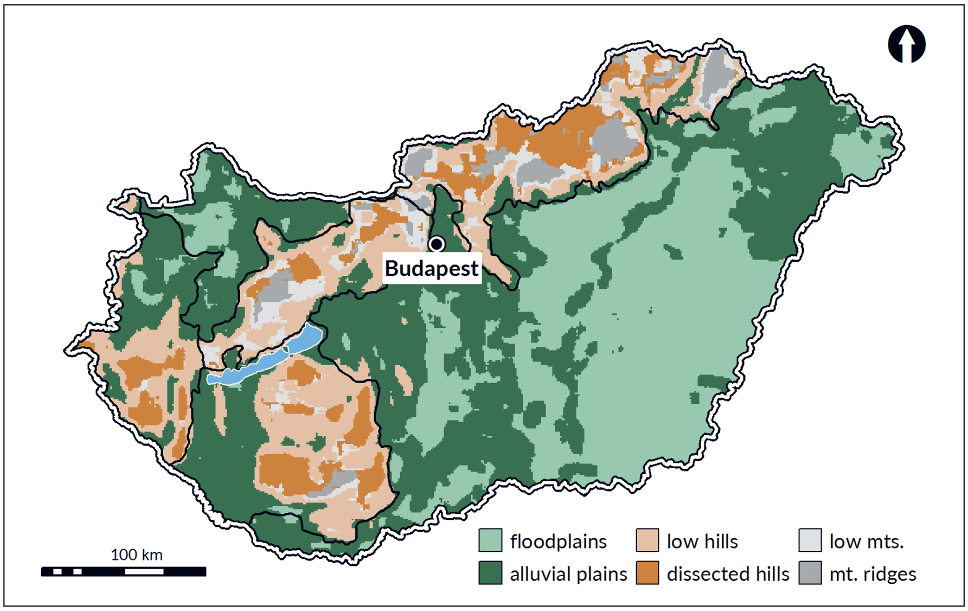

Fig. 6. Algorithm-delineated geomorphic landscapes. (Edited by: E. Józsa)

Table 2

Distribution of macroregions and results of validation. (Colours represent the main geomorphic landscape types from Fig. 4)

	rate	*matching micro-regions/all*	*characteristics of landscape types*
GHP	55.1%	55.5/70	unclear expert categories missing units of alluvial plains
LHP	5.8%	9/12	floodplains underestimated alluvial plains correct location
WHB	7.9%	17/25	mapped units better represent complexity floodplains misinterpreted
TDH	12.3%	16.5/25	expert map generalized reinterpretation
TDR	7.0%	22/47	mostly correct boundaries categories vary
NHR	11.9%	37.5/68	mapped categories represent relief types well

QUALITY ASSESSMENT

After the visual comparison, we expected a strong similarity between the maps, which was confirmed by the statistical analyses. The most evident way to compare the reference map (Fig. 1) and the result of our geomorphic landscape mapping algorithm (Fig. 6) was to calculate the proportion of the main landscape categories. On the reference map 69.7% of the microregions belong to plains, 24.0% to hills and 6.3% to low mountains. In case of the raster dataset 70.9% of the cells were categorized as plains, 22.2% as hills and 6.9% as low mountains.

A more complex part of the quality assessment was the fuzzy category comparison on the basis of the microregions (Fig. 1). In every macroregion we checked how many of the microregions were categorized correctly to the most dominant geomorphic landscape type, which meant the category represented by the majority of cells in the given area. The comparison was carried out in a sense of fuzzy logic, because we gave half scores in cases when at least the main landscape type was correctly identified. The best match was detected on the Hungarian plains, while relatively low number of microregions was appropriately categorized in the mountain ranges.

Analysing the spatial distribution of geomorphic landscape types and the location and accuracy of unit boundaries we evaluated the results and the reference map as well. Most of the differences between the datasets were expected. Distinguishing floodplains and alluvial plains based on a landform map that shows unreal features over wooded floodplains (e.g. Gemenc floodplain forest on the right bank of the Danube's southern course) even with the supervised classification technology. The topographic similarity of hilly and mountainous environments was already expressed by the authors and the quality assessment also proved the observations. On the other hand, we found that as a result of generalization the extent and spatial arrangement of the landscape types on the reference map are not representing well the real topography in every region. However, as our results were obtained using an elevation dataset containing erroneous height values, we can't apply our results automatically without further verification to modify the questionable areas on the traditional relief type or geomorphic region maps.

CONCLUSIONS

The scientific results of the presented work are twofold: one aspect is that we managed to create an objective and quantifiable map of landforms and geomorphic landscapes of Hungary, while on the other hand we successfully applied the available methods and evaluated the applicability of the SRTM1 model for geomorphological purposes. Revealing the potentials of using the topographic grain value as a new approach to objectively select the search parameter for the delineation of landform elements is our contribution to the methodology.

Even though the GIS-based approach is not producing geomorphological maps in the traditional sense, where a multi-colour map contains information about the topography, genesis and geology of the region, we consider our results an important step towards the creation of flexible scale digital geomorphological maps. The outputs of the quality assessment and the visual assessment carried out by experienced geomorphologists confirm the applicability of the landform and landscape maps as well. In the case of Hungary, we determined that in overall the differences between the expert-based reference maps and the algorithm-based geomorphic landscape map are minor, and their explanation lies in the fact that the latter was created explicitly on the basis of elevation data and spatial pattern of landforms, omitting auxiliary geological information. Additionally, we once again want to highlight, that the error propagation from height dataset narrow the range of further applications of the maps and that the results must be interpreted with considering the horizontal and vertical resolution and accuracy of SRTM1.

We can confirm the advantages listed by the developers of the presented methodology (Jasiewicz, Stepinski 2013; Jasiewicz et al. 2014). The algorithm sets the framework for the generation of objective and comparable maps – still allowing the user to tune the results for specific applications. We would like to express that our approach to set the Topographic Grain as search parameter enabled the production of a landform map fitting the various topography of the country, while keeping the computational cost low and avoiding trial-and-error method. The reclassification of the landform map based on the auxiliary morphometric parameters also an improvement of our approach.

Despite of the errors related to the height dataset we conclude that the generated landform and landscape maps are useful to review expert-based geomorphological and relief type maps. Furthermore, the current results confirm that the SRTM1 satellite-based DSM is a fairly good base dataset even for complex geomorphometric analysis. However, we have to take into consideration that the model is loaded with local outliers and erroneous values of surface objects and vegetation, which are only reduced but not completely eliminated after pre-processing. The SRTM1 dataset provides the possibility to the spatial extension of the analysis, thus as a future research we consider to generate the landform and landscape map of the total Carpathian Basin, as the physical geographical units continue over our borders.

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