Physically-based segmentation of the Western Carpathians (Central Europe)

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Abstract— **Results of a physically-based methodology to delineate morphometrical-morphostructural subdivision of the Western Carpathian region (Central Europe) from DEMs and their derivatives are presented. Previous suitability evaluation of an object-oriented methodology showed its potential in recognition of morphostructural features. In this study we moved towards a more complex object-oriented approach – fusion of segmentation and classification on several hierarchical levels. In addition, physically-based geomorphometric variables were used as input data, resulting in enhancement of subsequent morphotectonic interpretations. Decrease of local variance of the delineated objects in comparison with simple segmentations without these upgrades confirms the efficiency of our approach.**

I. Introduction

Physically-based land surface segmentation is basically characterized by using physically interpretable input variables. However, the applied method should also reflect a concept of mapped landforms (regions), including their scale dependence, variable spatial structures and influence of a natural attractor (e.g. steady state) on their formation. This and more theoretical background is outlined in the specific contribution [1].

Here we present a technique of application of physically-based segmentation using object-based image analysis (OBIA) for the morphostructural segmentation of the Western Carpathians. Since the first application of OBIA in geomorphometry and geomorphology in 2006 [2, 3] its usage for landform mapping has been increasing. However, most studies focused on rather detailed scales, e.g. individual exogenous landforms [4], and resulted in morphographic or morphogenetic classifications. This work is aimed rather at delineation of larger objects at regional scale primarily formed by endogenous geomorphic processes, emphasizing their physical-geomorphic definition and interpretation.

Morphostructural subdivision of mountain systems is important for several reasons; mainly as a basis for various subsequent geological, geomorphological and geoecological analyses. With a long tradition, the geomorphological research of the Western Carpathians has produced a whole set of geomorphological divisions, which can be compared with semi-automated results. The location of the Western Carpathians with boundary after [5], complemented with the traditional geomorphological regions, is displayed in Fig. 1.

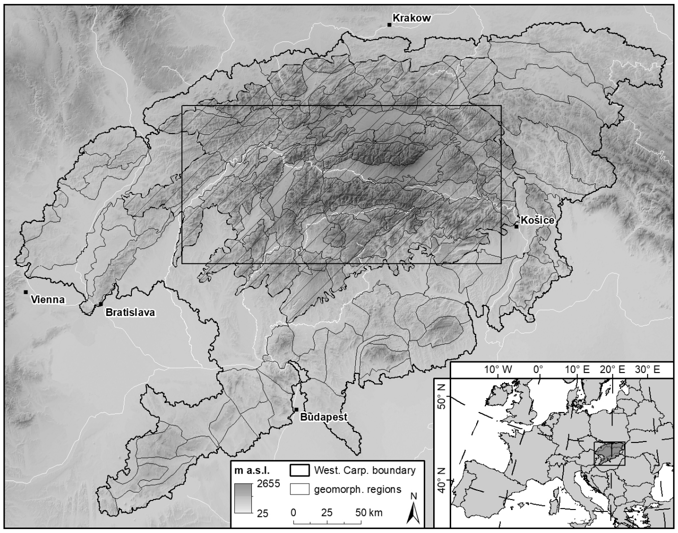

Figure 1. Location of the Western Carpathians, rectangular extent of the central test area and geomorphological regions (hatched polygons belong to its eccentric core area) as compiled by [5].

Our initial evaluation of OBIA for delineation of morphostructural features proved to be efficient [6], though with limitations caused by fixed segmentation scale applied globally on the highly contrasting terrain (i.e. over- and under-segmentation of various parts of the area). [7] and [8] addressed these issues by partitioning DEM into more homogeneous domains, combined with the nested means approach [9] and structured into three hierarchical levels. We adapted these

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principles in combination with selecting and setting apart distinct individuals that tend to influence the level of overall homogeneity in segmentation. Moreover, as improvement of [6] we consistently applied the theoretical principles of physically-based land surface segmentation [1], which consists in use of physically-modified input data. This should make the subsequent morphotectonic interpretations more straightforward.

II. Data and Methods

A. Computation of input data and their pre-processing

A part of the SRTM V4 dataset [10] at sufficient rectangular extent to cover our study area and its neighbourhood was employed as input DEM. A geological map of the study area [11] was used as a spatial basis for representation of the rock density (compiled on the basis of available regional geophysical research works) needed in the calculation of the layers. Therefore, physical component of the layers consists of the rock density (σ) and gravity acceleration (g).

The Focal Statistics tool in the Spatial Analyst Extension in ArcGIS 10.4 (ESRI) was used to compute geomorphometric components of the layers – maximum, mean, and range of elevation. The diameter of the circular moving window was set to the mean topographic grain computed with a size-changing window for the central part of the area (depicted in Fig. 1), i.e. 1800 m [12]. The r.stream module in GRASS GIS [13] was used to derive a morphologically-based stream network (r.stream.extract) according to the procedure in [14] and downstream distance to it (r.stream.distance). To generalise it to the scale of other layers, mean distance to stream using the same window size (d = 1800 m) was computed.

Then, three physically-based geomorphometric variables [1] were computed:

- EnW – describing minimum endogenous work expended on tectonic uplift of the unit volume (1 m^3):

$$EnW = \text{maximum elevation} \times \sigma \times g/2 \quad (1)$$

- ExW – minimum exogenous work describing minimum elimination of the EnW by exogenous processes:

$$ExW = (\text{maximum elevation} - \text{mean elevation}) \times \sigma \times g/2 \quad (2)$$

- RBF – unit relief brake force describing gravity force braking a mass point (1 kg) passing the relief:

$$RBF = \text{range of elevation} - (2 \times \text{mean distance to streams}) \times g \quad (3)$$

Prior to the segmentation processing, values of all input layers were normalized to bring them closer to a normal (Gaussian) frequency distribution using the square root function, as well as normalized to range within the interval 0-255 to avoid emphasizing either of them.

These physically-based variables effectively replace pure geomorphometric variables elevation, vertical dissection of terrain and slope gradient used in [6], for more detail see [1].

B. Object-oriented workflow

The Estimation of scale parameter 2 tool (ESP 2) [15] was used for delineation of objects of interest (morphometrical-morphostructural individuals) as automated iterative replacement of original multiresolution segmentation (MRS) algorithm in the eCognition® Developer software [16]. Optimisation of the iterative segmentation scale was therefore defined not through Scale parameter (SP), but its step size (value of increment of SP increase in the ESP2). The tool is based on the concept of Local variance; for more technical and theoretical details of the concept as well as MRS reader is referred to [15].

Values of shape and compactness parameters in the MRS were set to 0.5 and 0.7, respectively. Contrary to the previous work [6] the values were adjusted based on the testing to ensure production of more compact objects, similar to tectonic blocks in shape and properties.

Two classification techniques were employed: classification on two separate domains based on the median elevation and feature describing object´s mean difference (MD) to its neighbours in elevation, i.e. relative height [5]. Threshold for selecting and setting apart distinct individuals was implemented as standard deviation (SD) of MD in both directions from the mean value.

Our approach included the following processing:

1. Segmentations with various fixed step sizes (100 ≈ super-regional scale, 10 ≈ regional scale, the values selected as determinants of different orders of objects magnitude) in combination with definition of High and Low domain based on median elevation of objects.

2. Selection of distinct individuals using the condition of > 2SDs from the mean value of MD.

Altogether, three segmentations (with step sizes 1 × 100 and 2 × 10), two differentiations of objects into domains, and one selection and removal of individuals, were used. The final object level was improved by removal (re-segmentation with step size 10 and merging with neighbours based on shape) of two wrongly delineated (elongated) objects located at the foothills. These objects were selected using discriminant condition – Density parameter in eCognition with threshold < 4SDs (0.8652) from the mean value (2.058) to the negative side. The workflow of this approach is detailed in Fig. 2.

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Compatibility of the Level 3 with the geomorphological regions (Fig. 2) was computed based on the overlay of both boundaries via a series of buffer zones, and quantitative measures suggested by [17] were used; for formulas and more technical details reader is referred also to [6].

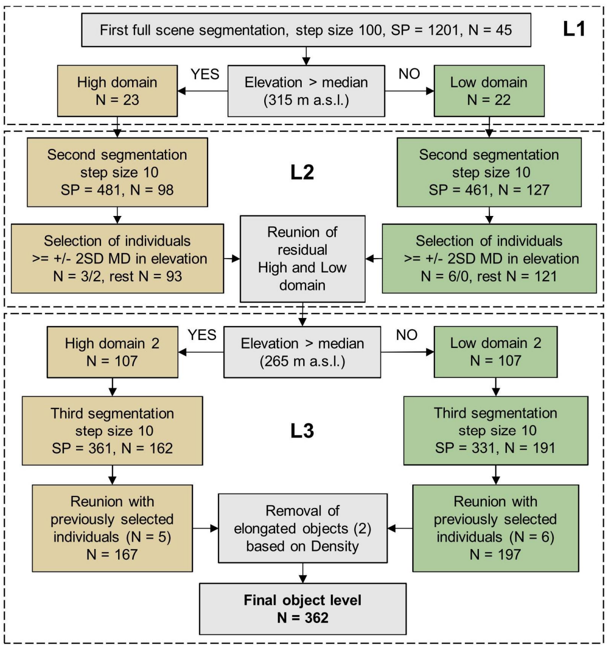

Figure 2. Detailed workflows of our object-oriented approach. L – Level, SP – Scale parameter, N – Number of objects, MD – Mean difference.

III. Results and discussion

Overall, four hierarchically-structured object levels were created in the top-down manner. Only three of them are displayed in Fig. 3. The number of objects systematically increases from Level 1 to Level 3. The object Level 1 with 45 objects represents basic super-regional features, Level 2 with 225 objects represents basic regional features, and in Level 3 with 363 objects, additional regional features were delineated and some of the previous were re-shaped. Since Level 3 still shows signs of under-segmentation, continuation of the process was tested. Repeated processing (selection of individuals, reclassification of the remaining objects into new domains and separated segmentations) resulted in potential object Level 4 with 254 objects. However, the segmentation scale increased and thus undesirable under-segmentation and generalization in less-rugged terrain was present. This could indicate that all regional features that should be represented by the step size 10 have been consumed and step size should be lowered to recognise even sub-regional features.

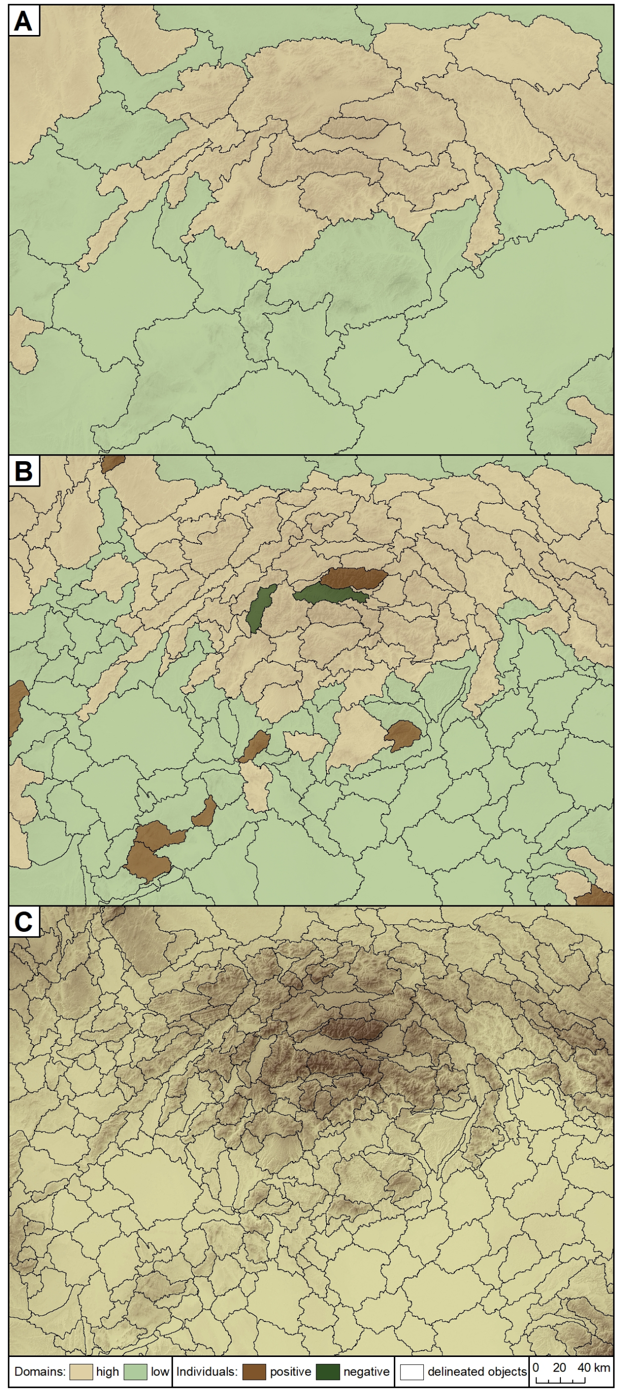

Figure 3. Results of the suggested object-oriented approach. Level 1 – segmentation and classification into domains (A), Level 2 – segmentation and classification into distinct individuals and reclassification into new domains (B) and the final Level 3 after removal of elongated objects (C).

Therefore, the Level 3 is considered as the final one in this approach, containing 364 objects after re-shaping selected objects. Nevertheless, the approach produced generally well-delineated objects with good visual compatibility against the traditional geomorphological regions: basic differentiation between mountains and intramontane basins is clearly intercepted, with higher success in more contrast areas. The results clearly benefitted from the division of the full scene into domains for separated segmentations. The compatibility of the delineated objects against the traditional regions (Quality measure) is ca. 50 % for the whole and ca. 60 % for the eccentric core part of the study area in the buffer of 2000 meters. Although the numbers are not very high, our goal was not to fully recreate them but only to get their general perception.

Due to its simplicity and minimal requirements for users´ interventions, this approach could be easily adapted to other areas. Another approach, targeting to objectively determine the most suitable segmentation step size adapted to various terrain properties, is currently under development but due to the limited space these results are not shown here.

To demonstrate improvements given by the developed approach, simple MRS was targeted to produce equivalent of our Level 3 with the same number of objects, using SP of 351. The value of local variance within the full scene, describing inner variability of input layers in the objects, decreased by 2.5 % (12.2 vs. 11.9). In comparison to the same simple MRS on the basis of former input layers [6], local variance decreased by 25.9 % (16.05 vs. 11.9), out of which 9.4 % can be explained by different SD values of the input layers.

IV. Conclusions

According to the results, use of complex object-oriented approach consisting of several segmentations and partitioning the scene into domains combined with removal of significant individuals enabled us to delineate basic morphostructural features in our study area, which vary in shape and properties and increase mean internal homogeneity of objects. Since the final object Level 3 resulted from three segmentations, it integrates these levels and reduces over- and under-segmentation of various parts of the area. Convenience of the physically-based input layers as well as complex object-oriented approach is confirmed by the significant decrease in local variance of the objects. Further work will be focused on improving the approach by determination of variable segmentation step size and its combinations with partitioning the scene into separated domains. However, already the results presented here can be used for initial morphotectonic interpretations; see in [1].

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