

Research Article

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Semi-automated recognition of planation surfaces and other flat landforms: a case study from the Aggtelek Karst, Hungary

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Abstract: This study deals with the possibilities of expert-driven semi-automated recognition of planation surfaces and other flat landforms in the area of the Aggtelek Karst, Hungary. Planation surfaces are the most debatable and vague landforms and can be defined as parts of terrain formed by long-lasting erosion-denudation processes under the stagnant erosion base conditions. In terms of denudation chronology they can be considered as morphological indicators of different evolution stages of area. In karst areas planation surfaces and river terraces are mostly correlated with cave levels, which originated in relation to the same stagnant erosion base. Because there is no general method of delineation of planation surfaces, the main objective of the study was to find a suitable method for semi-automated recognition of flat landforms in the Aggtelek Karst, which should correspond to different phases of the Jósza River incision and therefore could be correlated to the multilevel cave system of the study area. Several methods for semi-automated landform classification were tested for recognition of flat surfaces in a relatively objective way. Slope gradient thresholding tool, and *r.param.scale* and *r.geomorphon* modules implemented in GRASS GIS were tested. As a result, the *r.geomorphon* module was proven as the most suitable method for delineation of relatively flat surfaces. Findings of the presented work can be used as a morphological indicator of the comprehensive reconstruction of evolution of the Aggtelek Karst and the Slovak Karst.

Keywords: Flat landform; planation surface; Aggtelek Karst; semi-automated recognition; GRASS GIS

1 Introduction

Planation surfaces [1–11] are one of the most discussed and disputable elements of landscape. They can be defined as a part of the Earth's surface, as a secant surface formed by the long-term activity of erosion-denudation processes under the conditions of stagnant erosion base. In terms of denudation chronology, planation surfaces and river terraces can be considered as morphological indicators of terrain evolution stages. In the karst landscape, they are often correlated with cave levels, synchronously originated in relation to the same stagnant erosion base. It is the assumption of relation between multilevel cave system formed by an underground stream and relatively flat erosion landforms on the surface that has led to the efforts to identify a suitable method for semi-automated recognition of planation surfaces and other flat landforms using geographic information systems (GIS), as a progressively developing tool for spatial data analysis.

Modern geomorphometry is focused on extraction of geomorphometric characteristics and segmentation of terrain into spatial features (e.g. landforms) from DEMs [12]. Landform can be defined as a bounded segment of land surface (terrain) while these segments do not have to be continuous, i.e. they do not need to cover the terrain completely. Geometrical, topological, spatial or any other characteristics of landforms are parts of the specific geomorphometry [13, 14]. According to the literature overview in [15], landform mapping can be based on morphological, genetic, chronologic or dynamic principle. Since geomorphological forms should generally follow morphological boundaries, the morphological principle should be considered as primary [15]. Landform mapping based on terrain morphology, which is applied here, consists of delineating boundaries of individual terrain entities (objects) according to the values of chosen morphometric parameters (in this paper called geomorphometric variables). Extensive overview of the multiple methodological approaches to manual and/or digital landform mapping is presented in [12, 13, 16, 17]. Overall overview of geomor-

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phometrical possibilities including landform mapping in GRASS GIS contains [18].

The presented methodology research is a part of our complex research in the Aggtelek Karst carried out with the aim of reconstruction of the area evolution based on a correlation between planation surfaces and cave levels. The origin of the multilevel Domica-Baradla cave system (longer than 25 km) has been linked with the gradual stages of the Jósua River incision [19–25]. Individual stages of the valley downcutting alternated with stages of erosion base stagnation, which is evidenced by several large pediments in the Jósua River valley. From among the studies dealing with this problematic we can mention [26], which used object based image analysis for semi-automated segmentation of slope gradient DTM for the delineation of planation surfaces. The absence of generally accepted method of planation surface mapping and the efforts to minimize subjective decisions in their manual delineation based on topographic maps has led to the testing of several ways of their recognition. Therefore, the main aim was to find, based on the testing, the most suitable method of semi-automated recognition of planation surfaces as relatively flat landforms in the Aggtelek Karst, which would fit the individual phases of the Jósua River incision and would correlate with the multilevel cave system in the study area.

Since there are several terms for flat landforms and not all of them refer to planation surfaces, we use the term “flat surfaces” for planation surfaces, relatively flat surfaces, as well as for other flat landforms recognized by the tested methods, not considering their genesis. By the term “planation surfaces” we refer only to the surfaces that meet our definition of their genesis mentioned earlier above.

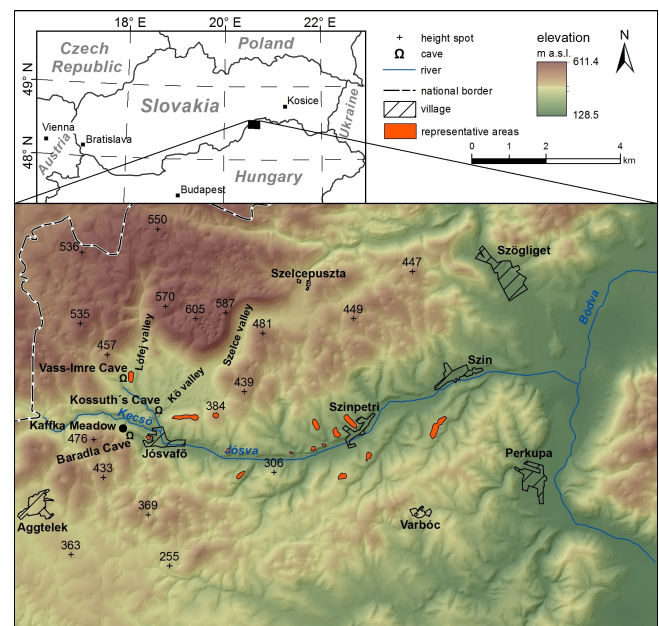
2 Study area

The Aggtelek Karst and the Slovak Karst (Fig. 1) represent a plateau karst of temperate climatic zone in Central Europe (the northern part of Hungary and the southern part of Slovakia) dissected by several canyons and gorges. Many abysses occurring on the top of karst plateaux, several outflow caves at the foot of karst plateaux and inflow caves at the contact of non-karst and karst area originated by sinking allochthonous streams are the result of intensive karstification of this limestone area. The well-known Domica-Baradla cave system and other significant caves have been included in the World Heritage List since 1995. Apart from caves, this area is also significant for its abundance of surface karst landforms (karren, dolines, uvalas, dry valleys,

blind valleys, poljes, and others). The original large upland planation surface (Sarmatian – Pannonian) was tectonically uplifted and inclined from the north to the south as a result of the more intensive uplifting of the Slovenské rudohorie Mts. [5, 27–29]. The Aggtelek Karst and the southern part of the Silica Plateau are tectonically separated from the northern part of the Slovak Karst by the fault line leading from the Plešivec Village through the Silická Brezová Village to the Turnianska Basin [30]. Within the morphostructural subdivision of the Western Carpathians, this lineament represents the border line between the Slovenské rudohorie Subregion and the Southeastern Marginal Subregion [31].

The fieldwork was carried out in the Jósua River valley and its close vicinity, located in the Aggtelek Karst (southeastern marginal part of the Western Carpathians north of the Pannonian Basin; Fig. 1). The valley of the Jósua River begins by a short pocket valley close to the Jósuaő Village and continues to the southeast where it mouths close to the municipality of Szin (Borsod-Abaúj-Zemplén, Hungary). The Jósua River is the right tributary of the Bodva River. Besides the mentioned pocket valley with the resurgence from the Long Lower Cave (200 m a.s.l.), the Jósua River is sourced by the Kecső Brook with tributaries from the Kossuth-Barlang Cave (218 m a.s.l.) and the Tohonya valley. The valley bottom reaches the elevation of 210 m a.s.l. at the Jósuaő Village, and of 150 m a.s.l. at the confluence with the Bodva River. Northeast of the Jós-

Figure 1: Location of the study area, Aggtelek Karst, Hungary.



vafő Village at the elevation of 275 – 325 m a.s.l., an extensive paleopolje is situated, closed by steep slopes (20 – 48°). The wide Szelce Valley mouths into it from northeast, and a significant fault line of northeastern direction runs through it. The plateaux northwest of the fault line are situated at the elevation of 400 – 600 m a.s.l., those southeast of the line are at the elevation of 300 – 450 m a.s.l. The Jósza River valley is bounded by distinctive pediments at the elevation of 250 – 280 m a.s.l., which correlate with the oldest outflow part of the Baradla Cave (275 m a.s.l.) [24].

The area north and east of the Jósza Village is built by two partial structures (klippes) of Silica Nappe [29, 32]. The reverse fault between them runs along the Jósza River valley, which partially appears as a dextral strike-slip fault. The Jósza River valley is built by less resistant Lower Triassic limestone and marly shale, which predetermined its formation. The limestone and marly shale of the Szin Formation are overlain by Middle Triassic Gutenstein limestone occurring in narrow belts, mostly in the close surroundings of the Jósza Village, and by Middle Triassic Wetterstein limestone and dolomite north of Jósza [33].

3 Theoretical and methodological background

In morphographic typology, planation surface can be identified with a relative plain or relatively flat landform that is not structurally conditioned. In common geographical practice, plain as a basic terrain type is understood and defined in terms of [34] and [35] on the basis of vertical segmentation of the terrain as an area with relative vertical difference (vertical dissection) up to 30 m. In this study relative plains are not divided into planation and structurally conditioned ones; we understand them uniformly as relatively flat surfaces that can be recognized by some of the tools implemented in GIS.

Creation of the digital elevation model (DEM) was a precondition of the semi-automated flat surface recognition. It was based on the data in the form of contour lines with the interval of 5 m (EOTR EOVD-1972, 1:10 000) provided by the National Park Aggtelek (Aggteleki Nemzeti Park). The DEM with the spatial resolution of 5 m was interpolated using Topo to raster algorithm implemented in ESRI ArcGIS software.

In order to gain an objective insight into planation surfaces and the accuracy of individual methods of their recognition, field mapping was realized in 2014. The aim was to delineate and digitize representative relatively flat surfaces on the basis of topographic maps of 1:10 000 scale

and their statistical evaluation by the tools of ESRI ArcGIS 10. The quantification was mostly focused on calculation of average diameter derived from average polygon area (m²), calculation of average slope gradient to the area unit of representative areas and calculation of average cross sectional curvature. These manually digitized areas are depicted in Fig. 1 and the used statistical values are in Tab. 1.

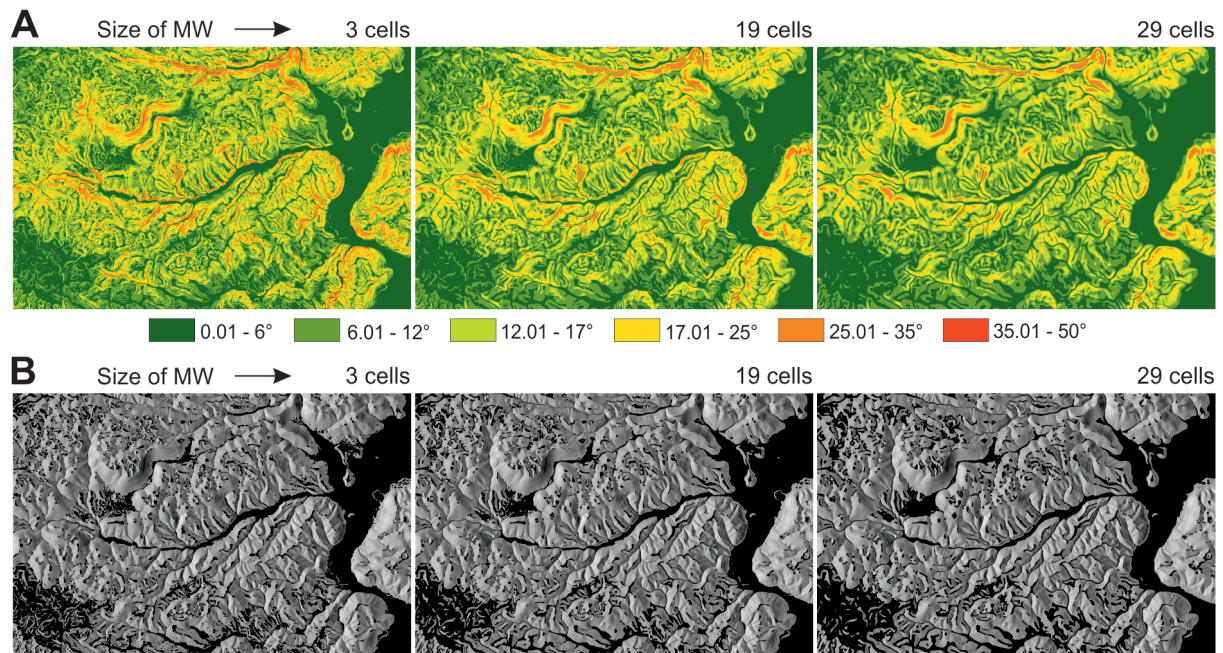
Table 1: Quantification of representative flat surfaces based on the field mapping.

Polygon	Area (m ²)	Slope (°)	Cross curvature
1	64850	3.51	0.0008
2	8300	7.33	0.0017
3	9575	8.58	0.0031
4	23125	4.10	0.0001
5	35800	5.56	0.0010
6	54875	5.14	0.0007
7	34700	3.33	0.0002
8	5550	10.28	0.0028
9	11075	2.00	0.0008
10	3425	8.10	0.0031
11	21450	3.85	0.0004
12	90675	4.01	0.0003
13	15550	5.51	0.0008
14	36275	3.70	0.0002
15	28375	4.13	0.0010
Mean	29573	5.27	0.0011
Average diameter 97.02			

3.1 Methods of semi-automated flat surface recognition

Three methods were tested for the semi-automated classification of landforms, in this case specifically of flat surfaces, based on DEM. According to [16] there are two categories of approaches to semi-automated classification. Methods in the first category [36, 37] classify terrain according to different geometries of individual forms. Semi-automated mapping is based on the different values of local geomorphometric variables – first and second derivatives of elevation [38, 39]. The second category contains new and progressive approach [16] of terrain classification based on its overall topographic pattern. It uses computer vision, which replaces the traditional visual classification of terrain, e.g. by expert processing of a topo-

Figure 2: Flat surfaces recognized with threshold values of slope gradient within interval from 0° to 6° . Slope gradient rasters (A) and their reclassified equivalents (B), MW = moving window.



graphic map. The approaches applied here, *i.e.* setting of slope threshold value (slope gradient thresholding), the module `r.param.scale` and the module `r.geomorphon`, their concept and application are outlined in the following text. It is also important to mention that for successful application of semi-automated methods it is crucial to use values obtained directly during field mapping.

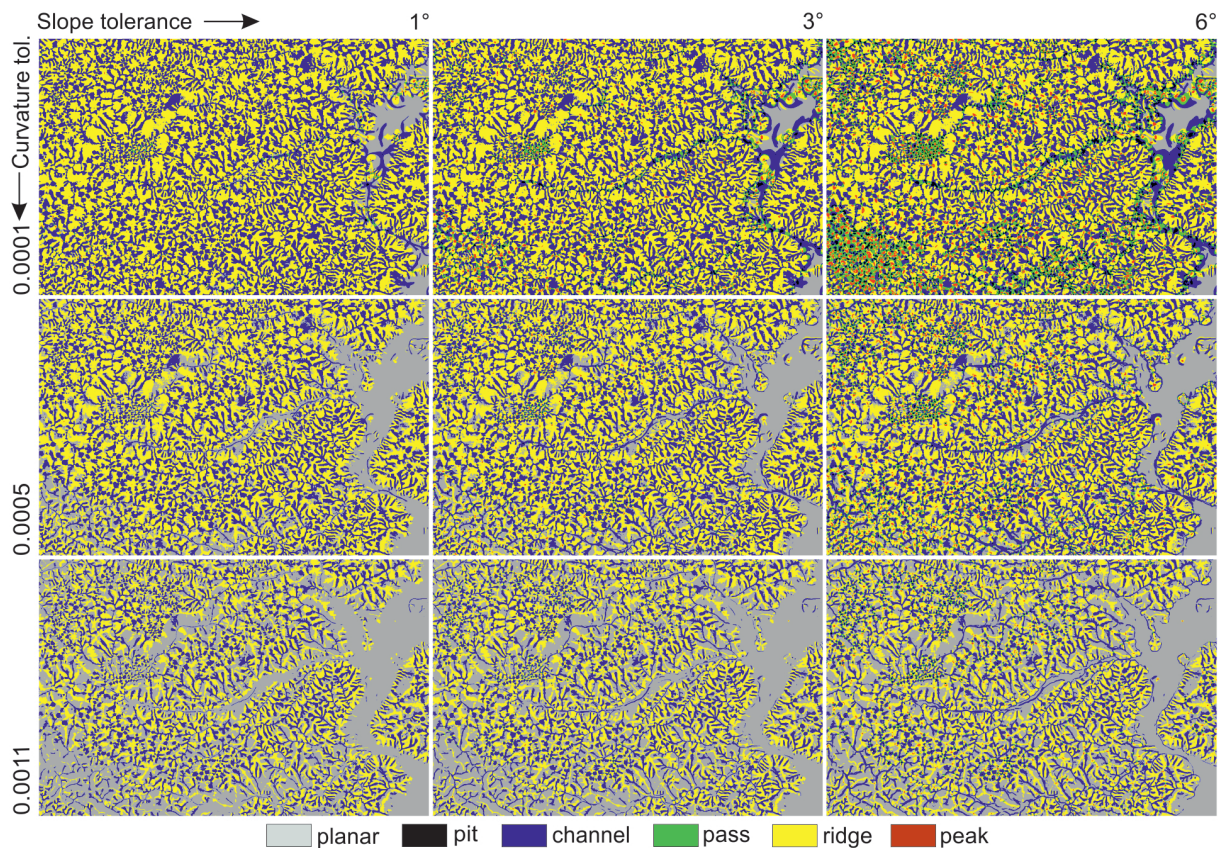
3.1.1 Slope gradient thresholding

Slope gradient of terrain can be considered as a basic criterion to define a relatively flat surface. The `r.param.scale` module implemented in GRASS GIS was used for its derivation from DEM. This module enables multi-scale analysis of fundamental local geomorphometric variables (*e.g.* slope gradient, curvatures) based on the multi-scale concept by [36]. This multi-scale analysis provides the possibility to set various sizes of a moving window, in which the calculation is performed (*e.g.* size of 5×5 , 7×7 , 11×11 cells, *etc.*) and thus removes disadvantages of default 3×3 window size most often used in such calculations. This approach enables derivation of variables based on larger surroundings of a focused cell in DEM (and thus reflecting influence of wider surroundings, not only of adjacent cells). Several sizes of moving window were tested for slope gradient raster computation – basic size of 3×3 cells, and 15×15 , 19×19 , and 29×29 cells as equivalents to 80,

100, and 150 meters to maintain compatibility with further analyses. Based on a hypothesis that planation surface can be defined as an area with relatively low slope gradient, we considered value of 6° as a threshold for relatively flat surface delineation. Although the settings of threshold of slope gradient values when terrain is considered as relatively flat is subjective, here it is based on the synthesis of visual evaluation of slope gradient raster and conditions observed during the field mapping. Slope gradient rasters resulting from calculations with different sizes of a moving window and relatively flat surfaces recognized by subsequent slope gradient thresholding can be seen in Fig. 2. In the figure results for only three window sizes are shown; due to great similarity of results for 15×15 and 19×19 window size, only results for 19×19 window size are shown.

3.1.2 Module `r.param.scale`

In addition to multi-scale computation of basic geomorphometric variables, the `r.param.scale` module also offers calculation and classification of six basic landforms, entitled as morphometric features. One of them is a feature called “planar”, which can be perceived as an equivalent to relatively flat terrain, and therefore could be associated with planation surfaces here. There are three input parameters that control behaviour of the feature computation: slope tolerance, which defines flat surface, curvature tol-

Figure 3: Landforms classified by the module *r.param.scale* with various settings of slope and curvature tolerance.

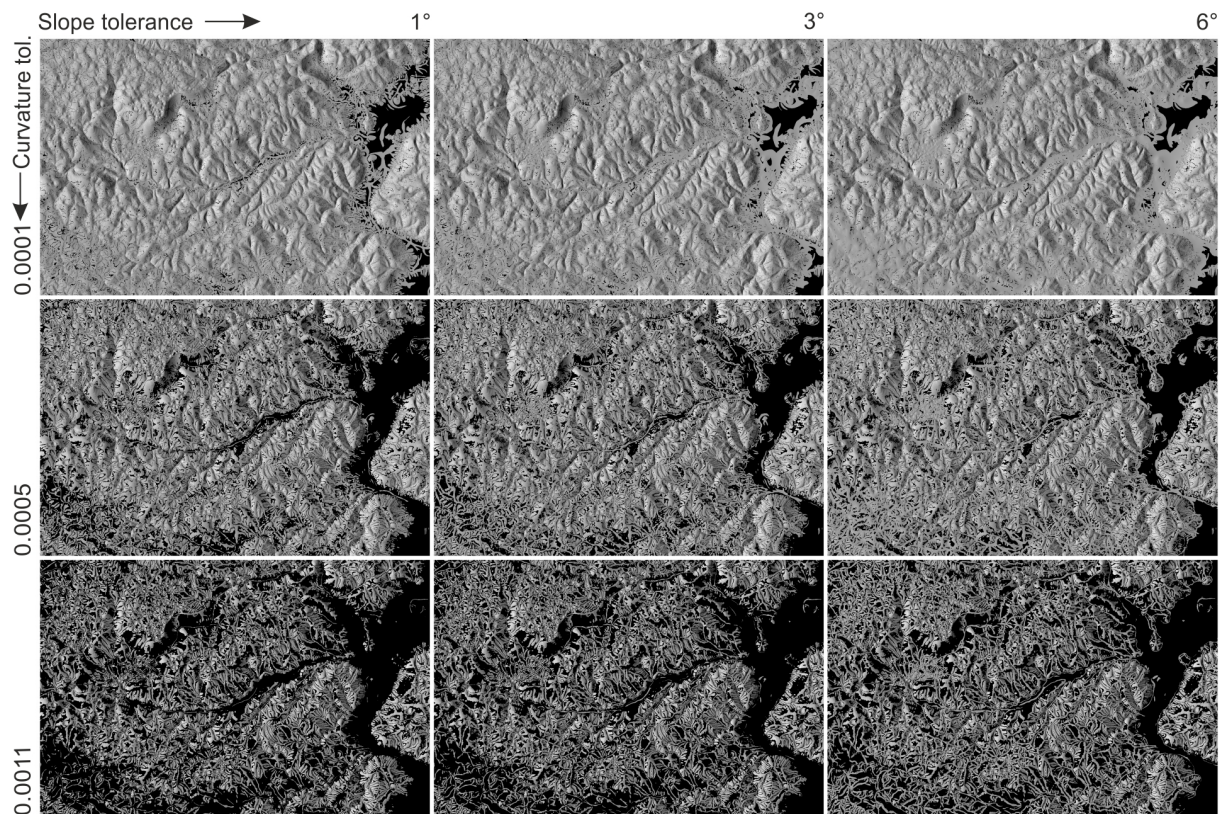
erance, which defines planar surface, and processing window, which refers to the size of a moving window [40]. For testing three values of slope tolerance (1°, 3° and 6°), four values of curvature tolerance (0.0001, 0.0005, 0.0011 and 0.0020) and four sizes of the moving window additional to the default one (5 × 5, 15 × 15, 19 × 19 and 29 × 29 cells) were selected (Fig. 3). Resulting rasters of relatively flat surfaces (in the module identified as “planar” features) are shown in Fig. 4. Due to limited extent and usefulness, only selected results are shown in the figures. Effect of different settings of input parameters is described in the section Results.

3.1.3 Module *r.geomorphon*

Geomorphons – geomorphologic phonotypes represent a new and, compared to *r.param.scale*, completely different approach to semi-automated classification of terrain. It was developed by [16] and is implemented in GRASS GIS as the module *r.geomorphon*. The calculation principle is based on the use of the concept of local ternary patterns for identification of terrain elements, only in DEM.

The method is based on a comparison of focus pixel value with values of surrounding pixels in eight principal directions (the algorithm compares whether the neighbouring pixels are higher, lower or the same, and the value is given by the value of zenith and nadir angle of view from the focus pixel). Classification of forms depends on values of two main parameters. Parameter *L* represents the maximum size of a search window in which the form will be identified, and parameter *t* represents the tolerance of slope values in which terrain is considered relatively flat. The result is a classification of landforms reflecting various mapping scales and is visualized by so-called geomorphic map. It is an interpreted DEM that includes all possible values of geomorphons (498) generalized into ten most frequent landforms. We recommend to the reader the publication [16] if interested in more details of the calculation principle. The precondition of successful and effective use of the method is calibration of the above mentioned input parameters based on study area. The crucial parameter is the *L* parameter, which defines the maximum size of the form to be identified, thus the value depends on study area and user preferences. Based on the field mapping, we set the following parameter values in the testing: *L* = 80, 100

Figure 4: Comparison of the flat landforms recognized by the module `r.param.scale` with various settings of slope and curvature tolerance.



and 150 m; $t = 4, 6$, and 8° (Fig. 5). Rasters of relatively flat surfaces were obtained by reclassification of the created rasters (Fig. 6). Effect of different settings of input parameters is described in the section Results.

3.2 Categorization of flat surfaces

Categorization of DEM values representing relatively flat surfaces was an essential precondition of their comparison and correlation with cave levels. Expert estimate of representative elevation intervals obtained at the field mapping was compared to the analysis of a hypsographic (clino-graphic) curve. Shape of hypsographic curve reflects the frequency of elevation categories and thus frequency of flat surfaces in elevation intervals. The parts of the curve with low slope represent less frequent categories and, *vice versa*, the parts with high slope represent more frequent categories. The hypsographic curve was constructed from a DEM of flat surfaces reclassified into elevation classes with a range of 5 m (96 classes) and converted into polygons with an attribute containing its area (m^2). These polygons were then used for construction of the curve. Boundaries of the categories of flat surfaces were determined ac-

cording to the elevation change and slope and curvature of the hypsographic curve. Slope of the curve was calculated based on the formula 1:

$$\text{slope} = \tan \left(\frac{z_y}{z_x} \right) \quad (1)$$

where:

slope – slope of a curve

z_y – change of value in y-axis direction

z_x – change of value in x-axis direction

Thus for a hypsographic curve defined by its points, change of value in x-axis direction in point A is equal to the difference between the value of point A and the value of the preceding point. Change of value in y-axis direction in point B is equal to the difference between the value of point B and the value of the preceding point. Curvature of the hypsographic curve was calculated according to the equation 2:

$$k = \frac{y''}{(1 + (y')^2)^{\frac{3}{2}}} \quad (2)$$

where:

k – curvature of a curve

y' – first directional derivative

y'' – second directional derivative

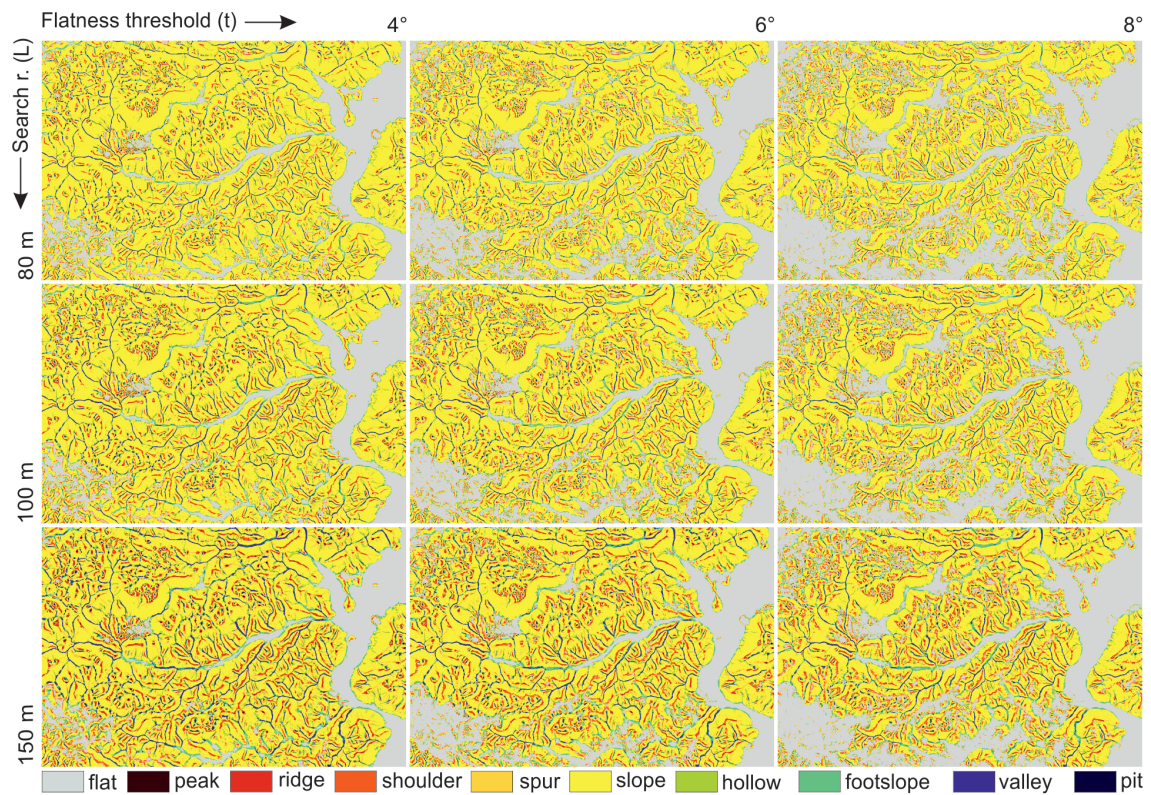
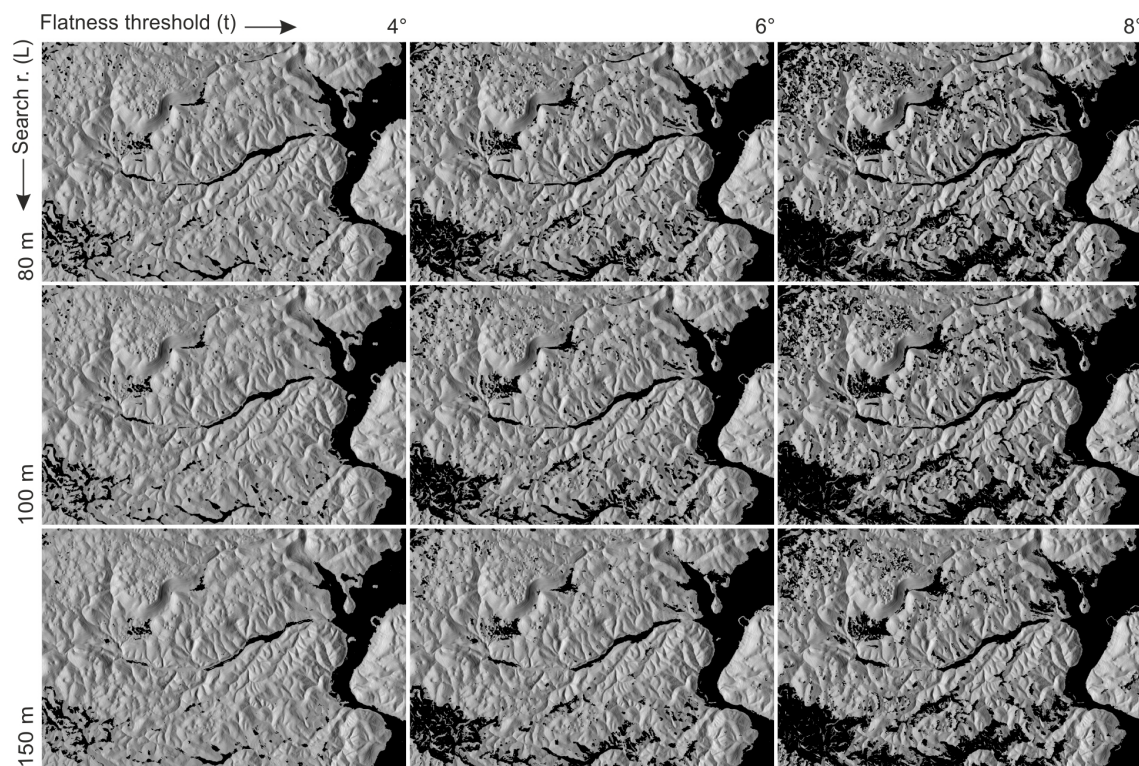
Figure 5: Landforms classified by the module *r.geomorphon* with various settings of both parameters *L* and *t*.**Figure 6:** Comparison of the flat landforms recognized by the module *r.geomorphon* with various settings of both parameters *L* and *t*.

Figure 7: Diagram of directional derivative calculation on a hypso-graphic curve defined by its points.

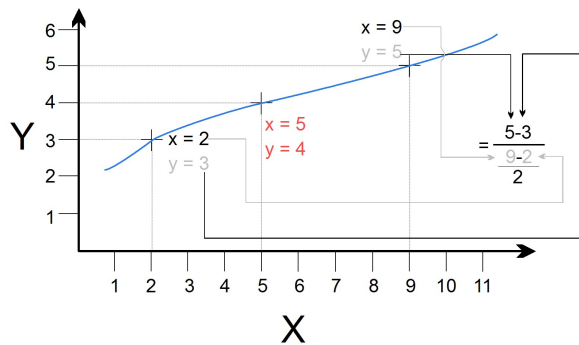
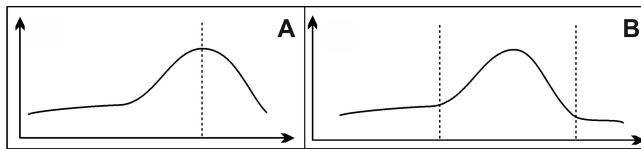


Figure 8: Two options of defining boundaries from curves of param-eters derived from a hypso-graphic curve. A. – boundary placed in the point of local extreme, B. – boundary placed at the beginning and end of significant deviation from trend.



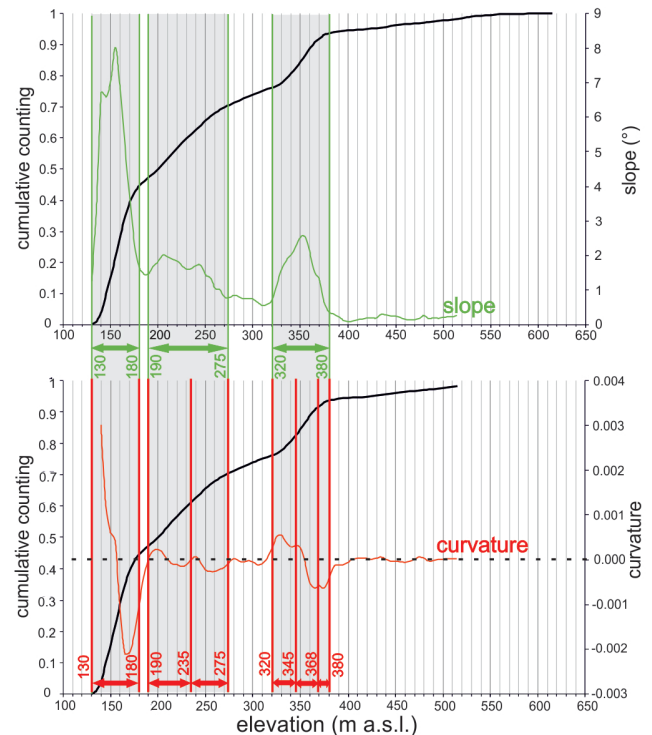
Directional derivatives were estimated according to the Lagrange's mean value theorem. The value of the direc-tional derivative in point A is given by a quotient of differ-ence between values of the following and preceding point and of a half of the distance between these points (Fig. 7). Category boundaries can be subsequently determined by two approaches. The first approach considers the bound-aries to be the local extreme values of the derived param-eters. The second one considers the boundaries to be the starting and ending point of a significant value deviation from trend (Fig. 8).

4 Results

Average values of slope gradient ($0^\circ - 6^\circ$), of cross sectional curvature (0.0011) and of radius of ideal circular surface (100 m) representing planation surfaces collected in the field (Tab. 1) were adapted into the settings of the applied methods. The results were compared across the tested methods as well as within each method comparing the various settings of input parameters. That helped us assess the accuracy of the obtained settings in comparison with randomly selected values.

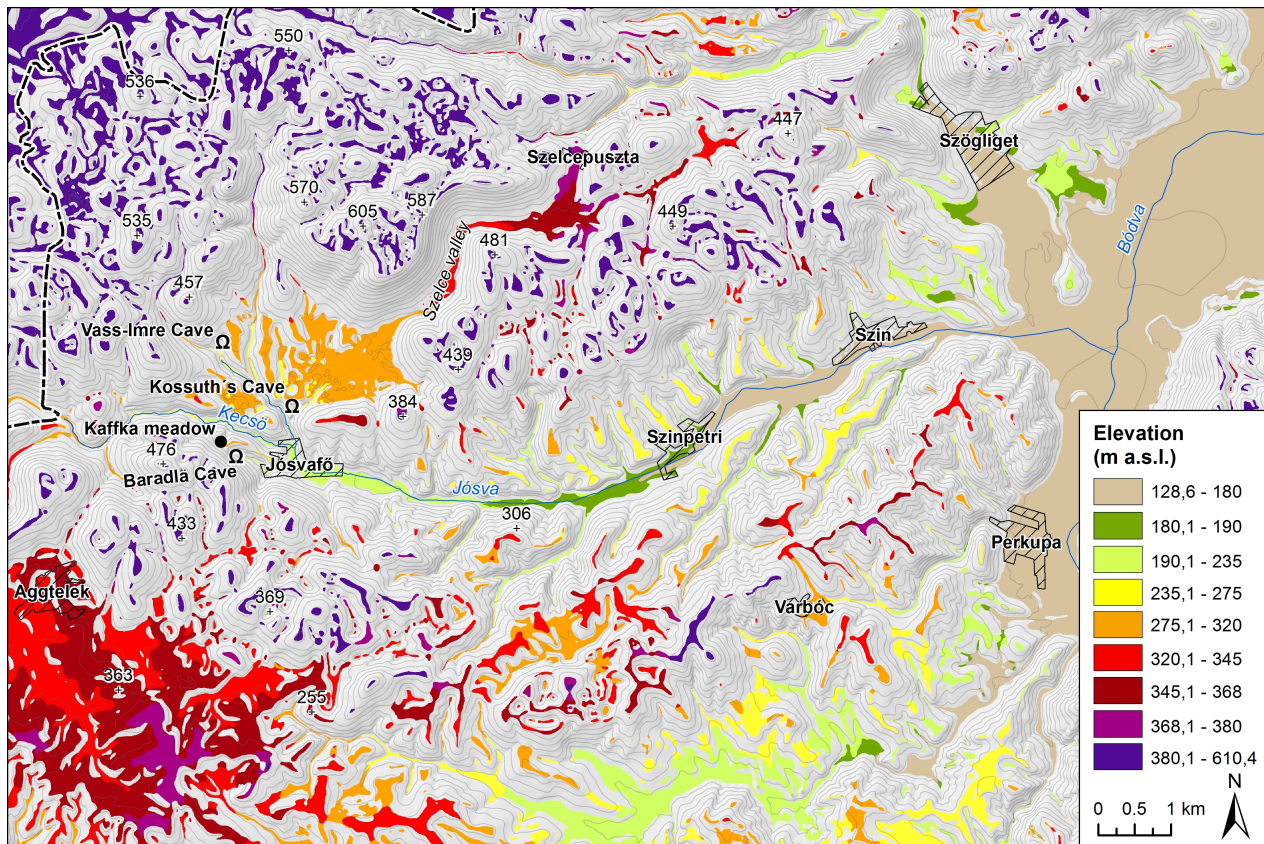
Calculation of the slope gradient rasters using the *r.param.scale* module allowed us to use several sizes of

Figure 9: The boundaries of elevation classes categorized according to slope and curvature of the hypso-graphic curve.



the moving window. Relatively flat areas extracted from the slope gradient raster calculated in the common 3×3 moving window contain small and narrow non-flat zones with shape similar to the contours (Fig. 2). These areas are mostly artefacts resulting from using a DEM interpolation algorithm, which has difficulties with processing dense contours as input data. The artefacts were partially eliminated or smoothed out by using a bigger moving window, which considering wider surrounding in the calculation resulted in more compact areas of flat surfaces. As the most appropriate size the moving window of 19×19 cells was chosen, in this resolution being an equivalent of 100 meters, which is a rounded average size of the planation surfaces (Tab. 1) mapped in the field. However, the method of setting slope gradient threshold as the indicator of pla-nation surface recognition did not prove to be suitable for classification of individual landforms. It is able to delineate relatively flat surfaces, however it cannot filter out thalwegs, ridgelines, passes and other forms. It provides an overview of elevation conditions in the study area, or of elevation of the local erosion base, and of relative ele-vation, but it cannot distinguish planation surfaces from other forms that meet the chosen slope criterion.

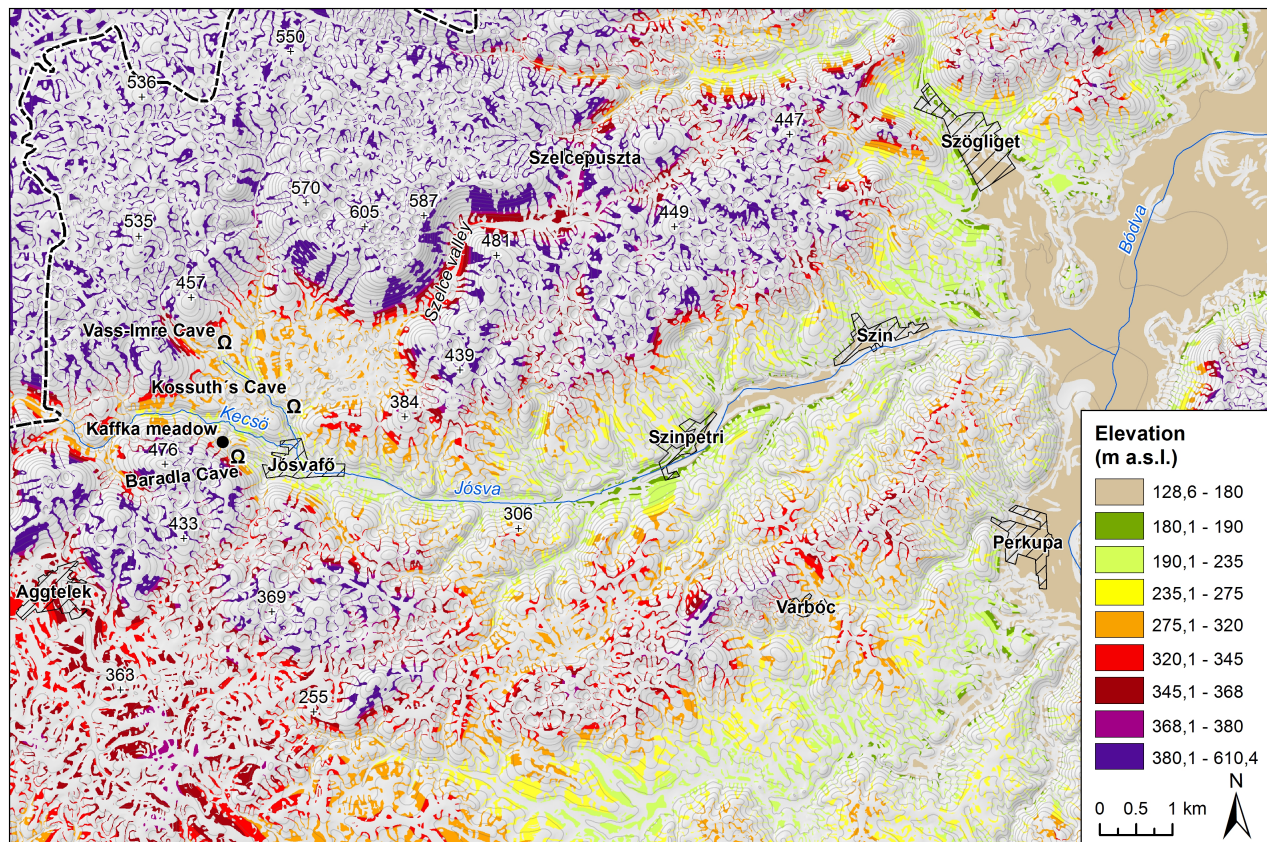
Figure 10: The hypsographic categories of flat surfaces obtained by the slope gradient threshold.



In the module `r.param.scale` we tested several settings of slope and curvature tolerance and size of a moving window (Fig. 3 and Fig. 4). Since the module recognizes mostly types of curvatures, the curvature tolerance parameter had major effect on the resulting rasters. Low slope and curvature tolerance (1° and 0.0001, respectively) delineated a large number of relatively small areas meeting the criteria of relative plains (Fig. 4). Increasing the value of curvature tolerance resulted in delineating more continuous flat areas, however, these no longer meet the properties of relative plains. Major problem is that increase in curvature leads to identifying not only flat areas, but also linear slopes as relatively flat surfaces. The maximal chosen value of curvature tolerance (0.0020, not shown in the figures) proved to be too high, with most of the surface resulting as planar. On the contrary, increasing the value of slope tolerance (from 1° up to 6°), the number of delineated relative plains decreased (Fig. 4), which is in contradiction to the logical hypothesis of planation surfaces. The change of slope tolerance mostly affected the definition criteria of other individual landforms and resulted in their increased number at the expense of planation surfaces. Value of curvature tolerance set to 0 resulted in de-

lineation of no planar landforms, while value of slope tolerance set to 0 had no effect on delineation of planar landforms. Size of a moving window had effect mainly on the compactness of the delineated landforms. Even a slight increase of its size to 5 cells led to better delineation. Bigger size of the window led to more compact landforms. In addition, higher size of the window caused smoothing of small irregularities and artefacts at the surface, which can be considered as advantage. Effect of bigger window on the extent of landforms is only minor. Though, the extent of planar landforms with bigger window slightly increased, thanks to smoothing of small parts of the foothills. Based on the visual comparison of the rasters resulting from several combinations of input values (Fig. 4), and values obtained at the field mapping, we identified the result with slope tolerance of 6° , curvature tolerance of 0.0005 and moving window size of 19×19 cells as the most plausible. Nevertheless, flat surfaces delineated in this way are not representative and the module `r.param.scale` is thus not considered as suitable for semi-automated recognition of flat surfaces.

In the `r.geomorphon` module we tested several settings of search radius `L` (80 m, 100 m, and 150 m) and

Figure 11: The hypsographic categories of flat surfaces obtained by the module *r.param.scale*.

flatness threshold t (4° , 6° , 8°). With the increase of flatness threshold (t) the area of delineated plains increased, too, at the expense of other landforms. On the other hand, the area decreased with the increase of search radius (L) (Fig. 5). Based on expert visual comparison of the results for various values of the input parameters t and L (Fig. 6) and of the respective values collected in the field we decided for the final settings $t = 6^\circ$ a $L = 100$ m. Results obtained by this method showed to be the best from among the tested methods.

DEM of the flat surfaces delimited by the *r.geomorphon* module was categorized according to the hypsographic curve and its slope and curvature (Fig. 9). The boundaries of elevation classes of most frequently occurring flat surfaces were defined in two steps:

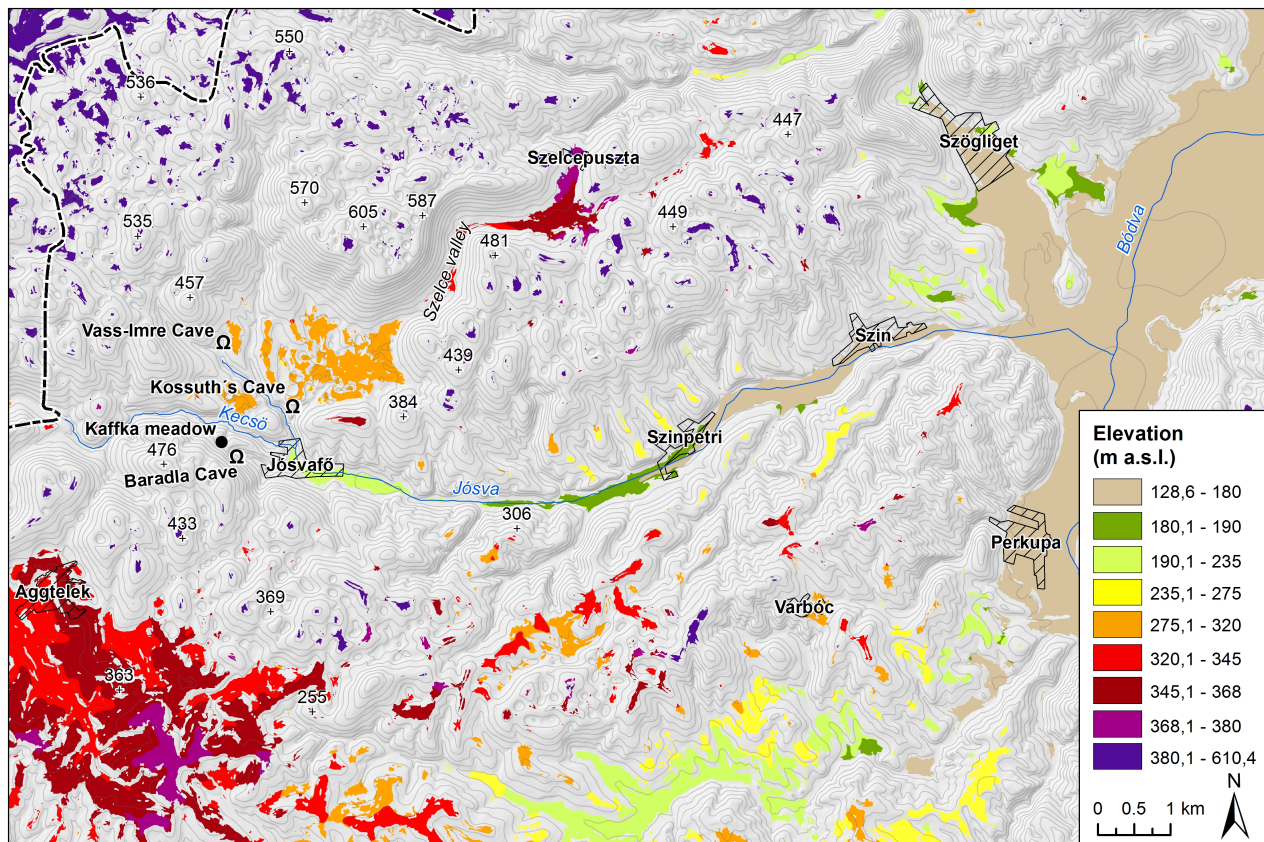
- (a) In the first step, beginning and end of a significant deviation of hypsographic curve slope from trend were considered as the interval boundaries. That means that the peaks of the slope curve delimited most numerous categories and defined their interval values. We defined three basic categories of flat surfaces as following:

- flat surfaces in the elevation interval of 130 – 180 m a.s.l.
- flat surfaces in the elevation interval of 190 – 275 m a.s.l.
- flat surfaces in the elevation interval of 320 – 380 m a.s.l.

- (b) In the next step, we divided the categories into smaller subcategories based on the inflection points on curvature curve of the hypsographic curve of flat surfaces. The initial three categories were thus divided into the following subcategories:

- flat surfaces in the elevation interval of 130 – 180 m a.s.l.
- flat surfaces in the elevation interval of 190 – 235 m a.s.l.
- flat surfaces in the elevation interval of 235 – 275 m a.s.l.
- flat surfaces in the elevation interval of 320 – 345 m a.s.l.
- flat surfaces in the elevation interval of 345 – 368 m a.s.l.

Figure 12: The hypsographic categories of flat surfaces obtained by the module r.geomorphon.



- flat surfaces in the elevation interval of 368 – 380 m a.s.l.

The elevation categories of relative plains obtained by the analysis of the hypsographic curve helped us recognize interval boundary values for the subsequent reclassification of the rasters of flat surfaces obtained by the three tested methods of semi-automated delineation (Fig. 10, Fig. 11 and Fig. 12).

5 Discussion

According to the comparison of the selected methods of semi-automated recognition of planation surfaces (Fig. 10, Fig. 11 and Fig. 12) as the most suitable method can be considered the module r.geomorphon, which, compared to the module r.param.scale, does not recognize flat surfaces mostly according to the curvature as well as is not dependent on the adjusting of the size of a moving window manually. Instead of a fixed window size it uses surroundings of a cell of shape and size, which are automatically adjusted to the local topography, ensuring that landforms

are identified in the most desirable spatial scale. Given its explicitness, relative simplicity of calculation and more than satisfactory results obtained by this method, it can be concluded that compared to the other two tested methods this one was the most suitable for the required purpose and thus can be considered as the most suitable available method of recognition of planation surfaces in karst areas.

Assuming the relation between multilevel cave system and flat erosion landforms on the surface, we can correlate the elevation categories of flat surfaces obtained by the analysis of the hypsographic curve with horizontal or slightly inclined cave corridors in the study area. We can correlate flat surfaces according to the elevation categories they belong to, not according to their absolute elevation. Planation surfaces originated in relation to change of base level, so it is difficult to correlate one specific elevation to one planation surface. Therefore we are interested in changes of elevation trend. As an example of correlation of semi-automated recognised flat surfaces and cave levels the slightly inclined main corridor of the Baradla Cave (260 – 280 m a.s.l.), which corresponds to the planation surfaces in the elevation interval of 235 – 275 m a.s.l. as well as with remnants of the large pediment

at 250 – 275 m a.s.l. originated in Pliocene [41], can be mentioned. The travertine occurrence in a slope depression at the Kaffka Meadow at the elevation of 270 m a.s.l. is considered by [42] to be the evidence of the oldest spring from the Baradla Cave. Based on the burial age 3.47 ± 0.78 Ma of quartz gravel (dated using cosmogenic nuclides ^{10}Be and ^{26}Al) the upper level of the Domica Cave originated in (or before) Middle Pliocene [43]. It is located 9 – 12 m above the slightly inclined main multilevel corridor (ca 7.5‰) of the Domica-Baradla cave system. Flat surfaces of lower elevations (190 – 235 m a.s.l.) represent the flood plain of the Jósva River.

6 Conclusion

Testing of three methods of semi-automated classification of landforms based on DEM helped us find suitable method for semi-automated recognition of planation surfaces as one of relatively flat landforms. According to the results we can consider the module *r.geomorphon* as the most suitable method for planation surface recognition in our study area. The most frequent elevation categories of flat surfaces can be considered as planation stages and can be correlated with elevations of cave levels. Results of slope gradient thresholding approach can be also considered as relatively plausible due to the use of the same basic criterion for flat surface delineation as in the module *r.geomorphon*. However, slope gradient thresholding does not remove landforms such as valleys and channels from flat surfaces and thus enlarges their extent. Therefore, use of this method depends directly on user's requirements. Since the module *r.param.scale* uses values of curvature for flat surface delineation, we do not consider it as a suitable and plausible method for recognition of flat surfaces. To conclude, the most suitable method for planation surface delineation in our study is proved to be the module *r.geomorphon*, due to the highest ability to remove valleys, channels and other relatively flat areas from resulting flat landforms. Nevertheless, it is difficult to reduce the recognition of planation surfaces only to using GIS. Each area is specific, so efforts to minimize subjective decisions include field mapping, creation of DEM, and application of suitable method of semi-automated planation surface recognition. Without field mapping the modules are calibrated only on the basis of random attributes. Presented evidences clearly show the relation between formation of cave levels and planation surfaces or river terraces. This correlation contributes to more comprehensive knowledge

about the evolution of the Aggtelek Karst and the Slovak Karst.

Semi-automated recognition of flat surfaces helps us obtain suitable indication, which can be helpful in the process of identifying basic stages of terrain evolution. However, here we focused on the evaluation of methods and further interpretation of geomorphological development of the study area is beyond the scope of this paper.

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References

- [1] Goudie A.S., Encyclopedia of geomorphology, Volume 1, Routledge, London, 2004.
- [2] Mazúr E., Kotliny ako význačný prvok reliéfu Slovenska [The basins as a significant terrain element of Slovakia], *Geografický časopis*. 1964, 16, 103–126 (in Slovak).
- [3] Mazúr E., Major features of the West Carpathians in Slovakia as a result of young tectonic movements. In: Mazúr E. (Ed.), *Geomorphological problems of Carpathians*, Bratislava (SAV), 1965, 9–54.
- [4] Lukniš M., Die Reliefentwicklung der Westkarpaten, *Wissenschaftliche Zeitschrift der M. Luther Universität, Halle-Wittenberg, Mathematik-Naturwissenschaften* 1962, 11, 1235–1244.
- [5] Lukniš M., Pozostatky starších povrchov zarovnávania reliéfu v Československých Karpatoch [Die Überreste älterer Verebnungsflächen des Reliefs in den tschechoslowakischen Karpaten], *Geografický časopis* 1964, 16, 3, 289–298 (in Slovak with German summary).
- [6] Zuchiewicz W., Tectonics and climate versus relief evolution: old controversy and new arguments, *Studia geomorphologica Carpatho-Balcanica*, Kraków, 1987, 21, 183–202.
- [7] Činčura J., Príspevok k veku poriečnej rovne v Západných Karpatoch (na príklade južnej časti Turčianskej kotliny) [Contribution to the age of river level in the Western Carpathians], *Geografický časopis* 1967, 19, 4, 316–326 (in Slovak).
- [8] Watchman A.L., Twidale C.R., Relative 'absolute' dating of land surfaces, *Earth Science Reviews* 2002, 58, 1–49.
- [9] Činčura J., Paleokarst breccias of the Biele hory mts. (Malé Karpaty mts., Western Carpathians), *Geologica Carpathica* 1992, 43, 2, 105–110.
- [10] Minár J., Bizubová M., Gallay M., General aspects of denudation chronology of the West Carpathians, *Studia geomorphologica Carpatho-Balcanica*, Kraków, 2004, 28, 5–22.
- [11] Minár J., Stredohorská roveň v Západných Karpatoch ako tekto-plén: náčrt pracovnej hypotézy [Midmountain level in the Western Carpathians as tectoplain: outline of the work hypothesis], *Geografický časopis* 2003, 55, 2, 141–158.

- [12] Wilson J.P., Bishop M.P., Geomorphometry. In: Schroder J.F., Bishop M.P. (Eds.), *Treatise on Geomorphology*, Vol 3, Remote Sensing and GIScience in Geomorphology. Academic Press, San Diego, 2013, 162–186.
- [13] Evans I.S., Geomorphometry and landform mapping: What is a landform? *Geomorphology* 2012, 137, 94–106.
- [14] Minár J., Evans I.S., Krcho J., Geomorphometry: Quantitative Land Surface Analysis. In: Schroder J.F., Switzer A.D., Kennedy D.M. (Eds.), *Treatise on Geomorphology*, Vol 14, Methods in Geomorphology. Academic Press, San Diego, 2013, 22–34.
- [15] Minár J., Evans I.S., Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping, *Geomorphology* 2008, 95, 236–259.
- [16] Jasiewicz J., Stepinski T.F., Geomorphons – a pattern recognition approach to classification and mapping of landforms, *Geomorphology* 2013, 182, 147–156.
- [17] Verstappen H.T., Old and New Trends in Geomorphological and Landform Mapping, *Developments in Earth Surface Processes*, Vol 15. Elsevier, 2011, 13–38.
- [18] Hofierka J., Mitášová H., Neteler M., Geomorphometry in GRASS GIS. In: Hengl T., Reuter H.I. (Eds.), *Geomorphometry: Concepts, Software, Applications*. Developments in Soil Science, Vol 33. Elsevier, 2008, 387–410.
- [19] Droppa A., Domica – Baradla, jaskyne predhistorického človeka [Domica – Baradla, the caves of prehistoric man], Šport, Bratislava, 1961 (in Slovak).
- [20] Droppa A., Príspevok k vývoju jaskyne Domica [Contribution to the development of the Domica Cave], *Československý kras*, 1972, 22, 65–72 (in Slovak with English summary).
- [21] Jakucs L., Aggteleki karsztvidék [Aggtelek Karst area]. Sport Kiadó, Budapest, 1975 (in Hungarian).
- [22] Jakucs L., Az aggteleki Baradla-Domica barlangrendszer [The Baradla-Domica Cave system in Aggtelek]. In: Kordos L. (Ed.), *Magyarország barlangjai*, Gondolat Kiadó, Budapest, 1984, 88–109 (in Hungarian).
- [23] Ford D.C., Caves Branch, Belize, and the Baradla-Domica System, Hungary and Slovakia. In: Klimchouk A.B., Ford D.C., Palmer A.N., Dreybrodt W. (Eds.), *Speleogenesis. Evolution of Karst Aquifers*, National Speleological Society, Huntsville, 2000, 391–396.
- [24] Bella P., Veselský M., Gaál L., Minár J., Towards the genesis of large karst depression (paleopolje) near Jósavő village in the Aggtelek karst, Hungary. In: Novotný, J. (Ed.), *Book of Abstracts, Scientific Conference “Geomorphology and Environmental Challenges”* (Snina 6.–8.10.2014), Association of Slovak Geomorphologists, Bratislava, 2014, 12–13.
- [25] Gaál L., Gruber P., Jaskynný systém Domica-Baradla. Jaskyňa, ktorá nás spája [The Domica-Baradla Cave System. The cave that connects us]. *Správa Aggteleckého národného parku, Jósavő*, 2014, 45–60 + map supplement (in Slovak with English summary).
- [26] Török-Oance M., Ardelean F., Onaca A., The semiautomated identification of the planation surfaces on the basis of the digital terrain model. Case study: The Mehedinți Mountains (southern Carpathians). *Studii și cercetări de geografie și protecția mediului*, 2009, 8, 8, 5–13.
- [27] Mazúr E., Jakál J., Podklad a reliéf [Ground and terrain]. In: Mazúr E. et al. (Eds.), *Slovenský kras. Regionálna fyzicko-geografická analýza*. Geografické práce, 1971, 2, 1–2, 6–22 (in Slovak).
- [28] Jakál J., Kras Silickej planiny [Karst of the Silická planina Plateau], Osveta, Martin, 1975 (in Slovak with English summary).
- [29] Gaál L., Geodynamika a vývoj jaskýň Slovenského krasu [Geodynamics and development of caves in the Slovak Karst], ŠOP SR, SSJ, Liptovský Mikuláš – Knížné centrum, Žilina, 2008 (in Slovak with English summary).
- [30] Gaál L., Bella P., Vplyv tektonických pohybov na geomorfologický vývoj západnej časti Slovenského krasu [The influence of tectonic movements on the geomorphological development of the western part of the Slovak Karst], *Slovenský kras*, 2005, 43, 17–36 (in Slovak with English summary).
- [31] Minár J., Bielík M., Kováč M., Plašienka D., Barka I., Stankoviansky M., et al., New morphostructural subdivision of the Western Carpathians: An approach integrating geodynamics into targeted morphometric analysis, *Tectonophysics* 2011, 502, 1–2, 158–174.
- [32] Less Gy., Triász [The Triassic]. In: Szentpétery I., Less Gy. (Eds.), *Az Aggtelek-Rudabányai-hegység földtana*. Magyar Állami Földtani Intézet, Budapest, 2006, 14–24 (in Hungarian).
- [33] Less Gy., Mello J. (Eds.), Elečko M., Kovács S., Pelikán P., Entelényi L., Peregi Zs., Pristaš J., et al., *Geological Map of the Gemer-Bükk Area (1:100 000)*, Geological Institute of Hungary, Budapest, 2004.
- [34] Lukniš M., Slovensko 2 – Príroda [Slovakia 2 – Nature], Obzor, Bratislava, 1972 (in Slovak).
- [35] Bezvodová B., Demek J., Zeman A., Metody kvarterně geologického a geomorfologického výzkumu [The methods of geological and geomorphological quaternary research], Stát. pedagog. naklad., Praha, 1985 (in Czech).
- [36] Dikau R., Brabb E., Mark R., Morphometric landform analysis of New Mexico, *Zeitschrift für Geomorphologie Supplement* 101, 1995, 109–126.
- [37] Wood J., The Geomorphological characterisation of Digital Elevation Models. Diss., Department of Geography, University of Leicester, U.K., 1996.
- [38] Evans I., General geomorphometry, derivatives of altitude, and descriptive statistics. In: Chorley R.J. (Ed.), *Spatial analysis in geomorphology*, Methuen, P., 1972, 17–90.
- [39] MacMillan R.A., Jones R.K., McNabb D.H., Defining a hierarchy of spatial entities for environmental analysis and modeling using DEMs, *Computers, Environment and Urban Systems*, 2004, 28, 175–200.
- [40] GRASS GIS 6.4 manual: r.param.scale <https://grass.osgeo.org/grass64/manuals/r.param.scale.html>
- [41] Sásdi L., Az Aggtelek-Rudabányai-hegység édesvízi mészkő előfordulásai [Occurrences of the freshwater limestones in the Aggtelek-Rudabánya Mountains], *Karsztfejlődés*, 2005, 10, 137–152 (in Hungarian).
- [42] Láng S., Geomorfológiai tanulmányok az Aggteleki-karsztvidéken [Geomorphological studies of Aggtelek karst], *Földrajzi Értesítő*, 1955, 4, 1, 1–16 (in Hungarian).
- [43] Bella P., Braucher R., Holec J., Veselský M., Burial age of cemented quartz gravel in the upper level of the Domica Cave, Slovakia. In: Novotný J. (Ed.), *Book of Abstracts, Scientific Conference “Geomorphology and Environmental Challenges”* (Snina 6.–8.10.2014), Association of Slovak Geomorphologists, Bratislava, 2014, 10–11.