Physically-based land surface segmentation: Theoretical background and outline of interpretations

Jozef Minár, Peter Bandura, Juraj Holec, Anton Popov
Department of Physical Geography and Geoecology
Comenius University in Bratislava, Slovakia
jozef.minar@uniba.sk

Lucian Drăguţ
Department of Geography
West University of Timişoara, Romania

Michal Gallay, Jaroslav Hofierka, Ján Kaňuk
Institute of Geography
Pavol Jozef Šafárik University in Košice, Slovakia

Ian S. Evans
Department of Geography
Durham University, England

Abstract — **Incorporation of a physically-based general geomorphological theory directly into the segmentation algorithm is fundamental to physically-based land surface segmentation. Topographical steady state for morphostructural segmentations with five types of elementary forms defined by the principle of equilibrium provides a basis for definition of input variables. Examples of application introduce two new physically-based geomorphometric variables: Index of Steady State (ISS) quantifying the closeness of regions to a topographic steady state; and Index of Slope Disequilibrium (ISD), expressing percentage deviation from an equilibrium state of gravitational Potential Energy of Surface (PES) for mass flow.**

I. INTRODUCTION

The land surface is formed by a set of geomorphological processes controlled by physical fields. Altitude is an approximation of the most important force – the gravity field. Hence all geomorphometric variables specific to the gravity field [1, 2] have a physical interpretation. However, this principle is not explicitly used in segmentation procedures that try to replicate traditional morphological or genetic classifications, most of which use empirical statistical approaches, e.g. [3, 4].

Physically-based land surface segmentation builds on the general geomorphological theory that is directly incorporated in the segmentation algorithm. Instead of pure statistical approaches, the input variables are selected and construed on the basis of their interpretational power. Consequently, the resultant segments have clear physical individuality, and interpretability is guaranteed.

The land surface has a fundamentally vague and scale-dependent nature. It is the consequence of a set of overlapping geomorphic processes with various horizontal, vertical, and time dimensions. The most distinct and stable landform structures appear at scales where landforms are adjusted to the dominant processes, defining equilibrium states, i.e. attractors of landform development. Physically-based land surface segmentation therefore should include a determination of the most suitable scale where the influence of attractors is the most visible.

We consider two autonomous sets of geomorphometric variables suitable for physically-based land surface segmentation. The first arises from the concept of long term-geomorphic work responsible for the character of morphostructures (big landforms formed dominantly by endogenous processes). The second describes a local distribution of potential gravitational energy and its physical-geomorphic consequences.

II. MORPHOSTRUCTURAL SEGMENTATION

Endogenous geomorphic work (EnW) is reflected in the elevation of summit envelope surfaces. It is the minimum work preserved in the recent topography, because endogenous work is continuously eliminated by exogenous work. A part of this exogenous work is also preserved in the topography (ExW) and is represented by the difference between the elevation of envelope surfaces and mean elevations (Fig. 1). The ratio between both types of work (EnW / ExW) should be stable in the long term if a mountain range achieves *steady state* (tectonic uplift and denudation are equal). Higher values of the ratio point to an initial stage of net uplift; lower values could be linked with decreasing tectonic activity. However the numeric value of an equilibrium ratio should depend on the climate, rate of the uplift and character of the rocks. All those factors influence the relief and drainage density that together make a barrier effect of the topography that can be physically expressed as relief brake force (RBF, Fig. 1).

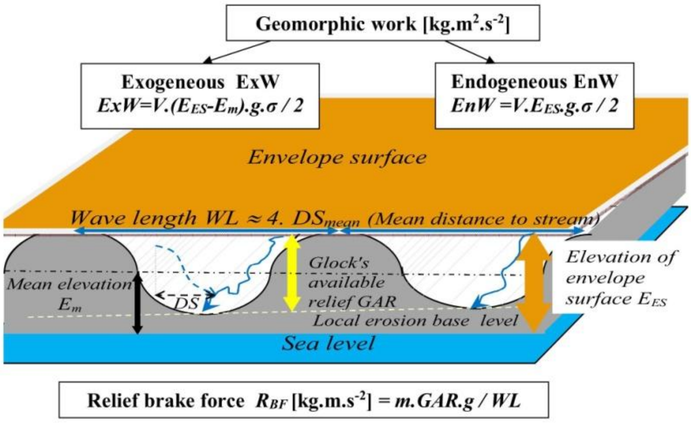

Figure 1. Three basic physical-geomorphic categories contained in the topography, suitable for morphostructural segmentation. Physical inputs: σ - rock density, g - gravitational acceleration. EnW represents the mean work expended on uplift of unit volume V = 1m^3 of a block, therefore both EnW and ExW have to be considered in units of work. Also RBF is the unit force (deceleration of the movement of unit mass point, m = 1 kg).

All three physically-based variables are analogous to standard geomorpometric variables frequently used for land surface segmentation. EnW corresponds to altitude, ExW matches the range of altitudes (amplitude or vertical dissection) and RBF expresses the average slope of an area. Inclusion of rock density (that can be estimated by reclassification of geological maps) helps to distinguish contrasting geological regions.

Because all inputs are local area-based variables [1] the measure of land surface generalization is strongly influenced by the size of moving window for their calculation. Setting of the window on the basis of the topographic grain concept [5] is one way to optimize identification of scale-dependent structures.

III. ELEMENTARY SEGMENTATION

Physically-based elementary land surface segmentation should reflect physical conditions of various types of stability of the smallest landforms. In line with [6] various types of stability can be linked with the homogeneity (constant values) of some geomorphometric variables (Fig. 2).

Long-term exogenous processes minimize differentiation of potential energy, and by planation they lead toward the most stable elementary forms - horizontal plains. The existence of linear slopes demonstrates stability thresholds, e.g. angle of repose [7], as well as equilibrium between the energy necessary for load transport and the down slope gravitational force. Curvatures determine interconnected mechanisms of mass flow acceleration / deceleration and concentration / diffusion [8] that can lead to curved elementary forms in dynamic equilibrium. Dynamic equilibrium states can be linked also with change of curvatures, e.g. homogeneous change of mass flow diffusion can allow for symmetrical growth of alluvial fans with constant slope such as those described e.g. by [9].

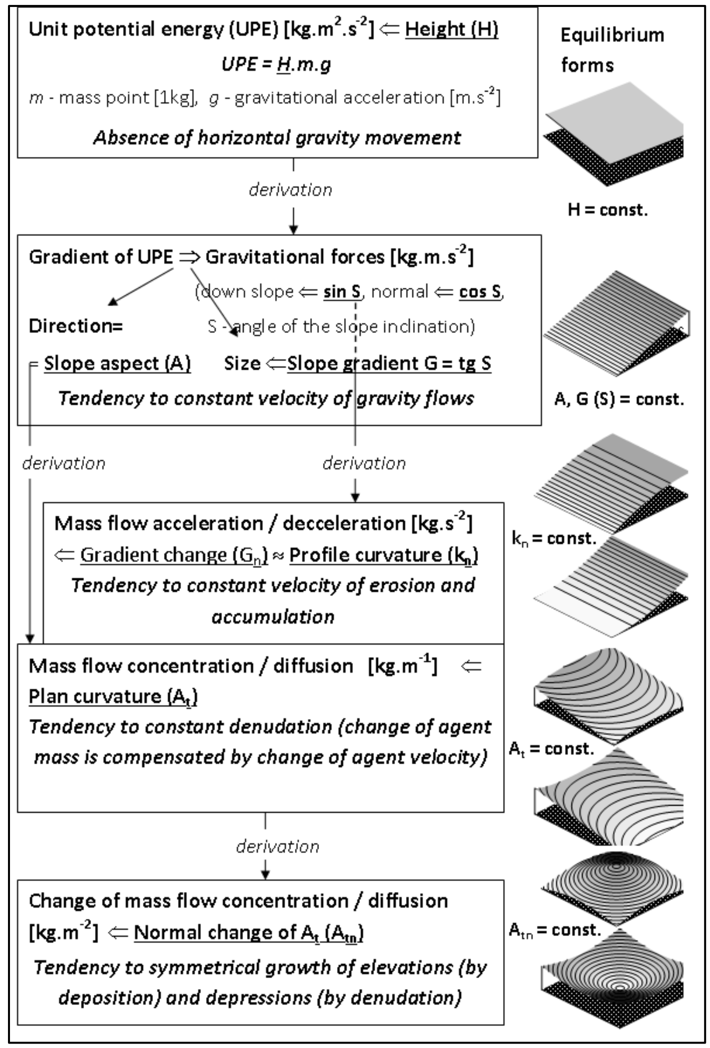

Figure 2. Basic variables of the physically-based elementary land surface segmentation and equilibrium forms defined by their constant values.

Other equilibrium elementary forms can relate to the influence of some other morphometric properties as well as non-morphometric characteristics (mainly rock and soil properties), and by various combination of all. E.g. unit potential energy defined by altitude can be replaced by local unit potential energy defined by relative height above local base of erosion (thalweg), which can lead to a better identification of gently inclined river terraces or pediments. However the maximum homogeneity of elementary forms from the point of view of unit potential gravitational energy and/or local gravitational forces, as well as mass flow characteristics (Fig. 2), should be a goal of physically-based elementary segmentation.

Theoretical assumptions about the affinity of exogenous landforms to constant values of normal gradient change (~ profile curvature) were supported by an empirical test in [10]. It can be used for meaningful generalization of DEMs for elementary landform segmentation [11].

IV. Applications

We apply physically-based land surface segmentation in the framework of object-based image analysis (OBIA). The techniques developed as upgrades of our already published algorithms [12, 13, 14] are complex, and will be presented elsewhere. Here, only two examples documenting the interpretive power of the concept are outlined.

First, morphostructural segmentation of the Western Carpathians (Fig. 3) uses data and techniques described in [15].

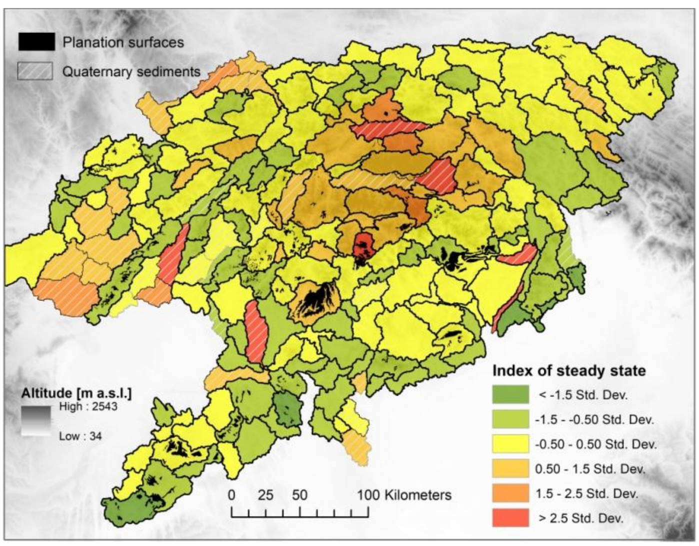

Figure 3. Physically-based morphostructural segmentation of the Western Carpathians. The Index of Steady State (ISS) is expressed as fractional standard deviations from its mean. Diagonal stripes indicate significant cover of Quaternary sediments.

From the variables used for morphostructural segmentation we derive the Index of Steady State (ISS). It should express the closeness of regions to a topographic steady state:

$$ISS = \frac{EnW.BF}{ExW^2} \cdot \frac{ExW_{mean}}{BF_{mean}}$$

where ExW_{mean} and BF_{mean} are mean values of ExW and BF in the whole analysed territory, (ExW and BF are explained on Fig. 1).

Values above the mean point to the dominance of endogenous work (younger and/or ampler uplift); below-average values imply dominance of exogenous work and can point to a relatively longer and/or more complex denudation history. The presence of thicker Quaternary sediments leads to overestimation of ISS. The results confirm several hypotheses of young morphotectonic development of the Western Carpathians [16]. Fig. 3 shows that ISS is independent of preservation of the most extensive planation surfaces, hence the old idea of full area planation can be rejected. Rather, this evidence supports the concept of spatially limited Neogene planation.

The second example concerns physically-based elementary segmentation of part of a complex glacial cirque (Fig. 4). A primary very detailed DEM produced by terrestrial laser scanning and UAV photogrammetry (see [17] for details) was generalized to a level suitable for elementary segmentation using analysis of third order derivatives [11]. Altitude, slope, aspect, plan and profile curvatures were used as input to the segmentation algorithm, in line with Fig. 2.

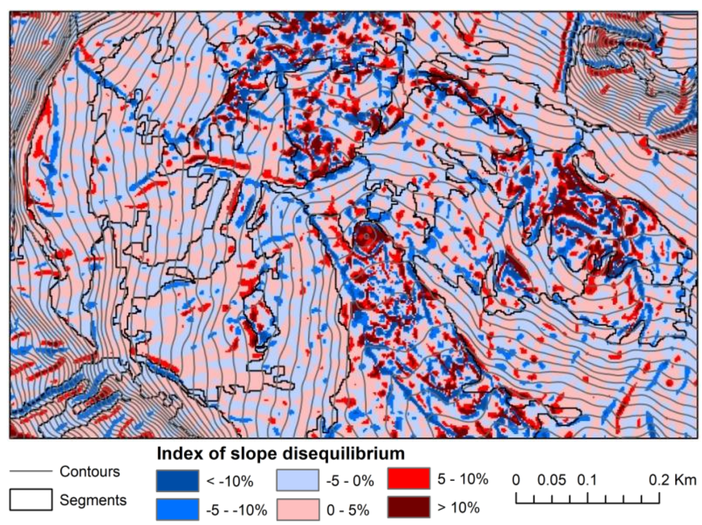

Figure 4. Physically based elementary segmentation of the glacial cirque in the Malá studená dolina (valley), Tatras, Western Carpathians.

Because of different scale and inputs, ISS is irrelevant here. But variables used for the elementary segmentation can by unified for interpretation on the basis of our new **I**ndex of the **S**lope **D**isequilibrium (ISD):

$$\text{ISD [\%]} = 100.\left(\frac{k_n}{\sin S} - A_t\right)$$

expressing percentage deviation of unit gravitational Potential Energy of Surface (PES) for mass flow from an equilibrium state (Symbols: S - slope, A_t, k_n plan and profile curvatures).

Development of the algorithm (an upgrade of that presented by [13]) is in progress and its ability to distinguish more and less balanced slopes is a performance criterion. Darker blue colours on Fig. 4 point to the highest gravitational potential for deposition: darker red colours, for denudation. Comparing it with the geomorphological map [18], this pattern of denudation/accumulation potentials is characteristic to the youngest glacial and nival landforms that are logically farthest from the gravitational equilibrium surface. On the other hand, surfaces of talus cones (with slopes close to the angle of internal friction) have ISD values closest to zero. Elementary forms basically match with the ISD distribution: however further work (including detailed field research) is necessary to confirm and explain this.

V. CONCLUSIONS

We consider the systematic connection of geomorphic theory and empirical investigation as strategic for the future development of geomorphometry. Segmentation based on geomorphometric variables derived from physical theory enables clear physical and geomorphological interpretation of the results. The main contribution of this paper is the new concept of physically-based land surface segmentation, including two related indexes (ISS and ISD), which support its application. .

We used one of the most developed segmentation techniques to document the feasibility of our theoretical concept. Nevertheless, the theory is not bound to a specific methodology. The settings and specifications of the algorithm used will be presented elsewhere.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-15-0054.

REFERENCES

[1] Evans, I.S., Minár, J., 2011. "A classification of geomorphometric variables." In: Hengl T., Evans I.S., Wilson J.P., et al. (eds) Proceedings of Geomorphometry 2011, Redlands, CA, 7–11 September 2011, 105–108. International Society for Geomorphometry. http://geomorphometry.org/EvansMinar2011

[2] Florinsky I.V., 2017. "An illustrated introduction to general geomorphometry." Progress in Physical Geography, 41:723–752.

[3] Foroutan, M., M. Kompanizare and A.H. Ehsani, 2013. "Semiautomatic morphometric land surface segmentation of an arid mountainous area using DEM and self-organizing maps". Arabian Journal of Geosciences, 6 (12): 4795-4810.

[4] Iwahashi, J., I. Kamiya, M. Matsuoka and D. Yamazaki, 2018. "Global terrain classification using 280 m DEMs: segmentation, clustering, and reclassification". Progress in Earth and Planetary Science, 5:1.

[5] Pike, R. J. and W. Acevedo, 1989. "Topographic grain automated from Digital elevation models." In: Proceedings 9th International Symposium on Computer Assisted Cartography, Baltimore.

[6] Minár, J. and I.S. Evans, 2008. "Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping." Geomorphology, 95: 236-259.

[7] Oguchi, T., K. Katsube, Z. Lin and Y.G. Chen, 2011. "Characteristic slope angle of V-shaped valleys in humid steep mountains with frequent slope failure." In Geomorphometry 2011 Conference Proceedings, Edited by: Hengl, T., Evans, I.S., Wilson, J.P., et al., Redlands, CA, USA.

[8] Mitas, L. and H. Mitasova, 1998. "Distributed soil erosion simulation for effective erosion prevention." Water Resources Research, 34 (3): 505-516.

[9] Lin, Z., T. Oguchi, Y.G. Chen and K. Saito, 2009. "Constant-slope alluvial fans and source basins in Taiwan." Geology, 37:787-790.

[10] Minár, J, M. Jenčo, I.S. Evans, J. Minár Jr., M. Kadlec, J. Krcho, J. Pacina, L. Burian and A. Benová, 2013. "Third-order geomorphometric variables (derivatives) – definition, computation and utilization of changes of curvatures". International Journal of Geographical Information Science, 27 (7): 1381-1402.

[11] Minár, J., J. Minár Jr. and I.S. Evans, 2015. "Towards exactness in geomorphometry". In Geomorphometry 2015 Conference Proceedings, Edited by: Jasiewicz, J., Zwoliński, Z., Mitasova, H. and T. Hengl, Adam Mickiewicz University in Poznań, Poland. http://geomorphometry.org/Minar2015

[12] Drăguţ, L., C. Eisank and T. Strasser, 2011. "Local variance for multi-scale analysis in geomorphometry", Geomorphology 130: 162–172.

[13] Drăguţ, L., J. Minár, O. Csillik, and I.S. Evans, 2013. "Land-surface segmentation to delineate elementary forms from Digital elevation Models." In Geomorphometry 2013 Conference Proceedings, Nanjing Normal University, China. http://geomorphometry.org/Dragut2013

[14] Bandura, P., J. Minár, L. Drăguţ, and T. Harciníková, 2017. "Evaluation of object-based image analysis for morphostructural subdivision of the Western Carpathians". Zeitschrift für Geomorphologie, 61 (Suppl. 2): 121-135.

[15] Bandura, P., J. Minár, L. Drăguţ and M. Bielik, 2018. Physically-based segmentation of the Western Carpathians (Central Europe). In Geomorphometry 2018 Conference Proceedings, Boulder CO.

[16] Minár, J., M. Bielik, M. Kováč. D. Plašienka, M. Stankoviansky, and H. Zeyen, 2011. "New morphostructural subdivision of the Western Carpathians: An approach integrating geodynamics into targeted morphometric analysis". Tectonophysics, 502: 158-174.

[17] Gallay, M., J. Kaňuk, J. Šašak, J. Šupinský, J. Hofierka and J. Minár, 2018. "High-resolution digital terrain modelling of a rugged alpine terrain by fusing data from terrestrial laser scanning and UAV photogrammetry". In Geomorphometry 2018 Conference Proceedings, Boulder CO.

[18] Lukniš, M., 1968. "Geomorphological map of the Vysoké Tatry Mts. (High Tatra Mts.) and their foreland, 1:50 000". Bratislava, State Geological Institute of Dionýz Štúr.