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Second-order derivatives of microtopography for evaluating soil erosion

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Abstract— **The relation of soil erosion induced by water and land surface morphology is usually reasoned by the influence of slope angle and slope length, or contributing area on the erosion-accumulation processes. These assumptions about geomorphometric properties often fail in flat topographies cultivated by humans in a long-term time span. This paper demonstrates the potential of various land surface curvatures in explaining the mosaic of erosion-accumulation processes in such flat regions taking the example of loess table of Danube Lowland (Slovakia). The area is covered by chernozems where erosion manifests itself as bright patches on aerial photographs for the reduced humic horizon. Soil samples from 185 soil cores are compared with the mosaic of various subforms of plan and profile curvature and also with mean and difference curvature and from *Index of Slope Energy Disequilibrium* (*ISED*). The analyses assumed generating a highly detailed and accurate terrain model capturing microtopography of the flat landscape. Curvatures that are best interpretable from the physical aspect are important for such an application. The historical structure of the land parcels determined the direction of ploughing. The historical structure mirrors itself in curvatures also after the land consolidation. The ISED parameter appears to be the most suitable in this context.**

I. Introduction

Soil erosion has been accompanying human land use and land management through millennia [1, 2]. Dependence of soil erosion on the geomorphometric variables reflects all generally used models of the soil erosion. Majority of them (e.g. RUSLE) consider a dependence of soil erosion on the slope gradient and slope length or contribution area. Only exceptionally the land surface curvatures are used, despite the influence of plan curvature on convergence or divergence and profile curvature on acceleration and deceleration of gravity flows is long term known, e.g. [3]. A suitable expression of the interplay of plan and profile curvature in the soil erosion process is a crucial problem. [4] suggested such unification of the influence of these two in the case of the transport capacity limited process. In their approach, the resultant net erosion/deposition is proportional to the sum of the plan and profile curvature, i.e. to the mean curvature.

We have derived a more general approach based on the analysis of Potential Energy on the land Surface applicable to mass flow - PES [5]. It points to the importance of the difference of profile and plan curvatures (i.e. difference curvature) on the erosion-accumulation process. Tillage erosion is a very important factor in relatively flat areas. Recent but also historical land use (size and orientation of fields) play a significant role not only in the soil profile change but also in microtopography modification. The last can also be identified using land surface curvatures.

A comparison of spatial variability of the soil erosion and land use structure and various kind of land surface curvatures is the main goal of the paper. However, because the soil erosion process is influenced by landforms of a small dimension and computation of land surface curvatures is strongly influenced by the DEM error, very detailed and precise DTM is a basic precondition for the realization of this goal.

II. Methods

A. Study area

The Voderady study area is situated in the northwestern part of the Danube Lowland, in the Southwest Foreland of the West Carpathians (48°17'01.4"N, 17°34'45.5"E) [6]. It belongs to the Trnavská pahorkatina Hilly Land - one of five loess hill-dominated lands within the region. The study area is characterized by relatively flat topography partially transformed by Quaternary

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tectonic uplift of micro-blocks up to 15 m above sunken micro-blocks [7]. The study area covers 2.6 km^2 with a part of a dry shallow valley situated on an uplifted block in the central part of the area (Fig. 1). The altitudes range from 122 to 147 m above sea level. The ridges are asymmetric in their altitude and slope with steeper SW-oriented hillslopes (up to 8°), while the majority of slopes lie between 0.75 and 3.5° in the area (Fig. 2). The valley bottom, in the central part of the area, is characteristic by concave-concave morphometric forms and slopes with inclination 0–1.7°. On the hillslopes, convex-convex morphometric forms are prevailing.

B. Soil erosion and related data

Soil erosion strongly influences the Chernozems in loess hilly land in the Slovak part of the Danube Lowland. It leads to the transformation of the original humus horizon to a brighter less humic horizon, which is easily distinguishable in terrain or on aerial photographs. Bright patches consist of eroded, non-eroded and accumulated soils. In non-eroded and accumulated parts, the mollic horizon is thicker due to in-situ development or accumulation of humus-rich material transported from the upper parts of slopes. The tilled parts of soils are being changed by the incorporation of bright material transported from eroded parts of slopes. There-fore visual interpretation of aerial images could bring incorrect results.

The more realistic picture of soil erosion is provided by the records of erosion and deposition from 314 soil cores [2, 8]. Difference between depth of the humic horizon in a given site and a standard depth of the humic horizon (not influenced by erosional – depositional processes) we considered as a measure of erosional (-) and depositional (+) processes (Fig. 1). As preliminary results pointed to a probable influence of the tillage erosion, the structure of historical land use was investigated too. The aerial orthoimagery valid to 1949 was used for visual comparison with the pattern of curvatures of the contemporary terrain surface. The historical orthoimage documents the distribution and orientation of small fields before the collectivization stage (Fig. 1).

C. Close-range UAV photogrammetry

The area was flown in two days of March 2018 with an unpiloted aerial quadcopter DJI Phantom 4 with an integrated 12-megapixel FC330 camera (focal length 3.61 mm) mounted on 3-axes gimbal. Prior to the flight, 19 ground control points (50 by 50 cm wooden cross marks) were placed in the field and located by a dual-frequency GNSS receiver Topcon Hyper II using real-time kinematic positioning method with a mobile broadband connection to the network of the Slovak real-time positioning service (SKPOS) within the national S-JTSK03 coordinate system (EPSG code: 5514) with vertical datum Baltic after adjustment (Bpv). The overall accuracy of the RTK GNSS positioning ranged between 1–2 cm (1σ). There were 2,244 natural colour images

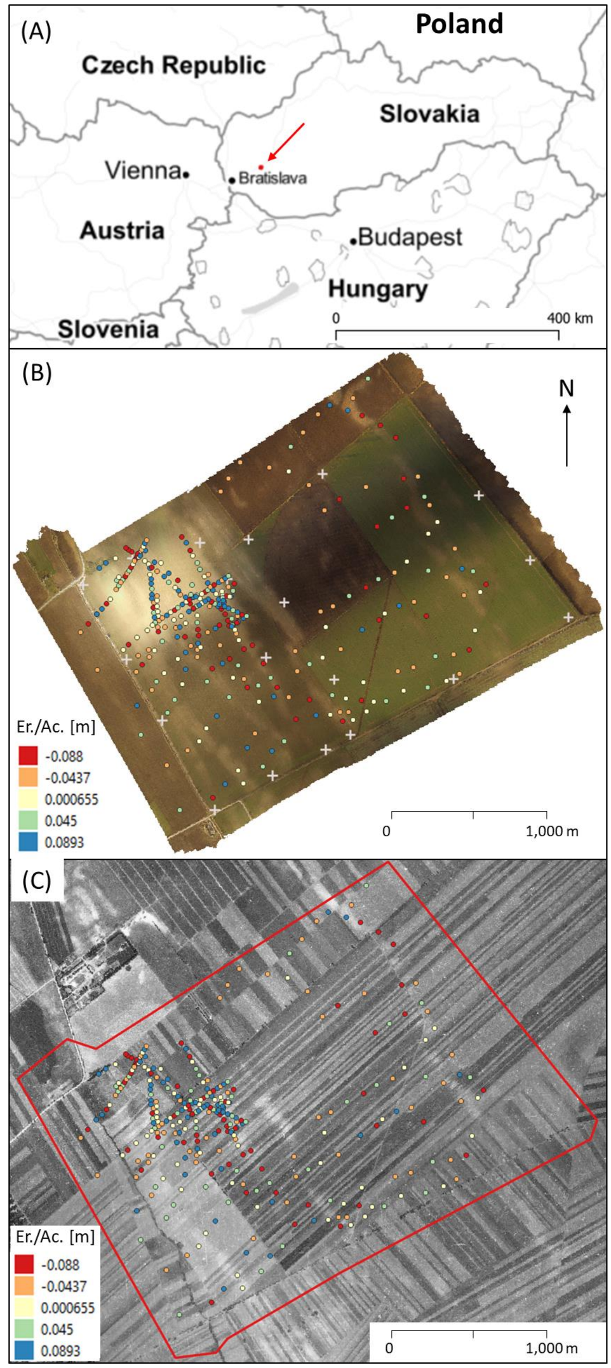

Figure 1. (A) Location of the study site in Slovakia, Central Europe with (c) Stamen Design Toner background layer. (B) Orthophotomosaic from UAV imagery acquired on 14 March 2018 with ground control points (grey cross hairs) and soil sampling locations coloured by the rate of erosion and accumulation in meters, (C) Orthophotomosaic from 1949 with the same soil sampling locations overlaid.

taken during 6 flights of 20 minutes duration from about 90 meters above the ground. The acquired imagery was processed by image matching method based on structure from motion in the Agisoft PhotoScan v1.4.1 software resulting in 3D point clouds and orthoimagery. Over 172 million points were extracted achieving an average point density of 55 points per m^2 a pixel size of 3.4 cm. The topography was reconstructed and from 4 to 9 overlapping images with a root mean square reprojection error of 0.85 pixels.

The original point cloud did not require extensive filtering of above-ground surface objects as the land was smoothly ploughed without crops on 2/3 of the area. About 1/3 were grown by wheat plants of 5 cm height which were not distinguishable from the ground (Fig. 1B). Points on trees and bushes were manually removed.

D. Digital terrain modelling

The cleaned point cloud was used to interpolate a digital terrain model (DTM) in the GRASS GIS software by regularized spline and smoothing implemented as the parallelized v.surf.rst module [9]. Default settings were used to generate a DTM of 25 cm cell size. The DTM was resampled to 2.25 x 2.25 m resolution by fitting a bivariate quadratic polynomial to a 9 x 9 cells moving window using least squares [10] implemented within the r.param.scale module of GRASS GIS. The purpose was to capture landforms above the scale level of particular furrows. Following land surface variables were then computed from the generalized DTM: slope gradient – S; profile curvature as normal slope line curvature [11] - $(k_n)_s$; profile curvature as the 2nd slope line derivative of altitude [12]; plan curvature as normal contour line curvature [13] – $(k_n)_c$; plan curvature as 2nd contour line derivative of altitude [12].

Mean curvature: $k_{mean} = \frac{(k_n)_s+(k_n)_c}{2}$

Difference curvature: $k_d = \frac{(k_n)_s-(k_n)_c}{2}$

Index of Slope Energy Disequilibrium [5]:

$$ISED = \frac{50k_d}{\sin S}$$

The ISED expresses the percentage deviation of unit gravitational Potential Energy of Surface (PES) for mass flow from an equilibrium state.

III. RESULTS AND DISCUSSION

The resulting data involve second-order derivatives as raster maps of parameters derived from the DTMs. Some of them are displayed in Fig. 2. The land surface curvatures provide generally higher correlation with erosion than the slope angle. The plan, profile, and mean curvatures (Fig.2) mirror the contemporary but also past cultivation/land use (Fig.1). The ISED parameter fuses the used curvatures and appears to be more relevant than the typically used kinds of curvature. The NE-SW oriented spatial structures visible in 1949 orthoimage are indicated by ISED. ISED pattern partially also follows the NW-SE direction of patterns from margins of the area. However, the scatterplot in Fig. 3 does not indicate a clear correlation of ISED and erosion/accumulation rates measured from the soil samples.

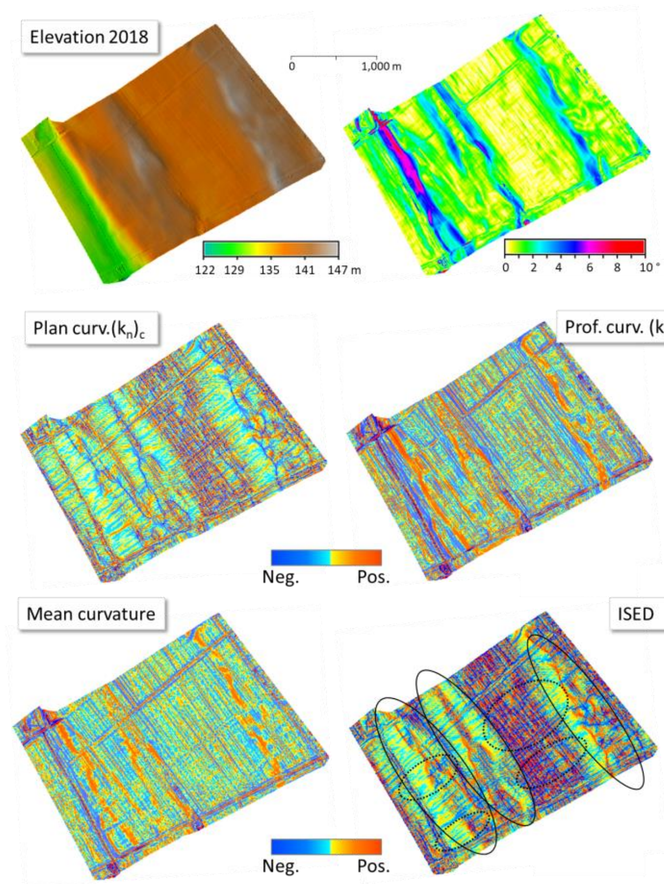

Figure 2. Terrain elevation and slope angle, and second-order elevation derivatives: plan curvature $(k_n)_c$, profile curvature as normal slope line curvature $(k_n)_s$ mean curvature, and index of slope disequilibrium (ISED) annotated with ellipses marking the reduced humic horizon (black solid line ellipses) and possible old morphological features resulting from past cultivation (black dotted ellipses).

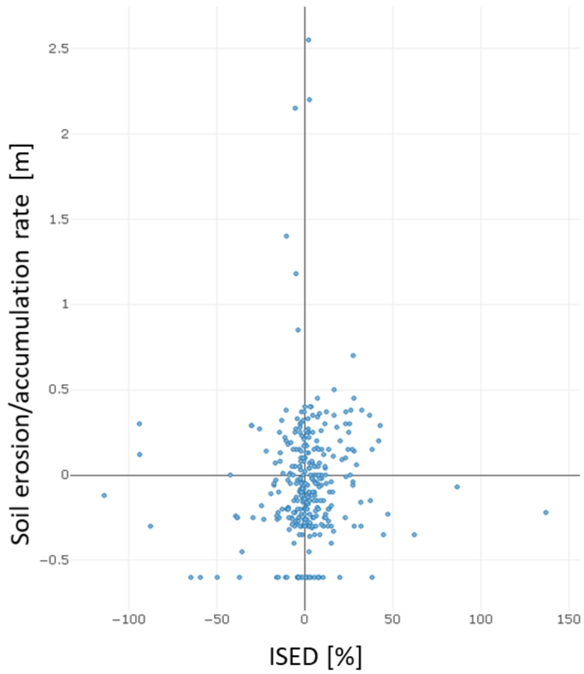

Figure 3. Scatterplot of the index of slope energy disequilibrium (ISED) and soil erosion (-)/accumulation (+) rate in meters.

IV. CONCLUSIONS

We used a high-resolution digital terrain model to derive first and second-order derivatives of elevation in a cultivated area with mild vertical relief and smooth topography. The pattern of cultivation at present markedly differs from the pattern from 70 years ago. The curvatures and index of slope disequilibrium (ISED) visually well correspond with the pattern of long-term erosion accumulation (with patches of the reduced humic horizon) but they also depict the pattern preserved from past cultivation (i.e. tillage direction). The newly defined ISED parameter was applied and it -better identifies both patterns. The visually apparent relationship of curvature-based parameters and erosion/accumulation values from soil cores is not convincingly supported by statistical analysis carried out so far. One of the reasons can be in varying scale-dependency of erosion and accumulation across the study area which requires further study. Therefore, the next steps will focus on multiscale analysis of the geomorphometric parameters and their relation with the field measured soil erosion/accumulation rate.

V. ACKNOWLEDGMENT

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