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High-resolution geomorphometry – towards better understanding the genesis and contemporary processes in erosional sandstone landscapes

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Abstract—**The paper explores the topic of how geomorphometric analysis of high-resolution digital elevation models can be used within a spectrum of current geomorphological research focused on sandstone areas of very complex topography. Geomorphometric approach is applied to the study of tabular hills, valley (canyon) systems and connectivity in surficial drainage patterns. It offers means to advance comparative studies of residual relief using various morphometric indices, helps to distinguish canyon reaches of various origins and is useful to identify sinks within plateaus and reconstruct drainage patterns and pathways. Additionally the study provides an assessment of available LiDAR-based DEMs in terms of their capability to represent such a complex relief.**

I. Introduction

In terms of complexity, land surfaces vary enormously. Whereas standard geomorphometric tools perform fairly well in most situations, areas of specific relief and high topographic complexity pose a challenge which tools to use and how to adjust them to receive a quantitative representation of relief which would be objective and faithful as possible.

Among such extremely complex areas are dissected sandstone tablelands, where intricate joint-controlled patterns of rock elevations and topographic depressions represent very unusual topography, lacking many features of typical fluvio-denudational landscapes such as hierarchical drainage patterns, well defined water divides and moderately inclined slopes. Instead, they host tabular hills, grid-like patterns of clefts and gorges, boulder-filled canyons and sinkholes. Therefore, they are an interesting case in geomorphic and geomorphometric studies and yet, remain well away from the mainstream of contemporary geomorphology.

Such highly complex erosional topographies are widespread in Central Europe, across Germany, Czechia and Poland (Fig. 1). They have generated scientific interest since the 19C, but very few attempts to quantify the relief have been made. However, things started to change in the recent decade [1] due to release of high-resolution, LiDAR-based digital elevation models which provide an excellent opportunity to examine the applicability of geomorphometric tools to these highly specific areas. Here, the focus is on geomorphology of sandstone-capped tabular hills (mesas and buttes), valley shapes and networks, and surface versus subsurface drainage systems.

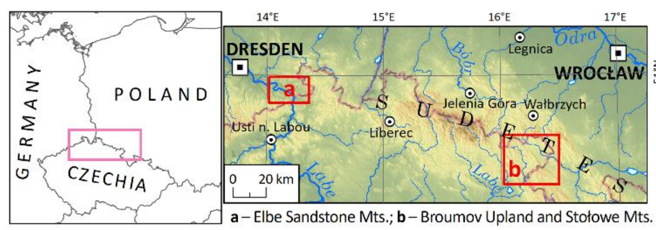

Figure 1. Location of study areas.

II. Methods

Software-wise, the study is based on existing tools and algorithms implemented in ArcGIS and SAGA-GIS environment. Additionally, Global Mapper 18 software was used during pre-processing of elevation data.

A. Remarks on the elevation datasets and data pre-processing

The location of the study areas dictated the use of three LiDAR-based digital elevation grid datasets, all of 1x1 m resolution:

a) Polish *Numeryczny Model Terenu* (NMT), based on point cloud of 4–6 pts/m^2 density (original .las point cloud is available); mean vertical error = 0.15 m [2];

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b) German *Digitale Geländemodell* (DGM1), based on point cloud of 10 pts/m^2 density (original .las point cloud is available); mean vertical error = 0.15 m [3];

c) Czech *Digitální model reliéfu České republiky 5. generace* (DMR5G), based on point cloud of 1.6 pts/m^2 density [4] (original .las point cloud is not available); mean vertical error up to 0.3 m [5].

While all the above DEMs provide currently the most accurate and detailed representation of the surface within the study areas, their accuracy may be remarkably lower within areas of complex relief at the local scale and considerable elevation differences within the rock-cut landscape [4]. Many times, field work revealed that even high-resolution DEMs failed to show some typical elements of sandstone landscape such as cubically-shaped boulders or whole caprock fragments. This is mainly because of errors during point classification [6] and the issue can be solved by customized filtering of the point cloud if such one is accessible (Fig. 2). Hence, it is recommended that within complex erosional sandstone landscapes, the elevation data preprocessing shall be intertwined with detailed on-site observations.

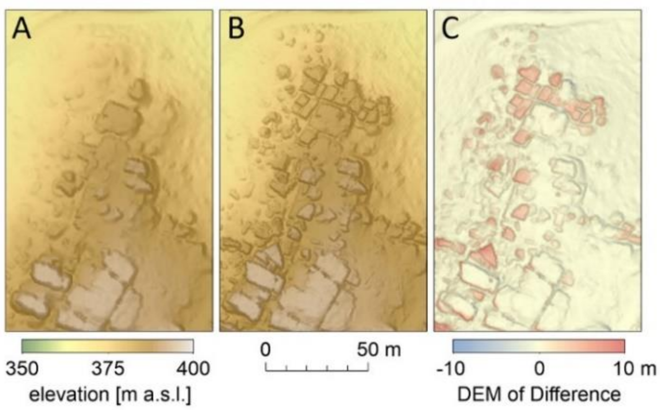

Figure 2. Labyrinth (Elbe Sandstone Mountains, Saxony, Germany), a fine example of how significant parts of caprock, while not represented by the raster version of DGM1 (A), can be restored after semi-manual filtering of primary point cloud (B). In this case, the elevation difference is up to 10 m (C).

B. *Morphometric features of tabular hills*

Tabular hills (mesas) are among characteristic landforms in platform areas and yet, it seems that no protocol exists to describe them quantitatively and hence, to facilitate comparative analysis. As an attempt to address the problem, selected mesas from the Elbe Sandstone Mountains were characterized by five morphometric parameters:

a) area of the mesa top surface;

b) Sinuosity Index of mesa rim (SI), defined as:

$$SI = P_{MR}/P_{mbr} \qquad (1)$$

where:

$P_{MR} - perimeter\ of\ mesa\ rim$

$P_{mbr} - perimeter\ of\ minimum\ bounding\ rectangle\ enclosing\ the\ mesa\ top\ surface$ (Fig. 3A)

c) the percentage of slopes > 45° within the mesa top surface (in plan) (Fig. 3B);

d) the percentage of slopes > 60° within the bounding escarpments (in plan) (Fig. 3C);

e) the percentage of surface where Morphometric Protection Index (MPI) > 0.6 within the mesa top surface. MPI is a SAGA-GIS algorithm which returns an equivalent to the positive openness [7]; herein, MPI values exceeding 0.6 indicate the development of deep clefts and thus, the degree of fragmentation of the mesa top surface (Fig. 3D).

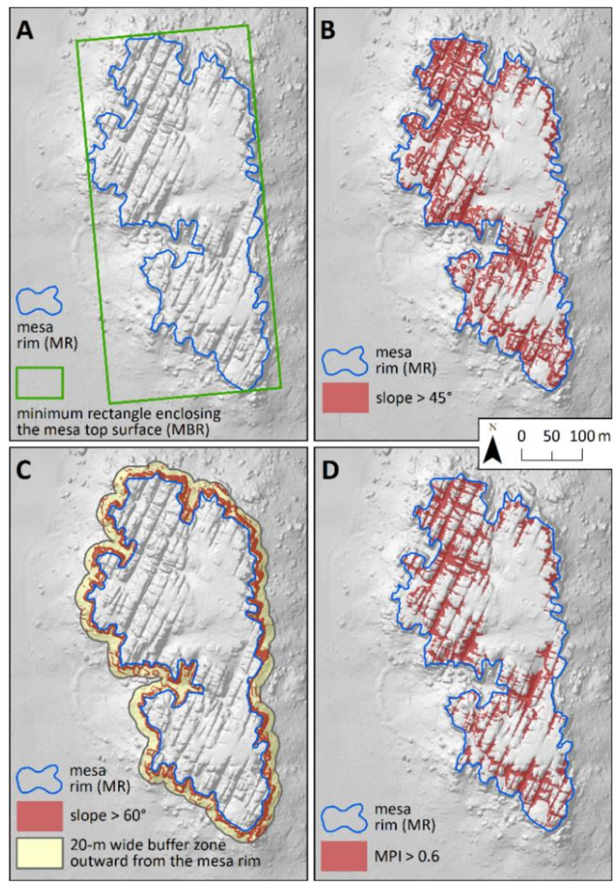

Figure 3. Selected morphometric parameters of a tabular hill on the example of Pfaffenstein (Elbe Sandstone Mts., Saxony, Germany).

Beside allowing for comparative analysis, in this particular area the variability of these parameters was explained in terms of directional evolution of residual hills, from a plateau through the mesa stage to a residual butte or boulder-covered hill [8].

C. *Morphological diversity of cleft-and-valley systems*

In regularly jointed sandstones grid-like patterns of passageways between bedrock elevations form, difficult to analyse using conventional measures pertinent to drainage networks. In addition, many passageways are dry and lack channels. Therefore, simple measures of valley form and pattern were supplemented by MPI analysis, found to provide valuable insights into the nature of concave landforms and their diversity (Fig. 4).

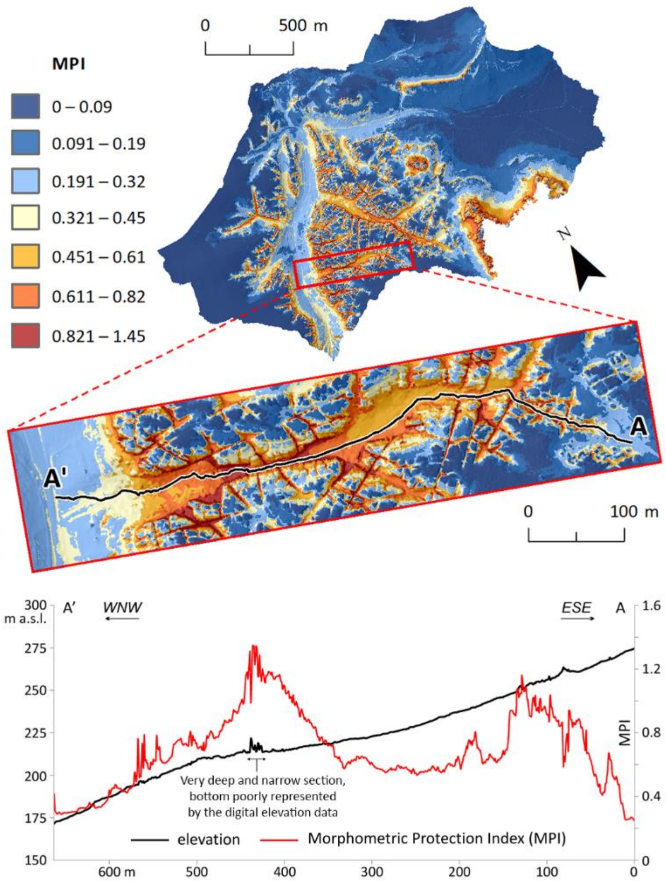

Figure 4. Geomorphic diversity of cleft-and-valley system on example of a small drainage basin located NE from Bad Schandau (Elbe Sandstone Mountains, Saxony, Germany). Longitudinal profile depicts morphological change along a selected canyon using Morphometric Protection Index, where high values coincide with narrow and deep sections.

Spatial diversity of valley forms includes unusual morphology of valley floors, with thick boulder fills. This topic was explored using Terrain Ruggedness Index (TRI) as a measure of variability [9]. The spatial extent of valley floor was, in this particular case, delimited automatically, basing on the criterion of maximum relative height above modelled stream network (2 m). Field work confirmed that high TRI values indicate particularly thick and irregular boulder fills, likely from long-term in situ disintegration of the sandstone rock mass.

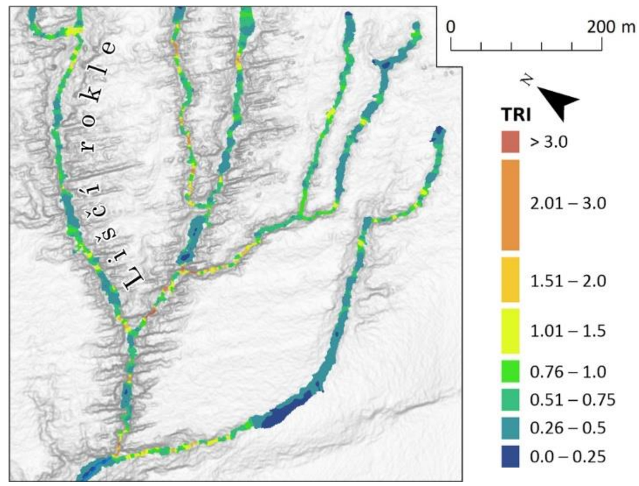

Figure 5. Spatial distribution of TRI values in the Liščí rokle cleft-and-valley system (Broumov Upland, Czechia).

D. *Drainage connectivity patterns*

Topographic and geological features of sandstone terrain may induce the occurrence of discontinuous surface drainage patterns and predominant subsurface drainage. We focused on spatial distribution of sinks as well as modelling of Topographic Wetness Index (TWI) [10] in contrasting geomorphic settings [11]:

$$TWI = \ln \frac{SCA}{\tan\beta} \qquad (2)$$

where:
SCA – *specific catchment area calculated using the Multiple Flow Direction method* [12]; β – *local slope in degrees*.

Further procedure of TWI analysis involved data reclassification and, thus, delimitation of zones of predicted surficial flow where TWI values were above mean value plus one or two standard deviations [13], leading to the identification of numerous disconnectivity sites within the system (Fig. 6).

III. Results and Pathways of Further Research

Up to now, the high-resolution morphometric approach has proved to be a significant aid in detailed studies of sandstone relief in terms of:

a) provision of quantitative information which, while not standalone, enables the reevaluation and enhancement of classic schemes of sandstone landform evolution [8, 14];

b) support to the study of distribution and genesis of thick boulder-fills within valley floors in the canyonlands, which are in some parts – regardless the season – impenetrable due to vegetation and terrain obstacles [15];

c) assessment of the variety of surficial and subsurface drainage patterns, depending on the topographic position within the specific landform types [11].

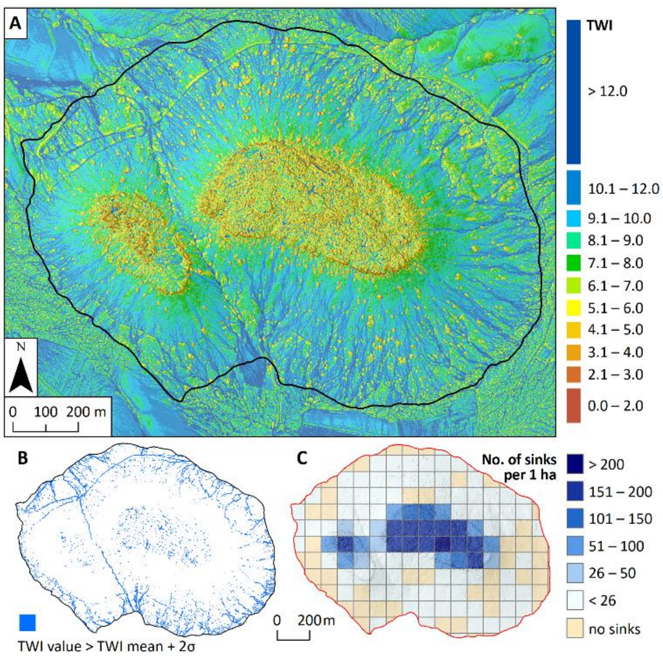

Figure 6. Disconnected surface drainage pattern of the Szczeliniec Wielki mesa (Stołowe Mts., Poland) revealed by TWI spatial distribution (A), zones of high (those above mean value plus two standard deviations) TWI values (B) and sink density map (C) [11].

The results, as well as the set of tools and indices, have to be seen as work in progress. Given the relatively broad spectrum of research undertaken so far or being planned, we aim to further develop the morphometric protocol, especially towards semi-automated classification of the different cleft/ valley/canyon types as well as to morphometrically-aided landform mapping. Still, notable obstacles in implementing any universal morphometric workflow basing on high-resolution LiDAR data reside in the quality of the data itself. These may vary quite significantly, depending on the study area location and, as such, may prevent any direct comparisons of morphometric features without detailed field prospection and validation. Nevertheless, ongoing improvement of the elevation data quality is indisputable and, hopefully, this will support synergic progress in sandstone geomorphometry which is very specific.

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