Identification and morphometric properties of landslides in the Bystrzyckie Mountains (Sudetes, SW Poland) based on data derived from airborne LiDAR

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Abstract—**Geomorphometric indices are used to characterize a group of recently recognized landslides in the Bystrzyckie Mts (SW Poland). LiDAR DEM was the primary data source. Geomorphometric approach helped to differentiate landslides in terms of form which likely reflects different mechanisms of movement. Topographic Wetness Index highlights drainage patterns within the landslides and emphasizes differences between slopes affected and not affected by landslides.**

I. Introduction

LiDAR-based Digital Elevation Models (DEMs) are powerful tools in landslide recognition, especially in vegetated areas with otherwise obscured local geomorphological features. They are also very useful in morphometric description of landslide terrains, which enables to express landform features quantitatively, helps landslide classification, and fosters comparative analysis. These high-resolution airborne spatial data have been recently made available in Poland, opening new perspectives for landform recognition and their quantitative characterization. In the Sudetes (SW Poland) screening of DEMs derived from LiDAR data has revealed, among others, an existence of a large number of relict landslides which so far have largely escaped attention during field mapping. In this contribution we apply selected geomorphometric indices for a group of newly recognized landslides in the block-faulted massif of the Bystrzyckie Mountains, Middle Sudetes.

II. Landslide occurrence and morphology

Three landslide affected terrains have been investigated in the Bystrzyckie Mountains (Fig. 1). Two of them (below Mt Jagodna and Mt Toczek) occur within the mountain fronts developed along fault zones that separate the western part of the Orlica – Śnieżnik Dome, which is built by crystalline rocks, from the Upper Nysa Kłodzka Graben filled with sedimentary rocks. The third landslide (at Mt Złota) is located within a complex fault-generated escarpment that bounds the Bystrzyckie Mountains

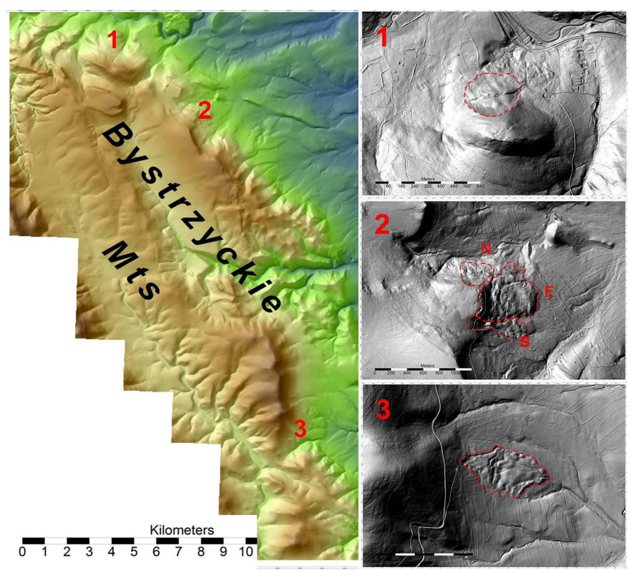

Figure 1. Location map of landslide terrains in the Bystrzyckie Mountains (1 – Złota, 2 – Toczek, 3 – Jagodna). Landslide extent indicated by dashed red lines.

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from the north. These landslides have been identified for the first time through detailed analysis of LiDAR-based digital elevation models and only one of them (Jagodna) has been briefly mentioned by Ranoszek [1], but whitout either boundary delimitation or more through analysis of landslide terrain.

The Jagodna landslide occurred within the lower section of the escarpment, genetically connected with the Kamieńczyk-Jagodna Fault and underlain by Cretaceous clastic deposits of Upper Nysa Kłodzka Graben in the zone of their flexural bending [1]. Kozdrój [2] mapped the position of the landslide on the Detailed Geologic Map of the Sudetes, sheet Poręba, indicating its partial fluvial dissection by streams fed from springs located in the fault zone. Landform inventory suggests that the slide was rather shallow and may have turned into mudflow in the distal part.

The second area with distinct geomorphic signatures of landslide activity is located on the northeastern edge of the Toczek plateau spur (753 m a.s.l.), whose eastern part is cut by the Długopole-Paszków Fault – a structure responsible for the origin of the Długopole Dolne-Polanica faulted escarpment. It likely consists of two separate landslides, with head scarps perpendicular to each other, that re-moulded morphology of the northern and eastern sides of the spur. In addition, surface morphology suggests the presence of a third landslide further to the south which travelled down a pre-existing valley. Upper Cretaceous jointed quartz sandstones are exposed in the main scarps of both landslides. Above the eastern head scarp a series of trenches occurs, indicating ongoing, probably deep-seated deformation of the rock mass. A LiDAR-based DEM reveals complex morphology of the slide area, with a range of second-order bulges, benches, linear depressions, and superimposed bodies in the toe area. Hence, the presence of a compound landslide may be inferred or alternatively, multiple phases of activity.

The third landslide occurs on the northern slopes of the Złota massif (635 m a.s.l.). Similarly to the previous case, jointed quartz sandstones, which build the upper part slope, have been moved downslope toward valley bottom of the Bystrzyca Dusznicka River. Landform pattern suggests rotational displacement of a single block.

III. Geomorphometry of landslide terrains

Morphometric characteristics of landslides have been measured directly from DEM or calculated from other parameters. They include: landslide area (A), maximum length (L), horizontal length (L_h), maximum width (W), L/W ratio, maximum height above sea level (H_{max}), minimum height above sea level (H_{min}), vertical range ($H = H_{max} - H_{min}$), slope (S), aspect (A), travel angle (α), main scarp height (h), main scarp slope (s), Topographic Wetness Index range ($TWI_{max} – TWI_{min}$) (Table I).

The Toczek landslide complex is characterized by the largest area among the landslides presented here. It reaches approximately 0.65 km^2 in total, but can be split into three separate landslides one next to another ("northern", "eastern" and "southern"), referred to as Toczek N, Toczek E and Toczek S from now on. Toczek E has the largest extent, about 0.43 km^2, which is the value far exceeding the area of other landslides, not only from the other parts of the Toczek complex (Toczek N – 0.10 km^2) and (Toczek S – 0.12 km^2), but also from the other parts of the Bystrzyckie Mountains – Jagodna (0.28 km^2) and Złota (0.04 km^2).

The landslides vary in terms of the maximum length and variation in this parameter appears to reflect the type of surface displacement. The longest feature (Jagodna, 917 m) represents a shallow translational slide and is more than five times longer than the shortest one (Złota, 178 m) recognized as a rotational slide. The L/W ratio further differentiates the landslides into three categories, likely corresponding with the type of movement. Jagodna and Toczek S have this index above 1.5 and both show features compatible with slides turning into flows. Values close to 1 characterize compound landslides at Toczek (N and E), while the rotational Złota slide has the L/W ratio close to 0.5.

Vertical range, defined as the difference between the most and least elevated spot within the landslide, varies from 80 m (Złota) to 182 m (Toczek E) and influences the travel angle value (α). This parameter is based on the landslide vertical range (H) and horizontal length (L_h) ($\alpha = \arctan(H/L_h)$) and can be used as an indicator of landslide mobility and the volume of displaced material [3, 4]. Because decreasing value of the travel angle is connected with an increasing volume of mass movement, this parameter suggests that the largest volume of displaced material typifies the Jagodna landslide ($\alpha = 8.8°$), whereas the smallest volume would have been involved in the Złota rotational landslide ($\alpha = 26.7°$). Assuming the average thickness of the Jagodna landslide body for 5 m, as suggested by landslide body cross-sections, the total volume displaced would be c. 1.4×10^6 m^3 of material. The depositional part of the Złota landslide (3/4 of the total area) has an average thickness of 10 m, hence the total volume involved is c. 0.37×10^6 m^3.

The height of the head scarp of the landslides computed from DEMs ranges from 13 m (Jagodna) to 32 m (Toczek E), whereas their inclination are from 30° (Jagodna) to 39° (Złota). It was difficult to delineate the head scarp of the Toczek S landslide and the very indistinct slope steepening in the valley head suggests a shallow translational movement in the first stage of activity.

Landslides of this sort, with obscured source areas but evident depositional parts are not uncommon in the Sudetes [5,6]. The varied morphology of the head scarp of the Jagodna landslide contrasts with the other ones, which are characterized by scarps with rather low sinuosity.

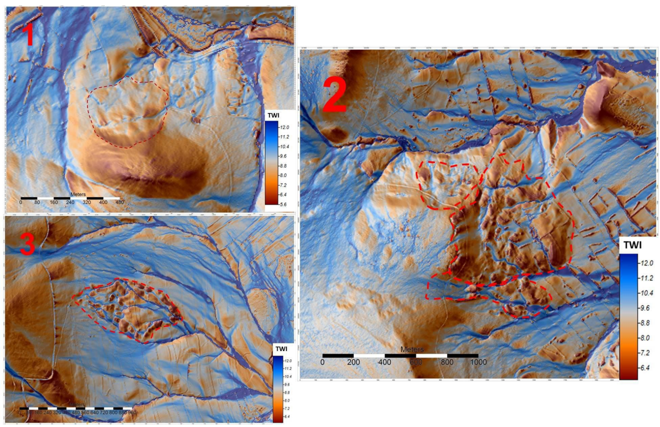

Figure 2. Map of Topographic Wetness Index of investigated landslide terrains derived using SAGA GIS software (1 – Złota, 2 – Toczek, 3 – Jagodna).

The presence of landslides is highlighted by the TWI (Topographic Wetness Index) (Fig. 2). Slopes affected by landslides are characterized by contrasting TWI values because of the varied morphology of the respective landslide bodies (low values assigned to the bulges and high to linear depressions). This is most evident in the case of Jagodna and Toczek E landslides. The differences between the maximum and minimum TWI values (dimensionless) assigned to grids within the perimeter of these landslides attain 20.0 and 19.3, respectively. TWI values on the adjacent parts of the slopes, whose morphology has not been affected by landsliding, are generally lower and in each case less diverse in space.

There are some similarities in theoretical water flow pattern between landslides of similar type. TWI images of simple (Złota) and compound (Toczek N and Toczek E) rotational landslides indicate linear outflow parallel to the main scarps. On the surface of the Toczek E landslide three zones of higher TWI values correspond to the linear depressions between rotated blocks, whilst there is only one such zone within the Złota landslide. In the other two landslides (Jagodna and Toczek S) preferential surface drainage is straight downslope, along the margins of the failed mass or within it.

IV. Final remarks

Landslide geomorphometry presented here helped to characterize surface morphology in more objectively way and proved a good tool to provisionally distinguish landslides of different types. However, this is a pilot study which will be extended in the future. Further research, apart from field work, will be aimed at more detailed quantitative description of particular landforms within the landslides and exploration of differences between slopes affected and not affected by large-scale mass movements. Comparative analysis with landslide populations from elsewhere in the Sudetes [5] will also be attempted.

TABLE I. Morphometric characteristics of landslides in the Bystrzyckie Mountains.

Morphometric characteristics	Landslide				
	Złota	***Toczek N***	***Toczek E***	***Toczek S***	***Jagodna***
area (A) [km^2]	0.04	0.10	0.43	0.12	0.28
max. length (L) [m]	178	334	752	758	917
horizontal length (L_h) [m]	159	313	730	744	906
max. width (W) [m]	308	418	755	266	473
L/W ratio	0.58	0.80	1.00	2.85	1.94
max. height a.s.l. (H_{max}) [m]	593	686	714	716	630
min. height a.s.l. (H_{min}) [m]	513	571	532	570	490
vertical range (H) [m]	80	115	182	146	140
slope (S) [°]	23.4	19.2	13.9	13.4	9.9
travel angle (α) [°]	26.7	20.2	14.0	11.1	8.8
main scarp height (h) [m]	28	32	23	*	13
main scarp slope (s) [°]	39	36	35	*	30
$TWI_{max} – TWI_{min}$	17.7	18.3	19.3	18.3	20.0

* head scarp difficult to delineate

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